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Impacts from Above-Ground Activities in the Eagle Ford Shale Play on Landscapes and Hydrologic Flows, La Salle County, Texas

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Abstract We assess the spatial and geomorphic fragmentation from the recent Eagle Ford Shale play in La Salle County, Texas, USA. Wells and pipelines were overlaid onto base maps of land cover, soil properties, vegetation assemblages, and hydrologic units. Changes to continuity of different ecoregions and supporting landscapes were assessed using the Landscape Fragmentation Tool (a third-party ArcGIS extension) as quantified by land area and continuity of core landscape areas (i.e., those degraded by "edge effects"). Results show decreases in core areas (8.7 %; ~33,290 ha) and increases in landscape patches (0.2 %; ~640 ha), edges (1.8 %; ~6940 ha), and perforated areas (4.2 %; ~16230 ha). Pipeline construction dominates landscape disturbance, followed by drilling and injection pads (85, 15, and 0.03 % of disturbed area, respectively). An increased potential for soil loss is indicated, with 51 % (~5790 ha) of all disturbance regimes occurring on soils with low water-transmission rates (depth to impermeable layer less than 50 cm) and a high surface runoff potential (hydrologic soil group D). Additionally, 88 % (~10,020 ha) of all disturbances occurred on soils with a wind erodibility index of approximately 19 kt/km^2/year (0.19 kt/ha/year) or higher, resulting in an estimated potential of 2 million tons of soil loss per year. Results demonstrate that infrastructure placement is occurring on soils susceptible to erosion while reducing and splitting core areas potentially vital to ecosystem services.

Keywords Eagle Ford · Landscape impacts · Fragmentation · Ecosystems

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Introduction

As human populations and new economies grow, so do our demands for natural resources. Concentrated energy extraction can potentially lead to ecosystem degradation, landscape fragmentation, and a loss of biodiversity. Research has shown that anthropogenically induced landscape disturbance transforms heterogeneous ecosystems to more simplified homogeneous ecosystems that support less diverse wildlife (Daily 1997; Haila 2002; Pardini et al. 2010). These disturbances stem from a variety of activities, including slash and burn agricultural practices, timber harvesting, road building (Burnett et al. 2011), urbanization (Wu 2009), and extraction of hydrocarbons such as coal, oil, and gas (Linke et al. 2005; Bi et al. 2011; Krauss et al. 2013).

Within the last 10–15 years, advancements in technology have revolutionized the extraction of hydrocarbons from tight geologic formations (e.g., shale and tight sands), greatly increasing oil and gas recovery in the U.S. (Driskill et al. 2012; U.S. Government Accountability Office 2012). In South Texas, for example, permits acquired for the Eagle Ford (EF) Shale play increased from 94 to 1010

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between 2009 and 2010, and permits issued in 2011 nearly tripled (2826) those issued in 2010 (Railroad Commission of Texas 2014). In April 2014, over 200 drilling rigs were maintaining operation in the EF play (compared to an average of 269 rigs in 2012, or 15 % of all 2012 U.S. rigs) (Gong et al. 2013), making it the most active shale play in the world (Dukes 2014). This rapid increase in oil and gas (O&G) drilling activity in South Texas is accompanied by the building of roads, pipelines, and other infrastructure, and by substantial economic and employment impacts. As of 2012, for example, the total economic impact in the 14-county core area of the EF was estimated at over $46 billion in revenues, with over 86,000 jobs created (Tunstall et al. 2013).

Several recent studies have found that the hydraulic-fracturing process itself has had little impact on environmental quality and that most incidences of contamination occurred on the surface (U.S. Government Accountability Office 2012). Considering the landscape, researchers in Pennsylvania analyzed early trends of land-cover change in the Marcellus Shale play. Preliminary results indicate the importance of well-pad location and support infrastructure to minimize soil erosion, stream sedimentation, alteration in stream flow rates, and landscape fragmentation (Johnson 2010; Entrekin et al. 2011; Drohan and Brittingham 2012; Drohan et al. 2012). This research examines the early years of play development and shows how exploration can be done with reduced above-ground impact. In the Marcellus, Drohan et al. (2012) suggested that land reserved for drilling competes somewhat with land previously reserved for food production, and that sites chosen for infrastructure development do not take into account soil and landscape factors, potentially leading to higher risk of soil-related issues and pollution of streams. Drohan and Brittingham (2012) characterized soil properties in locations where shale-gas infrastructure was built. They concluded that reclamation practices will be most successful if site characteristics such as revegetation potential, soils, climate, and topography are considered on a case-by-case basis. In China, Bi et al. (2011) showed that above-ground issues, such as landscape fragmentation and changes in hydrologic flow pathways from disturbances, continue to be ecologically important throughout the life of a play. They showed that older oil-field infrastructure altered the ecological function of wetlands and played a larger role in overall landscape fragmentation, when compared to more recent oil-field developments, because little to no ecological considerations were used in the placement of the initial infrastructure.

Considering hydrologic changes, researchers (Entrekin et al. 2011; Olmstead et al. 2013) identified threats to streams, including increased sedimentation and chloride concentrations determined to be from shale-gas activities. Entrekin et al. (2011) demonstrated that gas-well development in the Fayetteville and Marcellus plays was located in close proximity to headwater streams, and that sediments and contaminants associated with drilling activities were entering surface-water systems. They suggested a need for more restrictions on siting infrastructure near surface-water resources and for in-depth research on the ecological impacts from the widespread development of shale resources. Drohan et al. (2012) found that pads in non-forested areas were located in closer proximity to streams than pads in forested areas. However, they also expressed concerns for headwater stream quality in forested regions and stressed the need for focused stream quality monitoring in core forest areas with concentrated drilling activity. Olmstead et al. (2013) also assessed surface-water impacts from development of the Marcellus Shale and concluded that elevated levels of suspended solids and Cl^- were migrating into surface waters because of inadequate erosion-control measures and improper treatment of produced water, respectively.

Landscape impacts are a potential issue in other energy-related projects as well. Diffendorfer and Compton (2014) examined fragmentation from wind-energy development across the United States. They examined new wind-energy developments and different scales of infrastructure, including individual turbines and roads, strings of turbines with roads and transmission lines, and entire facilities. They concluded that entire facilities had the greatest impact on landscape fragmentation, though geographic variables (topography and land cover) played a large role in quantifying land change. Their results suggest that land change from wind is not yet understood and thus cannot be compared to other types of energy development; however, they also suggested preferentially choosing sites for new wind development on already disturbed or degraded land.

