LANDSCAPE FRAGMENTATION AS AN IMPACT
OF SHALE GAS DRILLING
IN NORTH TEXAS

by

ANJANA PRADHANANGA

Presented to the Faculty of the Graduate School of

The University of Texas at Arlington in Partial Fulfillment

of the Requirements

for the Degree of

MASTERS IN LANDSCAPE ARCHITECTURE

THE UNIVERSITY OF TEXAS AT ARLINGTON

May 2014

Acknowledgements

First of all, I would like to express my sincere thanks to my thesis chair, Dr. Pat D. Taylor. I am very grateful for his guidance and support throughout my graduate study at UT Arlington. I would like to thank Dr. Taner R. Ozdil for giving me right directions. I always learned something new from him. I want to thank Prof. James P. Richards for his input to this research and sharing his observation on this research topic. I would like to acknowledge The Energy Institute, The University of Texas at Austin, for supporting me to take part in CELA Conference 2013, Austin, Texas, and 1st CIGR Conference Bari, Italy to present this research at their conferences.

My special thanks to my dear husband for supporting me throughout my thesis and my entire graduate study. To my family for believing in me and letting me study abroad. These three years were full of knowledge and experiences which would not have been possible without their support. To my two lovely sisters, thank you for taking care of our parents while I was away from home. Thanks to my in-laws for their belief and support.

I would like to express my gratitude to my other professors at UT Arlington: David Hopman, John Fain, Rhonda Fields and "Bo" Bass and the rest of the faculty for their dedication to teaching and the profession of landscape architecture. Thank you Joshua Been and Mitch Stepanovich for helping me find GIS data for my thesis. I am thankful to Joshua Atherton for his help in editing this report. Last but not the least, I want to thank my classmates and friends for encouraging and supporting me throughout my study at UT Arlington.

April 16, 2014

Abstract

LANDSCAPE FRAGMENTATION AS AN IMPACT

OF SHALE GAS DRILLING

IN NORTH TEXAS

Anjana Pradhananga, MLA

The University of Texas at Arlington, 2014

Supervising Professor: Pat D. Taylor

The objective of this study is to determine the degree to which shale gas drilling contributes to the fragmentation of landscapes in North Texas, especially in prairies. The study is conducted on the Barnett Shale area where shale gas exploration began in the 1980's (Arthur et al. 2008). The Barnett Shale area lies under much of the developed regions of the Dallas-Fort Worth metropolitan area as well as beneath an extensive amount of rural countryside mainly used for private recreational lands, exurban residential development, suburbs, and improved pasture and ranching. However, most of the drilling is occurring in the Grand Prairie and Plains ecoregion, where the dominant land cover is prairie. This research is aimed at producing data and information for local, regional, and state policy-makers engaged in activities related to surface drilling.

More specifically, findings from this study are expected to be useful for understanding and foreseeing the long term ecological impacts of surface drilling on prairies in North Texas and for identifying ways to ameliorate these potential adverse impacts. Findings from this study are expected to influence the setting of priorities that can reduce the adverse impacts of surface drilling on landscapes.

In order to quantify fragmentation, analyses of three sample sites are carried out in this study. Each sample site differs from another in terms of the intensity of shale gas drilling within the sample site area. This means each sample site has a different number of well pads though the size of the three sample sites is the same.

To conduct this quantitative study, longitudinal land cover data for the three sample sites are collected. Well pad data, impoundment area data, and road data are then prepared using the Geographic Information System (GIS). These data are then analyzed using the Landscape Fragmentation Tool (LFT), which maps fragmentation for any type of land cover, for example, grassland, and categorizes the land cover type into *patch, edge, perforated, small core, medium core,* and *large core*. LFT is a python script that runs in ArcGIS (Vogt et al. 2007).

The study concludes that *patch*, *edge*, and *small core* landscape conditions increase as a result of shale gas drilling. *Patch conditions* are mostly observed where roads crisscross. With more intense drilling activity, *edge conditions* form the dominant landscape conditions. With less intense drilling activity, *perforated conditions* are dominant, signifying the early stage of fragmentation. On the other hand, *medium core* and *large core conditions* decrease with the increase in the drilling activity.

Outcomes for this study include the identification of components of shale gas drilling that are responsible for landscape fragmentation. Additionally, the research identifies procedures and steps that landscape architects, planners, and policy makers can follow to lessen future surface impacts from shale gas drilling.

Keywords: Landscape fragmentation; shale gas drilling; land cover; longitudinal data; and Landscape Fragmentation Tool (LFT).

Table of Contents

List of Illustrations

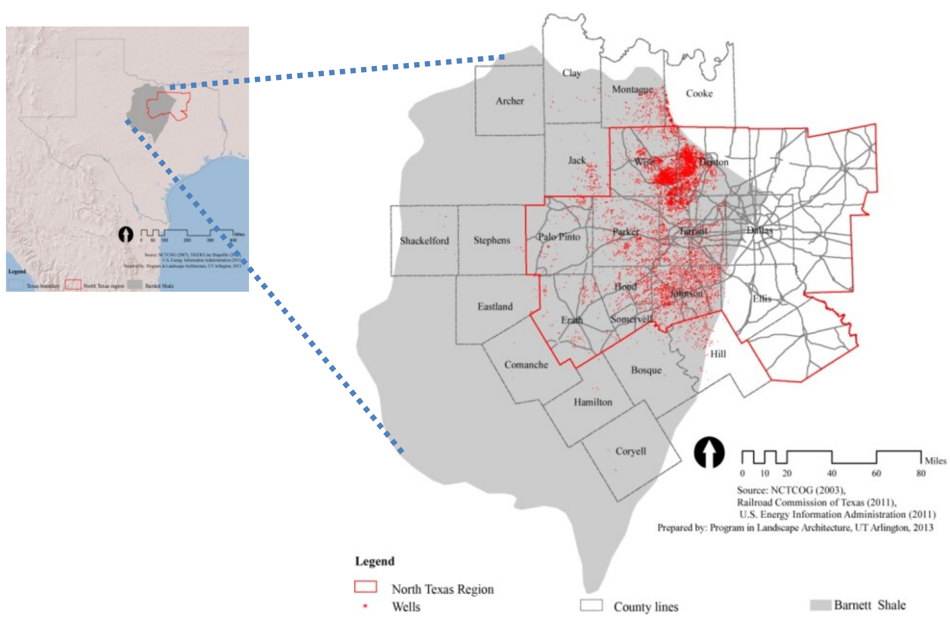
List of Tables

Chapter 1

Introduction

1.1. Introduction

Increased demand for clean energy and an advancement of key technologies, specifically horizontal drilling and hydraulic fracturing, have led to a rapid increase in U.S. natural gas production from shale formations. On one of these shale formations, the Barnett Shale of the Fort Worth Basin, extensive drilling and production began when gas prices increased in the late 1990's (Railroad Commission of Texas 2014). The productive portion of the Barnett Shale is known as the Newark, East Field. The Newark, East Field well count is now 17,494 as of December 13, 2013 (Railroad Commission of Texas 2014). According to Williams (2012), each well pad requires an area of about three to ten acres of land (130,680 to 435,600 square feet).

