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Time Series Analysis of Energy Production and Associated Landscape Fragmentation in the Eagle Ford Shale Play

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Abstract Spatio-temporal trends in infrastructure footprints, energy production, and landscape alteration were assessed for the Eagle Ford Shale of Texas. The period of analysis was over four 2-year periods (2006–2014). Analyses used high-resolution imagery, as well as pipeline data to map EF infrastructure. Landscape conditions from 2006 were used as baseline. Results indicate that infrastructure footprints varied from 94.5 km^2 in 2008 to 225.0 km^2 in 2014. By 2014, decreased land-use intensities (ratio of land alteration to energy production) were noted play-wide. Core-area alteration by period was highest (3331.6 km^2) in 2008 at the onset of play development, and increased from 582.3 to 3913.9 km^2 by 2014, though substantial revegetation of localized core areas was observed throughout the study (i.e., alteration improved in some areas and worsened in others). Land-use intensity in the eastern portion of the play was consistently lower than that in the western portion, while core alteration remained relatively constant east to west. Land alteration from pipeline construction was ~65 km^2 for all time periods, except in 2010 when alteration was recorded at 47 km^2. Percent of total alteration from well-pad construction increased from 27.3% in 2008 to 71.5% in 2014. The average number of wells per pad across all 27 counties increased from 1.15 to 1.7. This study presents a framework for mapping landscape alteration from oil and gas infrastructure development. However, the framework could be applied to other energy development programs, such as wind or solar fields, or any other regional infrastructure development program.

Graphical abstract Landscape alteration caused by hydrocarbon pipeline installation in Val Verde County, Texas

Keywords Eagle Ford · Infrastructure · Landscape impacts · Ecosystems · Fragmentation

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Introduction

The growing world population will require an increase in energy production to maintain the quality of life expected in industrialized societies. Currently, most scalable energy sources including oil and gas (O&G) extraction (Pitman et al. 2005; Sawyer et al. 2006; Copeland et al. 2009; Jones et al. 2015; and Pierre et al. 2015), wind energy (McDonald et al. 2009; Diffendorfer and Compton 2014), and solar power (Tsoutsos et al. 2005; Lovich and Ennen 2011) are accompanied by some type of land impact and habitat loss. Researchers have identified land-use change as a cause of increased stress on ecosystem health and biodiversity through habitat loss and landscape fragmentation (Noss and Cooperrider 1994; McGarigal and Cushman 2002; Pitman et al. 2005; Sawyer et al. 2006; Sorensen et al. 2008), and as one of the most important factors affecting the biodiversity of Earth's terrestrial ecosystems (e.g., Wilson 1999).

The International Energy Agency (2016) reports that investments in oil and gas will continue throughout the first half of the 21st century, even as renewable energy sources increase. It is widely expected that onshore, unconventional (shale-based) oil and gas will remain a dominant source of fossil energy. The rapid increase in exploration and production of unconventional hydrocarbon reserves within the last decade has already led to landscape and ecosystem change. For example, Allred et al. (2015) reported that the amount of land altered in central North America is equivalent to three times the size of Yellowstone National Park (or just smaller than the area of Belgium); these changes have decreased net primary production through the reduction of vegetative resources, and degraded habitat quality and ecosystem services. While O&G exploration recently declined because of depressed energy prices, activity will eventually rebound with increasing prices; understanding the impacts to land resources now can guide mitigation procedures in the future. Our knowledge of land impacts from the recent development of shale deposits is growing (Entrekin et al. 2011; Drohan et al. 2012; Allred et al. 2015; Pierre et al. 2015; Slonecker and Milheim 2015; Milt et al. 2016a). However, these works focus primarily on the Marcellus Shale (Pennsylvania and West Virginia) (Entrekin et al. 2011; Drohan et al. 2012; Milt et al. 2016a); the northern Great Plains (Allred et al. 2015); and in the grasslands of Canada (Great Sand Hills Scientific Advisory Committee 2007; Antoniuk et al. 2009; Nasen et al. 2011) where cumulative impacts from O&G exploration and related activities were assessed, in some cases over a 50-year time frame.

Researchers considering land impacts in the Marcellus Shale have demonstrated the importance of restoration practices in reducing soil and vegetation recovery times (Fink and Drohan 2015). Considering the typical productive lifetime of unconventional wells, Fink and Drohan (2015) emphasize the importance of implementing interim recovery efforts on inactive portions of drilling infrastructure (i.e., staging areas on pads) while wells continue to produce. Researchers in China at sites with a humid subtropical climate have reported that full vegetative recovery takes anywhere from 3 to 5 years, while return to predevelopment vegetation-species diversity requires at least 7 years (Feng et al. 2015). Milt et al. (2016b) have shown substantial reductions in environmental impacts from infrastructure by using conservation-oriented planning at relatively low costs. One such tool, known as Marxan (Ball et al. 2009), has recently been used for regional planning in the context of energy development (Antoniuk et al. 2009; Thorne et al. 2009). Implementing such practices, especially within those potential habitats of species considered for listing under the Endangered Species Act, can reduce long-term economic impacts (Parke 2012) and avoid after-the-fact mitigation efforts by limiting adverse impacts to species.

Given the focus of research on landscape impacts of unconventional O&G on the Marcellus Shale of Pennsylvania—and the different climates of Texas landscape—there is a need to study Texas specifically to increase our understanding of potential impacts from rapid expansion of energy development. The body of work examining the water footprint of hydrocarbon extraction from shale in Texas continues to evolve (Nicot and Scanlon 2012; Scanlon et al. 2014a; Scanlon et al. 2014b). However, the surface footprint of O&G infrastructure in Texas—where climates and landscapes vary dramatically from east to west and from north to south—is less well-studied. One important area in Texas where exploration is robust is the Eagle Ford Shale play, which continues to produce over 1 million barrels of oil per day (US EIA 2017). The Eagle Ford play region is one of the largest oil producers in the United States. It is the southernmost play in the country and it straddles fragile ecosystems ranging from the semi-arid Southern Texas Plains to the more humid East Central Texas Plains. Understanding the impacts in this region will fill an existing gap in landscape-disturbance mapping that has focused primarily on the relatively humid northeast portion and the arid western portion of the United States.

Researchers examining the water footprint of shale hydrocarbon development have compared water-use intensity to energy intensity (Scanlon et al. 2014a). Here, parallel to this work, we introduce the metric of "land-use intensity," defined as land alteration (km^2) per unit of energy (mmBOE = millions of barrels-of-oil equivalent). Low land-use intensity can be interpreted as relatively small areas of landscape alteration per unit of energy produced. Best management practices leading to low land-use intensity may include using multi-well pads (i.e., more than one well), or locating new pipelines and roads along existing right of ways.

To date, only La Salle County in the semi-arid Eagle Ford Shale (EF) play of Texas (Pierre et al. 2015) has been examined. That study showed that approximately 114 km^2 of land (3% of the county land area) had been altered from

2001 to 2012 by infrastructure development, but that ~550 km^2 of the large core area (contiguous vegetated patches > 2 km^2) were lost. Pierre et al. (2015) focused on core areas as potential habitats for terrestrial species. Approximately 87% of land disturbance that contributed to core-area alteration was from pipeline installation; the remaining alteration was from well-pad construction. (We did not consider new roadways constructed from O&G development because of the inability to determine if roadways were a result of O&G development or simply roadways used to support ranches/farms or previous surveys.) Pipeline construction dominated landscape alteration because linear features of pipeline more effectively bisect land areas and species habitats, unlike well pads, which perforate core areas.