Very little, if any, research has examined the spatial and geomorphic fragmentation effects of the recent shale boom in the semiarid climate of South Texas (or in any semiarid climate). Here, reduced rainfall rates may minimize water erosion and contaminant transport, but may also lengthen landscape reclamation periods following drilling and infrastructure development on soils susceptible to wind erosion. In recent years, investigators have been focusing research on the effects of fragmentation in semiarid environments. For example, Saiz and Alados (2011) observed in semiarid fragmented landscapes that habitat subdivision was complicated by shrub and grass competition and facilitation. In the context of anthropogenic land use coupled with regional climate change, John et al. (2009) concluded that land disturbances on a local level can quickly manifest into changes at the regional biome level. Secondary detrimental effects from man-made impacts to ecosystems have long been noticed by researchers in ecology (John et al.

2009; Saiz and Alados 2011; Alados et al. 2011). Lowe (1985) found that encroachment from urbanization and agriculture into headwater (first-order ephemeral streams) riparian areas was the largest threat to obligate riparian amphibian and reptile species in the American Southwest (Arizona, USA and Sonora, Mexico). Alados et al. (2009) modeled extinction probabilities in semiarid Spain and found that the temporal and spatial autocorrelation of disturbance regimes could reach a critical threshold of habitat destruction capable of causing an extinction event. They recommended both considering spatial patterns of disturbance when predicting fragmentation effects and improving management strategies.

Given the findings of research conducted in the Marcellus Shale (Entrekin et al. 2011; Drohan and Brittingham 2012; Drohan et al. 2012; Olmstead et al. 2013), the potential complications caused by landscape fragmentation in semiarid climates (Lowe 1985; John et al. 2009; Saiz and Alados 2011; Alados et al. 2011) and the pace at which development is proceeding in the semiarid Eagle Ford (Martin et al. 2011), we set out to lay the framework and build a foundational dataset for future comparative analyses. To this end, the goal of this research was to answer the following questions:

(1) How much landscape fragmentation has occurred in La Salle County from O&G activities?
(2) What soil characteristics are associated with landscape disturbance regimes?
(3) Can the hot spots of core-area degradation and hot spots of stream disruptions be statistically identified?

The results of this research could be used to create a development guide—as suggested previously by Drohan and Brittingham (2012)—that can help avoid and limit potential harmful effects from land disturbance and fragmentation. To our knowledge, no such work is being carried out in the EF or any other semiarid shale play.

Methods and Materials

This study focuses on landscape conversion resulting from O&G infrastructure development over a 12-year period (March 30, 2001–December 11, 2012) in La Salle County, Texas. We defined "disturbance" as the area (ha) of a landscape that, as a result of O&G infrastructure, was bare earth or developed during the time period the 2012 imagery was taken. We then defined "landscape fragmentation" as a change in size (ha) of landscape classes established by Vogt et al. (2006) and analyzed using the Landscape Fragmentation Tool (LFT) (Parent and Hurd 2007). Landscape ecology and spatial statistical techniques were used to quantify disturbance regimes and to identify landscape-alteration hot spots and stream-disruption hot spots. Analyses were performed across the entire EF play to eliminate edge effects and to account for O&G activity across the entire play, but we are reporting only on the methods and results from La Salle County.

Site Description

The EF play spans an area in Texas from the southwest border of Webb and Maverick Counties to Leon and Madison Counties in the east (Fig. 1). Early exploration activity in the EF began in La Salle County in July 2008. La Salle County is situated in the West Gulf Coastal Plain in South Texas Brush Country. La Salle County consists of croplands (52 %), Mesquite–Granjeno Woods (40 %), Mesquite–Blackbrush Brush (4 %), and developed or not classified (4 %) (Homer et al. 2007). Five soil orders are present in La Salle County: Aridisols (30 %), Alfisols (26 %), Mollisols (13 %), Vertisols (12 %), Inceptisols (5 %), and unclassified (14 %) (Soil Survey Staff 2013). For the 25-county EF play, precipitation ranges from 23 to 119 cm, respectively, in the west and east, and vegetation biomes range from a forest grassland mosaic of mesquite, blackbrush, and blue stem in the west to post-oak woods in the east. The dominant soil orders in La Salle County are similar across the play. The bulk of activity in the EF is occurring in South Texas, which is dominated by an Ustic soil moisture regime.

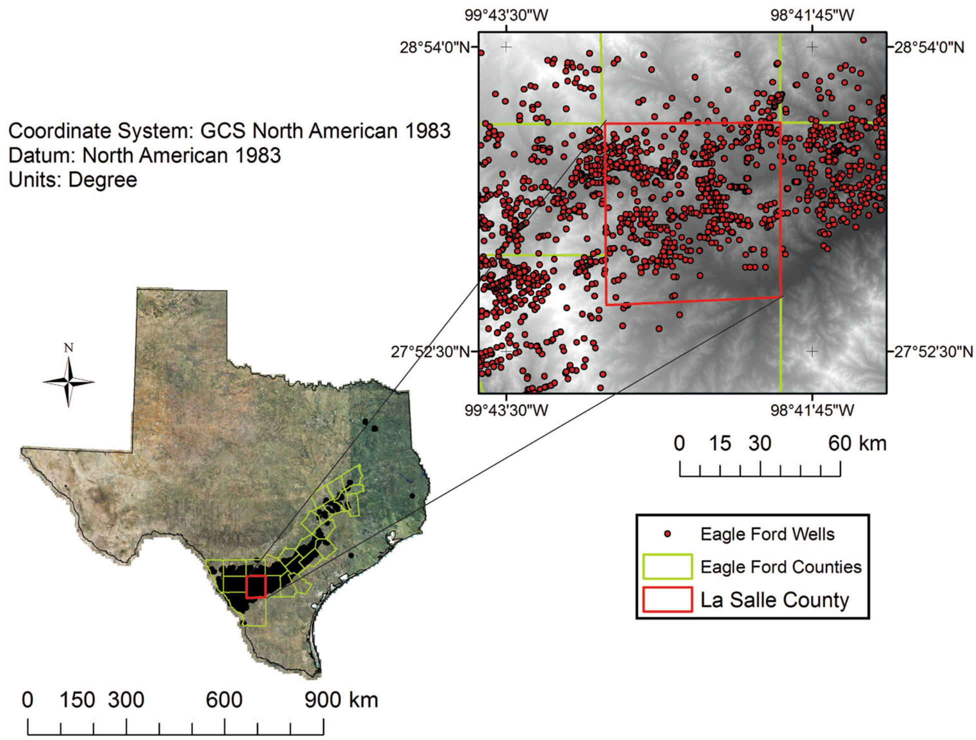
La Salle County was chosen for this case study because it provides the best representative subset of the entire play with regards to climate, vegetation, and soil. Additionally, owing to discoveries of liquid rich reservoirs where prolonged development is likely to occur, La Salle County is situated in an area of substantial EF activity (Gong et al. 2013).