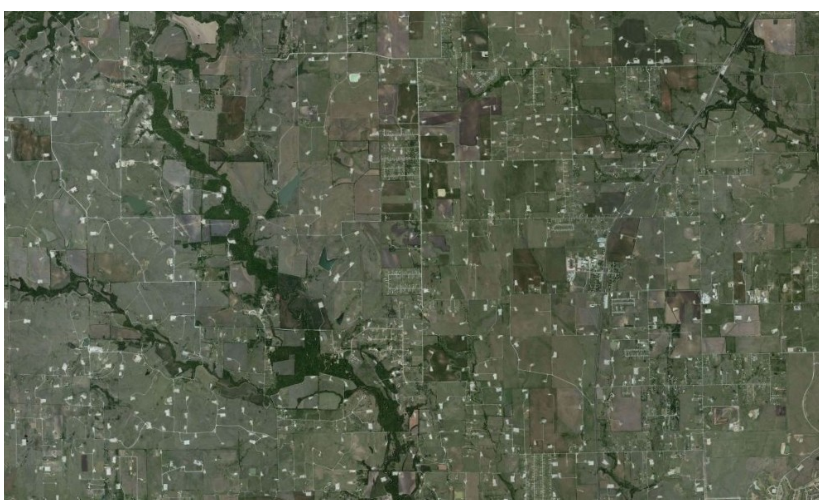


(Image source: Taylor et al. 2014)

Figure 1-1: Map showing geographic location of counties covered by Barnett Shale formation

Clearing vegetation for well pads along with the construction of roads, pipelines, and impoundment areas has had a significant impact on landscapes. For example, land disturbances created by the construction of well pads, roads, pipelines, and impoundment areas cause storm water runoff, soil erosion, sedimentation, surface water contamination, deforestation, and fragmentation (Paleontological Research Institute 2012, Forman and Alexander 1998, and Slonecker et al. 2012).

Shifting attention from a single site of productive Barnett Shale formation at 10 acres to a combined 3,200,000 acres (5000 sq miles) of sites located in all 18 counties of North Texas, the impact of these patches, formed by drilling pads and roads, becomes obvious. Patches formed by drilling pads and roads form a mosaic pattern that change over time (Forman 1995). Other changes occur at the spatial scale of landscapes as a result of urbanization, loss of wetlands, and conversion of forests and prairies into cropland. These changes are seen cumulatively as they alter spatial patterns in the landscape (O'Neill et al. 1997).



(Image source: Bing Maps 2012)

Figure 1-2: Small patches formed by drilling pads on the landscapes of North Texas

To study changes on the landscape from shale gas exploration, this research examines pre-drilling and post-drilling landscape patterns in North Texas from 1995-2010. The results of this study reveal significant differences between the pre- and post-drilling landscape patterns, and suggests that actions need to be taken to lessen any future impacts that drilling may cause on the landscapes of North Texas.

Analyzing the dynamics of land surface changes is made possible by use of tools such as Geographic Information Systems (GIS) and remote sensing (O'Neill et al. 1997). This study of landscape changes in North Texas is useful for planners, conservationists, designers, and policy makers who can help ameliorate impacts resulting from extensive shale gas drilling.

1.2. Brief History of Shale Gas Drilling in North Texas

Under the leadership of George P. Mitchell, pioneer of horizontal drilling technology for shale gas, Mitchell Energy Inc. started horizontal drilling and hydraulic fracturing to produce gas from the Barnett Shale in the 1980s (Arthur et al. 2008; The Energy Institute 2012). Though hydraulic fracturing has been used in limestone and sandstone gas deposits since the 1940s, it was not used in shale deposits until the 1970s (Trembath et al. 2012). Shale gas was first extracted in Fredonia, New York in the 1820s and was limited to very small scale operations until the 1980s when shale gas extraction was economical (Trembath et al. 2012).

The unconventional technology of horizontal drilling is used to extract natural gas from the Barnett Shale area of North Texas, one of the largest natural gas reservoirs in the United States (Wynveen 2011). The production ratio for horizontal wells versus vertical wells (conventional practice) is 3.2 to 1, while the cost ratio of horizontal versus vertical wells is 2 to 1 (Directional and Horizontal Drilling 2012). This implies that horizontal drilling is more profitable and cost effective as compared to vertical drilling.

Shale gas has also been in production for many decades, but rapid advancement in unconventional drilling technology and hydraulic fracturing took place in the mid-2000s. Shale gas production grew at a rate of more than 45% per year between 2005 and 2010 (The Horinko Group 2012).

With the increase of shale gas drilling, questions about its environmental impacts and the ability of current policies to regulate them have emerged. It is challenging for planners, regulators, and policy makers to identify adequate solutions. Each state has its own regulatory agencies that oversee wells in terms of their design, location, spacing, environmental activities, discharge, waste disposal, air emission, wildlife impacts, and worker's health and safety. The Barnett Shale gas development is regulated by the Texas Railroad Commission (Arthur et al. 2008).

Shale gas development on federally-owned land is managed mainly by the Bureau of Land Management (BLM) and the U.S. Forest service, although most federal laws are administered by the U.S. Environmental Protection Agency. Federal agencies, however, do not regulate all oil and gas sites in the country, and they are not always effective at regulating all environmental programs related to shale gas development (Arthur et al. 2008). Hence, states are granted certain rights to develop their own sets of regulations.

1.3. Research Objectives

The objective of this study is to determine the impact of shale gas development on the landscapes, specifically prairies, of North Texas over a period of time and to identify the components of shale gas drilling that contribute to landscape fragmentation. The findings are expected to be useful for understanding and foreseeing ecological impacts over time and finding solutions to lessen the impacts of future shale gas drilling. Longitudinal studies of the impacts of shale gas drilling provide guidance in setting priorities to reduce adverse impacts on landscapes. The lessons learned from this study of the Barnett Shale area are expected to be applicable to other natural gas drilling sites throughout the United States.