The research by Pierre et al. (2015) was also limited to a single county and a single time period. A study of potential landscape impacts in all 27 counties of the play is needed, given differences across the play in hydrocarbon production, water use, and price sensitivities that force operators to explore for hydrocarbons with greatest value (i.e., oil compared to gas) (Scanlon et al. 2014a). Additionally, assessing landscape impacts across different time periods allows for comparative analyses as installation techniques improve, or as new wells are added to existing infrastructure (e.g., larger emphasis on multi-well pads). Therefore, the goals of this research are to answer the following three questions:

1. How is the areal footprint of O&G infrastructure changing with time or activity, and has technology reduced the relative degree of land alteration?
2. What spatio-temporal trends exist in landscape alteration across the 27-county extent of the EF play?
3. Given the current O&G activity, to what extent could potential species habitats be affected?

These questions are addressed by building a database that allows us to assess, in both time and space, land impacts from unconventional energy infrastructure construction across the EF play.

Materials and Methods

Study Area

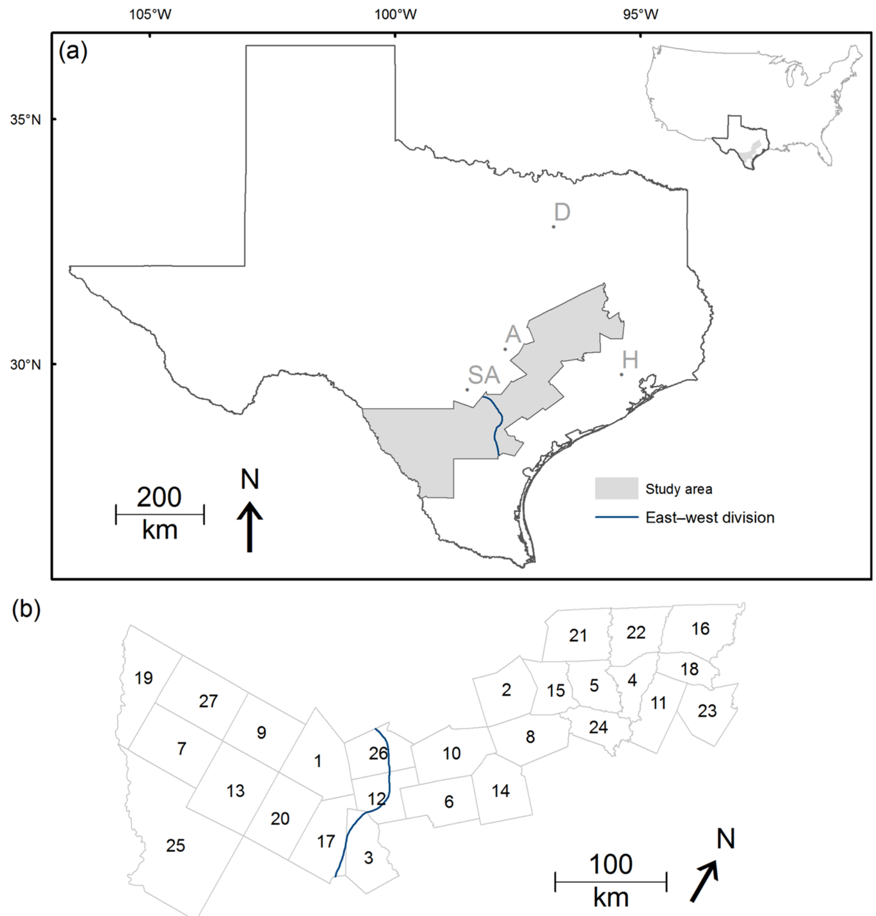
The study area focuses on 27 counties (73,146 km^2) considered by the Railroad Commission of Texas (RRC) in June of 2016 to encompass the EF Shale play (RRC 2016; Fig. 1). The number of counties in the play has varied somewhat with time and continues to vary as the play is developed. The 27-county study area also includes the Eaglebine Shale play, which is a combination of the Woodbine and Eagle Ford Groups (Hentz et al. 2014). The study area also hosts conventional O&G production in the Austin Chalk (Martin et al. 2011) and other formations (IHS 2016). Five ecoregions are represented: the Southern Texas Plains (43%; 31,328 km^2), East Central Texas Plains (40%; 29,440 km^2), Texas Blackland Prairies (9%; 6905 km^2), South Central Plains (3%; 2191 km^2), and the Western Gulf Coastal Plain (1%; 1158 km^2) (Fig. S1, Omernik and Griffith 2014; Texas Parks and Wildlife Department 2012a–e).

Precipitation across the study area ranges from ~56 cm/yr in the semi-arid west to ~110 cm/yr in the more humid east (PRISM Climate Group at Oregon State University 2012). The 71 cm/yr boundary of the precipitation gradient was used to divide the study area into east and west portions, established because of differences in vegetation and climate (Fig. 1). The eastern portion of the study area is dominated by grassland (~51%), cold-deciduous forest and woodland (CD forest, 26%), and cold-deciduous shrubland (CD shrub, 6%). The remaining 17% of the eastern area is a mix of woodlands, row crops, broadleaf evergreen forests (BLEG), and urban and water areas (Elliot et al. 2009a–2014a). The western portion of the study area is dominated by CD shrub (52%), grassland (24%), and CD forest (11%). The remaining 13% of the western area is a mix of evergreen shrubland, row crops, BLEG, and water areas (Elliot et al. 2009a–2014a).

Time Series of Oil and Gas Well Permits

Information was retrieved (IHS 2016) on all wells (e.g., production, injection, horizontal, vertical, abandoned, and wildcat) permitted in the study area from 3 January 2006 to 24 October 2014. These dates were used because, prior to 2006, almost no horizontal wells were drilled and stimulated; thus, any alteration prior to 2006 was considered part of the baseline conditions. Additionally, the cut-off date corresponds with acquisition data for aerial imagery used to map landscape alteration. All wells are accompanied by the American Petroleum Institute (API) number to which well-specified data (e.g., permit date, target formation, and volume oil/gas recovered) are linked.

To examine impacts on the landscape, we did not consider wells coded as recompleted, deepened, or re-drilled (RDR) as unique, but, rather, as a reworking of an existing well on a pre-existing pad. Therefore, RDR wells were not included in calculations of impact on the landscape (i.e., when calculating the number of wells per pad). However, RDR wells *were* used to calculate BOE when the API number is associated with a "parent" well permitted within our time frame. The reason for this apparent inconsistency of rejecting RDR wells for land-disturbance calculations but including them for energy production is that energy production is reported by API number rather than by individual borings. Thus, the dataset combined all energy production into a single BOE value with the permit date of the parent well established as the starting point for that well. Any RDR



Cross-reference map for counties

1	Atascosa	6	DeWitt	11	Grimes	16	Leon	21	Milam	26	Wilson
2	Bastrop	7	Dimmit	12	Karnes	17	Live Oak	22	Robertson	27	Zavala
3	Bee	8	Fayette	13	La Salle	18	Madison	23	Walker		
4	Brazos	9	Frio	14	Lavaca	19	Maverick	24	Washington		
5	Burleson	10	Gonzales	15	Lee	20	McMullen	25	Webb		

Fig. 1 **a** Study area (*shaded gray*). East–west division (*blue line*) and major cities: San Antonio (SA), Austin (A), Houston (H), and Dallas (D). **b** Cross-reference map for counties

wells with parent wells permitted outside of our time frame were removed from the database.