Data and GIS methods

Landscape Fragmentation

To avoid unrealistic edges created by arbitrary county boundaries and to account for fragmentation effects from energy development in surrounding counties, we performed analyses on all 25 counties of the play, applying a 3000-m buffer to ensure that core areas found at county edges would be accurately assessed in fragmentation analyses. Extending the buffer into counties outside the study area leads to a more accurate assessment of landscape classification, particularly when assigning edge areas and assessing core areas where the status of adjacent pixels is needed. Coordinates and associated attributes for wells permitted between March 2001 and December 2012 were obtained from Information Handling Services, Inc. (2013).

Fig. 1 Study area of La Salle County, Texas, with oil and gas wells



We plotted wells and then overlaid the plots onto 1-m resolution aerial imagery from 2012 obtained from the National Agricultural Imagery Program (NAIP) (U.S. Department of Agriculture Aerial Photography Field Office 2012). Land adjacent to each well and disturbed from the development of O&G infrastructure (well pads, containment ponds, staging areas, etc.) was manually digitized at a 1:4000 scale. Areas with uncertain cause of disturbance were not included. We obtained O&G pipeline data from the Railroad Commission of Texas (2013). Based on observations at field sites in the area, we applied a 90-m buffer to the pipelines when extracting disturbance from classified NAIP images. Disturbance was assessed by identifying where bare ground existed in the 2012 NAIP imagery.

Because the pipeline network in LaSalle County is extensive, we performed unsupervised image classification on the spectral signature (amount of red, green, and blue) of the NAIP imagery to automate the extraction of pipeline disturbance. This avoided the extensive man-hours needed for manually digitizing the disturbance. Through comparison with NAIP, we verified the locations and obtained accurate values for bare ground (disturbed), and then reclassified these results into two valued groups representing disturbed (bare ground or developed) and undisturbed (vegetated) landscapes. The resulting raster was resampled to 30-m resolution to allow for later incorporation into the 2001 National Land Cover Dataset (NLCD) (Homer et al. 2007). Additionally, the pipeline data contain both regulated and non-regulated pipeline segments with potential positional inaccuracies ranging from within 15 to over 300 m with potentially some unknown positional accuracies (Railroad Commission of Texas 2013). Through extensive visual inspection using the NAIP photography, we found a 90-m buffer accurately captured disturbance from pipeline installations. The 30-m raster cells, all within the 90-m pipeline buffer, were extracted to obtain disturbance areas from recent pipeline installation. Where pipelines crossed over pads (drilling or waste water injection), the disturbance was attributed to the pads to avoid counting disturbances twice.

The NLCD of 2001 was downloaded from the USGS Landcover Institute (Homer et al. 2007) to establish a baseline—that is, any features that showed evidence of vegetation or water—before EF development. As with the NAIP imagery, we reclassified the NLCD raster image into two groups: disturbed and undisturbed. Only values representing bare ground or development were classified as disturbed; all vegetated and water elements were classified as undisturbed. The reclassified NLCD image represented pre-EF (2001) conditions and will be referred to as "pre-EF" in further discussions. The reclassified NLCD image with the incorporated disturbances from drilling pads, wastewater injection pads, and pipelines represented 2012 EF conditions and will be referred to as "2012-EF" in further discussions. Although the 2001 NLCD is rather coarse (30-m resolution) compared to NAIP (1-m resolution), these data are created from digitized photography, using a methodology similar to that described above for extracting pipeline disturbance. Use of NLCD as a land cover dataset is well documented in the literature (Niu and Duiker 2006; Scanlon et al. 2014), and this dataset readily serves as a baseline for play-wide or nationwide analyses. We are reporting our La Salle County results to establish a methodology for on-going analyses with expanded areas of interest.

We used the LFT (Parent and Hurd 2007), a python script that serves as an extension in ArcGIS, to assess landscape fragmentation based on methods established by Vogt et al. (2006). We assessed cumulative landscape fragmentation by considering the impacts of all three disturbance regimes (drill pads, injection pads, and pipelines) simultaneously. Because disturbances overlap, analyzing each disturbance regime individually will produce results that vary slightly from the simultaneous analysis of disturbances. LFT classifies four different types of landscapes in a specified area: (1) "core" areas (in our case, vegetated land) containing pixels greater than 90 m from nonvegetated pixels; (2) "perforated" areas containing vegetated pixels within 90 m of nonvegetated pixels; (3) "edge" areas containing vegetated pixels along the outside edge of a core area; and (4) "patch" areas containing vegetated pixels that do not contain core areas (within 90 m of disturbed areas). Core areas are then further subdivided into small (<100 ha), medium (100–200 ha), and large (>200 ha) areas. Edge and perforated areas both contain pixels within 90 m of a core area; however, perforated areas exist only on the interior (concave) edge of a core area, while edge areas exist on the exterior (convex) edge of a core area. Though previous investigators (Goodrich et al. 2004; Howell et al. 2006; Svobodová et al. 2010; Robson et al. 2011) have used a 100-m edge distance [two to three times tree height in a forested environment (McGarigal et al. 2005)], we maintained a 90-m edge distance, as did Neel et al. (2004), considering the lower height of vegetation in our study area and the upward bias in edge lengths that are created by the stair-step outline of raster data (McGarigal et al. 2005). Additionally, a 90-m edge maintained consistency with our cell size (i.e., edge = 3 cells).

Soil Survey Geographic (SSURGO) data, which range in resolution from 1:12,000 to 1:63,360, were downloaded from the USDA Natural Resources Conservation Service (NRCS) National Geospatial Center of Excellence (USDA/NRCS 2014). Representative data containing soil order, great group, soil series, particle size, hydrologic soil group, wind erodibility index, and other attributes were extracted from SSURGO using the dominant component when applicable for each O&G disturbance regime. Soil taxonomic data, soil order, and great group provide information on differences in dominant pedogenic processes, and the hydrologic soil group (HSG) provides runoff potential in thoroughly saturated, unfrozen bare ground with fully expanded clays (Soil Survey Staff 1993). Runoff potential for HSG's is ranked from A to D, where A has low potential and D has high potential.

