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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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Impacts from above-ground activities in the Eagle Ford Shale play on landscapes and hydrologic flows, La Salle County, Texas

by

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Thesis

Presented to the Faculty of the Graduate School of

The University of Texas at Austin

in Partial Fulfillment

of the Requirements

for the Degree of

Master of Science in Energy and Earth Resources

The University of Texas at Austin

August, 2014

Dedication

I dedicate this thesis to my wife, partner, and best friend Mary Jane Minehart. She encouraged me to take a chance and redefine myself by returning to school. She has been a solid foundation of support throughout this entire process. Furthermore, to the memory of my late father, James Joseph Pierre, who spent his life passionately studying and practicing the science of geology.

Acknowledgements

I thank my supervisor and mentor, Dr. Michael Young, for sharing his vision and encouraging me to be a part of this research. He consistently and patiently provided me with invaluable advice and guidance that will serve me well for the years to come. Additionally, I thank Dr. Bridget Scanlon because she provided invaluable instruction that enabled me to broaden my skillsets and analytical abilities. I thank Dr. Richard Kyle who was willing to co-supervise this thesis with Dr. Young. His input to this work provided an alternative viewpoint that helped to refine the scope of this work. I also thank the many researchers at the Bureau of Economic Geology who assisted me and guided me throughout this process.

Lastly, I am grateful for the support of the State of Texas Advanced Resource Recovery (STARR) program that provided the funding for this project.

Abstract

Impacts from above-ground activities in the Eagle Ford Shale play on landscapes and hydrologic flows, La Salle County, Texas

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The University of Texas at Austin, 2014

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Expanded production of hydrocarbons by means of horizontal drilling and hydraulic fracturing of shale formations has become one of the most important changes in the North American petroleum industry in decades, and the Eagle Ford (EF) Shale play in South Texas is currently one of the largest producers of oil and gas in the United States. Since 2008, more than 5000 wells have been drilled in the EF. To date, little research has focused on landscape impacts (e.g., fragmentation and soil erosion) from the construction of drilling pads, roads, pipelines, and other infrastructure. The goal of this study was to assess the spatial fragmentation from the recent EF shale boom, focusing on La Salle County, Texas. To achieve this goal, a database of wells and pipelines was overlain onto base maps of land cover, soil type, vegetation assemblages, and hydrologic units. Changes to the continuity of different ecoregions and supporting landscapes were then assessed using the Landscape Fragmentation Tool as quantified by land area and continuity of core landscape areas (those degraded by “edge effects”). Results show an increase in ecosystem fragmentation with a reduction in core areas of 8.7% (~333 km^2) and an increase in landscape patches (0.2%; 6.4 km^2), edges (1.8%; ~69 km^2), and perforated areas (4.2%; ~162 km^2) within the county. Pipeline construction dominates sources of landscape disturbance, followed by drilling and injection pads (85%, 15%, and 0.03% of disturbed area, respectively). This analysis indicates an increase in the potential for soil loss, with 51% (~58 km^2) of all disturbance regimes occurring on soils with low water-transmission rates and a high runoff potential (hydrologic soil group D). Additionally, 88% (~100 km^2) of all disturbances occurred on soils with a wind erodibility index of approximately 19 $kt/km^2/yr$ or higher, resulting in an estimated potential of 2 million tonnes of soil loss per year. Depending on the placement of infrastructure relative to surface drainage patterns and erodible soil, these results show that small changes in placement may significantly reduce ecological and hydrological impacts as they relate to surface runoff. Furthermore, rapid site reclamation of drilling pads and pipeline right-of-ways could substantially mitigate potential impacts.

Table of Contents

List of Tables x

List of Figures xi

Chapter 1: The Eagle Ford Shale play..1

1.1 Eagle Ford Shale Play Background 1

1.2 Objectives 3

1.3 Thesis organization 4

Chapter 1: References 7

Chapter 2: Literature Review..8

2.1 An outline of well and infrastructure development 8

2.2 Above ground disturbance associated with infrastructure development ..9

2.3 Landscape Fragmentation 11

2.4 Land change and habitat fragmentation 15

2.5 Spatial analysis...19

Chapter 2: References 23

Chapter 3: La Salle County case study 28

3.1 Introduction...29

3.2 Methods and materials 35

3.2.1 Site description..35

3.2.2 Data and GIS methods 36

3.2.2.1. Landscape fragmentation 36

3.2.2.2. Stream fragmentation..39

3.2.3. Statistical analysis of geospatial data.......................................39

3.3 Results and Discussion 42

3.3.1. Landscape fragmentation 42

3.3.2. Soil characteristics of disturbance regimes...............................44

3.3.3. Spatial statistical analyses...45

3.4. Conclusions...47

3.5 Acknowledgements..50
Chapter 3: Tables 51
Chapter 3: Figures...55
Chapter 3: References 61
Chapter 3: Supplementary Tables 66
Chapter 3: Supplementary Figure 69

Chapter 4: Discussion 70
4.1 Limitations and uncertainties 70
4.2 Implications of Landscape Change and fragmentation...........................72
    4.2.1 Restricted movement of animals...72
    4.2.2 Encroachment by invasive species...73
    4.2.3 Loss of biodiversity and ecosystem services 74
    4.2.4 Changes in hydrologic flowpaths...75
    4.2.5 Desertification 76
4.3 Final Statements...77
Chapter 4: References 78

BIBLIOGRAPHY 81

List of Tables

Table 3.1: Potential wind erodibility across disturbance regimes. 51

Table 3.2: Soil surface texture across disturbance regimes. 52

Table 3.3: Hydrologic soil group-dominant condition across disturbance regimes. 53

Table 3.4: Global statistics for core-area loss and stream-area loss at three fixed-distance band thresholds. 54

Table 3.S1: Change in landscape composition from each disturbance regime analyzed separately. 66

Table 3.S2: Soil properties across disturbance regimes. 67

List of Figures

Figure 1.1: EIA map showing three phase window: oil, wet gas/condensate, and dry gas 5

Figure 1.2: Annual permit and completion numbers for horizontal wells in the Austin Chalk 6

Figure 2.1: Phases of well development. 22

Figure 3.1: Study area of La Salle County, Texas, with oil and gas wells. 55

Figure 3.2: Workflow diagram used to (a) identify and quantify disturbance regimes and (b) assess landscape composition. 56

Figure 3.3: Changes in landscape classes after 12 years of Eagle Ford development. (a) pre–Eagle Ford development in 2001, and (b) post–Eagle Ford development in 2012. 57

Figure 3.4**:** Change in landscape classes after 12 years of EF development. (a) 2001 pre-EF conditions by area, (b) 2012 post-EF conditions by area, (c) 2001 pre-EF conditions by percent of county area, and (d) 2012 post-EF conditions by percent of county area. 58

Figure 3.5: Cluster maps weighted by percent decrease of core area based on fixed-distance band. (a) LISA, and (b) Gi*. 59

Figure 3.6: Cluster maps weighted by percent decrease of stream area based on fixed-distance band. (a) LISA, and (b) Gi*. 60

Figure 3.S1: Incremental spatial autocorrelation results using Moran's *I* for both core-area and stream-area loss. 69

Chapter 1: The Eagle Ford Shale play

1.1 EAGLE FORD SHALE PLAY BACKGROUND

The Eagle Ford Shale formation (EF) has been known as a hydrocarbon source for many years. The EF, considered to be the source rock for the Austin Chalk, hosts well-known fields such as the Giddings and Brookeland in East Texas, and the Pearsall formation in West Texas (Martin et al., 2011). The Austin Chalk has been the target of oil and gas (O&G) extraction for over 80 years (IHS, 2013) and Austin Chalk production areas occur within the same footprint as the EF (Martin et al., 2011). This region of south Texas is not new to O&G production and related activities, and has also experienced the rapid infrastructure development that accompanies these boom periods of O&G extraction. Today with advancements in horizontal drilling and hydraulic fracturing (HF), operators are now targeting the EF source rock, particularly in the window where oil and gas condensate reservoirs have been proven (EIA, 2010; Driskill et al., 2012) (Fig. 1.1).

In recent years, the increase in oil prices and collapse of gas prices have shifted extraction to more oil-rich pay zones; oil prices are now 4-6 times the price per unit of energy compared to gas (EIA, 2014). As a result of these factors the EF has quickly evolved to be the most important play in Texas with respect to O&G production (Dukes, 2014; Gong et al., 2013). Based on capital investments the EF play is ranked as the largest O&G development in the world (Dukes, 2014). The severance taxes collected by the State of Texas on oil production, and the local wealth created from exploration and production have greatly relieved financial stresses in south Texas. Tunstall et al. (2013)

examined the economic impact from development of the EF in the 14 largest producing counties and six adjacent counties that are experiencing growth from activities beyond the scope of drilling and exploration. They estimate that, in 2012 alone, an estimated 116,000 jobs were supported with over $61 billion in economic impacts (Tunstall et al., 2013). By 2022, Tunstall et al. (2013) estimate that the economic activities will expand, supporting over 127,000 jobs and generating over $89 billion for the 20-county south Texas economy. To date, the growth rate of the EF development has been similar to the pace of the Austin Chalk development in the early 1990's (Martin et al., 2011). However, Austin Chalk production peaked in the early 1990's and tapered off by the late 1990's (Fig 1.2, Martin et al., 2011); whereas, EF production is expected to continue at its current pace for the next two to three decades (Gong et al., 2013). Although techniques for horizontal drilling were not as advanced as they are today, the Austin Chalk was produced by both horizontal and vertical drilling techniques in the early 1980's (Meehan, 1995). Compared to the EF, the Austin Chalk has a much higher permeability because flow to the well bore relied on secondary porosity that resulted from naturally occurring fractures (Hill et al., 1978), but it was still considered a low productivity unit. As far back as the mid-1970's, interest existed in hydraulically fracturing the Austin Chalk (Hill et al., 1978; Meehan, 1995; Shelkholeslami et al., 1991) and some operators were employing the technique. However, as was the case for horizontal drilling, hydraulic fracturing practices were not as advanced as they are today.

1.2 OBJECTIVES

This investigation focused on landscape conversion that is a result of O&G infrastructure development over a 12-year period (March 30, 2001 to December 11, 2012) in La Salle County, Texas. Spatial statistical techniques were used to quantify disturbance regimes and to identify landscape alteration hot spots. Analyses were performed on the entire play to eliminate edge effects, but I report only results from La Salle County, which is representative of the activity throughout the play, and one of the top four producing counties in the EF (Scanlon et al., 2014).

The three main objectives for this analysis were to:

(1) quantify current degree of landscape fragmentation in La Salle County during this 12-year period;
(2) identify “hot spots” (and “cold spots”) of core area degradation in LaSalle County; and
(3) identify “hot spots” (and “cold spots”) of stream disruptions in LaSalle County.

Considering that development of the EF is at an early stage and that continued activity is expected to occur over the next 20-30 years (Gong et al., 2013), the methodology developed in this work can serve as a guide to limit fragmentation of habitats and promote both preservation of ecosystem services and development of a natural resource that is vital to the Texas economy.

1.3 THESIS ORGANIZATION

The remainder of this thesis is organized into three additional chapters. Chapter 2 consists of a literature review focusing on O&G infrastructure development, theory and concepts of the relatively new field of landscape fragmentation, and spatial analysis techniques. Chapter 3 consists of a case study of La Salle County Texas. This chapter was designed to stand as a manuscript, outside of this thesis. Along with the abstract at the beginning of this thesis, Chapter 3 was submitted as a manuscript to *Environmental Management* on July 8th, 2014. For this reason, some discussion may be repeated within this thesis. Lastly, Chapter 4 discusses limitations and uncertainties involved with the methodologies used in the La Salle case study, and it provides a discussion with a broader focus on the impacts that often accompany land change and the associated fragmentation.