Mapping of Landscape Alteration and Fragmentation

Our workflow identified landscape alteration associated with O&G activity and excluded land alteration caused by other anthropogenic factors (e.g., urbanization, agricultural activities). Landscape alteration was mapped using 1 m resolution aerial images from the National Agriculture Imagery Program (NAIP/USDA-NAIP 2008, 2010, 2012, and 2014). For each period, 100 landscape classes were created using ISO unsupervised image classification in ArcGIS (version 10.2) (Tables S1, S2, S3, and S4). Resultant classes were chosen following the methods used by Pierre et al. (2015), resampled to 10-m resolution, converted into polygon form, and filtered to remove overlaps with roadways buffered by median and right-of-way (ROW) widths (TXDOT 2015), roadway lines (TXDOT 2016), and urban areas (Texas Natural Resources Information System 2016). The resulting “bare-earth” polygons were used to identify and quantify landscape alteration likely associated with well-pad and pipeline construction.

To temporally correlate landscape alteration caused by well-pad development, the wells were grouped using the most recent NAIP acquisition date corresponding to each time period (cutoff dates in parentheses): 2006–2008 (13 Jan 2009), 2008–2010 (23 Aug 2010), 2010–2012 (7 Aug 2012), and 2012–2014 (24 Oct 2014). These periods are referred to as 2008, 2010, 2012, and 2014, respectively. Bare-earth polygons within 90 m of one or more wells were converted to a 10-m raster form for each period.

Custom software developed in C++ was used to further refine landscape-alteration rasters using data on boreholes, wells (individual laterals and verticals), and pipelines (Fig. S2 provides the workflow). Note that a “borehole” is herein defined as a surface expression of a well or lateral, and a "well" is defined as either a single, conventionally drilled vertical well or a horizontally drilled lateral. Thus, a tally of wells per pad includes the number of vertical wells and horizontal laterals, while boreholes represent the surface expression of the vertical hole required for either a conventional (vertical) or unconventional (horizontal) well.

Using well locations associated with the API number, well pads were distinguished from bare soil or other non-vegetated land and assigned the number of boreholes associated with each mapped landscape-alteration cluster. Wells without pads were either repositioned to an altered-landscape cluster or removed from the dataset. When wells occurred in alteration clusters larger than 4.5 ha (more 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, only cells in these large alteration clusters within a 30-m radius of a well were classified as alteration from O&G operations. Situations with two or more wells within 100 m of each other were classified as multiple wells on a single pad.

To identify land impact from pipelines, we rasterized bare-earth polygons and reclassified 10-m pixels that overlapped with pipelines (RRC 2014). Alteration was assessed as the percentage of each square kilometer cell overlapped by cells containing well pads or pipelines (Fig. S2). This workflow was repeated for each of the four-time steps.

Changes in the vegetated landscape structure were assessed by analyzing the amount of core areas (contiguous vegetative patches) degraded during each period. Data from the Ecological Mapping System of Texas (EMS) (Elliot et al. 2009a–2014a) were used as the baseline for analyses, which considered all vegetated landscapes and water bodies to be suitable habitat for most species. Urban and developed areas were considered unsuitable habitat. GUIDOS Toolbox (Soille and Vogt 2009) and morphological spatial-pattern analysis (MSPA) (Vogt et al. 2007) were used to establish structural landscape classes for the baseline (circa 2006) and for each subsequent period. To be consistent with others (Howell et al. 2006; Johnson 2010; and Drohan et al. 2012), a 100-m edge distance and an eight-cell connectivity rule (Schadt et al. 2002 and Adriaensen et al. 2003) were used as input for all MSPA analyses.

Statistical Analyses of Core-Area Alteration

Similar to Pierre et al. (2015), the Gi* statistic (Getis and Ord 1992) was used to map statistical trends of altered and unaltered core-area features at a 1-km^2 scale across the study area for each period. The percent of core area alteration was determined within each 1-km^2 cell for the Gi* statistic, and a false discovery-rate correction, and distance band of 3193.2 m (average distance to 30 nearest neighbors) were used. All statistical tests are considered significant at $p < 0.10$ with a z-score < -1.65 or > 1.65.

Land-Use Intensity

To place land alteration into the context of energy production, a main point of this manuscript, we used BOE equivalent—a standardized metric used to report production of gas, condensate, and oil—as a normalizing factor. For each time period, monthly BOE data were linked to specific wells, binned into 1-km^2 grids and aggregated at a county level for mapping and data analysis. BOE was calculated using the following equation (Scanlon et al. 2014a):

$$\mathrm{BOE} = (\mathrm{barrels\_oil}) + (\mathrm{barrels\_condensate} \times 0.85) + \left(\frac{\mathrm{mcf\_gas}}{5.8}\right). \quad (1)$$

For wells within the 1-km^2 grid, it was relatively simple to determine corresponding land alteration and to calculate land-use intensity as a ratio of land alteration-to-mmBOE (BOE $\times 10^6$) produced during each period.

Potential Impacts of Landscape Alteration on Habitats

Data on Federal- and State-listed endangered species, as well as any known occurrences (known hereafter as "element occurrences" [EOs]) of rare, threatened, or endangered species, were obtained within the 27-county study area (Texas Parks and Wildlife Department 2016). Alteration of different ecological land-cover types was determined by comparing O&G infrastructure for each period to the EMS data. To ease data management and reporting, the 189 different land-cover types found in our study area were simplified into 16 different modeled land-cover types (Table S5; Elliot et al. 2009b–2014b). Alteration land-cover types from O&G activities were aggregated by Omernik ecoregions Level III (Omernik and Griffith 2014) to report potential habitat alterations by ecoregion. Results from the Gi* statistic were aggregated and analyzed at the county and ecoregion levels to 1-km^2 cells of highly altered and unaltered core areas.