Stream Fragmentation

"Stream fragmentation" is defined as the direct intersection of O&G infrastructure with the NHDPlusV2 flowlines (Horizon Systems Corporation 2013). NHDPlusV2 flowlines are produced by an interdisciplinary team from the USGS, the EPA, and private contractors. These flowlines are a digitized form of stream networks found on USGS orthophoto quadrangles. Polylines were converted to raster form and then overlaid onto the O&G infrastructure land disturbance layer. All stream fragmentation was performed on the 3000-m buffered extent of the entire (25-county) EF play, to remain consistent with the fragmentation analyses.

Statistical Analysis of Geospatial Data

Spatial autocorrelation (SAC) was assessed using global and local statistics. In this study, we used Moran's I and Getis-Ord General G statistics as global statistical metrics, as has been done by Roberts et al. (2000), Chen et al. (2012), and Chas-Amil et al. (2013) to analyze landscape disturbances. Moran's I (Moran 1950) indicates whether a spatial pattern exists in the study region or whether the feature is dispersed. The General G statistic (Getis and Ord 1992) indicates whether the clusters have a high or low specific attribute within a specified distance in relation to the entire study area (e.g., whether the cluster of core areas identified in Moran's I has a high or low amount of disturbance). The General G statistic determines (1) whether pre-EF core polygons (derived from the 2001 NLCD) show a high degree of landscape or hydrologic fragmentation when their neighbors are also fragmented (known as H–H polygons), and (2) whether core polygons and their neighbors also have a low degree of fragmentation (known as L–L polygons). We used P value and z score to determine the significance of the spatial autocorrelation, using P value <0.01 and a z score >1.96 for cases dominated by clusters showing fragmentation and a z score <1.96 for cases dominated by clusters showing little or no disturbance. Data based on the percentage of disturbance with core areas and stream areas were then analyzed on pre-EF core polygons using local indicators of spatial autocorrelation (LISA) (Anselin 1995) and Gi* (Hot Spot Analysis) (Getis and Ord 1992). Features can be clustered with statistically significant high values (hot spots) and low values (cold spots).

In the analysis, each pre-EF polygon was weighted by the percentage decrease in the original area of the core itself and the percentage of new O&G infrastructure that intersects with stream area within the pre-EF core. To examine the effects of scale and to determine an appropriate size for a fixed-distance (band) threshold to use in local spatial analyses, we first performed an incremental SAC analysis with Moran's I global spatial statistics, using an incremental distance of $\sim$658 m. We observed a peak in spatial autocorrelation at 8480 m for the percentages of core-area loss and stream-area intersection with O&G infrastructure; therefore, we chose this value as the fixed-distance band threshold for all subsequent local spatial statistical analyses (Horta e Costa et al. 2013). Fixed-distance band conceptualizations can be based on knowledge of the feature and the parameters under investigation (Mitchell 2005). Though the approach is often used for organisms, we generalized the approach and used the distance corresponding to the first z score peak as the fixed-distance threshold for all local statistical tests. All statistical tests were executed using row standardization.

Results

Landscape Fragmentation

We identified 724 permitted wells in La Salle County, with 628 wells with visual evidence of associated O&G infrastructure in the 2012 NAIP imagery. Because we are interested in land impacts, which begin at construction, we used permit dates for the wells as our benchmark for measuring land disturbance rather than spud dates. A considerable lag time can exist between permit date and when pad construction actually begins; however, our methods only captured disturbance when it was visually evident in the 2012 NAIP. Whether or not a well was spudded, abandoned, or producing was not considered important relative to land impact. By manually digitizing pads at a scale of 1:4000 using the 2012 NAIP, we identified a total of 585 drilling pads, of which only 5.4 % had three or more wells per pad. Most are still single-well pads, and only 23 % of well pads host two or more wells. Our analyses showed a median drilling-pad size of $\sim$2.3 ha (maximum $\sim$20 ha). The area disturbed from construction of wastewater injection pads was the smallest of all the disturbance sources, with a median pad size of 0.2 ha (maximum 15 ha). As stated above, we classified disturbance as the actual footprint created by infrastructure development and fragmentation as the change in landscape classes as a result of this disturbance. Pipeline disturbance (9700 ha) was five times greater than the resultant disturbance from drilling pads (drilling pads $\sim$1700 ha; injection pads <100 ha). We also found that 110 ha of infrastructure (combining pads and pipelines) intersected stream networks ($\sim$1 % of all infrastructures), of which 70 ha were first-order streams. Using a 10-m resolution digital elevation model (DEM) from the United States Geological Survey National Elevation Dataset (2013), an area of 160 ha of pipeline development was present on slopes between 3 and 20 %, while an area of 28 ha of drilling pads occurred on slopes between 3 and 13 %. Injection pads were not constructed on slopes exceeding 3 %. We were not able to verify slope values in the field.

Using the 2001 NLCD thematic land classifications, we observed that $\sim$48 % of all disturbance regimes (pads and pipelines) occurred on land classified as shrub/scrub, $\sim$22 % occurred on land classified as herbaceous, $\sim$12 % on hay/pasture land, $\sim$6 % on low intensity developed land, and $\sim$5 % on land used for crop cultivation. Approximately 11 % of infrastructure development occurred on land already classified as developed/disturbed. Assessing the impacts from each disturbance regime separately, we noted that disturbances from pipelines and drilling pads were nearly identical to the values listed above, but that water injection pads, which had the smallest landscape impact, occurred on $\sim$42 % hay/pasture land, $\sim$36 % on land already developed, and $\sim$14 % on shrub/scrub land.

Though the disturbed area from new O&G infrastructure was $\sim$3 % of the total county area, $\sim$33,300 ha of core areas (all three size classes of core) were lost or converted to another classification due to O&G infrastructure, accounting for 8.7 % of county area. Results indicate that the total vegetated area decreased from 91 to 89 % of the county area, and that core areas declined (either lost or converted to new classification) from 76 to 68 % of the county area. The difference between these two impacts is that disturbances from (mostly) pipeline networks intersect and subdivide large core areas, resulting in an increase in smaller (i.e., <100 and 100–200 ha) core areas (Fig. 2) as well as in patch, edge, and perforated areas. Figure 2 highlights the areas to the east and south of Cotulla, where pipelines (shown as white linear features) subdivide the larger core areas into medium and smaller core areas. Figure 3 represents changes (in both area and percentage of county area) in landscape classes for the entire county as a result of O&G activity. Results show a 55,100 ha (27.6 %) reduction of large core areas, from 254,600 to 199,500 ha, with a redistribution of this land area to patch (600 ha), edge (7000 ha), perforated (16,200 ha), and smaller core areas (9800 and 12,000 ha for medium and small core areas, respectively). The remaining 9,500 ha is now classified as developed, 11 % of which was on already disturbed or degraded land. We also note that, of the 96 permitted wells for which no visible disturbance was observed in the 2012 NAIP imagery, approximately two-thirds (64) will