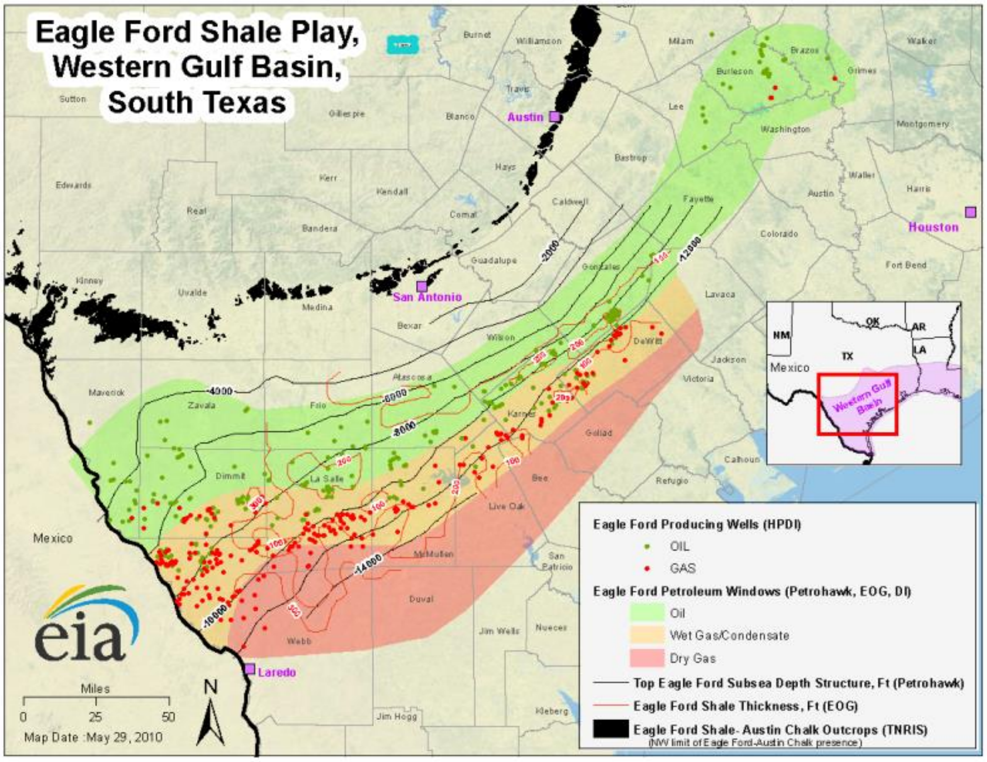

Figure 1.1: EIA map showing three phase window: oil, wet gas/condensate, and dry gas

Source: (http://www.eia.gov/oil_gas/rpd/shaleusa9.pdf)

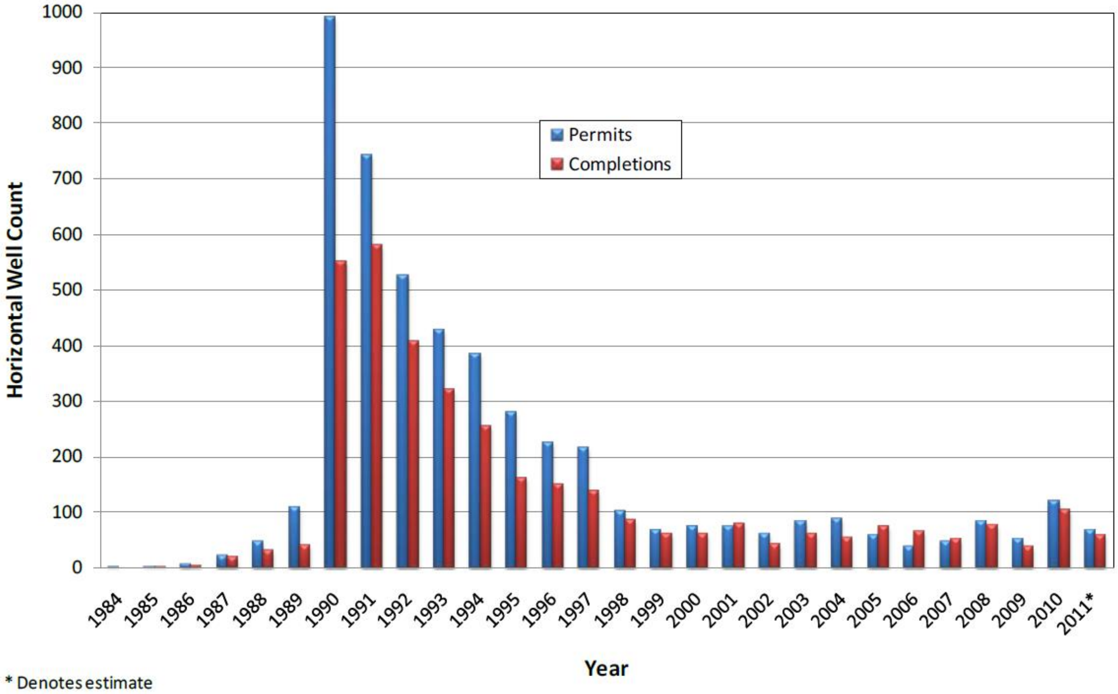

Figure 1.2: Annual permit and completion numbers for horizontal wells in the Austin Chalk (Sourced from Martin et al., 2011 based on 2011 IHS data.)

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Chapter 2: Literature Review

2.1 AN OUTLINE OF WELL AND INFRASTRUCTURE DEVELOPMENT

Development of infrastructure for O&G is a complicated process. A simplified and brief overview of well development is provided here. A general understanding of the steps involved with infrastructure development is necessary if a development guide that limits impacts to the landscape is to be designed.

Exploration to identify potential hydrocarbon reserves is the first step in identifying new well locations. This process involves geologic studies, petrophysical assessments, and seismic interpretation coupled with negotiation of surface access and leasing of mineral rights. These are necessary preliminary steps in deciding where to drill (Britt and Schoeffler, 2009; King, 2012). Permitting is the next phase of development, which requires acquisition of any necessary federal, state, and local permits. This phase may also involve meetings with concerned citizen groups, and/or wildlife experts, and/or various environmental groups, etc. These discussions can take anywhere from a few months to a few years to complete. States with extensive hydrocarbon development infrastructure have regulatory oversight responsibilities in every phase of oil and gas development (King, 2012).

Initial drilling/exploratory activities occur next. This process may take anywhere from a few weeks to a few months. Drilling into the reservoir is done to assess the composition of fluids in the rock and to assess the productive capacity of the formation. At this stage, the development areas and pay zones are remapped with newly gathered information. This is also the point where drilling shifts focus from exploration to production with equipment and technology matched to local geology. Any hazards or avoidance zones are recognized in this stage and development is focused on the best pay zones to produce (King, 2012; Mroz and Schuller, 1990). The next phase involves drilling and testing of the well, hydraulic stimulation, (fracfocus.org, 2014 accessed June 2, 2014; King, 2012) and finally connection of the well to facilities for separating gas, oil, and water before transportation (pipelines or trucking facilities) of hydrocarbons (Britt and Smith, 2009; King, 2012). The last and final stage occurs when production from the well ceases and the site is ready for abandonment and reclamation. Figure 2.1 (Marathon Oil Corporation, 2013) outlines the phases involved with well development.

2.2 ABOVE GROUND DISTURBANCE ASSOCIATED WITH INFRASTRUCTURE DEVELOPMENT

After well locations have been established and lease and access agreements have been signed, drill pad construction commences (King, 2012; Marathon Oil Corporation, 2013). These construction activities involve upgrading roads and electrical supplies, clearing and grading land, storing topsoil for later reclamation, and implementing erosion controls (Marathon Oil Corporation, 2013). We are unaware of any published literature on drill pad construction, but based on personal observations at field sites, soil cementing agents and gravel aggregates are being used to construct drill pads. To upgrade temporary roads, Wachal et al. (2009) reported the practice of adding Flex Base, a commercial product used as a base for asphalt roads.

Regulation of these activities is controlled by local and state authorities, and no specific federal laws are in place to regulate these construction activities. In 2006, the U.S. Environmental Protection Agency (EPA) issued a final ruling to exclude oil and gas operations from obtaining National Pollutant Discharge Elimination System (NPDES) storm water permits, under the jurisdiction of the Clean Water Act. The ruling states that as long as contaminants such as oil, grease, and hazardous substances are not present, oil and gas exploration is exempt from obtaining NPDES permits. EPA also issued a statement encouraging the oil and gas industry to implement best management practices (BMPs). As a result, the petroleum industry has improved upon a 2004 document entitled Reasonable and Prudent Practices for Stabilization (RAPPS) (FracFocus.org, 2013). RAPPS provides a basic engineering guide to site development in order to limit runoff and release of contamination. RAPPS does not account for local ecosystems in the consideration of the placement of these sites.

Wachal et al. (2009) modeled a number of best management practices (BMPs) using the revised universal soil loss equation (RUSLE 2.0), predicted sediment yields and evaluated the effectiveness of different combinations of BMPs using multiple combinations of conditions commonly found on gas drilling sites near Denton, TX. Their results highlighted the importance of choosing appropriate BMPs based on site conditions. For example, they found that sediment yields were reduced anywhere from 52-93% when using BMPs.

In the Marcellus Shale play in Pennsylvania, Drohan and Brittingham (2012) examined soil and topographic characteristics along with the physical disturbance from O&G to begin the development of a landscape level knowledge base. They found that, as of 2012, 16% of pads had been reclaimed. They also reported that one of the largest risks to reclamation could be surface runoff and erosion across their study area. Pennsylvania requires a 70% restoration of perennial vegetation to disturbed sites (PACode, 2012).

In Texas, the Cesar Kleberg Wildlife Research Institute (CKWRI) along with South Texas Natives (STN) have begun collaborative research on pipeline right-of-way restoration in the EF (Smith et al., 2010). This effort includes development and production of native seed specifically designed for south Texas. In 2009, they announced the release of a *Digitaria californica* (Arizona Cottontop) seed that is selected for a germplasm (La Salle Germplasm) specific to the region (Smith et al., 2009). This collaborative research between CKWRI and STN is under way on the Hixon Ranch in La Salle County near Cotulla, TX. The goals of these efforts are to prevent the spread of invasive species, encourage use of native seed with appropriate provenance, and achieve a high success rate for O&G reclamation.

2.3 LANDSCAPE FRAGMENTATION

Two terms are used frequently within this thesis: disturbance and landscape fragmentation. Disturbance is defined as the area (km^2) of landscape that, as a result of O&G infrastructure, was converted to bare earth or developed with infrastructure. Landscape fragmentation is defined as a change in the composition of the landscape that has a splitting or isolating effect on ecological and even hydrological systems (Jaeger, 2000). Landscape fragmentation breaks apart contiguous sections of undisturbed landscapes, ultimately causing habitat destruction and fragmentation that threatens biodiversity (Tilman et al., 1994).

Drohan and Brittingham (2012) and Drohan et al. (2012) have carried out some preliminary investigations into land fragmentation caused by drilling and production activities in the Marcellus Shale region of the Alleghany Plateau. They stated that a significant degree of fragmentation has occurred and is likely to continue. Their conclusions suggest that drilling is somewhat competing with food production, infrastructure siting is often poorly selected, and soil drainage problems are likely to occur. They recommend further investigations on the impacts of landscape fragmentation. And, they stress a need for a development guide that can avoid and limit potentially harmful effects from land disturbance and fragmentation. Currently, little if any research is being done on the effects of landscape fragmentation as a result of the development of the EF play in the semi-arid southern Texas climate.

One-third of the global land surface is occupied by semi-arid and arid regions and they constitute and important means of living for many societies (Hille Ris Lambers et al., 2001; Thomas, 2011). These semi-arid and arid regions of the world can be used as indicators to desertification (Alados et al., 2011; Helldén, 1991). The region under development by the EF play is an already water-stressed environment (Nicot and Scanlon, 2012). Intensive landscape fragmentation in the EF has the potential to change soil water infiltration potential, alter runoff (Drohan and Brittingham, 2012) and contaminant pathways (Banks and Wachal, 2007) as well as alter faunal and floral distribution and diversity.

Biodiversity within a semi-arid landscape is heavily dependent on factors such as spatial and temporal distribution of herbaceous and woody plant species (Maltchik and Medeiros, 2006), and the ratio of herbaceous to woody plants depends on variation of soil moisture both laterally and at depth (Breshears and Barnes, 1999). In turn, soil moisture variation is a result of patch (contiguous areas with same biome) density of woody and herbaceous species (Ludwig et al., 2005). Landscape fragmentation has been shown to increase homogeneity within semi-arid vegetation, by reducing areas of patches and increasing invasive species (Svoray et al., 2007). Fragmentation of landscapes has been observed to reduce soil porosity, infiltration rate, and productivity while increasing evaporation rates, particularly when soil resources are mishandled during excavation (Avirmed et al., 2014; Drohan et al., 2012; Skousen et al., 1994). Demographic processes such as seed germination, establishment, and maturation have been observed to be affected by the ratio of herbaceous to woody species as well as density of colony patches (Alados et al., 2009; Breshears and Barnes, 1999).

Even with what has been published to date, a research gap exists in understanding semi-arid landscape fragmentation. Recent attention has been paid to the semi-arid Mediterranean by researchers, due to concerns regarding changes in climate and ecosystem services that could potentially have severe anthropogenic consequences (Kéfi et al., 2007; Puigdefábregas and Mendizabal, 1998; Saiz and Alados, 2011; Shoshany, 2002). Saiz and Alados (2011) observed changes to composition of plant communities that resulted from a change in competition regimes because of anthropogenic disturbances. Kéfi et al. (2007) observed shifts in patch-size distribution of vegetation that indicated increased desertification as a result of anthropogenic activities. Through modeling, they suggest that patch-size distribution can be used as a warning signal for the onset of desertification. Puigdefábregas and Mendizabal (1998) noticed deterioration in soil quality and water quality (both surface and underground sources) because of the overexploitation of land and water resources and predicted desertification hot spots using spatial analyses. In semiarid Israel, Shoshany (2002) observed shifts in floristic composition and soil albedo, indicating a slow landscape fragmentation with a continuation of soil loss over an ~30 year time period. In Inner Mongolia, John et al. (2009) noticed that disturbances on a local level can manifest themselves into changes at the regional biome level, in the context of regional climate change and water stresses.