Results

Time Series of Oil and Gas Well Permits

Within the 27-county footprint, the RRC permitted 28,331 wells during the time frame of this study, with 76% of these wells permitted during 2011–2014 (Table S6). The largest

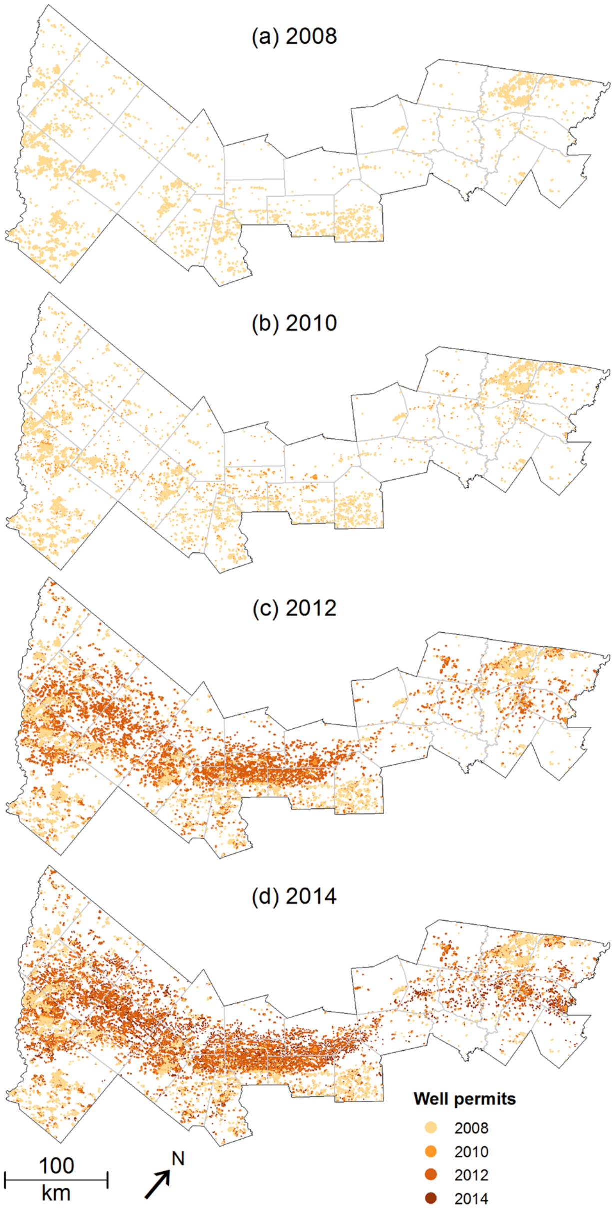


Fig. 2 Eagle Ford well permits over time. **a** 2008, **b** 2010, **c** 2012, and **d** 2014

number of wells were permitted in the 2014 period (13,358 wells), or nearly 50% of all wells in the study area (Table S6 and Fig. 2). Webb and La Salle counties consistently ranked within the top six counties for the highest number of new permits issued during each 2-year period. Bastrop, Grimes, Lee, and Walker counties consistently ranked among the bottom third of counties with the lowest number of new permits. Using the 2006–2008 period as baseline, and overall across the play, issued permits varied by −51%, +267%, and +64% for the 2-year periods of 2010, 2012, and 2014, respectively, reflecting changes in the overall activity in the play. The highest number of new permits during the 2008 and 2010 periods were issued in Webb County; afterward, the most new permits during the 2012 and 2014 periods were issued in Dimmit County. The rate in approved permits per time period increased in 21 of 27 counties; of the six counties where permit approval decreased with time, five were in the eastern portion of the play, again illustrating the focus on the western region. New permit approvals increased nearly four-fold between the 2010 and 2012 periods. It is important to note that well permits only foretell future land activity; operators can delay drilling and field activity for several years after signing lease agreements with land owners and receiving the drilling permit from the Railroad Commission of Texas, the state regulator.

Landscape Alteration and Fragmentation Over Time

Results show that more well pads were constructed in Webb County than any other county in the play (2384 total; Fig. 3), resulting in nearly 22 km^2 of alteration or 13.6% of alteration across all 27 counties. At the end of 2008, 25.8 km^2 of the study area was already occupied by well pads. In each successive 2-year period from 2010 through 2014, new well-pad construction increased by a rate of 53, 88, and 53%, respectively, with an increase in alteration of 49, 161, and 61%, respectively (Table S7 and S8).The large variance in construction rate and alteration rate in 2012 is due to a combination of factors. First, we noticed that average pad

Fig. 3 Number of well pads over time.

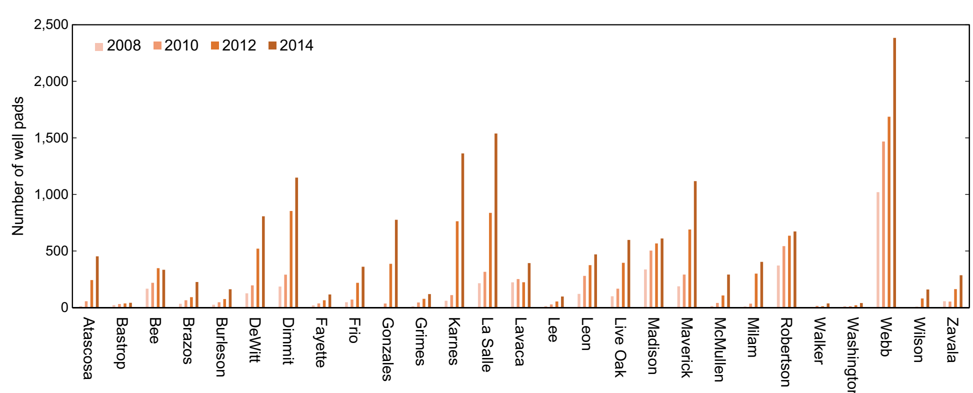
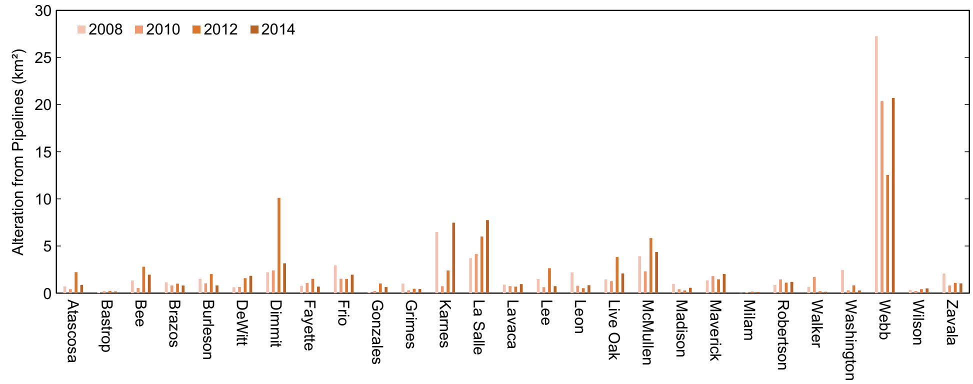


Fig. 4 Alteration (km^2) from pipelines for each period.



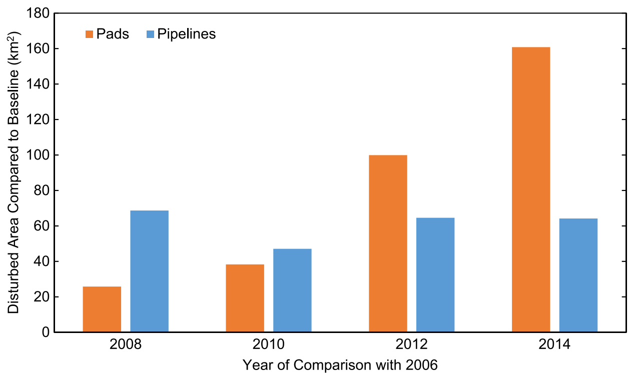


Fig. 5 Causes of landscape alteration with time across the entire play

sizes became larger and remained larger starting in the 2012 period. Average pad sizes were 0.76, 0.69, 1.34, and 1.18 ha in 2008, 2010, 2012, and 2014, respectively. Secondly, as we progressed through the time periods of the study some older pads became smaller as revegetation occurred. However, considering these observations, results show that land altered from well-pad development increased across the play at a nearly consistent rate of ~23 km^2 per year, when estimated using linear regression ($r^2 = 0.94$). The highest percentages of land altered from well-pad construction (Fig. S3) vary by period, but generally shifted from Robertson County at the beginning of the study to McMullen and Karnes Counties as the study progressed toward 2014. The five counties with the highest rate of alteration, as a percentage of county area, were all located in the western portion of the play. In some cases, such as McMullen and Karnes Counties, the percentage of county area altered increased four-fold and ten-fold, respectively, during the 2012 period. The rates of alteration in McMullen and Karnes Counties (determined as the change in the percent of county land altered by O&G activity with time) were found to be statistically significant using linear regression ($p < 0.05$ and $p < 0.10$, respectively).