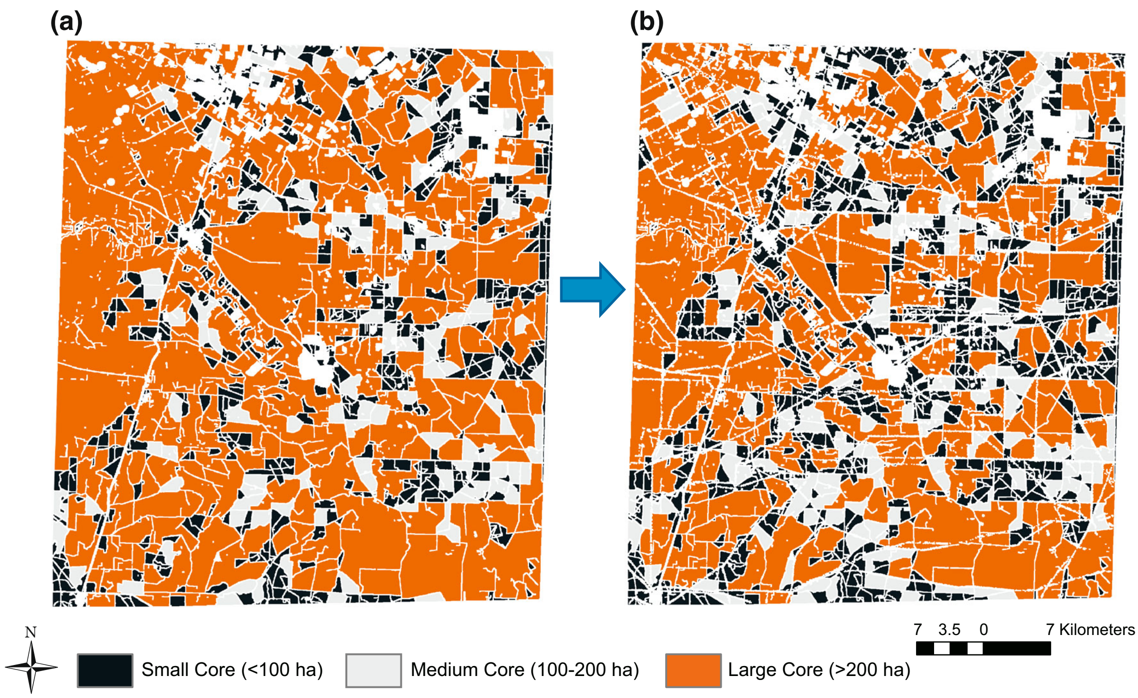


Fig. 2 Changes in landscape classes after 12 years of Eagle Ford development. **a** Pre-EF development in 2001 and **b** EF development as of 2012

fall into core areas if they are developed; thus, further reduction in large core areas is expected.

Our results show that pipeline installation accounted for ~84 % of the changes in landscape-class composition across the county. Analyses of all O&G disturbance showed the greatest reduction in larger core areas, with increases in medium core, small core, perforated, patch, and edge classes. As indicated above, we are reporting the cumulative areas of disturbance and simultaneously assessing impacts from drilling pads, injection pads, and pipeline installation. Because of overlapping disturbance between pipelines and pads, these numbers differ slightly when impacts from these sources are assessed separately (Table S1).

Erosion Characteristics of Disturbance Regimes

For this study, soil erosion from disturbed lands is considered to occur from either wind or water. Estimates of wind erosion can be determined using a wind erodibility index (WEI) based on several soil properties that affect resistance to soil blowing in cultivated areas, or, in this case, disturbed areas (see USDA/NRCS National soil survey handbook 2014). From the analyses conducted, approximately 88 % of O&G disturbance occurred on soils with a WEI of 0.19 kt/ha/year or more (Table 1), with the SSURGO dominant component soil surface texture being clay (38 % of disturbed area) and very fine sandy loam soil (34 % of disturbed area) (Table 2). Using the dominant component for WEI data from SSURGO, we estimate that 2 million tons of soil could be lost per year from wind erosion (using area of disturbance multiplied by WEI factor in SSURGO) on landscapes disturbed by O&G infrastructure, particularly if the land is not quickly reclaimed using revegetation and/or land contouring practices.

According to the geomorphic description in SSURGO, 74 % of the infrastructure has been built on interfluvial areas, and 24.6 % has been built on drainageways or floodplains, where concentrated flow from convective storms could enhance water erosion. Although >98 % of the soils in La Salle County are considered well drained or moderately well drained (Soil Survey Staff 2013), 51 % of soils underlying disturbed areas have low infiltration and transmission rates (hydrologic soil group D) (Soil Survey Staff 1993; USDA 2009) and may be susceptible to erosion during heavy rainfall events (Table 3).

Spatial Statistical Analyses

Moran's *I* incremental analysis showed that, at distances exceeding 28,900 m, the percent core-area loss was no longer clustered and became random ($z < 1.96$). This illustrates the nature of how exploration proceeds: operators drill wells on some parcels of land, but other parcels are left undisturbed, leading to patches of disturbed areas. When this analysis was applied to stream-area intersection with O&G infrastructure, we found that disturbance remained clustered ($z > 1.96$) at all incremental distances up