As land fragmentation alters the vegetative diversity of the landscape, it may also alter the faunal diversity, not only through the introduction of exotic species (Lehmann, 1984) but also through the alteration of flow paths. Landscape fragmentation from O&G in south Texas is accompanied by soil disturbance and compaction that could alter runoff patterns and concentrate flow more capable of carrying sediment or contaminants with a higher potential for bypassing natural attenuation processes (Entrekin et al., 2011; Olmstead et al., 2013; Wachal et al., 2009). In northern Idaho, for example, King and Tennyson (1984) found that hydrologic behavior of small watersheds were altered when only a small area of land was disturbed by road construction. Restricting their study to watersheds with only 5% of their area affected by logging road construction, they observed a 25% overall increase in exceedance flows in one watershed and a 5% decrease in exceedance flows in another. Jones et al. (2000) studied larger watersheds in a more humid climate with more disturbance from road construction, and found that road construction modified flood and debris flow. They speculate these changes may affect ecosystem resiliency and recovery of patches disturbed by these changes. Construction of infrastructure in south Texas may change perennial flows to seasonal flows, potentially altering hydrologic connections within streambeds. These types of changes could have a significant effect on the sustainability of both invertebrate (Stanley et al., 1997) and vertebrate inhabitants (Trombulak and Frissell, 2000) of these hydrologic ecosystems. Relatively few studies are available on the hydrologic patterns of non-perennial streams (Maltchik and Medeiros, 2006; Medeiros and Maltchik, 1999; Stanley et al., 1997). Finn et al. (2007) discovered in their Death Valley investigations that taxa without the means of aerial migration can become disconnected by stream length of tens of kilometers and may become completely distinct from other populations that can limit their genetic adaptability to water stresses.

2.4 LAND CHANGE AND HABITAT FRAGMENTATION

In the past two decades, research has demonstrated that anthropogenic influence on land cover change dominates natural processes and that uncertainties exist on the long term impact of these influences on the environment (Nagendra et al., 2004; NRC, 1999). Socio-economic activities such as, resource exploitation, industry development, urban sprawl, and other factors like land ownership are the dominant drivers of land use that lead to anthropogenic land cover change (Corvalán et al., 2005; Macie and Hermansen, 2002; Martínez de Anguita et al., 2008; Nagendra et al., 2004; Sampson and DeCoster, 2000). Habitat fragmentation consists of both the splintering of large habitat areas into disconnected patches and the physical loss of natural habitat areas (Fahrig and Merriam, 1985; Fahrig, 2003) most often caused by landscape fragmentation. The resultant habitat loss and fragmentation are the main determinants of ecosystem processes within and among remaining vegetation patches. These processes include plant regeneration, supply of propagules, seed dispersion, pollination, and survival from seed predators. Exotic species introduced during fragmentation suppress the regeneration and diversity of native propagules (Chapin III et al., 2000; Debuse et al., 2009; Olson and Doherty, 2012).

Sites with less remaining natural cover have less favorable rates of regeneration, which may be a result of lack of available water in the seedbed (top 20 cm), increased soil temperatures, high percolation rates through the seedbed (Caldwell et al., 2009; Debuse et al., 2009) and soil loss and degradation resulting from a lack of vegetative cover (Skousen et al., 1994) . The initial degree to which habitat loss occurs will affect both the time to achieve equilibrium as well as the patterns of occupancy within patches (Vellend, 2003). Isolated patches found in older mostly cleared landscapes show a more favorable colonization by species that have an ability to cross larger gaps (Hermy, 1992; Matlack, 2005). Micro-climate edge effects facilitate within-patch colonization of woody species of irregularly shaped patches with greater perimeter to area ratios (Debinski and Holt, 2000; Ochoa-Gaona et al., 2004; Saunders et al., 1991).

Disturbance regimes, climate, and alteration of limiting resources can have strong effects on ecosystem functioning. Commonly these effects can be caused by one introduced species (Hooper, 1997; Tilman, 1997). For example, the salt cedar (*Tamarix spp.*) was introduced into the Mojave and Sonoran Deserts of North America with the intention of controlling erosion along stream banks. This introduction increased soil solute levels, soil water uptake, surface litter, and surface salts. As a result many native species were consequently out competed. Regeneration of native plant species was inhibited while biodiversity was greatly reduced (Berry, 1970). The ultimate reduction in agricultural and municipal water supplies from the introduction of salt cedar is estimated to cost $65-180 million per year (Zavaleta, 2000). Narrowed river channels, a result of cedar introduction, has increased flood damages by an estimated $50 million annually (Zavaleta, 2000). Using another example, a grass species (*Agropyon cristatum*) was widely introduced into the Great Plains of North America after the 1930's dust bowl. This aggressive grass stores 25% less carbon compared to native grasses (Christian and Wilson, 1999). The invasion of the introduced cheatgrass (*Bromus tectorum*) has increased the risk of fires by ten-fold (Whisenant, 1990).

Microclimates created by introduced species can be just as important as direct impacts of environmental change (Chapin III et al., 2000). Furthermore, interactions between species determine the characteristics of the ecosystem; these functions are generally non-additive. The loss or addition of a certain species in a functioning ecosystem increases the probability of cascading effects across the whole system (Chapin III et al., 2000). Changes in biota can alter nutrient cycles that in turn can influence the carbon balance within the entire system.

Factors that promote native plant diversity, such as the disturbance regime and soil type, can also promote species invasion at the landscape scale (Stohlgren et al., 1999). This is because community composition affects invasibility through competition and trophic interaction (Chapin III et al., 2000). The addition or loss of a species from a natural ecosystem can be costly in both ecosystem functioning and economic senses. Assigning a monetary value to changes in biodiversity is a recent field of study that has the interests of both ecologists and economists, though significant uncertainty exists involved with predicting value of losses induced by changes to biodiversity within ecosystems, and in how to value those changes. As a result, managers often make myopic decisions regarding the preservation of land (Chapin III et al., 2000).

There is strong evidence to support that changes in biodiversity have consequences for both ecosystem services and society. On a global scale, changes in land use are thought to impart the greatest impacts to ecosystem function and biodiversity (Chapin III et al., 2000); thus, ecological and social consequences need to be considered during all stages of land use planning. With proper management and planning practices, landscapes can support a greater portion of regional biodiversity (Chapin III et al., 2000). Improvements in land and watershed management will decrease the likelihood of invasive species introduction and enhance biodiversity.

Regarding South Texas, a number of invasive grass species were introduced during the 1940's to control soil erosion and mitigate overgrazed rangelands (Flanders et al., 2006). Two grasses in particular, Lehman lovegrass (*Eragrostis lehmanniana*) and buffelgrass (*Pennisetum ciliare*) have been shown to simplify ecosystems and reduce biodiversity through the displacement of native species (Anable et al., 1992; Cox et al., 1988). Bock et al. (1986) demonstrated that simplification of floral diversity also resulted in the simplification of vertebrate and invertebrate diversity as well. In the Chaparral Wildlife Management Area (CWMA), which is in both Dimmit and La Salle Counties, Flanders et al. (2006) demonstrated that spider, beetle, and ant species were less abundant in exotic grass stands compared to native grass stands. These exotic grass species were not planted in CWMA and they became established through accidental introduction by vectors such as livestock, vehicles, or wind dispersal (Lehman, 1969). Spiders, beetles, and bees and wasps are primary food sources for the Northern Bobwhite quail (Lehmann, 1984), a species that attracts hunters and, subsequently, income to South Texas.

It is clear that habitat loss leads to habitat fragmentation (Balvanera et al., 2006; Chapin III et al., 2000). The analysis that follows in Chapter 3 does not include a detailed examination of landscape fragmentation effects that are occurring because of O&G activity. Rather, it serves to quantify land conversion from the development of O&G infrastructure and to identify concentrated areas of this disturbance.

2.5 SPATIAL ANALYSIS

The location of oil and gas wells is not a random process with respect to the subsurface geology. However, it is a random disruption above-ground in relation to surficial geology and the landscape classes that exist in these locations. Many factors are considered in the ultimate placement of oil and gas infrastructure. These factors include land ownership, mineral rights, road access, and pipeline access among many others. The fragmentation of ecosystem services for the most part traditionally does not play a role when industry decides where to locate oil and gas infrastructure. Spatial analysis techniques can play a role in analyzing the changes that are occurring to the above ground landscape and help to reduce potential impacts to ecosystem services.

For example, in their investigation of wildfire ignition points in Galicia in Northwest Spain, Chas-Amil et al. (2013) employed spatial analysis techniques to identify high risk areas for wildfire occurrences, which is the highest in Spain. Their approach used the contact zone between the human built environment and the vegetation of the wildland, which they called the wildland-urban interface (WUI). It is well known that a direct relationship exists between the WUI and wildfires, and recent change in Galician law now requires the clearing of vegetation within 100 m of buildings that are found within 400 m of forestland. Based on previous work that demonstrates that wildfire spread is more likely to occur in forested areas greater than 500 ha, the researchers identified forested areas that were 500 ha or more using landcover datasets and applied a 400m buffer around these areas. To differentiate the WUI's into classifications, Chas-Amil et al. (2013) used a forest fragmentation analysis based on the methods proposed by Vogt et al. (2007), as was done in this thesis and reported in Chapter 3, to assign three fragmentation classifications: low, high, and non-forested. They also further classified the WUI's by building intensity classes of: isolated, dispersed, dense clustered, and very dense clustered. The end result was the classification of 12 WUI categories based on building density and forest fragmentation.

Chas-Amil et al. (2013) then used both global and local measures of spatial autocorrelation at the parish level to analyze spatial association of the WUI's. This included Global Moran's *I* (Moran, 1950) to assess the density of WUI's at the parish level, and then used the Gi* statistic (hot spot analysis) developed by Getis and Ord (1992) to identify clusters with a positive spatial autocorrelation. This provided local density patterns across the entire study using the density of WUI's at a given parish and its neighbors. The results identified clustering of parishes with statistically high (hot spots) and low (cold spots) WUI densities. The work done by Chas-Amil et al. (2013)

serves to promote the protection of property, human lives, and economic well-being of this region.

Chen et al. (2012) used spatial statistical analyses to map changes in thermokarst lake areas in the Yukon Flats National Wildlife Refuge, Alaska. Using 30 m resolution Landsat imagery, they compared areal extent of identified thermokarst lakes between two time periods, and then classified each lake as shrinking or expanding. The mapped clusters of lakes with similar long term change trends were identified with local Moran's *I* (Anselin, 1995); short-term change (inter-annual and intra-annual variability) was then assessed using the coefficient of variation as an indicator variable in subsequent local Moran's *I* analyses. Their results indicated strong spatial autocorrelation in both the shrinking/expanding lakes and the highly variable/stable lakes. They concluded that expanding lakes clustered along floodplains, shrinking lakes clustered along alluvial terraces, and temporally variable lakes were the result of ice jam flooding events.

Roberts et al. (2000) used spatial analysis techniques to assess anthropogenically and naturally induced forest fragmentation. They analyzed forest fragmentation using spatial autocorrelation to track changes over time and showed clustering between forest patches and connecting corridors of Caledon, Ontario. Their methodology is complex, but can be used as an easily implementable habitat fragmentation model to provide insight into the preservation of these areas within the context of conservation policy.

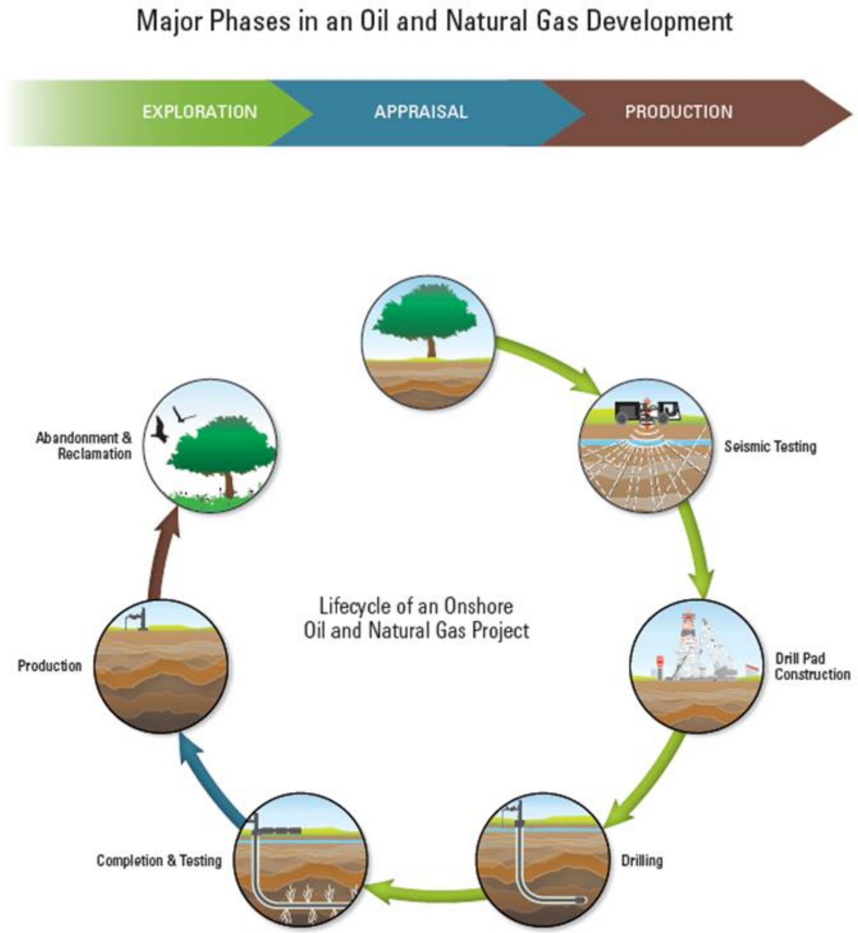

Figure 2.1: Phases of well development. (Marathon Oil Corp., 2013)

CHAPTER 2: REFERENCES

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Authors note: The following manuscript (Chapter 3) was submitted to *Environmental Management* on July 8th, 2014. The abstract at the beginning of this thesis accompanied the submitted manuscript.