Landscape alteration from pipeline construction was more dynamic than well-pad construction when viewed from county to county and between periods (Fig. 4, Table S9). Between 2008 and 2014, the cumulative land area altered by pipeline installation ranged between 47.1 km^2 in 2010 to 68.7 km^2 in 2008. Subsequent to 2010, land alteration remained just below 65 km^2 (Fig. 5). Results show a number of other interesting trends. First, altered land areas decreased in 17 of 27 counties between 2008 and 2010, as determined from NAIP imagery. A decrease in altered land area indicates that pipeline construction activity after 2008 either decreased or site revegetation increased (either through natural recruitment or active revegetation efforts). From 2010 to 2012, total altered area from pipeline infrastructure increased by 37.2%, with a decrease in alteration observed in only eight counties. No discernible geographic trend was noted in pipeline construction during the 2014 period when total land-area alteration decreased in 16 counties. Second, the geographic distribution of disturbance from pipeline installation mirrored the general trend of well-pad construction, with a higher proportion of alteration occurring in the northern or western portion of the play, further into the oil portion of the production zone. Third, pipeline construction in the 2008 period accounted for 73% of all alteration across the play (68.7 km^2 of a total 94.5 km^2) (Fig. 5). However, this percentage decreased for each successive 2-year period, eventually constituting only 28.5% of all land alteration in 2014, as the land alteration from pads increased and land alteration from pipelines decreased or remained constant. Finally, a spatial comparison of landscape alteration revealed that land alteration in the western portion (158 km^2), compared to the eastern portion (68 km^2), increased at a higher rate, especially in the 2014 period, when more than twice the land alteration was recorded (Fig. S4).

Results show that core-area alteration (Fig. 6) increased for each time period, except in 2010, but the sources of disturbance changed with time. For example, pipeline construction represented 62% of total core-area alteration in 2008 (when pipelines overlapped 58.8 km^2 of core area and well pads overlapped 20.7 km^2; Fig. S5). During subsequent time periods, the percentage of total core-area alteration from new pipeline construction (not including re-entry into a previously impacted area) ranged between 5.0 and 10.3% between 2010 and 2014, a relatively moderate impact when

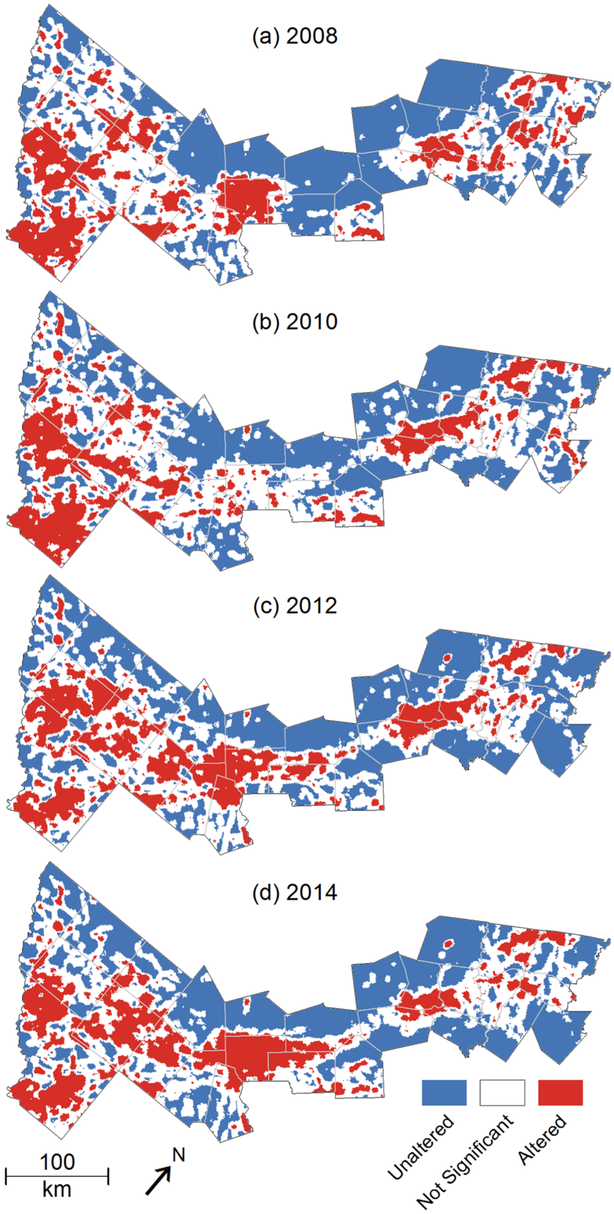


Fig. 6 Results of Gi* statistics (Getis and Ord 1992) for core-area alteration. Intensity of percent core-area loss analyzed at 1-km^2 scale. **a** 2008, **b** 2010, **c** 2012, and **d** 2014