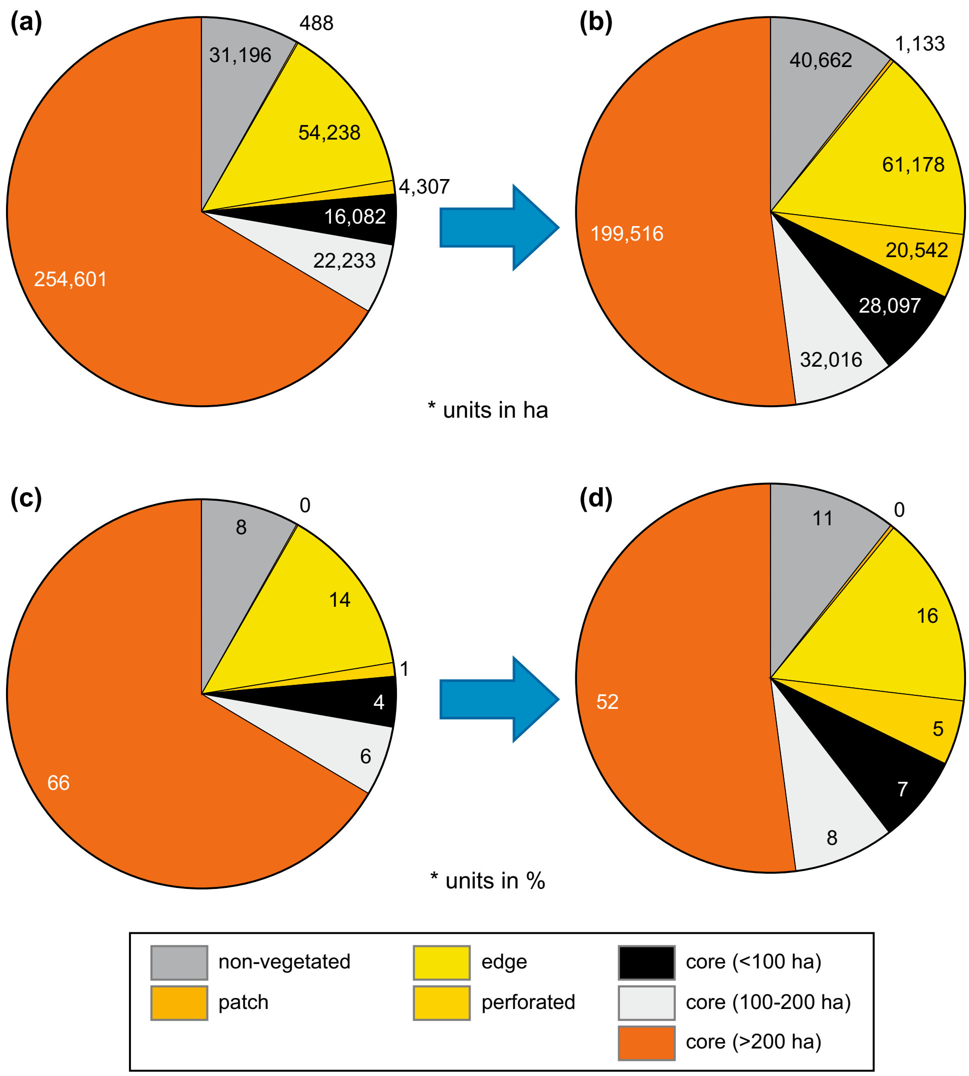


Fig. 3 Change in landscape classes after 12 years of EF development: **a** 2001 pre-EF conditions by area, **b** 2012 EF conditions by area, **c** 2001 pre-EF conditions by percent of county area, and **d** 2012 EF conditions by percent of county area

Table 1 Summed SSURGO values for potential wind erodibility across disturbance regimes

Wind erodibility index (kt/ha/year)	Drilling pads (kt/year)	Pipelines (kt/year)	Injection pads (kt/year)	All disturbance regimes (kt/year)	Percentage of all disturbance regimes
0	0	0	0	0	2.6
0.11	2.07	12.08	0	14.15	1.2
0.13	14.07	97.53	0	111.59	7.8
0.19	256.96	1465.20	0.73	1722.90	78.7
0.30	59.69	264.83	0	324.53	9.5
Missing	0	0	0	0	0.2
Totals	332.80	1839.64	0.73	2173.16	100

to and beyond 28,900 m. Subsequently, we confirmed spatial autocorrelation at specific distance ranges using the global General G statistic at three separate metrics: the minimum neighbor distance (5190 m), the peak Moran's I z score distance (8480 m), and the maximum distance at which the Moran's I z score for percent core-area loss was

Table 2 SSURGO values for soil surface texture across disturbance regimes

Surface texture	Drilling pads (ha)	Pipelines (ha)	Injection pads (ha)	All disturbance regimes (ha)	Percentage of all disturbance regimes (%)
Clay	696	3613	1	4309	37.9
Very fine sandy loam	564	3304	3	3871	34.0
Clay loam	83	1067	0	1150	10.1
Loamy fine sand	204	877	0	1081	9.5
Fine sandy loam	78	226	0	304	2.7
Gravelly sandy clay loam	9	238	0	247	2.2
Sandy clay loam	47	126	0	174	1.5
Loam	20	108	0	128	1.1
Silty clay loam	15	35	0	50	0.4
Very gravelly sandy clay loam	14	28	0	42	0.4
Very gravelly sandy loam	9	2	0	11	0.1
Missing	0	12	0	12	0.1

Table 3 SSURGO values for hydrologic soil group-dominant condition across disturbance regimes

Hydrologic soil group	Drilling pads	Pipelines	Injection pads	All disturbance regimes	Percentage of all disturbance regimes
Dominant condition	ha	ha	ha	ha	%
B	422	3019	2	3443	30.3
C	349	1750	1	2100	18.5
D	923	4870	1	5794	51.0
Missing	9	16	0	25	0.2

correlated (28,900 m) (Table 4). Beyond 28,900 m, no clustering was observed for percent core-area loss, and disturbances were random.

Results of local statistics (e.g., LISA map in Fig. 4a) show core-area loss (H–H) clustered in two general areas: one east of Cotulla and north of FM 624, and the other in the southwest corner of the county. The Gi* map (Fig. 4b) shows hot spots in the same two general areas, where clustering of disturbance is considered most likely. Results also show two smaller areas of cold spots appearing in the northern section of the county, highlighting core areas that were not degraded by recent O&G activity during the study period. We also noted the presence of H–L outliers, which represent clusters of highly disturbed core areas adjacent to core areas with low levels of disturbance. As with core-area fragmentation, H–H clusters are also present for hydrologic fragmentation (Fig. 5a). Hot spots for hydrologic fragmentation partially overlap hot spots of core-area fragmentation; however, the overlap is more pronounced in the east-central region of the county. Figure 5b also indicates the presence of cold spots for hydrologic fragmentation in the northeastern portion of La Salle County. Strategies focused on limiting potential impacts can use cold spots as areas where future infrastructure development could be avoided.