Chapter 3: La Salle County case study

Impacts from above-ground activities in the Eagle Ford Shale play on landscapes and hydrologic flows, La Salle County, Texas

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Submitted:
Environmental Management
July, 2014

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3.1 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 swidden agriculture; timber harvesting; road building (Burnett et al., 2011; McDonald et al., 2004); urbanization (Wu, 2009); and extraction of hydrocarbons such as coal, oil, and gas (Bi et al., 2011; Linke et al., 2005).

Within the last 10–15 years, extracting oil and gas (O&G) from tight-formation source rocks through horizontal drilling and hydraulic fracturing has evolved from a novel to a common practice with enormous economic implications (Driskill et al., 2012; GAO, 2012). For example, in south Texas between 2009 and 2010, permits acquired for the Eagle Ford (EF) Shale play increased from 94 to 1010, and permits issued in 2011 were nearly triple (2,826) those issued in 2010 (Railroad Commission of Texas, 2014). In April 2014, over 200 drilling rigs were operating in the EF play (compare to the 2012 average of 269 rigs; 15% of all U.S. rigs [Gong et al., 2013]), making it the most active shale play in the world (Dukes, 2014). This rapid increase in activity in south Texas is accompanied by roads, pipelines, other infrastructure, and substantial economic and employment impacts. For example, as of 2012, the total economic impact in the 14-

county core area of the EF is 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 (GAO, 2012). Considering changes to 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 (Drohan and Brittingham, 2012; Drohan et al., 2012; Entrekin et al., 2011; Johnson et al., 2010). 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) suggest that the land reserved for drilling competes somewhat with land previously reserved for food production, and that sites for infrastructure are often poorly selected, leading to higher likelihood of soil-drainage problems. 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. Bi et al. (2011) also showed at their region in China that above-ground issues, such as landscape fragmentation and changes in hydrologic flow pathways from disturbances, will be ecologically important throughout the life of the play, and that older infrastructure from oil-field development played an overall larger role in long-term landscape fragmentation because little to no ecological considerations were used in the placement of the initial development.

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. 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 did suggest 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 any semiarid climate), where 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.

Research has been done on land impacts 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, where increased homogeneity in vegetation was a result of reduced minority cover species. John et al. (2009) concluded that these disturbances on a local level can quickly manifest themselves as changes at the regional biome level, in the context of anthropogenic land use coupled with regional climate change. Detrimental effects from man-made impacts to ecosystems of less humid climates often take more time to be expressed, but they have long been noticed by researchers in ecology (Alados et al., 2011; John et al., 2009; Saiz and Alados, 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, Sonora, and 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 considering spatial patterns of disturbance when predicting fragmentation effects and improving management strategies.

Recent research demonstrates how spatial statistics can be used to track and identify trends in areal loss of geographic and geologic features. Roberts et al. (2000) analyzed forest fragmentation using spatial autocorrelation to track changes over time and showed clustering between forest patches and connecting corridors of Caledon, Ontario. Their methodology can be used as an easily implementable habitat fragmentation model to provide insight into the preservation of these areas within the context of conservation policy. Chen et al. (2012) used spatial statistics (e.g., Global and Local Moran's *I*) to map changes over time in thermokarst lakes in the Yukon to identify lakes with similar tendencies. They found that lakes with the same change trends formed clusters, where shrinking lakes were mostly found on alluvial terraces and expanding lakes were mostly found on floodplains. Estiri (2012) tracked urban sprawl with spatial statistics via Local Moran's *I* and found that areas threatened by urban sprawl could be readily mapped. He concluded that urbanization trends could not be represented through linear statistical techniques. He noted that a substantial challenge exists in identifying appropriate conceptualizations of spatial relationships (e.g., distance thresholds). Finally, Chas-Amil et al. (2013) used spatial statistics (e.g., Global Moran's *I* and Getis-Ord Gi* Hot Spot Analysis) and mapped the incidences of forest fire in relation to the wildland-urban interface (WUI). They used the Gi* statistic to map WUI (classified by building density and forest fragmentation) as a percentage of parish area, and intersected this map with forest-fire ignition points. These techniques can be used for a variety of purposes and will be used herein to assess “hot spots” of landscape and hydrologic disruptions from O&G operations. We consider fragmentation hot spots to be areas of concentrated core-area degradation and hydrologic hot spots to be core-areas with concentrated occurrences of O&G infrastructure development intersecting NHDPlusV2 flowlines (digitized USGS orthoquad flowlines) (Horizon Systems Corporation, 2013).

This study focuses on landscape conversion resulting from O&G infrastructure development over a 12-year period (March 30, 2001, to December 11, 2012) in La Salle County, Texas. We defined “disturbance” as the area (km^2) of 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 (km^2) of landscape classes established by the methods of Vogt et al. (2006) and analyzed by Landscape Fragmentation Tool (LFT) (version 2.0; 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 in the entire play, but we are reporting only on the methods and results from La Salle County. The four main objectives for this analysis were to:

(1) quantify the degree of landscape fragmentation in La Salle County from O&G activities;

(2) quantify soil characteristics associated with landscape disturbance regimes;

(3) identify the hot spots of core-area degradation; and,

(4) identify the hot spots of stream disruptions.

The results of this research could be used to create a development guide, as also suggested by Drohan and Brittingham (2012), which 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 in any other semiarid shale plays.

3.2 METHODS AND MATERIALS

3.2.1 Site description

Our study was done on the EF Shale play, which spans an area in Texas from the southwest border of Webb and Maverick Counties to Leon and Madison Counties in the east (Fig. 1). We chose La Salle County for our case study because exploration activity began here early in the play and is representative of other counties. In La Salle County, the shale formation varies in thickness from ~61 m (at ~2400 m deep) in the northern portion of the county to ~30.5 m (at ~3050 m deep) in the southern portion (EIA, 2010). Liquid-rich (oil and gas condensate) sections of the play are also of interest (Driskill et al., 2012). As a result, O&G activity is highly concentrated here. Operators could also increase well density; for example, Rosetta Resources, Inc., an operator in the EF, suggests a 29% increase in production by reducing spacing between wells from 100-acre spacing to 55-acre spacing (Hagale, 2012).

La Salle County is situated in the West Gulf Coastal Plain in South Texas Brush Country. The climate is semiarid, with an annual precipitation range from 51 cm in the southwest to 64 cm in the northeast and an average of 58 cm. 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%) (USDA/NRCS, 2014).

3.2.2 Data and GIS methods

3.2.2.1. Landscape fragmentation

To account for edge and fragmentation effects from energy development, we performed analyses on the 25 counties of the play, applying a 3000-m buffer (see Figure 2 for the steps taken). We obtained from Information Handling Services, Inc. (2013) well coordinates, spud date, operator name, geologic province name, and other available attributes associated with each well (whether used for production or wastewater injection) constructed between March 2001 and December 2012. We plotted wells and then overlaid the plots onto 1-m resolution aerial imagery of 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. The entire area of the pipelines was not used, to maintain consistency with undisturbed and disturbed areas being vegetated and nonvegetated, respectively. We did not consider disturbance from pipelines that were reclaimed (revegetated) before the acquisition of the 2012 NAIP imagery.

We performed unsupervised image classification on NAIP imagery, leading to the assignment of up to 10 land classes. We compared results to NAIP imagery and verified to obtain an accurate value for bare ground (disturbed). We 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. The 30-m raster cells, within the 90-m pipeline buffer, were extracted to obtain disturbance areas from recent pipeline installation. When an overlap occurred between pipelines and pads (drilling or injection), the disturbance was attributed to pads.

The National Land Cover Dataset (NLCD) of 2001 was downloaded from the USGS Landcover Institute (Homer et al., 2007) to establish a baseline (any features that showed evidence of vegetation or water) before EF development. Similar to NAIP imagery, the NLCD raster image was reclassified 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 post-EF (2012) conditions and will be referred to as “post-EF” in further discussions.

The Landscape Fragmentation Tool (LFT) (version 2.0; Parent and Hurd, 2007) used in this study is based on the work of 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 of overlapping disturbances, analyzing each disturbance regime individually will produce results that vary slightly from the simultaneous analysis of disturbances. The LFT classifies four different types of landscapes in a specified land area: (1) “core” areas (in our case, vegetated land) having pixels greater than 90 m from nonvegetated pixels, (2) “perforated” areas having vegetated pixels within 90 m of nonvegetated pixels, (3) “edge” areas having vegetated pixels along the outside edge of a core area, and (4) “patch” areas having vegetated pixels that do not contain core areas. Core areas are then further subdivided into small (<1 km^2), medium (1–2 km^2), and large (>2 km^2). Edge and perforated areas both contain pixels within 90 m of a core area; however, perforated areas exist only on the interior edge of a core area, while edge areas exist on the exterior edge of a core area. Though previous investigators (Goodrich et al., 2004; Howell et al., 2006; Robson et al., 2011; Svobodová et al., 2010) have used a 100-m edge distance, we maintained a 90-m edge distance to be consistent with the cell size.

Soil Survey Geographic (SSURGO) data were downloaded from the USDA Natural Resources Conservation Service (NRCS) National Geospatial Center of Excellence (USDA/NRCS, 2014). Data containing soil order, great group, soil series, particle size, hydrologic soil group, wind-erodibility index, and other attributes were extracted from SSURGO 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 Division Staff, 1993). Runoff potential for HSG's is ranked from A to D, where A has low potential and D has high potential.

3.2.2.2. 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. To be consistent with the methods used to analyze landscape fragmentation, all stream fragmentation was performed on the 3000-m buffered extent of the entire (25-county) EF play.

3.2.3. Statistical analysis of geospatial data

Spatial autocorrelation (SAC) is a measure of how similar (systematic) or dissimilar (random) attribute values vary in space. SAC can be subdivided into global and local statistics. Global statistics assume that the type and magnitude of SAC are stable across the study area, whereas local statistics do not assume stability. In this study, we used the Moran's *I* and Getis-Ord General G statistics as global statistical metrics. Moran's *I* (Moran, 1950) calculates the difference between the mean of all features and the target feature (e.g., percent change in vegetated areas, or interval-level soil attributes such as hydrologic soil groups) as well as the difference between the neighbor and the mean. Moran’s *I* 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). We used the General G statistic to determine whether (1) core polygons (derived from the 2001 NLCD) show a high degree of landscape or hydrologic fragmentation (clusters of disturbance) when their neighbors also have high degrees of the same fragmentation type (known as H-H polygons), and (2) core polygons have a low degree of fragmentation when their neighbors also have low degrees of fragmentation (known as L-L polygons). We used p-value and z-score to determine significance of the spatial correlation, rejecting the null hypothesis (complete spatial randomness or an independent random process exists within the disturbances) for p-value <0.01 and a z-score > 1.96 (i.e., dominated by clusters showing fragmentation) or < 1.96 (i.e., dominated by clusters showing little or no disturbance). When the null hypothesis is rejected, we analyze data on a local level for each feature of interest (in our case, core polygons), using the same clustering and significance levels as described above. In this study, we focused on 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).

Each pre-EF core-area polygon was analyzed with both global (Moran's *I*, General G) and local (LISA and Gi*) statistics by weighting each pre-EF polygon by the percent decrease in original area of the core itself and the percent decrease in original stream area within the core. The cumulative disturbance layer (drill pads, injection pads, and pipelines) was overlaid on the pre-EF core polygons to calculate both a decrease in original core area and a decrease in original stream area within the 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 ~658 m; the "incremental distance" is defined as the radius from the target feature's weighted point (in our case, the area represented by the center point of each core polygon) used to measure the degree of association of the resultant concentration of weighted points within this radius (Getis and Ord, 1992). We observed a peak in spatial autocorrelation at 8480 m for the percentages of core-area loss and stream-area loss; 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.