1.4. Research Questions

1) What are the components of shale gas drilling that result in landscape fragmentation?
2) What is the degree of landscape fragmentation caused by shale gas exploration on the three sample sites and how has this changed over time?
3) How is LFT used in this study to analyze the three sample sites?
4) What are the procedures and steps that landscape architects, planners, and policy makers can follow to lessen surface impacts from shale gas drilling in the future?

1.5. Definition of Terms

Barnett Shale: A hydrocarbon producing geological formation consisting of sedimentary rocks. The productive part of Barnett Shale is estimated to stretch from the city of Dallas west and south covering 5,000 square miles (Railroad Commission of Texas 2012).

Conventional gas: The gas found in a pocket beneath a rock layer which is relatively easy and inexpensive to extract (Cooley and Donnelly 2012.)

Directional or horizontal drilling: A process that enables wells to be extended vertically for a distance below the surface, then horizontally through the gas-containing rock formation, thereby increasing exposure to the target formation (Cooley and Donnelly 2012)

Ecoregions: Areas that have similarities in geology, physiography, vegetation, climate, fauna, and so on. Ecoregion frameworks allow for logical ways to conduct landscape level research, assessment, and management (Griffith et al. 2007).

Fracturing or hydraulic fracturing: A process of injecting fluid (mix of water, sand, and chemical additives) into wells under high pressure to form cracks and fissures in rock formation. The process is utilized to improve production of gas wells (Cooley and Donnelly 2012).

GIS: Geographic Information System allows users to visualize, question, analyze, interpret, and understand data to reveal relationships between input variables (Esri 2012).

Land cover: The visible physical material at the surface of the earth that we see and which directly interacts with electromagnetic radiation thereby affecting the level of reflected energy. Land cover includes grass, asphalt, trees, bare ground, water, and so on (Comber et al. 2005).

Landscape fragmentation: Landscape's lack of connectivity, the mechanisms that cause it and the subsequent alteration of ecological processes (Serrano et al. 2002).

Land use: A description of how people use land. It includes urban land use, agricultural land use, institutional land use, residential land use, and so on (Comber et al. 2005).

Longitudinal study: An observational study of the same group of individuals or data collected over an extended period of time. The study allows looking at the changes over time (Cherry 2012).

Natural gas: A naturally formed hydrocarbon gas which is associated with petroleum fields. It is composed of methane, sometimes ethane, butane, or propane (U.S. Geological Survey 2012).

Shale: A fine- grained sedimentary rock formation that can be a rich source of petroleum and natural gas (U.S. Energy Information Administration 2012).

Shale gas: Natural gas trapped within shale formations (U.S. Energy Information Administration 2012).

Railroad Commission of Texas (RRC): The state agency that regulates the oil and gas industry, gas utilities, pipeline safety, and safety in the liquefied petroleum gas industry, and surface coal and uranium mining. Despite its name, it no longer regulates railroads (Railroad Commission of Texas 2012).

Unconventional gas: A natural gas that is difficult to extract because it is trapped in rock with very low permeability.

1.6. Research Methods

This study uses a quantitative research method using the Landscape Fragmentation Tool (LFT) in ArcGIS (Geographic Information Systems) 10.1. The LFT is a python script that runs in ArcGIS and quantifies landscape fragmentation. This tool is based on the research done by Vogt et al. (2007). To measure fragmentation, the tool analyzes land cover data and categorizes the land cover into six landscape conditions: patch; edge; perforated; small core; medium core; and large core.

This research is undertaken by studying three sample sites located in North Texas, each having a different intensity of shale gas exploration. The sample sites are chosen using the deductive approach (Harwell 2011). Longitudinal studies are carried out for each sample site to study pre-drilling and post-drilling landscape conditions. The chosen timeframes for the study are 1995, 2005 and 2010. The LFT is used to quantify the landscape conditions in these study timeframes. The landscape conditions obtained as outputs after running the LFT are *patch*, *edge*, *perforated*, *small core*, *medium core*, and *large core*, in the order of the most to least fragmented landscape conditions.

Hence, the six landscape conditions characterized by LFT identify the degree of fragmentation in each study timeframe, which allows a comparison of the pre-drilling and post-drilling landscape conditions of the sample sites.

1.7. Significance of The Study

This research quantifies landscape fragmentation as an impact of shale gas drilling by conducting an empirical study on three sample sites. The study maps fragmentation, which helps to identify areas on which to focus management efforts aimed at minimizing landscape fragmentation. The knowledge obtained from this type of study is also useful in identifying regional landscape trends, which helps in guiding shale gas infrastructure development, in minimizing fragmentation, and in advancing long-term monitoring of development in the region (Drohan et al. 2012a).

Due to fluctuations in the estimates of extractable natural gas, natural gas prices, and the economic impact of drilling, it is difficult to project potential spatial and disturbance footprints of shale gas development (Drohan et al. 2012a). However, the results of this study suggest that shale gas exploration impacts a substantial amount of prairies in North Texas. Furthermore, this study describes how tools such as LFT and GIS can be used to identify the temporal changes in core landscapes as an aftermath of shale gas exploration.

This study is geographically limited to three sample sites in North Texas. Although magnitude and disturbance of shale gas drilling varies according to region and physiographic setting (Arthur and Cornue 2010), the results of this study are expected to be applicable to other shale gas drilling areas.

1.8. Limitations of The Study

- The study uses three sample sites in North Texas focusing on fragmentation of prairie habitat. The sample sites are chosen where most of the land cover is grassland, which includes prairies. Hence, the results might be different for areas where grassland is not the dominant land cover.

- Although tallgrass prairie ecosystems can range up to 10,000,000 acres, because the focus of this study is more concerned with prairie grasses, the study size is limited to 1,000 acres. This size is sufficient land for prairie grasses to flourish (Minnesota Department of Natural Resources 1998).
- The primary data, well pads, impoundment areas, and roads, are prepared using aerial images in ArcGIS. The accuracy of data is highly dependent on the quality of aerial images.
- Only those variables that can be identified from aerial images are included in this study. For example, this study uses well pads, impoundment areas, and roads as variables. However, pipelines are not included in this study even though they are one of the fragmenting elements.

1.9. Summary

This study presents an analysis of landscape change and fragmentation from three sample sites in North Texas where shale gas drilling occurs. The analysis is done using GIS techniques overlaid with aerial imagery from 1995, 2005, and 2010. This research is concerned with:

1. Mapping and documenting landscape changes, land disturbance and fragmentation due to shale gas exploration in North Texas;
2. Contributing to the understanding of the landscape and ecological impacts of shale gas exploration on prairies; and
3. Presenting the implications of the landscape disturbance to planners and policy makers.