Table 4 Moran's *I* and general G *z* scores for (A) percent core-area loss and (B) percent stream-area intersection with O&G infrastructure

Distance Threshold (m^2)	Moran's *I* *z* score	General G *z* score
Percent core-area loss		
A		
5190	8.07	7.79
8480	10.16	9.72
28900	1.98	2.86
Percent stream-area intersection		
B		
5190	3.51	3.33
8480	4.62	4.46
28900	4.70	3.23

Discussion

Landscape Fragmentation

Results showed that pipeline construction was the dominant source of land disturbance and therefore had the largest influence on fragmentation effects. Moreover, because pipelines tend to be long, linear features or corridors rather

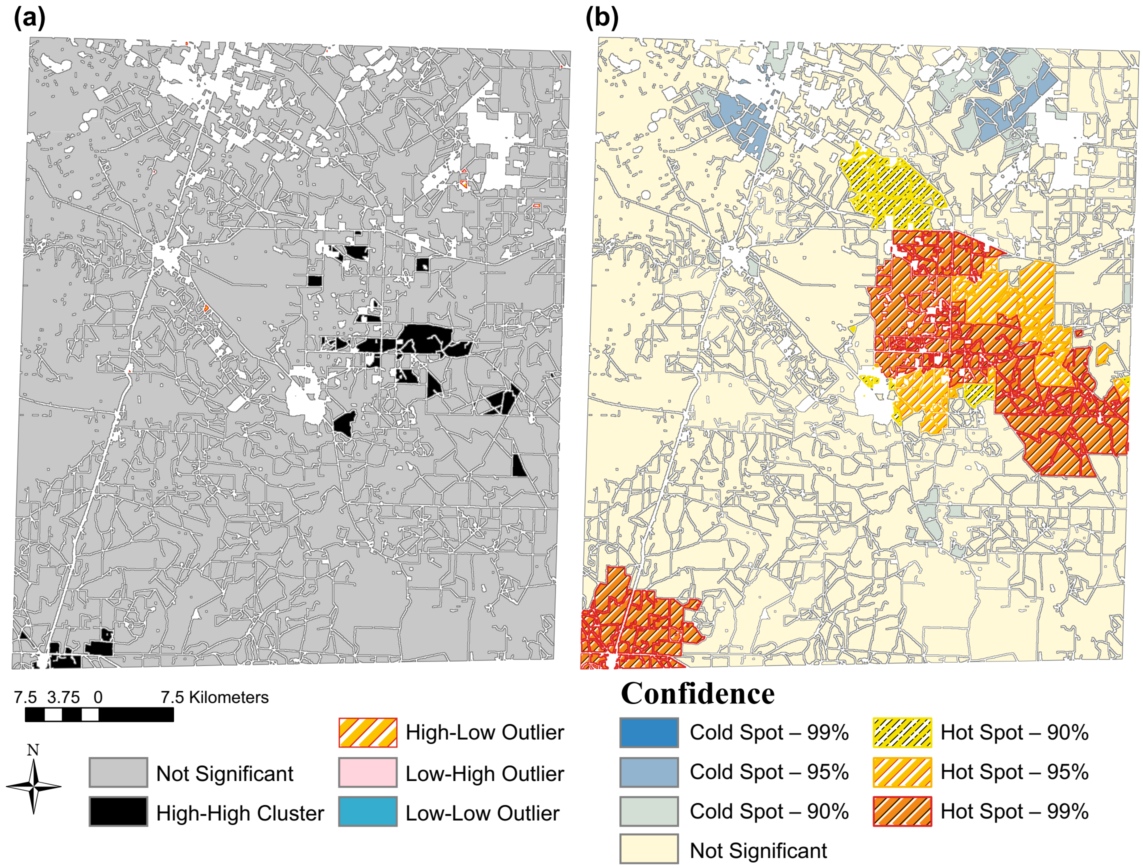


Fig. 4 Cluster maps weighted by percent decrease of core area based on fixed-distance band. **a** LISA and **b** Gi*

than isolated "islands" of disturbance, there is a greater chance that wildlife movement could be curtailed or influenced by the infrastructure (Albrecht et al. 2000; Johnson 2010; Kalyn Bogard and Davis 2014; Buchanan et al. 2014; Brittingham et al. 2014). Depending on the species or process of concern, this shift to a smaller number of large core areas and a larger number of smaller core areas—along with a substantial increase in transitionary (edge) and localized (perforated) disturbances—could lead to degeneration and loss of habitat (Johnson 2010; Krauss 2013; Kiviat 2013; Kalyn Bogard and Davis 2014; Brittingham et al. 2014).

We note that construction of pipelines is a relatively short process compared to the productive lifetime of drill pads. Areas set aside for pipelines are often reclaimed after installation is complete. Native restoration guidelines tailored specifically to South Texas are currently being researched and developed (Smith et al. 2010; TPWD 2013). If seasonal timing is suitable for native seed establishment, these sites could be returned to approximate original conditions, reducing long-term impacts.

We also note that infrastructure development is preferentially occurring on land classified as shrub/scrub, herbaceous, and hay/pasture land. Only a small percentage of development is occurring on cropland or already developed land. This indicates that preferred habitat of native species is likely to be removed or altered with increased development.

Trends in La Salle County differ from infrastructure development in the Marcellus Shale of Pennsylvania. For example, in La Salle County, ~48 % of development occurs on shrub/scrub land (equivalent in LFT to forested land in Pennsylvania), whereas only ~5 % of development occurs on cropland; in the Marcellus Shale, Drohan et al. (2012) found that 45–62 % of development occurred on agricultural land and 38–54 % occurred on forested land. Diffendorfer and Compton (2014) found that land transformation from wind development occurred less on agricultural land than in forests or shrublands. Diffendorfer and Compton (2014) suggested two explanations for this difference: first, agricultural land typically already has road networks capable of supporting heavy agricultural equipment, essentially eliminating the need for additional road networks to support wind facilities; and, second, agricultural land is likely to be quickly replanted and restored to agricultural production, whereas with other land cover types this land was not quickly re-used.