3.3 RESULTS AND DISCUSSION

3.3.1. Landscape fragmentation

We identified 724 permitted wells in La Salle County, with 628 wells showing visual evidence of associated infrastructure in the 2012 NAIP imagery. We identified a total of 585 drilling pads, of which only 5.4% had three or more wells per pad—most continue to be single-well pads. Our analyses showed a median drilling-pad size of 0.03 km^2 (maximum 0.26 km^2). The area disturbed from construction of wastewater injection pads was the smallest of all the sources, with a median pad size of 0.002 km^2 (maximum 0.15 km^2). Pipeline disturbance was the dominant source of land disturbance and hence had the largest influence on fragmentation effects. 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. In overall area, pipeline disturbance (97 km^2) was five times greater than the resultant disturbance from drilling pads (drilling pads=17 km^2; injection pads <1 km^2). Moreover, because pipelines tend to be long, linear features or corridors, rather than isolated "islands," of disturbance, there is a greater chance that wildlife movement could be curtailed or influenced by the infrastructure. We also found that an area of 1.1 km^2 directly intersected stream networks (~1% of all infrastructure), of which 0.7 km^2 were first-order streams. An area of 21.9 km^2 of disturbance occurred on slopes between 3 and 5% (slope values do not exceed 5% in La Salle County).

Though the disturbed area was ~3% of the total county area, approximately 333 km^2 of core areas (all three size classes of core) were lost 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, but that core forest areas declined from 76% to 68% of the county area. The difference between these two impacts is that disturbance from (mostly) pipeline networks intersect and subdivide large core areas, resulting in an increase in smaller (i.e., <1 km^2 and 1–2 km^2) core areas as well as in patch, edge, and perforated areas (Fig. 3). Although subtle and perhaps obscured by the overall activity, note in particular in Fig. 3 the areas to the east and south of the city of Cotulla, where installation of pipelines (shown as linear features) subdivides the larger core areas. Fig. 4 represents changes (in both area and percent of county area) in landscape classes for La Salle County as a result of O&G activity. The results show a 551 km^2 (27.6%) reduction of large core areas, from 2546 km^2 to 1995 km^2, with a redistribution of this land area to edge (70 km^2), perforated (162 km^2), smaller (98 km^2 and 120 km^2 for medium and small core areas, respectively) core areas, and nonvegetated (95 km^2) areas. Ten km^2 (~9%) of disturbance was located on already disturbed or degraded land. Depending on the species or process of concern, this shift to a fewer 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 ecological or hydrological impacts. 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 fall into core areas when they are developed; thus, further reduction in large core areas is expected.

The results show that pipeline installation accounted for the majority (~84%) of the documented changes in landscape-class composition across the county, with the greatest reduction in larger core areas and increasing medium core, small core, perforated, patch, and edge classes. As indicated above, we are reporting the cumulative areas of disturbance when simultaneously assessing impacts from drilling pads, injection pads, and pipeline installation. These numbers differ slightly when separately assessing impacts from these sources (see Table 3.S1 in the Supplementary Tables section).

3.3.2. Soil characteristics of disturbance regimes

Generally, soils in semiarid regions are eroded more from the forces of wind than from water (Brady, 1990; Ravi et al., 2011; USDA, 2011). Approximately 88% of O&G disturbance is occurring on soils with a wind erodibility index (WEI) of 19 kt /km^2/yr or more (Table 3.1). Though site-specific measurements of wind erodibilty were not made, an estimated 2 million tonnes of soil could be lost per year from wind erosion on landscapes disturbed by O&G infrastructure based on reported WEI values, particularly if the land is not quickly reclaimed using revegetation and/or land contouring practices. Approximately 38% percent of disturbance occurs on soils with a clay texture and 34% on soils with a very fine sandy loam texture (Table 3.2). Both textures were reported to be susceptible to wind erosion (clays more so when disturbed), ultimately resulting in a loss of soil productivity (Avirmed et al., 2014) and high dust emissions (Lyles, 1975; USDA, 2011).

Most (74%) of the infrastructure has been built on interfluvial areas, while close to one-quarter (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 this county are considered well drained or moderately well drained (USDA/NRCS, 2014), 51% of soils underlying disturbed areas have low infiltration and transmission rates (Soil Survey Division Staff, 1993; USDA, 2009) and may be susceptible to erosion during heavy rainfall events (Table 3.3). Approximately 50% of all disturbance regimes occur on partially hydric soils. Based on site visits to drilled locations in La Salle County, industry uses soil cement to create the drill pads; techniques like this will reduce wind and water erosion. Conversely, soil cement and compaction from heavy equipment will eliminate potential water storage in the upper 50 cm of the original undisturbed soil profile, which was calculated as an estimated 1,064,000 m^3 in available soil water storage, using the available water storage provided by SSURGO. We note that construction for pipeline installation is relatively short-lived compared to the productive lifetime of drill pads, which could last for many years. Areas set aside for pipelines are often rapidly reclaimed after installation is complete. If seasonal timing is suitable for native seed establishment, the site can be returned to original conditions. A more extensive breakdown of soil characteristics associated with O&G infrastructure development in La Salle County is provided in Table 3.S2 of the Supplementary Tables section.

3.3.3. Spatial statistical analyses

The results of the Moran’s *I* incremental analysis showed that, at distances exceeding 28,900 m, the percent core-area loss was no longer clustered and became a random occurrence (z<1.96). However, stream-area loss remained clustered (z>1.96) at all incremental distances up 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 correlated (28,900 m) (Table 3.4 and Fig. S1 in Supplementary Figures). Beyond 28,900 m, no clustering was observed for percent core-area loss, and disturbances were random.

In this research, we considered landscape fragmentation (the percent decrease in area for each core feature) and hydrologic fragmentation (the percent decrease in stream area for each core feature) to be potential disruptors to ecosystem functioning. The results of the local statistics (e.g., LISA map in Fig. 5a) show core-area loss (H-H) clustering in two general areas: one to the east of Cotulla and north of FM 624, and the other in the southwest corner of the county. The Gi* map (Fig. 5b) shows hot spots occurring in the same two general areas; here, hot spots are those where clustering of disturbance is considered most likely. The results show two smaller areas of cold spots appearing in the northern section of the county; cold spots represent core areas that have not been degraded by recent O&G activity. As with core-area fragmentation, H-H clusters are also present for hydrologic fragmentation (Fig. 6a). We also noted the presence of H-L outliers, which represent clusters of highly disturbed core areas adjacent to core areas with a low level of disturbance. 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. Fig. 6b also indicates the presence of cold spots for hydrologic fragmentation in the northeastern portion of La Salle County. Analyses of both core-area and stream-area fragmentation highlight cold spots within the county that are not highly fragmented. Avoiding these areas for future infrastructure development could limit additional impacts.

3.4. CONCLUSIONS

The results show 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 core areas. Most (88%) of these disturbances occur 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. Additionally, the low precipitation rates could extend reclamation periods and promote the invasion of exotic plant species. If disturbances from new roadways were included, the total area of disruption would exceed 3% of the county land area. Recent estimates suggest that only 10% of the expected number of wells have been drilled to date in the EF (Gong et al., 2013). 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. Identifying these hot spots may be useful for deciding where to place new infrastructure, as well as for guiding stream monitoring of pollutants and sediment, or correlating disturbance regimes with threatened or endangered species. Further work will be done to determine appropriate setbacks to avoid ecologically sensitive areas and fragmentation of larger core areas. Further work will also include the use of geographically weighted regression (GWR) schemes to identify the influence of certain practices on ecosystem degradation. For instance, GWR could be used to map the influence of well density on drilling pads with the loss of core vegetated areas or disruptions to stream networks.

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 way would be to encourage multi-well pads, also referred to as pad drilling. Our analysis indicates that only 23% of well pads in La Salle County host two or more wells. Increasing the density of wells on pads will 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 hindering reclamation efforts (Drohan et al., 2012). Reclamation success could also be enhanced 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

(DellaSala et al., 2003; Drohan and Brittingham, 2012; Skousen et al., 1994). Soil stabilization practices where cement or other stabilizers are added to permanent infrastructure (e.g., pads or permanent access roads) will help to reduce wind and water erosion. Careful handling of soil resources during shale development can preserve original substrate, water-holding capacity, fertility, and pH, all of which can improve restoration success (DellaSala et al., 2003; Drohan and Brittingham, 2012; Skousen et al., 1994). Work has been done that focuses on controlling the erosive forces from surface runoff on O&G infrastructure in more humid regions of Texas (Wachal et al., 2009); however, very little work has focused on drier regions of Texas where erosive forces from wind are the dominate sources of soil erosion. Finally, more passive measures that prevent landscape fragmentation and degradation should be considered in predevelopment planning; for example, O&G infrastructure could be located next to existing infrastructure or already degraded lands to maintain intact core habitat areas and critical habitat corridors when possible (DellaSala et al., 2003; Diffendorfer and Compton, 2014; Johnson et al., 2010).

The increase in land disturbance outlined here does not include derivative impacts from increased housing, retail stores, restaurants, and so on, that support the increased activities in these rural regions. Moreover, we note that this area of south Texas was historically disturbed by numerous unpaved roads, many of which are used today for ranch operations. Because of the difficulty of identifying whether unpaved roads were installed to support O&G activity, unpaved roads were not considered in this analysis. We recognize that fragmentation in the EF is not solely the result of O&G activity; many other factors are contributing to landscape fragmentation.

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.

3.5 ACKNOWLEDGEMENTS

Funding for this project was made available by the State of Texas Advanced Resource Recovery (STARR) program. We appreciate the support of the Railroad Commission of Texas, which provided data on locations of pipelines. We thank Stephanie Jones, who helped edit the manuscript. Publication approved by the Director, Bureau of Economic Geology.

CHAPTER 3: TABLES

Table 3.1: Potential wind erodibility across disturbance regimes.

Wind Erodibility Index	Drilling Pads	Pipelines	Injection Pads	All Disturbance Regimes	Percentage of All Disturbance Regimes
(kt/km^2/yr)	(kt/yr)	(kt/yr)	(kt/yr)	(kt/yr)	%
0.00	0.00	0.00	0.00	0.00	2.6
10.76	2.07	12.08	0.00	14.15	1.2
12.55	14.07	97.53	0.00	111.59	7.8
19.28	256.96	1,465.20	0.73	1,722.90	78.7
30.04	59.69	264.83	0.00	324.53	9.5
Missing	0.00	0.00	0.00	0.00	0.2
Totals	332.80	1,839.64	0.73	2,173.16	100.0

Table 3.2: Soil surface texture across disturbance regimes.

Surface Texture	Drilling Pads	Pipelines	Injection Pads	All Disturbance Regimes	Percentage of All Disturbance Regimes
	km^2	km^2	km^2	km^2	%
Clay	6.96	36.13	0.01	43.09	37.9
Very fine sandy loam	5.64	33.04	0.03	38.71	34.0
Clay loam	0.83	10.67	0.00	11.50	10.1
Loamy fine sand	2.04	8.77	0.00	10.81	9.5
Fine sandy loam	0.78	2.26	0.00	3.04	2.7
Gravelly sandy clay loam	0.09	2.38	0.00	2.47	2.2
Sandy clay loam	0.47	1.26	0.00	1.74	1.5
Loam	0.20	1.08	0.00	1.28	1.1
Silty clay loam	0.15	0.35	0.00	0.50	0.4
Very gravelly sandy clay loam	0.14	0.28	0.00	0.42	0.4
Very gravelly sandy loam	0.09	0.02	0.00	0.11	0.1
Missing	0.00	0.12	0.00	0.12	0.1

Table 3.3: 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	km^2	km^2	km^2	km^2	%
D	9.23	48.70	0.01	57.94	51.0
B	4.22	30.19	0.02	34.43	30.3
C	3.49	17.50	0.01	21.00	18.5
Missing	0.09	0.16	0.00	0.25	0.2

Table 3.4: Global statistics for core-area loss and stream-area loss at three fixed-distance band thresholds: (a) Moran's *I* for percent of core-area loss, (b) Moran's *I* for percent of stream-area loss, (c) General G for percent of core-area loss, and (d) General G for percent of stream-area loss.