Chapter 2

Literature Review

2.1. Introduction

While many studies have been conducted on the economic and health issues of shale gas exploration, studies on the geographic profile and spatial arrangement, the ecological impacts, and the landscape impacts of these activities are often overlooked (Slonecker et al. 2012). The rapid pace of shale gas exploration calls for urgent attention to study land disturbances such as land use and land cover change, landscape fragmentation, and other ecological impacts. This chapter discusses previous studies related to landscape fragmentation, and Barnett Shale and other shale gas exploration studies related to the surface impacts, ecological impacts, and land disturbance from drilling activities. This chapter also reviews the ecological characteristics of prairie habitats because this research focuses on the prairie grasses in North Texas where most of the Barnett Shale gas exploration is taking place.

2.2. Introduction to Landscapes

Landscapes can be defined as the mosaic repetition of local ecosystems or land uses in similar form over a wide area (Forman 1995). Examples of landscapes include forested, suburban, cultivated, and dry landscapes. Landscapes also are the totality of natural and cultural features, such as fields, hills, and forests, throughout the land (Ndubisi 2002). Landscape elements can be categorized as either tangible or intangible (Brown 2001). Tangible landscape elements include transportation corridors and junctions, utilities, and land cover. Intangible landscape elements include political boundaries, ecoregional boundaries, ownership boundaries, and land use. For this study, the tangible elements of landscapes taken into consideration are well pads, impoundment areas, roads, and land cover. The intangble elements in this study include the ecoregional boundary and the regional boundary.

Tangible elements change the physical character of the landscape and often have a direct impact on ecosystems (Brown 2001). For example, a road network introduced on an undisturbed forest decreases the quality of habitat for large mammals. Similarly, the installation of utility networks such as pipelines requires the clearing of vegetation, which can result in fragmentation (Brown 2001).

The spatial arrangments of the landscape elements that change with time make up a landscape's mosaic pattern, which is a central characteristic of every landscape. These patterns are created by three mechanisms:

- Substrate heterogeneity, such as hills, wet spots, and different soil types;
- Natural disturbances, such as fire, tornados, and pest fields; and
- Human activities, such as plowing, cutting woodlots, and constructing roads (Forman 1995).

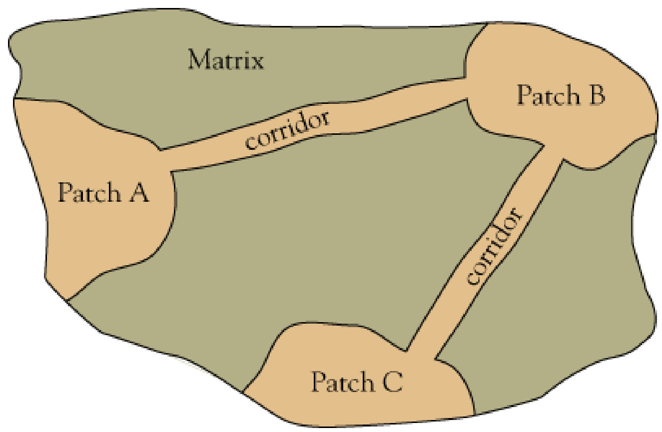
2.3. Patch, Corridor, and Matrix

The mosaic pattern of landscapes has three spatial elements. These are patches, corridors, and matrices (Forman 1995). Patches are areas that differ from the surrounding context (Forman 1995). Patches are the areas that are heterogeneous when compared to the whole (Barnes 2000). Patches can be large to small, elongated to round, and convoluted to smooth (Dramstad et al. 1996 and Forman 1995).

A corridor is also a kind of a patch. It differs from a patch in that it is a strip that aids in the flow between patches. Corridors can be wide to narrow, meandering to straight, and have high to low connectivity (Dramstad et al. 1996 and Forman 1995).

A matrix is the most extensive component of landscapes and controls regional dynamics (Forman 1995). It is the dominant component in the landscape (Barnes 2000).

Matrices can be extensive to limited, continuous to perforated, and variegated to nearly homogenous (Forman 1995). As shown in Figure 2-1, landscape composition is the amalgamation of patches, corridors, and matrices that exist in a landscape (Betts 2000 and Forman 1995).



(Image source: Barnes 2000)

Figure 2-2: Landscapes consist of patches, corridors, and matrices

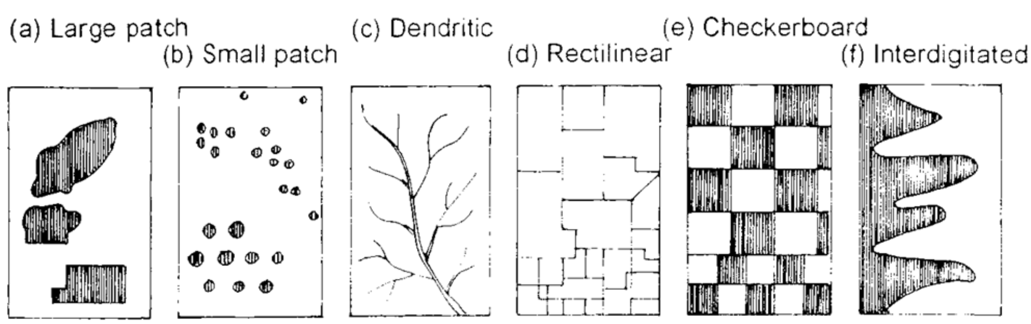


Figure 2-3 Patch-corridor-matrix arrangements (Forman 1995)

There are six spatial arrangements of patches, corridors, and matrices. They are large patch, small patch, dendritic, rectilinear, checkerboard, and interdigitated as shown in Figure 2-3. The North Texas landscapes resemble a hybrid mosaic pattern, consisting of small patch and dendritic spatial arrangements (Figure 2-3), formed by well pads, impoundment areas, and the associated roads. The well pads and impoundment areas form small patches while the roads form dendritic patterns in this spatial arrangement as shown in *Figure 2-4*. Such patterns have unequal but spatially extensive effects on landscapes (Drohan et al. 2012b). This study focuses on such spatial arrangements created by shale gas drilling in North Texas prairies.

(Image source: Bing Maps 2012)

Figure 2-4: Hybrid pattern formed by well pads and roads of North Texas landscapes

2.4. Literature on Prairies

This research focuses on the fragmentation of grassland, specifically prairies of North Texas as an impact of shale gas drilling. This section is a general overview of prairies and their ecological significance.