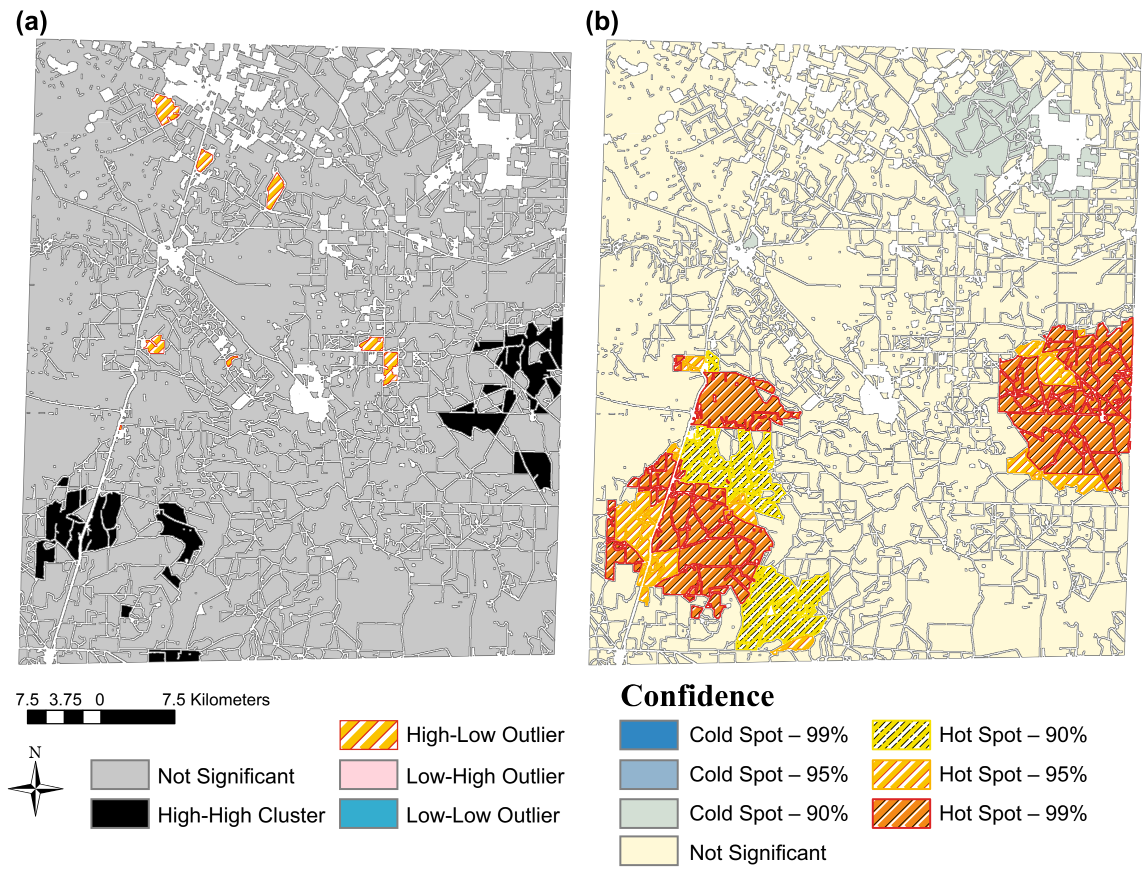


Fig. 5 Cluster maps weighted by percent O&G infrastructure intersection with stream area based on fixed-distance band. **a** LISA and **b** Gi*

Important Soil Characteristics Associated with O&G Development

Reclamation success is potentially more likely if pre-existing (baseline) conditions are assessed before development begins (DellaSala et al. 2003; Drohan and Brittingham 2012). For example, soil characteristics (e.g., bulk density, pH, and hydraulic conductivity) and vegetation assessments could be measured at the site before development. Amelioration efforts could then be tailored to match prior conditions (Skousen et al. 1994; DellaSala et al. 2003; Drohan and Brittingham 2012). Soil stabilization practices, where cement or other stabilizers are added to permanent infrastructure (e.g., pads or permanent access roads), will help reduce wind and water erosion but may hinder reclamation when O&G production ends. Careful handling of soil resources during site development can preserve original substrate, water-holding capacity, fertility, and pH, all of which can improve restoration success (Skousen et al. 1994; DellaSala et al. 2003; Drohan and Brittingham 2012). Generally, soils in semiarid regions are eroded more from the forces of wind than from water (Ravi et al. 2011). Some research has been conducted on controlling the erosive forces from surface runoff on O&G infrastructure in more humid regions of Texas (Wachal et al. 2009); however, we are unaware of research focusing on drier regions of Texas, where erosive forces from wind are the dominate sources of soil erosion. For comparative purposes, we used the SSURGO database to assess the susceptibility of existing cropland soils in La Salle County to wind erosion. We found that approximately 16,000 ha of cropland exists—with a potential for 3.5 million tons of soil loss from wind erosion—compared to $\sim$11,000 ha of disturbance from new O&G infrastructure with a potential for 2 million tons of soil loss from wind erosion. Finally, more passive measures that prevent landscape fragmentation and degradation could be considered in pre-development planning; for example, O&G infrastructure could be constructed next to existing infrastructure or already degraded lands to maintain intact core-habitat areas and critical habitat corridors when possible (DellaSala et al. 2003; Johnson 2010; Diffendorfer and Compton 2014).

Applying Spatial Statistical Analyses

Spatial statistical analyses in the decision-support process for infrastructure siting (Porter et al. 2009) can guide development and minimize further impacts to the landscape.

In our study, the analyses of core-area and stream-area fragmentation show “cold” spots within the county (i.e., those with low fragmentation during the study period). Depending on the conditions written into land leases and distances from drill pads to target areas, these areas could be avoided, which would preserve larger core areas while allowing operators to continue exploration practices.

Conclusions

Our results indicate that approximately 3 % of the total area of LaSalle County has been disrupted by O&G infrastructure (drilling pads, injection pads, and pipelines), causing an 8.7 % decrease in what we defined as core areas. Most (88 %) disturbance has occurred on soils highly susceptible to wind erosion. Although precipitation is low in La Salle County, 51 % of soils underlying O&G disturbance are susceptible to erosion during runoff from heavy rainfall events. Recent estimates suggest that only 10 % of the expected number of wells have been drilled to date in the EF (Gong et al. 2013; Scanlon et al. 2014). This estimate stems from a potential tenfold increase in wells drilled over the next 20–30 years, before the hydrocarbon reserves in the EF are depleted (Pack 2012; personal communication with T. Tunstall).

In this study, local spatial statistics provided a means for mapping likely hot spots and potential disturbances to ecosystems; these statistics also show areas where disturbances are minimal, perhaps guiding decisions about which areas to avoid in the future. Identifying these hot spots could also be useful for deciding where to place new infrastructure—if regional planning and operator cooperation were used to manage the lands in a more integrated fashion. Knowing hot spots could help guide stream monitoring of pollutants and sediment or correlate disturbance regimes with threatened or endangered species.

Oil and gas exploration in the EF play will continue for the foreseeable future, but landscape impacts could be reduced or minimized by employing best management practices. One such practice would be to encourage a continued increase in multi-well pads. Increasing the density of wells on pads could centrally locate other supporting infrastructure (e.g., roadways, pipelines, and electrical service) and could ultimately reduce the level of landscape disturbance from pad construction (Drohan et al. 2012; Thuot 2014). Paradoxically, though, the density increase could extend the operational period of individual drilling pads and thus result in a longer time until reclamation (Drohan et al. 2012). Collaborative research at a national level comparing landscape impacts from shale development will help us develop a broader understanding of how shale exploitation is changing the landscape.

This analysis highlights the possibility that removal or degradation of core-habitat areas may have compounded effects on the landscape composition available to wildlife. In this case study of La Salle County, the disturbance from infrastructure development (3 % of county area) decreased the available core areas by almost three times the area of disturbance (8.7 % decrease in county core areas). Careful and considered placement of future infrastructure will help preserve the landscape, soil resources, and ecosystem services of this area.

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