(a)

Distance Threshold (m²)	Moran's Index	Expected Index	Variance	Z-score	P-value	SAC
5190	5.96E-02	-7.90E-04	5.60E-05	8.07E+00	<0.001	(+) clustered
8480	4.69E-02	-7.90E-04	2.20E-05	1.02E+01	<0.001	(+) clustered
28900	1.61E-03	-7.90E-04	1.00E-06	1.98E+00	0.048	(+) clustered

(b)

Distance Threshold (m²)	Moran's Index	Expected Index	Variance	Z-score	P-value	SAC
5190	2.50E-02	-7.90E-04	5.40E-05	3.51E+00	<0.001	(+) clustered
8480	2.05E-02	-7.90E-04	2.10E-05	4.62E+00	<0.001	(+) clustered
28900	4.82E-03	-7.90E-04	1.00E-06	4.70E+00	<0.001	(+) clustered

(c)

Distance Threshold (m²)	Observed General G	Expected General G	Variance	Z-score	P-value	SAC
5190	1.35E-03	7.90E-04	0.00E+00	7.79E+00	<0.001	high clusters
8480	1.24E-03	7.90E-04	0.00E+00	9.72E+00	<0.001	high clusters
28900	8.49E-04	7.90E-04	0.00E+00	2.86E+00	0.004	high clusters

(d)

Distance Threshold (m²)	Observed General G	Expected General G	Variance	Z-score	P-value	SAC
5190	1.40E-03	7.90E-04	0.00E+00	3.33E+00	<0.001	high clusters
8480	1.30E-03	7.90E-04	0.00E+00	4.46E+00	<0.001	high clusters
28900	9.20E-04	7.90E-04	0.00E+00	3.23E+00	<0.001	high clusters

CHAPTER 3: FIGURES

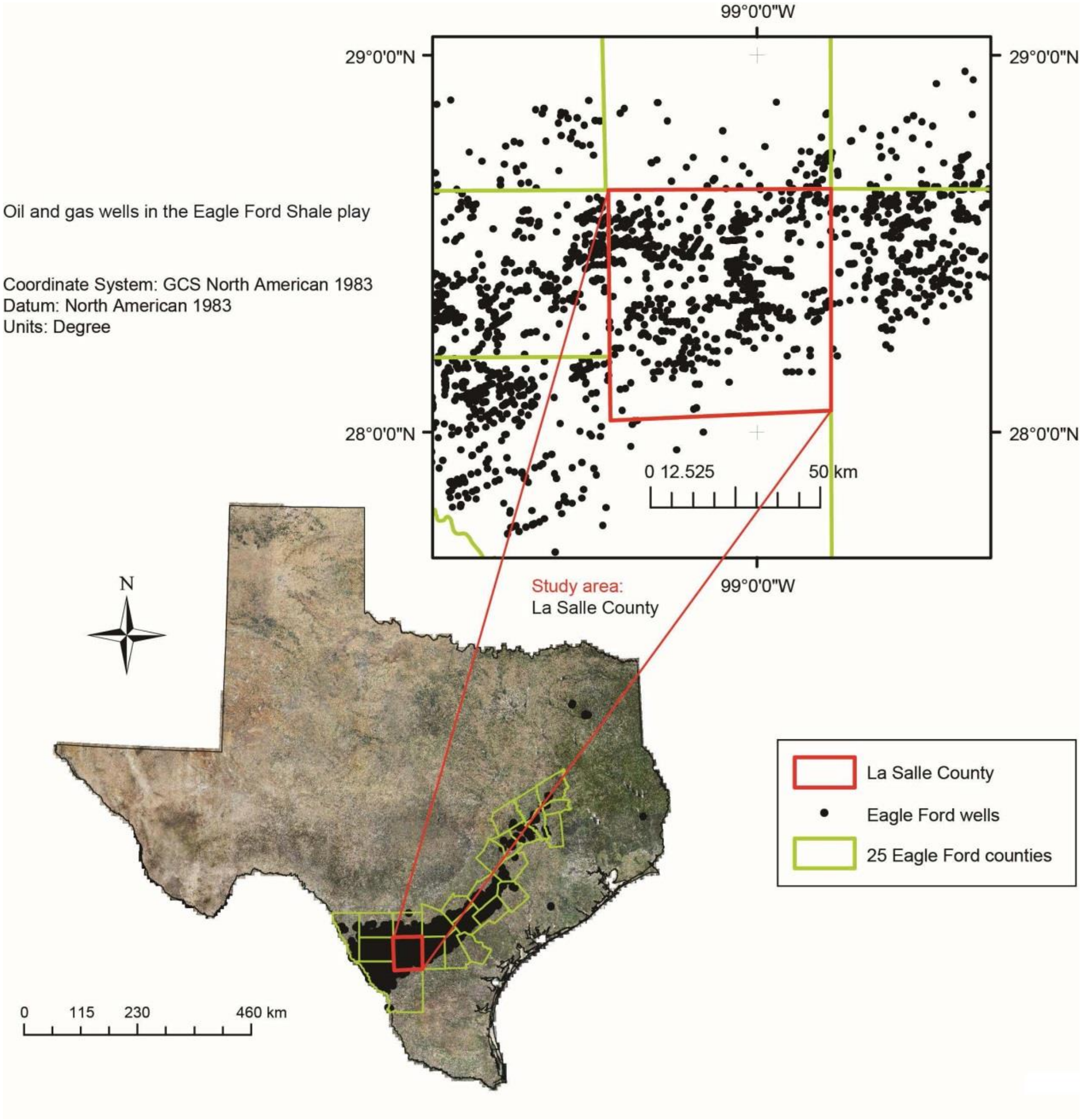

Figure 3.1: Study area of La Salle County, Texas, with oil and gas wells.

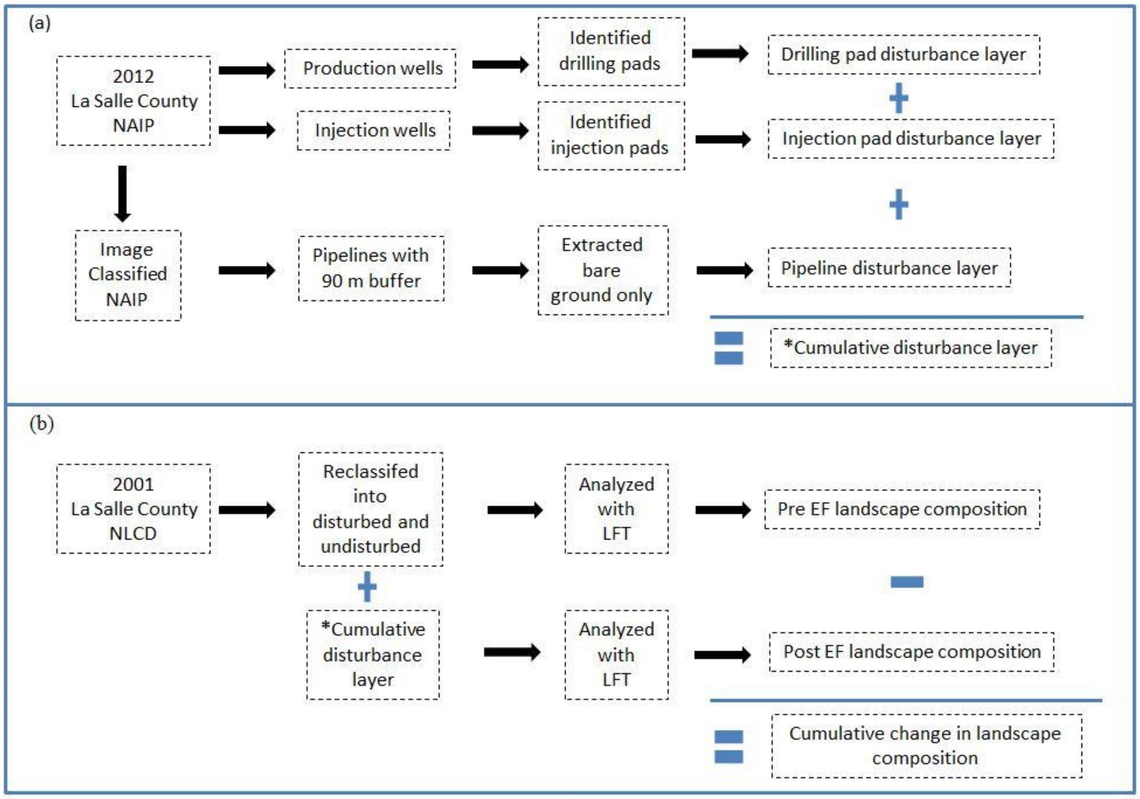

Figure 3.2: Workflow diagram used to (a) identify and quantify disturbance regimes and (b) assess landscape composition.

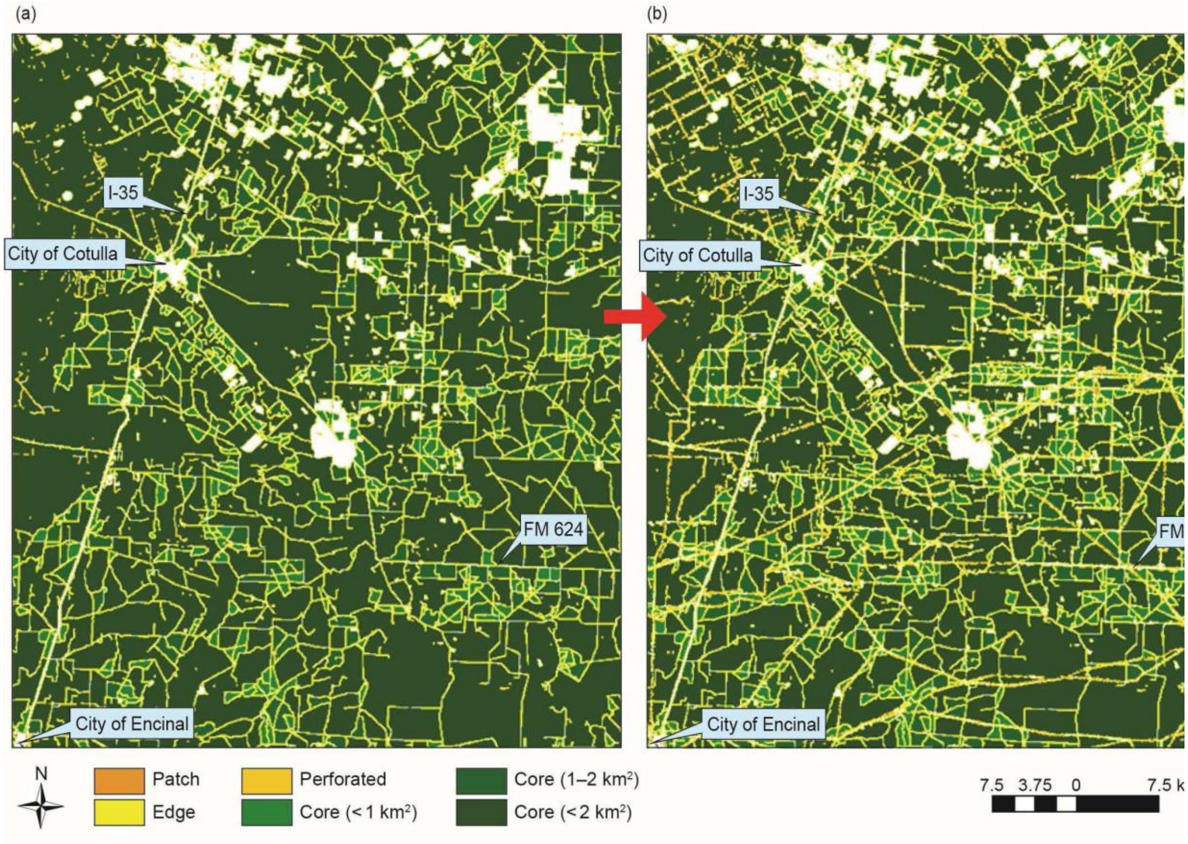

Figure 3.3: Changes in landscape classes after 12 years of Eagle Ford development. (a) pre–Eagle Ford development in 2001, and (b) post–Eagle Ford development in 2012.