"Prairie" is a French word which means a tract of grassland or meadow grazed by cattle. Early French explorers used the term to the vast inland area of North America mostly treeless and covered with wide varieties of tall and short grasses and colorful wildflowers. Hence, prairies are a type of grassland, landscapes dominated by herbaceous plants either without trees or with trees widely scattered on the landscapes (Robertson 2008). Grasslands cover about 15% of the land area of North America.

Prairies are the grasslands found in the central part of North America and are subject to extreme range of temperatures (Robertson 2008).

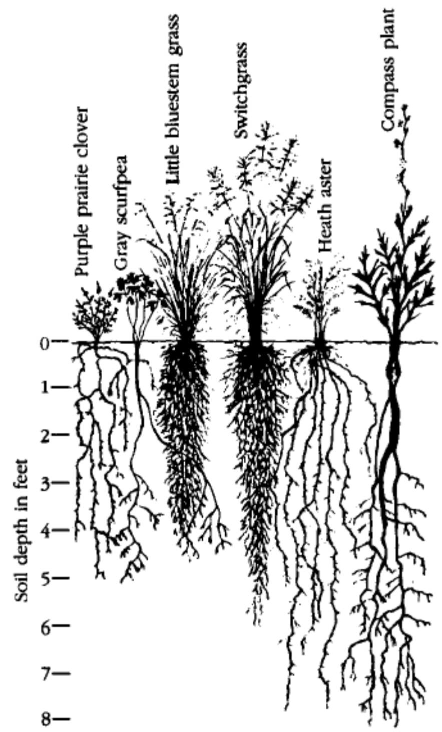


Figure 2-5: Example of prairie plants' root systems (Minnesota Department of Natural Resources 1998)

Along with being adaptive to extreme temperatures, prairies can withstand prairie fire and grazing. In fact, natural disturbances such as grazing, fire, and drought are integral parts of prairie ecosystem because prairie plants have deep root systems with enough energy preserves to survive following grazing fire, and drought (Minnesota Department of Natural Resources 1998 and Robertson 2008). Prairies have extensive deep root systems as storage structures. The growing point are about an inch below ground are not harmed by prairie fire or grazing (Robertson 2008).

Some prairie plants have shallow, fine roots to maximize collection of rainwater while others have roots deep into the ground to extract water from deep in the soil (Robertson 2008; and Minnesota Department of Natural Resources 1998). For example, little bluestems, and June grasses have shallow roots while big bluestems have 7 feet or deeper root systems under the ground. During periods of drought, prairie plants get moisture from their roots. Though the above ground part of prairie plant dies, the underground structures keep most prairies alive. However, some roots might die and decompose. This provides large amount of organic matter to the soil and makes it fertile because two thirds of the plant tissue in the prairies are below ground as roots and rhizomes (Minnesota Department of Natural Resources 1998 and Robertson 2008).

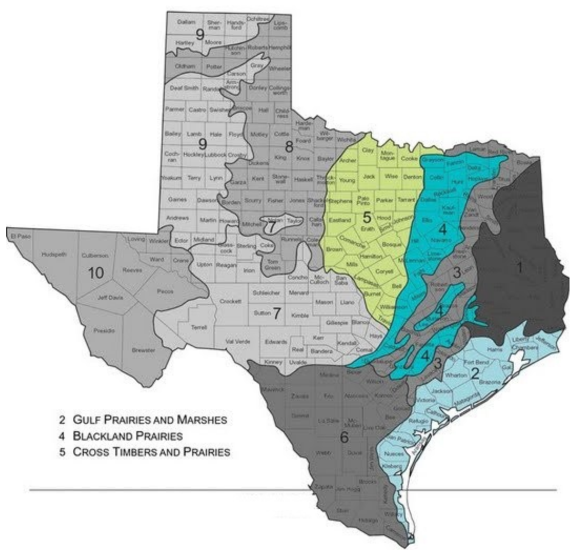


Figure 2-6: Gulf Prairie and Marshes (#2), Blackland Prairie (#4), and Cross Timbers and Prairies (#5) are the tallgrass prairie regions of North Texas (Native Prairies Association of Texas 2014)

The species diversity within a prairie system depends on the size of the habitat patch of species (Robertson 2008). For example, over 100 plant species can be found in an area of less than 5 acres. However, all species are not noticeable at the same time of a year (Robertson 2008).

Prairies also have ecological problems such as fragmentation, invasion of exotic species, and habitat destruction and degradation. Roads, fields, woodlots, and developments easily fragment prairie ecosystem into small isolated remnants (Minnesota Department of Natural Resources 1998). Isolated prairies lack pollinator species hence affecting reproduction of many other species. Besides, greater edge-to-volume ratio of small sites results increase in the number of invasive exotic species (Minnesota Department of Natural Resources 1998 and Robertson 2008). Prairie remnants often do not recover following disturbances such as development, conversion of prairie land to other uses, and so on. While, soil disturbance for conversion of land use causes loss of species diversity and integrity in prairie ecosystem (Robertson 2008).

2.5. Literature Review on Landscape Fragmentation

Landscapes change over time, sometimes in tune with natural processes, and sometimes altering them (Forman 1995 and Ndubisi 2002). Fragmentation is a phase in the broader sequence of transforming land by natural or human causes from one to another (Forman and Collinege 1996). The five major spatial processes resulting from transformation of land from one form to another are perforation, dissection, fragmentation, shrinkage, and attrition as shown in Figure 2-7 (Forman 1995).

Spatial processes

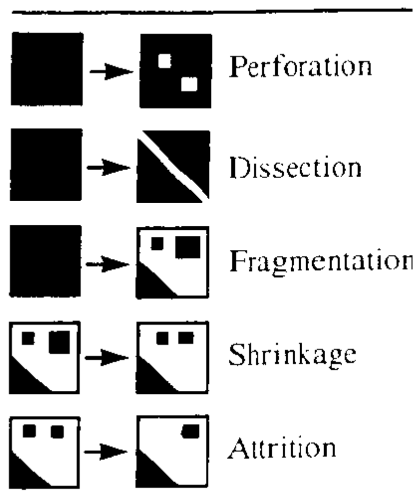
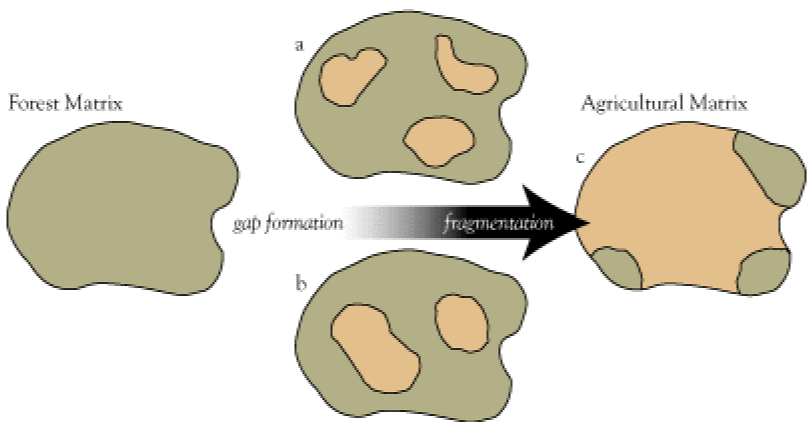


Figure 2-7: Based on dominant spatial patterns, landscapes can be divided into perforation, dissection, fragmentation, shrinkage, and attrition (Forman 1995).