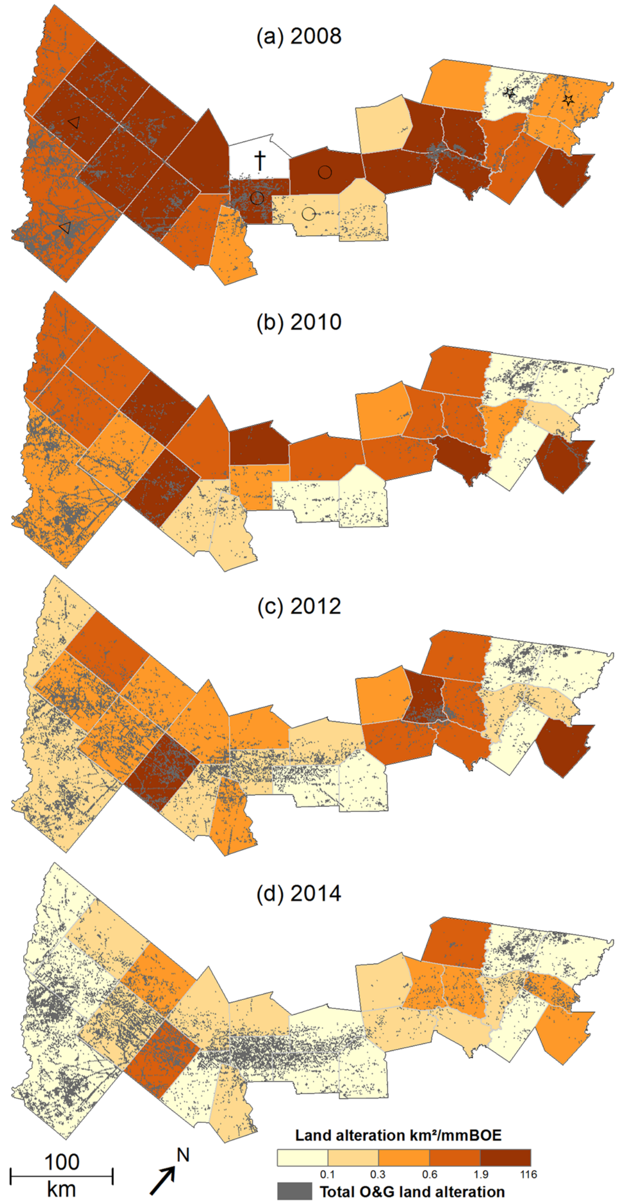


Fig. 7 Total land alteration per unit of energy produced. **a** 2008, **b** 2010, **c** 2012, and **d** 2014. † indicates an undefined number. Wilson County did not have any energy production from wells in our dataset for 2008 period. Note that color scale is not linear. Data sorted by quantiles. Dimmit and Webb counties are marked with a *triangle*, Robertson and Leon counties are marked with a *star*, and Karnes, Gonzales, and Dewitt counties are marked with a *circle*

considering the larger core-area alteration from well-pad construction, especially at the county level (Fig. S6). It is apparent that pipeline networks were being installed throughout the play in 2008, mostly in the northeastern and northwestern regions, with relatively little impact of pad construction on core areas. With time, the majority of core-area impact was caused by construction of new well pads (Figs. S5 and S6). Since 2008, 490 km^2 of land in the western portion and 417 km^2 of land in the eastern portion were no longer recorded as disturbed, indicating revegetation (Fig. S7).

Land-Use Intensity

Although a general increase in the percent of county area altered was observed in 2014 (as observed in most other counties during most periods, Fig. S8), results indicate a substantial decrease in land-use intensity (i.e., km^2 of landscape altered/mmBOE), which could be roughly interpreted as a trade-off between land productivity from energy production and land alteration. For example, note the relatively low land-use intensity in the northeastern portion of the play from 2008 to 2012 (Fig. 7), especially in Robertson and Leon Counties. As operators moved toward the central (Karnes, Gonzales, and DeWitt Counties) and western (Dimmit and Webb Counties) portions of the play in the 2014 period, land-use intensities were eventually equal to or less than those of the northeastern counties (Fig. 7). In some cases (e.g., Dimmit County), land-use intensity decreased over every 2-year period from 2008 to 2014 (2.5, 0.8, 0.4, 0.1 km^2/mmBOE, respectively). Considering the last time period, land alteration decreased from 21.6 to 15.0 km^2 between 2012 and 2014, whereas energy production increased from 49.2 to 239.2 mmBOE during the same period. Land-use intensity for other counties in the western portion of the play followed similar trends. The land-use intensity in the eastern portion was approximately 6, 5, 3, and 2 times less in 2008, 2010, 2012, and 2014, respectively, than in the western portion (Fig. S9). These results show a combination of increased productivity and decreased land alteration—both a function of innovation in drilling technology—as well as (likely) land revegetation.

Potential Impacts of Landscape Alteration to Habitats

At least seven species of concern in the Texas Natural Diversity Database (Texas Parks and Wildlife Department 2016) were found in all 27 counties of the play. The three counties with the most EOs by county in descending order are Walker, Brazos, and Webb (113, 87, and 80 species, respectively). Other counties with relatively high EOs include Fayette and Bastrop (54 and 46, respectively), surrounding significant stream segments along the Colorado River, and Leon (66 species), at the far northeast of the study area (Fig. 8).

Results indicate that nearly two-thirds of grasslands in the eastern portion (originally composed of ~51% grasslands) were altered during the study period, while 54% of CD shrub in the western portion (originally composed of ~52% CD shrub) were altered (an increase from 41% in 4 years) (Figs. S10, S11, and S12). When aggregated by area of each of the five ecoregions, alteration was consistently highest in the Southern Texas Plains throughout the study, and increased from 61.8 to 130.7 km^2 during the 8-year study period (Fig. 9). The dominant land-cover types altered in the Southern Texas Plains were EG shrub, ranging from 1.2% (2.2 km^2) in 2008 to 4.0% in 2014 (7.6 km^2), and CD shrub, ranging from 1.3% (32.4 km^2) in 2008 to 3.1% in 2014 (77.3 km^2) (Fig. S13).

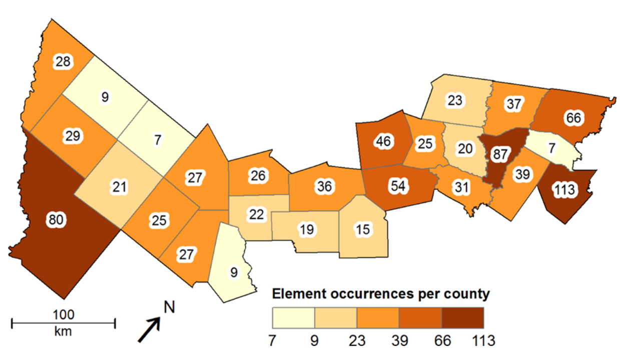


Fig. 8 Reported observations of unique terrestrial and aquatic elements of natural diversity. Numbers indicate count of element occurrences (EOs) in each county (Texas Parks and Wildlife Department 2016). Note that color scale is not linear. Data sorted by natural breaks (Jenks 1967)

To better interpret current trends and potential future states of core areas, we determined trends in changes in altered and unaltered core areas for each county during the study period. The Gi* statistic (Getis and Ord 1992) assesses the change in core area within each 1-km^2 cell allowing for the identification of three categories: significantly altered, impacted (but not significantly altered), or significantly unaltered. A loss of unaltered core during a specific time period, due to installation of O&G infrastructure, would translate into a gain of either impacted or altered land area, depending on the degree of disturbance. Calculating the status of each 1-km^2 cell during each time period, using the data also shown in Fig. 6, and the change in time (i.e., slope) shows whether the landscape situation improved with time (e.g., either a reduction in altered core or a gain in unaltered core) or worsened with time (e.g., either a gain in altered core or a loss of unaltered core). Table 1 shows that fragmented land areas are decreasing in 11 of 27 counties, but increasing in 16 counties, with eight of these counties occurring in the eastern portion of the play. Though only a handful of trends were significantly different from zero, we noted that the underlying data showing either altered or unaltered lands, were tested for significance at the $p < 0.05$ level.