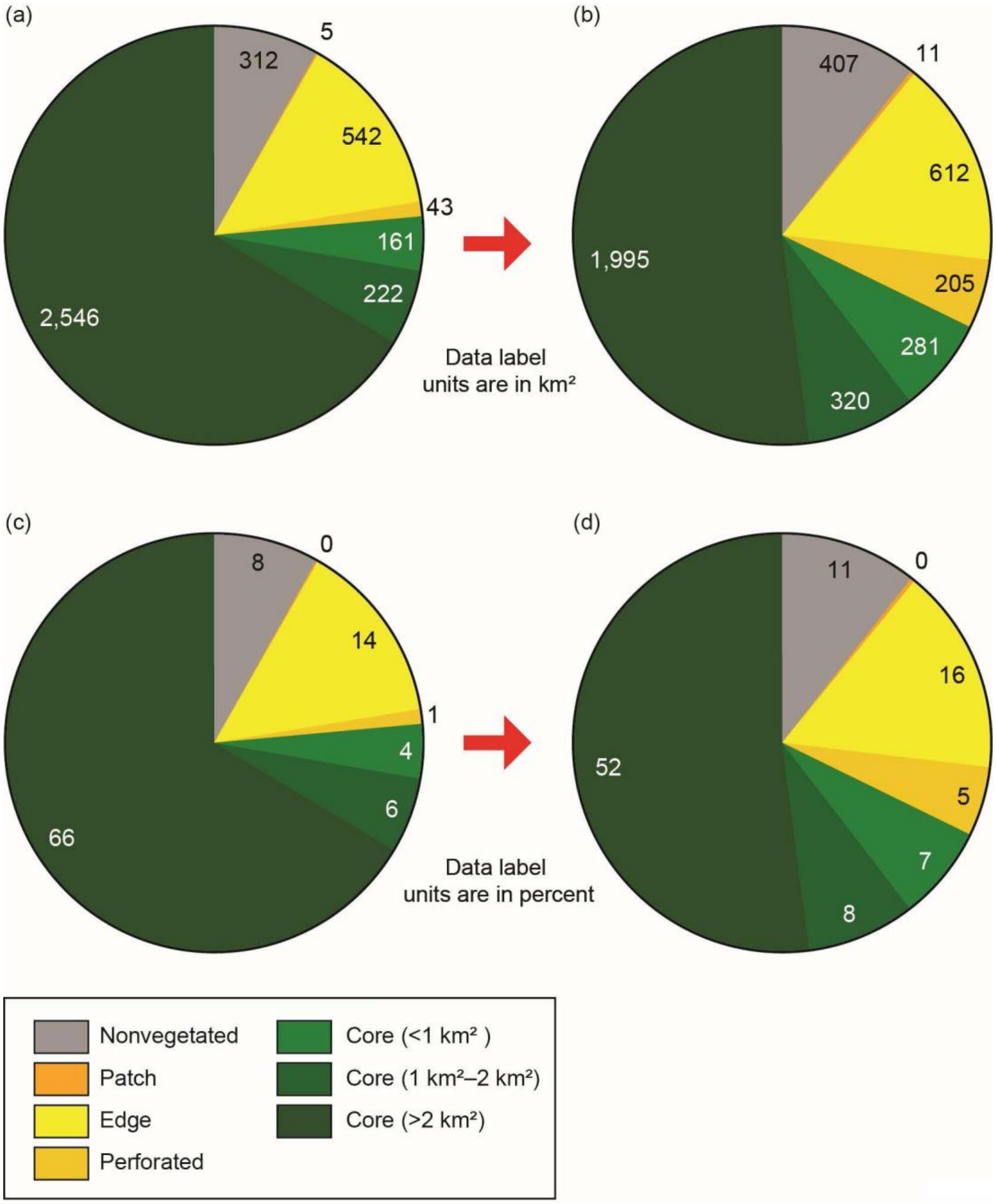

Figure 3.4**:** Change in landscape classes after 12 years of EF development. (a) 2001 pre-EF conditions by area, (b) 2012 post-EF conditions by area, (c) 2001 pre-EF conditions by percent of county area, and (d) 2012 post-EF conditions by percent of county area.

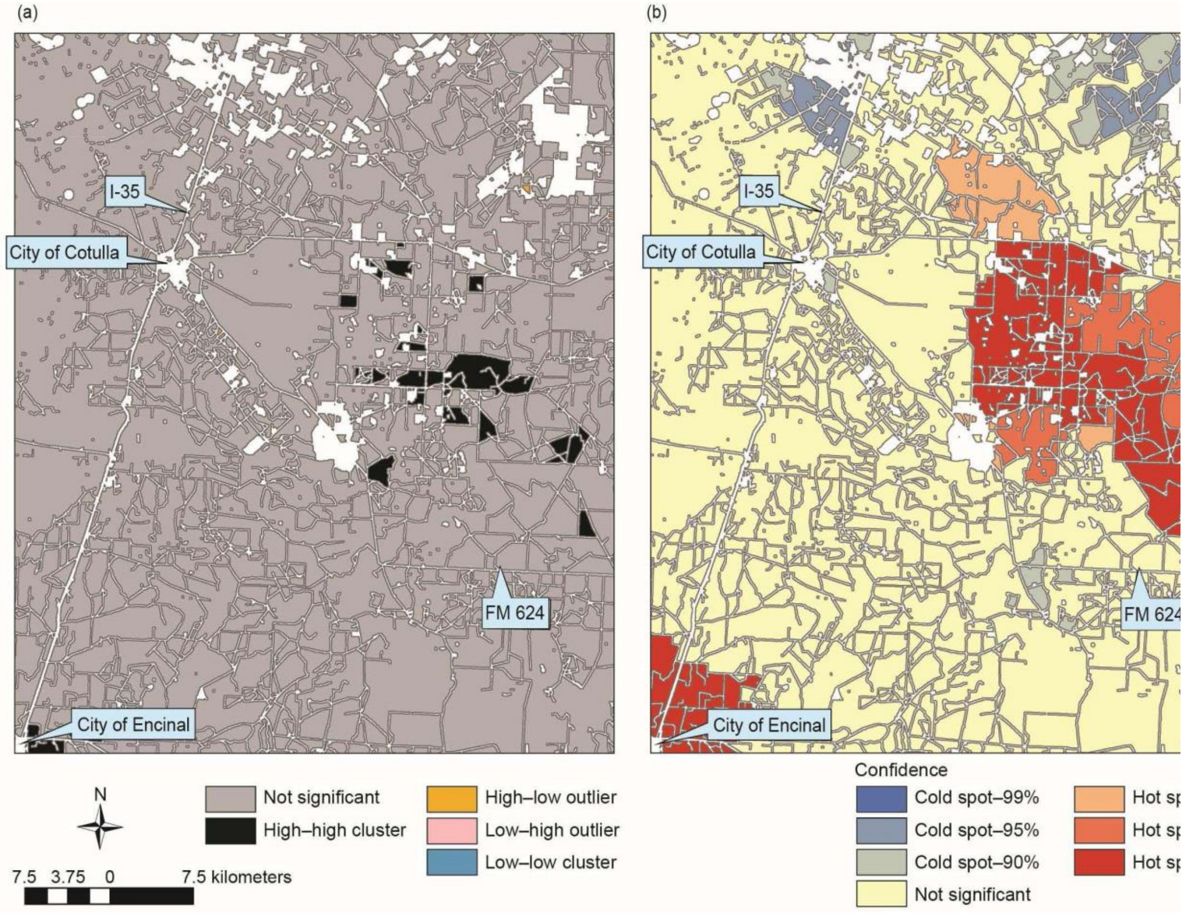

Figure 3.5: Cluster maps weighted by percent decrease of core area based on fixed-distance band. (a) LISA, and (b) Gi*.

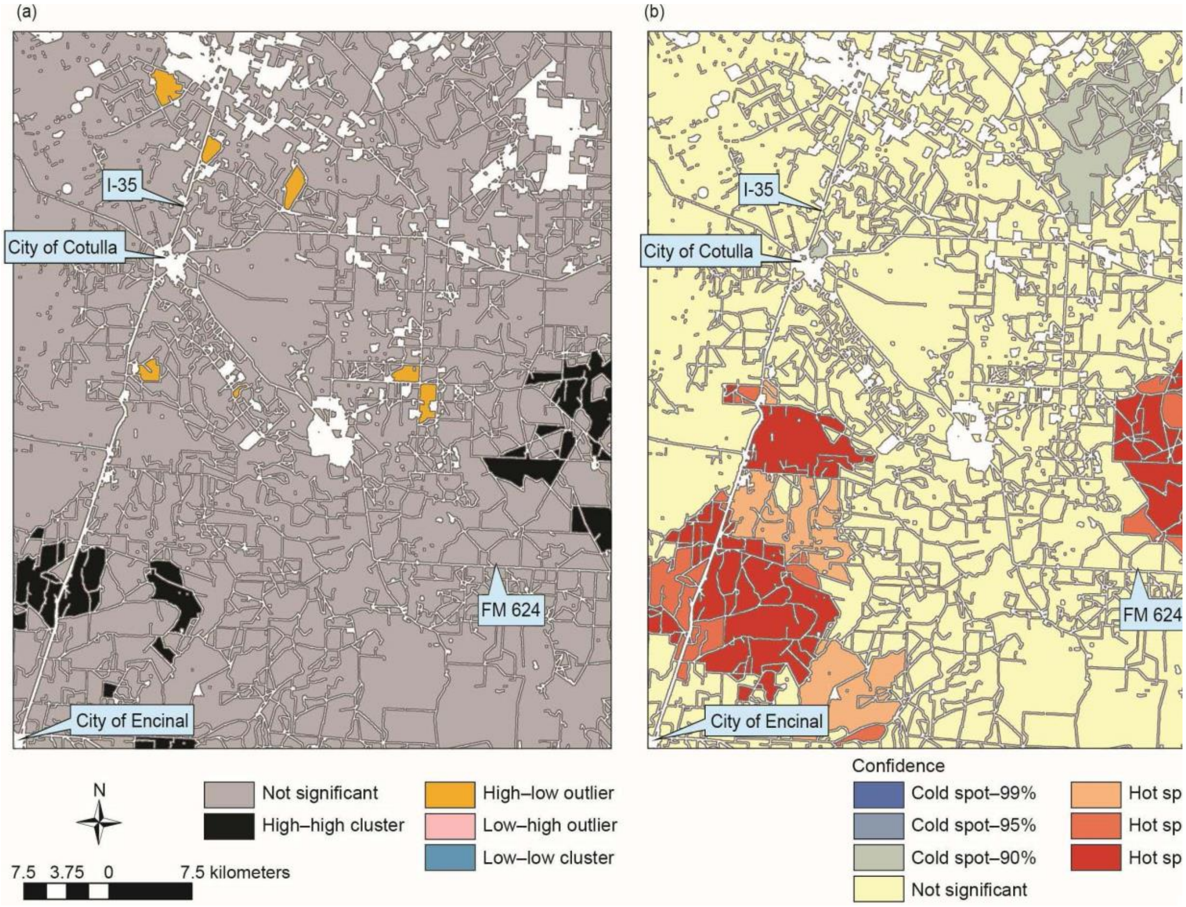

Figure 3.6: Cluster maps weighted by percent decrease of stream area based on fixed-distance band. (a) LISA, and (b) Gi*.

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CHAPTER 3: SUPPLEMENTARY TABLES

Table 3.S1: Change in landscape composition from each disturbance regime analyzed separately.

	Percent Change from Drilling Pads	Loss or Gain from Drilling Pads	Percent Change from Injection Pads	Loss or Gain from Injection Pads	Percent Change from Pipelines	Loss or Gain from Pipelines
	%	km²	%	km²	%	km²
Nonvegetated	5.1	15.84	0.0	0.02	25.3	78.80
Patch	2.6	0.13	0.0	0.00	122.5	5.97
Edge	2.1	11.60	0.0	0.00	9.4	51.14
Perforated	23.5	10.11	0.2	0.09	394.3	169.85
Core (<1 km^2)	1.4	2.32	0.0	0.00	70.2	112.93
Core (1 km^2–2 km^2)	0.3	0.71	0.0	0.00	47.8	106.34
Core (>2 km^2)	-1.6	-40.72	0.0	- 0.12	-20.6	-525.03

Table 3.S2: Soil properties across disturbance regimes. (a) soil order, (b) great group, (c) drainage class, and (d) flooding frequency.

(a) Soil order

	Drilling Pads	Pipelines	Injection Pads	All Disturbance Regimes	Percentage of All Disturbance Regimes
	km^2	km^2	km^2	km^2	%
Alfisols	5.53	29.84	1.98E-02	35.39	31.2
Aridisols	4.12	26.32	5.40E-03	30.44	26.8
Vertisols	4.96	24.40	1.80E-03	29.36	25.8
Mollisols	2.12	10.73	9.90E-03	12.86	11.3
Inceptisols	0.21	5.10	9.00E-04	5.30	4.7
Missing	0.09	0.16	0.00	0.25	0.2

(b) Great group

	Drilling Pads	Pipelines	Injection Pads	All Disturbance Regimes	Percentage of All Disturbance Regimes
	km^2	km^2	km^2	km^2	%
Haplustalfs	2.92	15.55	0.00	18.47	16.3
Chromusterts	2.73	12.47	0.00	15.19	13.4
Haplusterts	2.24	11.81	1.80E-03	14.05	12.4
Camborthids	1.98	11.75	5.40E-03	13.73	12.1
Paleustalfs	2.01	10.77	1.89E-02	12.80	11.3
Paleustolls	1.30	7.42	9.90E-03	8.72	7.7
Calciorthids	0.65	6.62	0.00	7.27	6.4
Natrargids	0.68	5.75	0.00	6.44	5.7
Ustochrepts	0.21	5.09	9.00E-04	5.30	4.7
Natrustalfs	0.60	3.52	9.00E-04	4.13	3.6
Argiustolls	0.67	2.97	0.00	3.64	3.2
Haplargids	0.81	2.20	0.00	3.01	2.6
Haplustolls	0.15	0.34	0.00	0.50	0.4
Missing	0.09	0.16	0.00	0.25	0.2
Pellusterts	0.00	0.12	0.00	0.12	0.1
Haplustepts	0.00	0.00	0.00	0.00	0.0
Calciustepts	0.00	0.00	0.00	0.00	0.0

(c) Drainage class–dominant condition

	Drilling Pads	Pipelines	Injection Pads	All Disturbance Regimes	Percentage of All Disturbance Regimes
	km^2	km^2	km^2	km^2	%
Moderately well drained	6.85	34.52	1.26E-02	41.39	36.4
Well drained	10.08	60.64	2.52E-02	70.74	62.3
Somewhat poorly drained	0.00	1.23	0.00	1.24	1.1
Missing	0.09	0.16	0.00	0.25	0.2