Perforation is the initial stage of land transformation process. It is the least disturbed condition that occurs on land. It is a process of creation of holes in an otherwise undisturbed landscape. Examples of perforated landscapes include a desert-grassland with scattered houses or an extensive forest perforated by logged or blow down clearings (Forman 1995).

Like perforation, dissection is also one of the ways to begin land transformation. Dissection occurs as a result of transportation networks such as roads and railroads on undisturbed landscapes. Dissection forms broken and isolated pieces of landscapes as shown in *Figure 2-7* (Forman 1995).

The further break down of landscapes into unconnected pieces cause fragmentation. Landscape fragmentation is defined as a landscapes' lack of connectivity, including the mechanisms that cause it and the subsequent alteration of ecological processes (Serrano et al. 2002). Fragmentation is the breaking up of habitat, ecosystem, or land-use type into smaller parcels (Forman 1995). Dissection could be considered as a type of fragmentation. However, these two spatial processes differ from one another in terms of the separating elements (roads, railroads, pipelines in case of dissection versus cultivated fields, housing developments, pastures and so on in case of fragmentation). The ecological impacts of dissection and fragmentation could be either very similar or totally different depending on whether the dissecting element eases or forms barrier for the movement of species.



(Image source: Barnes 2000)

Figure 2-8: Fragmentation begins with a perforation in the matrix. Over time, the perforations might get larger resulting in a shift in the matrix.

Shrinkage refers to the spatial process in which the patch size decreases. Example of shrinkage includes shrinkage caused by the removal of remnant woodlots for housing or agriculture (Forman 1995).

The most disturbed condition, attrition, occurs when there is loss of habitat or patches all together (Forman 1995). Usually attrition occurs in small patches though occasional disappearance of large patch is also possible.

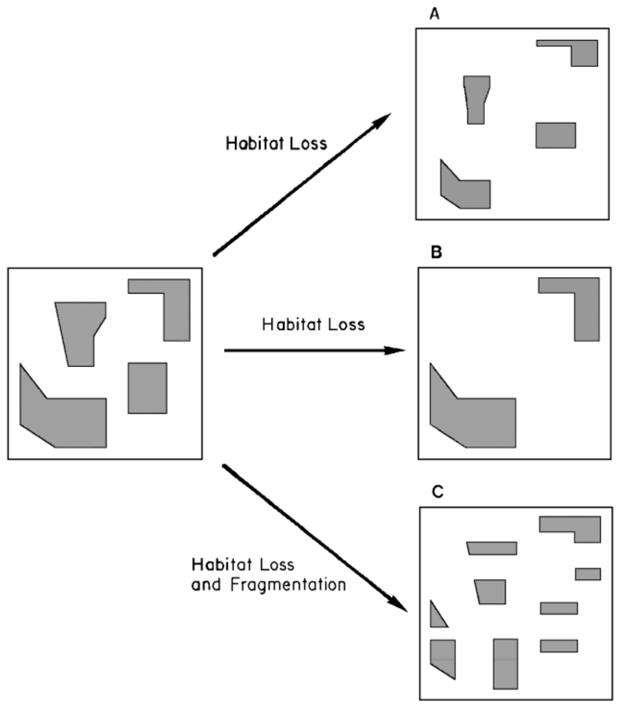


Figure 2-9: Habitat loss and fragmentation are the later stages of land transformation.

Each of these five spatial processes has their own spatial attributes and impacts on ecological characteristics. Perforation, dissection, and fragmentation affect the landscape as a whole or a patch within it where as shrinkage and attrition mainly affects a patch or corridor within a landscape. This study mainly focuses on fragmentation. It also includes discussion of perforation as the initial stage of fragmentation.

Fragmentation is the disintegration of existing geographic patterns brought-on by the introduction of new elements or structures, in such a way that the existing or desired functions are impaired (Gulinck and Wagendorp 2002). Usually human activities are the cause of fragmentation (Bogaert et al. 2005). For example, it occurs when large areas of natural landscapes are intersected by human activities such as the development of settlements, conversion of forested land into agricultural land use, development of infrastructure such as transportation, pipelines, and so on (Forman 1995; Llausàs and Nogué 2012; Slonecker et al. 2012; Ndubisi 2008). Over time, fragmentation can alter landscapes by creating numbers of isolated small patches of habitat that must serve as home to a number of species.

2.6. Well Pads, Impoundment Areas and Roads as Causalities of Landscape Fragmentation

Landscape fragmentation is a dimension of land disturbance that affects ecological processes (Llausàs and Nogué 2012). Shale gas development creates a number of disturbances across the landscapes (Arthur and Cornue 2010 and Slonecker et al. 2012). Such disturbances include construction of well pads and impoundment areas, roads, pipelines, and disposal activities that have structural impact on the landscapes. Clearing land for constructing well pads, impoundment areas, roads, and pipelines cause erosion and sedimentation of the top soil and loss of vegetation (Paleontological Research Institute 2012).

The unevenly distributed well pads require vehicular access and truck activities for various purposes such as movement of equipments, hauling fractured water and wastes, and so on in different stages of shale gas exploration (North Central Texas Council of Government 2012). Besides structural impact such as road distresses (especially on the road that have received little activity historically) due to increased truck traffic, the ecological impact of construction of road networks include forest loss, fragmentation and edge effect (Slonecker et al. 2012, Huntington G and Khaled K. 2009).

In ecological literature, roads are an important cause of fragmentation because they create barriers for animal movement and plant dispersal, and they create isolated habitats with weak ties. For example, high traffic volume causes restrictions of animal movement (Wynveen 2011; and Alexander et al. 2005 and Gagnon 2007). Shale gas exploration requires copious of truck trips to and from the site to transport equipment, construction materials, construction wastes, and waste water. A study of the Marcellus region concluded that a typical drilling rig can require 20,000 to 30,000 truckload movements per year. Truck traffic also increases noise and air pollution, erosion on local roads, and the risk of groundwater and surface water contamination from spills (The Horinko Group 2012).