Figure 10 is a mosaic of counties, in which the rates of unaltered/altered land gains/losses are represented graphically. The maps are binned according the strength of the trend assessed over the 8-year study, with hot (*red*) colors indicating steeper trend (*slope*) away from unaltered core area and toward more fragmented landscapes and cold (*blue*) colors indicating a gain in unaltered core area or loss of fragmented lands. No obvious pattern is apparent in these mosaics, though improving conditions are evident toward the eastern and western portions of the play and worsening conditions are observed in the central portion of the play. Figure 10 also includes the EO's shown in Fig. 8, so that a direct comparison can be made between landscape status and areas of viable habitats. Results do show a co-occurrence of higher EO's in counties trending toward improved conditions (e.g., Leon and Walker Counties in the eastern portion and Webb County in the

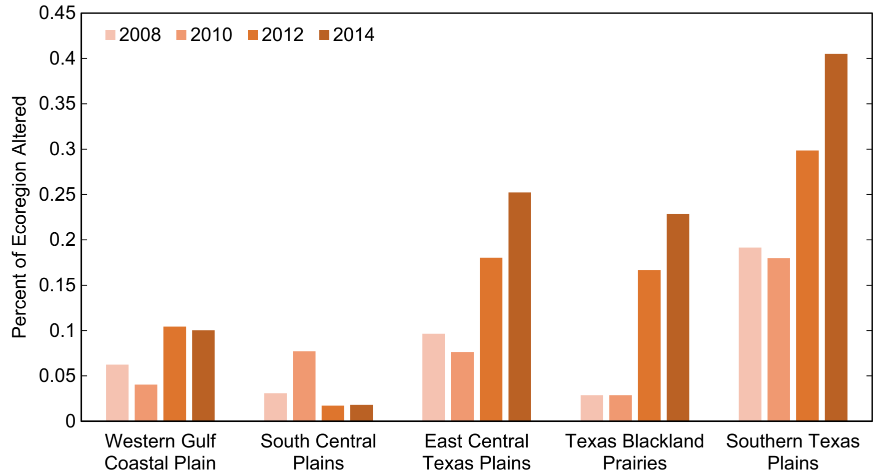


Fig. 9 Alteration by period in the Southern Texas Plains ecoregion (44% of study area)

Table 1 County aggregated rate and trends in gain/loss of altered and unaltered core areas with corresponding EO counts

County	Altered Core km^2/2 year	Unaltered Core km^2/2 year	Number of EOs
Atascosa	40.2	-112.5	27
Bastrop	2.7	-14.6	46
Bee	35.5	-29.6	9
Brazos	-15.1	-30.5	87
Burleson	-9.5	-12.5	20
DeWitt	116.6**	-190.8	19
Dimmit	80.3	-13.3	29
Fayette	6.4	-19.2	54
Frio	-36.1	5.5	7
Gonzales	84.5**	-148.6*	36
Grimes	-31.65	74.0	39
Karnes	77.0	-8.0	22
La Salle	168.3*	-18.9	21
Lavaca	-14.1	-12.3	15
Lee	49.1	-28.1	25
Leon	-55.6	117.9	66
Live Oak	48.8	26.3	27
Madison	-17.8	12.6	28
Maverick	2.5	19.3	25
McMullen	93.8*	-22.6	7
Milam	7.6*	-38.4	23
Robertson	20.7	-75.2	37
Walker	-16.0	168.0	113
Washington	-48.2	123.8*	31
Webb	-244.5	76.5	80
Wilson	8.7	-32.5*	26
Zavala	-39.5*	211.0*	9

Counties shaded light gray are found in the eastern region of the play. Dark gray shaded cells indicate a worsening condition and cells not shaded indicate an improving condition. Single asterisk indicates that trend is significant at $p < 0.10$ and double asterisk indicates trend is significant at $p < 0.05$. Note differences in sign (indicating slope) for cells under altered and unaltered core

western portion). Scatter subplots of EO vs. status subdivided by counties in the eastern and western portions of the play (Fig. 10) also help to illustrate this point. For example, the scatterplot in Fig. 10a allows the viewer to quickly note trends in landscape status and where EO's are higher, and those counties with high EO's and negative trends (e.g., Brazos County). Though no claims to correlation between landscape trends and EO's are being made, and none is apparent in the scatterplots, the maps and scatterplots do provide the means to quickly assess improving or worsening conditions and the potential impacts to habitats.

Discussion

Mapping of landscape alteration revealed a shift in activity during development of the play, which focused initially on pipeline installation, then to a broader build-out dominated by construction of well pads and a slow incorporation of multiple wells per pad. The rapid pace of exploration during EF development (Fig. 2) is shown by the increased number of wells, from 4587 wells in 2008 to 28,331 wells at the end of 2014 (Table S6). The decrease in the percent of new permits issued for the 2010 period (52% decrease in the east and 51% decrease in the west) (Fig. S14) led to a decline of 9.1 km^2 in landscape alteration, which could point to either revegetation of pipeline ROWs or the re-entering of ROWs to install additional capacity without leading to more land alteration. Total land alteration in the western portion was more than twice that in the eastern portion for all periods (Fig. S4).

Although previous research by Pierre et al. (2015) identified pipelines as the dominant source of landscape alteration in La Salle County, Texas, the broader impact from a play-wide assessment is more nuanced. Specifically, landscape alteration from pipeline construction was

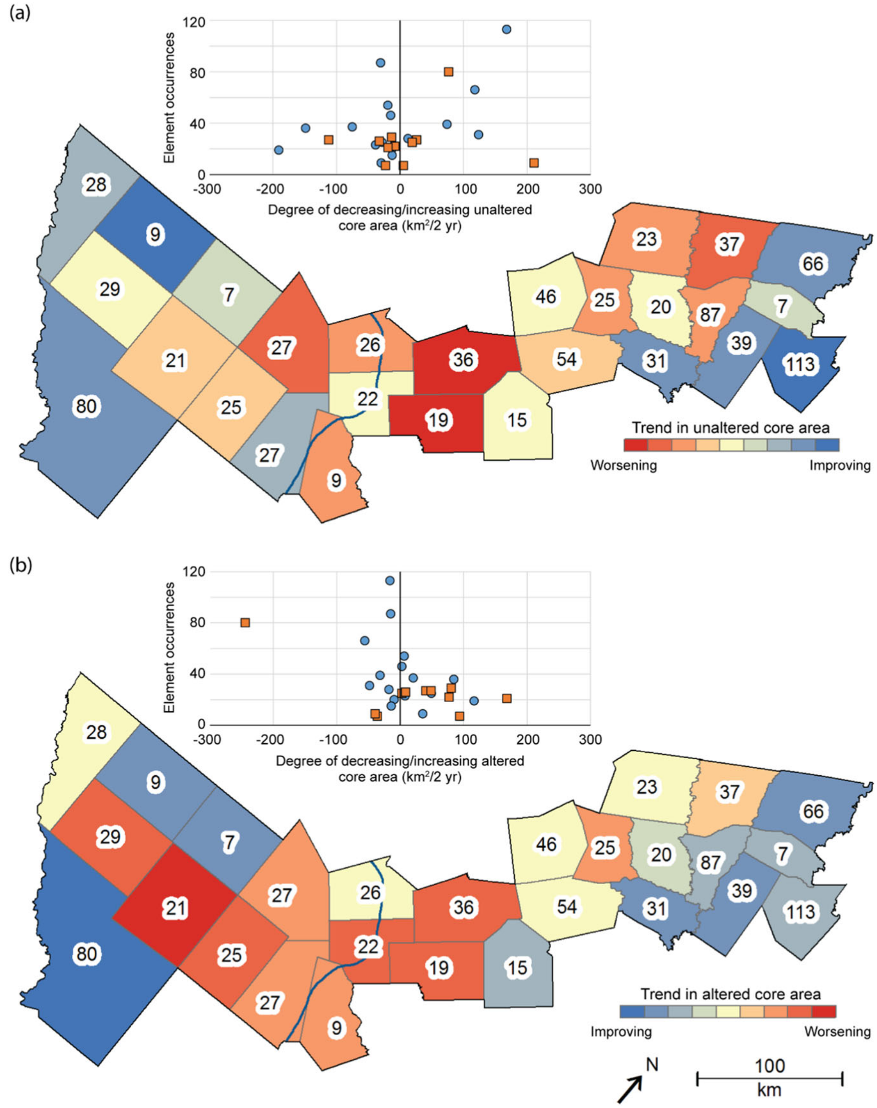


Fig. 10 Schematics showing trends in **a** Unaltered core area and **b** Altered core area, as determined by the change in area during each 2-year time period. Numbers in each county indicate Element Occurrences. Symbols in inset graphs: *blue circles* are counties in eastern portion of the play, and *orange squares* are counties in western portion