(d) Flooding frequency–dominant condition

	Drilling Pads	Pipelines	Injection Pads	All Disturbance Regimes	Percentage of All Disturbance Regimes
	km^2	km^2	km^2	km^2	%
None	1.83	86.12	2.70E-02	87.97	77.4
Occasional	14.88	7.95	1.08E-02	22.84	20.1
Frequent	0.23	0.16	0.00	0.39	0.3
Missing	0.09	2.32	0.00	2.41	2.1

CHAPTER 3: SUPPLEMENTARY FIGURE

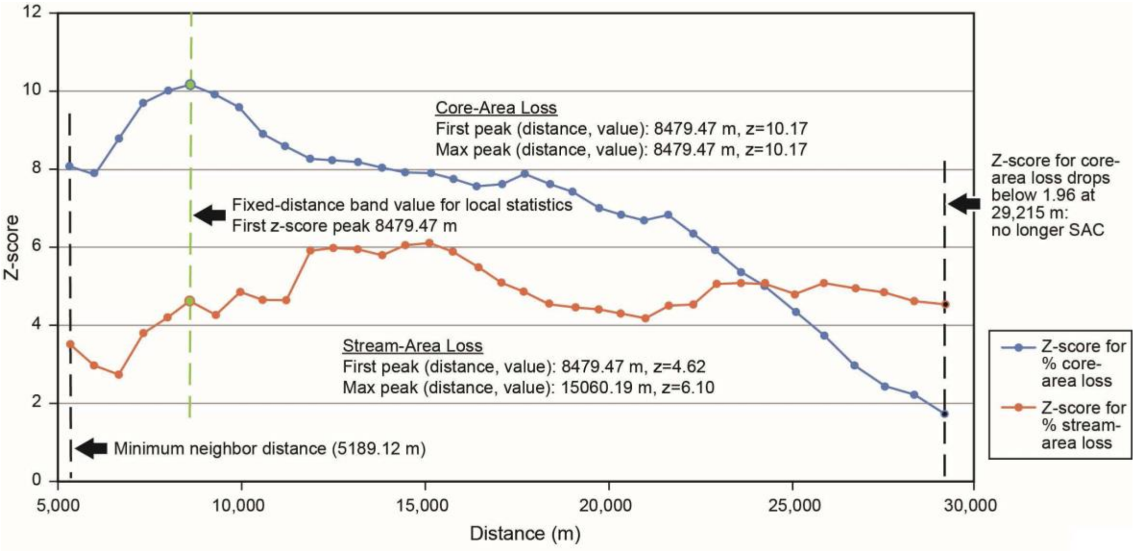

Figure 3.S1: Incremental spatial autocorrelation results using Moran's *I* for both core-area and stream-area loss.

Chapter 4: Discussion

4.1 LIMITATIONS AND UNCERTAINTIES

Limitations and uncertainties exist with the methods described in Chapter 3. For instance, pipelines were the dominant source of disturbance and landscape fragmentation. Based on observations at field sites, a decision was made to apply a 90 m buffer to pipeline polylines supplied by the RRC. Many pipeline segments were found to be in the range of 90 m wide during the construction and installation phase, and the 2012 NAIP imagery was image classified and extracted within the 90 m buffer. All bare ground areas within this 90 m buffer were attributed to pipeline installation, except in the case where drilling pads or injection pads overlapped within this buffer. In some cases, other infrastructure such as O&G pipeline compressor stations fell within this 90 m buffer and would have been attributed to pipeline disturbance, which in the case of compressor stations would be appropriate. However, any other bare ground area that was not the result of O&G activity that fell within this buffer would also have been attributed to pipeline disturbance and may result in an overestimation of total pipeline disturbance. Manual inspection of the areas within the pipeline buffer indicated that bare ground areas, not obviously created by O&G activity, were often classified as bare ground in the 2001 NLCD. Therefore, these areas would not have been included as part of the total disturbance from pipelines. The pipeline network within La Salle County is vast and manual inspection of all of this area within the buffer was not possible.

Additionally, as stated by Drohan and Brittingham (2012), when pipeline installation is complete, these areas can be immediately reclaimed. Other infrastructure (such as pads, roadways, compressor stations, etc.) will be exposed to surface activity until the production cycle is complete. Furthermore, researchers such as CKWRI and STN are making efforts to put in place native plant restoration programs. A conversation with a ranch manager in La Salle County indicates that many of the surrounding landowners have a strong interest in similar native restoration programs, which could preserve environments that bring hunters to the area and promote grazing of livestock, both activities that bring important income. Incorporating a fragmentation analysis before O&G placement can help to ensure that environments are preserved for wildlife of interest.

Another limitation is the relatively coarse NLCD data (30 m) resolution, while the NAIP resolution (1 m) is much finer. The data extracted from the image classified NAIP was therefore degraded to 30 m resolution. However, cell alignment in the resampled layer is in some cases slightly shifted from its original position which can affect the landscape fragmentation analysis. Also well pads were outlined manually; thus; O&G infrastructure not located near a well would not have been included as disturbance in our analysis. Lastly, road networks installed for recent O&G activity were not included in this analysis (unless they fell within the 90 m pipeline buffer) and electrical installations were not included in this analysis. Although our fragmentation analysis may not include all O&G disturbance regimes in the EF, it provides relevant insight into the extent of the fragmentation that may be occurring.

4.2 IMPLICATIONS OF LANDSCAPE CHANGE AND FRAGMENTATION

Saunders (1991) stated that management agencies need to realize the consequences of fragmentation to ecosystems and adopt policies that will manage the remnants of fragmentation in order to achieve conservation goals. Landscape fragmentation disrupts ecological interrelations between spatially connected parts of the landscape. This is a result of obstacles put in place that can prevent movement of animals (Jaeger, 2000; Linke et al., 2005), spread exotic species (Gelbard and Belnap, 2003; Stohlgren et al., 1999) that outcompete native species (Flanders et al., 2006), threaten biodiversity (Kiviat, 2013), change hydrologic flowpaths (Jones et al., 2000; King and Tennyson, 1984; Soeder et al., 2014), and possibly accelerate the onset of desertification (Belnap, 1995).

4.2.1 Restricted movement of animals

Linke et al. (2005) recognized the worldwide importance that extraction activities, such as mining, O&G exploration and production, and logging have on the composition and configuration of landscapes. They investigated the movement and habits of grizzly bears in the Rocky Mountain foothills of Alberta, Canada in response to seismic cutlines that were made during O&G exploration activities. Globally, anthropogenic activities are a key factor that affects wildlife and their habitats (Forman, 1995). As is the case with the EF, Linke et al. (2005) realized that increased levels of extraction were inevitable. The results of their study indicated that patch sizes of forest that remained after the cutlines were made were more important than the cutlines themselves. They found that the bears preferred larger patch sizes, particularly during mating. They also found that bears would avoid some of the small patches altogether and would not use medium and small patches if they were not consistently spaced.

Hobbs et al. (2008) concluded that fragmentation can be drastically restrictive to some animal inhabitants of semiarid and arid climates, particularly those who are not highly mobile. They argued that a change in the spatial heterogeneity of resources can remove a much needed buffering effect for some animals and can result in ecosystem degradation and ultimate harm to human livelihood. Fryxell et al. (2005) discovered that an extinction of local populations of ungulates in the Serengeti was the result of restricted access to spatiotemporally available vegetation that, according to Illius et al. (1998), is common in semiarid regions. As a result of different restrictive factors that prevent animal movement, populations may become genetically isolated or even extinct (Jaeger, 2000).

4.2.2 Encroachment by invasive species

Development of the EF brings an increased need for access roads to infrastructure, along with an increased volume of large truck traffic passing mostly through rural areas. Von Der Lippe and Kowarik (2007) found that roadways, particularly those which pass through rural areas, provided preferential corridors for invasive species migration. They conducted their studies inside long highway tunnels in Berlin, Germany to ensure that seed rain collected originated from vehicular traffic only, thus eliminating any other natural mechanisms of seed dispersal (i.e., wind dispersal). They showed that ~20% of the samples they collected were considered to be aggressively invasive species that caused biodiversity degradation in other parts of the world, including the U.S. Their results indicate that long distance (>250 m) vehicular dispersal of non-native species was common and significantly more frequent than native species. Thus, they concluded that rapid changes to biodiversity composition could result from accelerated vehicular assisted plant invasions, as also suggested by Cain et al. (1998) and Soons and Ozinga (2005).

Exotic species typically have a slow spread following their initial introduction and establishment, and vectors of long distance dispersal are critical to an exponential expansion of their range (Kowarik, 1995; Pyšek and Hulme, 2005). Additionally, anthropogenic vectors provide an alternative mechanism for long distance migration to species with seed morphology not adapted to long distance dispersal (Higgins et al., 2003; Pyšek and Hulme, 2005). Repetitive short distance traveling along with long term attachment of seeds (usually in a soil matrix) contributes to deposition along road verges and enhance dispersal through airflow (Von Der Lippe and Kowarik, 2007). Von Der Lippe and Kowarik (2007) also suggested that anthropogenic dispersal accounted for half of all seed dispersal along roadways.

4.2.3 Loss of biodiversity and ecosystem services

Invasive species, particularly grasses that were introduced in the 1930's for erosion control and range restoration purposes, are known to outcompete native species in south Texas (Flanders et al., 2006). A reduction in biodiversity can be the result (Lehman, 1969), which has repercussions for other organisms (Kiviat, 2013; Lehmann, 1984). Human well-being and ecosystem services are a growing concern because of the consequences of biodiversity loss (Balvanera et al., 2006). However, this is a contentious issue. Biodiversity has positive effects on most ecosystem services because trophic links are increased between organisms, limiting negative effects on overall productivity of the system (Jaeger, 2000; Kiviat, 2013).

Disturbances to the distribution of species, biogeochemical cycles, and land resources will continue to satisfy consumption by humans. As a result, concerns of the sustainability of ecosystem services are increasing (Hassan et al., 2005). The publication of the Millennium Ecosystem Assessment (MEA; Corvalán et al., 2005) has introduced the science of fragmentation, habitat loss, and biodiversity loss to the global stakeholder and policy communities. The MEA recognizes that biodiversity increases the "buffering" capacity of ecosystem services and plays a significant role in providing ecosystem goods and services (Hassan et al., 2005). Research has focused on understanding the relationships between services and goods provided by ecosystem processes and the level of biodiversity (Naeem and Wright, 2003), yet the results of a number of significant studies (e.g., Balvanera et al., 2006; Hector, 1999) are inconsistent. Simple generalizations are difficult to sustain and disentangling the effects of the loss of biodiversity on individual ecosystem functions remains a major challenge (Balvanera et al., 2006).

4.2.4 Changes in hydrologic flowpaths

Soeder et al. (2014) claim that the largest risks to surface hydrology from O&G extraction is land disturbance and discharge to streams. They state changes in drainage patterns, soil compaction, ground cover, slopes, and hydrology can all result from O&G construction activities such as pipeline construction, road construction and widening, land clearing, and pad construction. Some changes can include runoff rates, flow regimes, water quality, and groundwater recharge, and they can all have detrimental effects to aquatic ecosystems, particularly critical headwater streams.

4.2.5 Desertification

Belnap (1995) reported that recovery from soil compaction in semiarid climates is estimated to take several hundred years, nitrogen fixation capability of disturbed soils requires a minimum of 50 years to recover, recovery rates for cryptobiotic crusts is not known and often hampered by moving sediment. She stated that with the "sensitivity of these resources and slow recovery times, desertification threatens millions of hectares of semiarid lands in the United States." Disturbance regimes are one of the factors that contribute greatly to the onset of desertification (Belnap, 1995). Cryptobiotic soil crusts play a large role in maintaining soil stability, aiding in seed germination, maintaining nutrient and water cycles, and maintaining diversity in soil biota (Belnap, 1995). Soil formation in semiarid climates is a slow process that may take anywhere from 5000-10000 years, and these soils are often highly erodible (Dregne, 1986). Researchers have found that climatic factors may play a larger role in desertification processes than once thought, but that anthropogenic factors still have a large role in shifts toward desertification (Puigdefábregas and Mendizabal, 1998; Wang et al., 2006). Regardless of the major factor in a shift towards desertification, a consensus exists that soils in semiarid climates are sensitive to disturbance and proper steps should be taken to protect them.

4.3 FINAL STATEMENTS

Developing natural resources and preserving ecosystem services are critical to the economy of Texas, the nation, and the world. Incorporating new energy development technologies with landscape scale approaches that limit disruptive effects on ecosystem productivity will preserve human well-being and the well-being of other inhabitants of these communities. The methods outlined in this study can serve as a baseline for the protection of animal and plant habitats, hydrologic systems, and biodiversity.

In Texas, many hydrocarbon reservoirs are actively being developed, some of them in regions more arid than the Eagle Ford. The Permian Basin, for example, would be a suitable area to extend this research. Many organisms are listed as endangered or threatened in regions that host active plays such as the Permian and Eagle Ford basins where invasive plants are of growing concern as well. Finally, given the importance of energy sources to Texas and the US, it is desirable to achieve a symbiosis between active development of these resources and proactive preservation of the ecosystem services we need to maintain our healthy economy and environment.

CHAPTER 4: REFERENCES

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