The construction of well pads and impoundment areas; along with the roads and pipelines result in landscape fragmentation, which in turn affects both the biodiversity value and the economic value society places on land (Jordaan, Keith, and Stelfox 2009). In fragmented landscapes, species are exposed to different ecosystems. An interaction between two different ecosystems through an edge creates a composition of species that are different than the rest of the bigger patch of landscapes. This effect is known as edge effect (Jordaan, Keith, and Stelfox 2009).

Removal of vegetation for well pads, roads, impoundment areas, and pipelines cause change in land cover. Land cover patterns change with the process of land use changes and monitoring this interaction is essential to understand human impacts on the environment (Nagendra, Munroe, and Southworth 2004). Such a study is also significant in identifying changes in road networks over time and their effects on landscape patterns. Roads connect people and resources and provide access for human use. However, roads are one of the most common fragmenting elements (Girveta, Thorne, Berry, and Jaeger 2008).

Roads are responsible for the disruption of landscape processes and the loss of plant and animal species. Road networks crossing landscapes cause erosion (Forman and Alexander 1998). A partial solution to lessen the negative impacts of road construction involves dense vegetation which can increase soil infiltration and storage.

For example, road runoff through grassy channels can reduce pollutant concentration on runoff. Some chemicals transported from roads occur in storm water runoff. Runoff pollutants may be absorbed by plants or get spread and diluted over long distances (Forman and Alexander 1998).

(Image source: Bing Maps 2012)

Figure 2-10: Well pads, roads, and impoundment areas causing fragmentation of grassland in Johnson County, Texas

2.7. Six Landscape Conditions as The Outcome of Landscape Fragmentation

Landscape fragmentation as an impact of shale gas drilling is measured and described in terms of six landscape conditions in this study. They are:

- *Patch*;
- *Edge*;
- *Perforated*;
- *Small core*;
- *Medium core*; and
- *Large core*

These categories are derived from the Landscape Fragmentation tool (LFT) used in this study to measure the landscape fragmentation as an impact of shale gas drilling. The LFT requires two classes of input datasets. Class 1 includes the variables that cause fragmentation and class 2 includes the land cover on which fragmentation is measured. After running the LFT using these two class dataset, the result is obtained as six landscape conditions: *patch*, *edge*, *perforated*, *small core*, *medium core*, and *large core*. The definitions of each of these landscape conditions are derived from landscape ecology literatures in this research (Forman 1995, Dramstad et al. 1996).

2.7.1 *Patch and Core*

A patch can be defined as a wide relatively homogenous area that differs from its surroundings. There are five different types of vegetative patches based on their origins. They are:

1. Disturbance patch, resulting from disturbance or alteration of a small area;
2. Remnant patch, appears when a small area escapes a disturbance surrounding it;
3. Environmental patch, caused by patchiness of environment such as rock or soil type;
4. Regenerated patch, resembles remnant patch, but instead has regrown in a previously disturbed site; and
5. Introduced patch, created by people planting trees or grain, erecting buildings and so forth (Forman 1995).

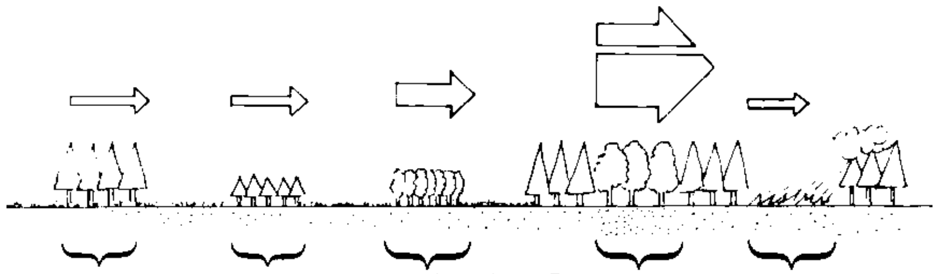
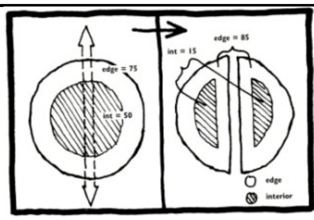


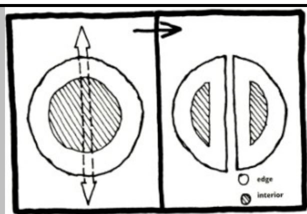
Figure 2-11: Patch types: The five types illustrated assume the original landscape was mature coniferous forest. Thickness of arrow over each patch type is roughly proportional to its persistence or half life (Forman 1995).

Patch size varies from a forest (large patch) to a single tree (small patch). Therefore, a patch can have an area of an acre to hundreds and thousands of acres. The LFT identifies large patches as a "*cores*" and small patches as a "*patches*". *Core* is further divided as small, medium, and large. Core with an area less than 250 acres is a "*small core*". A core having an area between 250 and 500 acres is a "*medium core*" and the one having more than 500 acres is termed as a "*large core*".

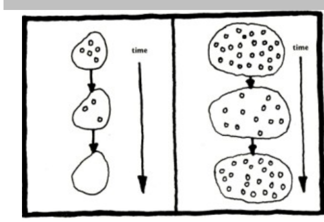
Large and small patches have their own benefits and shortcomings. The following figures explain characteristics of small and large patch.



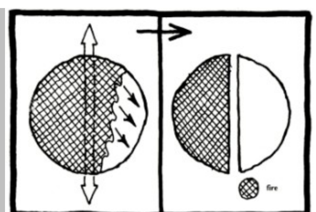
Edge habitat and species: Dividing a large patch into smaller ones forms additional edge habitat, causing higher population sizes and greater number of edge species.



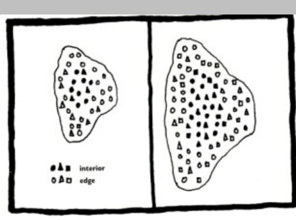
Interior habitat and species: Dividing a large habitat into smaller ones eliminates interior habitat, leading to reduced population sizes and number of interior species.



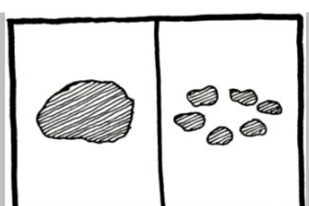
Local extinction probability: It is less likely that the species (which fluctuates in population size) will extinct in large patch because a large patch normally has a large population size for a given species than a smaller patch.