time-dependent. Results indicate that 73.0% of total impact during 2008 period was due to pipelines. By 2014, however, pipeline construction accounted for only 28.5% of total landscape impact, with the remainder due to well-pad installation (Fig. 5). When compared to our baseline, an additional 3914.0 km^2 of core areas were classified as altered; however, 906.8 km^2 of core areas were revegetated since development of the EF began (Fig. S7), again, primarily along pipeline ROWs. However, what is unclear from this study, and what could benefit from future research, is the proportion of areas revegetated with invasive or native vegetation, or whether native vegetation can be re-established into previously-disturbed lands that have become inhabited with invasive species. Research in other plays, especially in grassland environments in the Williston Basin in North Dakota (Preston 2015) and in Saskatchewan (Nasen et al. 2011) has shown increases in non-native species. The type of early successional vegetation that colonizes following alteration has important implications regarding the suitability of potential habitats for species of interest and overall ecosystem services (Moran et al. 2017).

The results showed geographical differences across the EF play. For example, core area alteration was 63% higher in the west during the study period than in the east (2412 km^2 compared to 1518 km^2; Fig. S7), and the rate of core revegetation was 7% higher in the more humid east than in the more arid west (27% compared to 20%). Although energy production was greater in the west, the land-use intensity in the eastern portion of the study area was less for all periods (e.g., 6, 5, 30, and 2 times lower for 2008, 2010, 2012, and 2014, respectively; Fig. S9). Thus, although energy production was lower in the east, land disturbance was correspondingly lower as well, showing how revegetation of altered areas (particularly from pipeline construction) in edge areas can help to increase contiguous core areas.

The following points relate directly to the questions posed in the Introduction section of this manuscript:

(1) The footprint from well-pad construction in the EF Shale play region increased by approximately 524% between 2008 and 2014 (from 25.8 to 160.8 km^2). However, the footprint from pipeline installations remained relatively constant during the same time frame, suggesting either that new pipeline capacity was not needed to handle new energy production or that the land altered by new pipeline construction was offset by restoration.

(2) Alteration of baseline core areas (i.e., contiguous vegetated areas not degraded by an "edge effect") per time period was highest (3331.6 km^2) at the onset of play development in 2008. Alteration at the end of the study period was estimated at 3913.9 km^2, or the area nearly 5 times that of New York City and just smaller than the area of Belgium. However, when period-to-period changes in core area are considered, rather than a comparison to baseline conditions, 621.7 km^2 were regained during the 2012 period and 401.7 km^2 were regained during the 2014 period. This return of core area is a result of revegetation, primarily in pipeline ROWs. Though obviously this is a positive finding, we recognize that the revegetation may not include native vegetation that has important implications for habitats of conservation interest.

(3) Pipeline installations caused the greatest impact on landscape alteration at the onset of initial play development, but the relative impact decreased with time (73, 55, 39, and 29% of total alteration during the 2008, 2010, 2012, and 2014 time periods, respectively) as the relative impact of well-pad development increased.

(4) Trends in landscape status, presented as either improving or worsening from the standpoint of core area gain or loss, were determined for each county in the play. Results show a mostly random mosaic across the play, but with tendencies of improving conditions at eastern and western portions of the play and worsening conditions in the central portion. Largest EO's were generally found in these improving regions, and smaller EO's were generally found in the worsening regions, but no co-association was identified.

(5) We presented land-use intensity as a means to assess whether land alteration was being offset by the value of energy production. Results showed that land-use intensity generally decreased with time in 25 of 27 counties as energy production progressed and as revegetation reduced altered lands. For instance, in 2008, land-use intensity was more than 0.20 km^2/mmBOE in 25 counties (i.e., land alteration was high relative to energy production in nearly all counties). However, by 2014, land-use intensity was below 0.20 km^2/mmBOE in 17 counties, or 63% of all counties in the play.

(6) The number of multi-well pads increased during the study period (120 in 2008 to 4832 in 2014); however, the play is still expanding, and the average number of wells per pads remains relatively low (average 1.2 in 2008 to 1.7 in 2014).

Conclusions

Understanding the current spatial distribution and structure of the landscape could potentially improve planning efforts for future infrastructure development, as described by (Milt et al. 2016a). Site-specific tailoring of simple management strategies can limit multiple impacts to specific habitats of concern and can benefit both O&G operators and the species sharing the use of the land (Cattaneo et al. 2006; Phalan et al. 2011; and Sayer et al. 2013). One potential difficulty in integrated regional planning in the EF play is the large number of private landowners, who individualize surface use agreements on their land. As noted by Milt et al. (2016a), private lands tend to be more fragmented in land use, and thus integrated planning could be less effective. Nonetheless, integrated planning using specialized software to improve placement of infrastructure, such as the Marxan approach, while avoiding impact can be useful (Milt et al. 2016b), though generally at some cost to operators.

An important strategy for limiting infrastructure footprint (Drohan et al. 2012; Bogard and Davis 2014; Abrahams et al. 2015; and Thompson et al. 2015) is increasing the number of wells per pad. Results show that, although the number of wells per pad increased over time (Table S10), this average remains below two wells per pad for all but Burleson County, which averaged two wells per pad for all periods. Another strategy to limit long-term land impacts is to improve revegetation of lands used for pipeline installation. The results described here show that land disturbance from pipelines decreased relatively to well-pad construction. Taken together, use of multi-well pads and reclamation of pipeline ROWs can minimize land impacts, even with the substantial aboveground activity needed for this type of energy production. These implications should be of great interest to conservation biologists, enabling them to collaborate with O&G operators to design infrastructure development plans that allow economic production of hydrocarbons while conserving potential habitats for species of concern.

This study presents a framework for mapping landscape alteration from O&G infrastructure development; however, it can also be applied to understanding how such development affects wind and water erosion, potential surface-drainage changes, or water-quality impacts (e.g., sedimentation). This approach, developed for the Eagle Ford Shale play, and in combination with regional planning tools (e.g., Marxan), could also be applied to other major U.S. hydrocarbon plays or combined with other studies (e.g., Johnson 2010, Slonecker and Milheim 2015, and Drohan et al. 2012 in the Marcellus area; and Unger et al. 2015 in Louisiana and Texas) to better understand regional- or national-scale impacts of energy development on landscapes. This study is clearly a retrospective. But, given that impacts to landscape has been shown to last decades (Nasen et al. 2011), approaches to improve future decisions of infrastructure placement, specifically by avoiding sensitive ecosystems or larger core areas, and by reducing infrastructure footprint through efficiency, rapid land revegetation, and more multi-well pads, could help to maintain landscape health and ecosystem services while energy development continues.

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Compliance with Ethical Standards

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

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