Barrier to disturbance: Dividing a large patch into smaller ones creates a barrier to the spread of certain disturbances such as fire.



Large patch benefits: Large patches maintain most of the interior species providing a core habitat and escape cover for most large-home-range vertebrates-this permits near-natural disturbance regime.



Small patch benefits

Small patches break extensive landscape matrix and act as stepping stones for species movement.

(Image source: Dramstad et al. 1996)

Figure 2-12: Properties on large patch (core) and small patch

To sum up, large patches (*cores*) provide larger ecological benefits. For example, large patches protect aquifers and interconnected stream networks, preserve viable population of most interior species, provide core habitat and permit natural landscape conditions (Dramstad et al. 1996). On the other hand, small patches act as stepping stones for species movement. Small patches also contain some uncommon species. Small patches provide supplemental ecological benefits. Hence, small patches should be considered as a supplemental to, but not a substitution for the large patches (Forman 1995, Dramstad et al. 1996).

2.7.2 *Edge*

The edge can be defined as the outer section of a large patch or small patch that differs completely from the inner environment (Dramstad et al. 1996). Edges separate ecosystem and land uses in a landscape. Edges are the areas where animals move along or across boundaries.

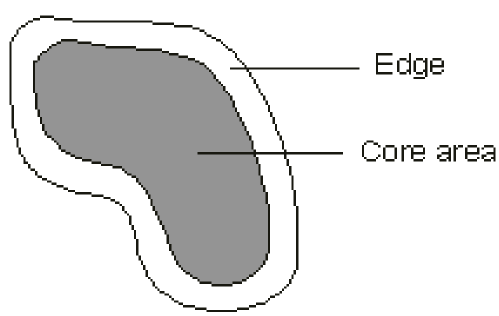


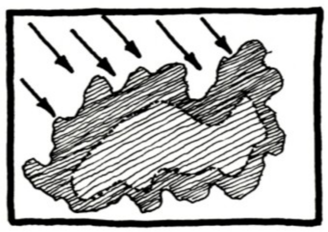
Figure 2-13: Edge around a patch

Edges are created by three mechanisms. They are:

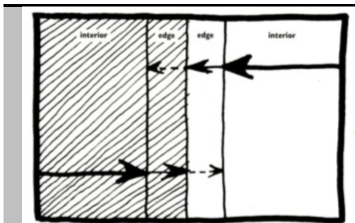
1. A patchy physical environment (such as mosaic of soil types or landforms);
2. Natural disturbances (such as wildfire and tornado); and

3. Human activities (such as deforestation and development for housing) (Forman 1995).

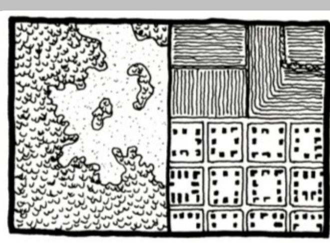
The following images show the characteristics of the edge (Dramstad et al. 1996).



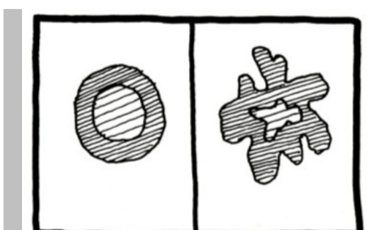
Edge width: Edge width is not same on all sides around a patch. Edges facing the predominant wind direction and solar exposure have wider edge width.



Edge as filter: Patch edges act like filters, which diminish influences of the surroundings on the patch interior.



Natural and human edges: Natural edges are mostly curvilinear, complex, and soft while humans tend to make straight, simple, and hard edges.



Edge and interior species: A convoluted patch will have more edge habitat than a circular habitat, thereby increasing the number of edge species and decreasing the number of interior species, increasing those of conservation significance.

(Image source: Dramstad et al. 1996)

Figure 2-14: Properties on edges

2.7.3 *Perforation*

As mentioned earlier, perforation is the initial stage of fragmentation. Perforations occur when holes are created in a habitat as shown in first image of Figure 2-15 (Forman 1995). Example of perforation includes conversion of natural vegetation to agriculture, developed land, and clear-cut land. As perforation increases, isolation of natural system occur resulting fragmentation, shrinkage, and attrition (Forman 1995).

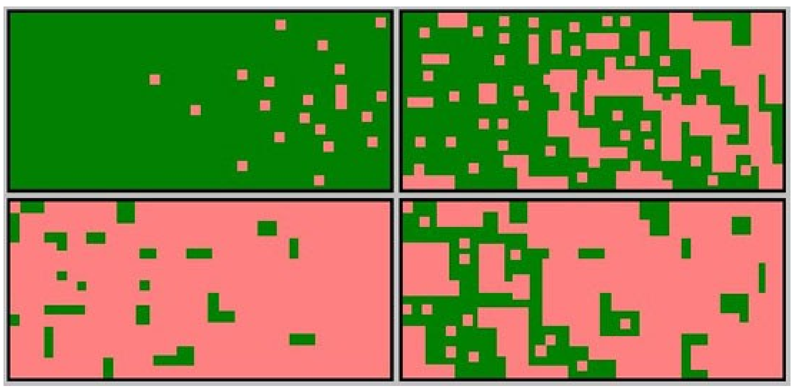


Image source: Michigan Forests Forever Teacher Guide (2010)

Figure 2-15: Image showing process of landscape fragmentation in four phases (Clark 2010).

2.5. Conclusion

This study (through literature review) identifies well pads, roads, pipelines, and impoundment areas as the causalities of landscape fragmentation as a result of shale gas drilling. So, to ameliorate the landscape conditions caused by construction of well pads, impoundment areas and associated roads and pipelines, necessary actions should be carried out from site to regional scale by operators, landscape architects, planners and policy makers.

Disturbed landscapes do not easily recover. So, it is essential to make efforts to minimize the impacts of development on landscapes. Operators and manufactures of equipment for shale gas drilling are working to improve technologies and practices that can lessen the environmental impact of shale gas drilling. Some of the examples of these include drilling multiple horizontal wells from a single pad, using smaller and lighter rigs for drilling phases, implementing low-impact development strategies for well pad and road construction, and recycling flowback water (Pickett 2011).

Landscape disturbances created by roads are persistent (Hawbaker et al. 2005). The impact of roads constructed for shale gas production sites for the transportation of equipment and water can be lessened if planned properly. This can be done by keeping new road construction to an absolute minimum and setting priorities to protect the areas without roads within the site (Hawbaker et al 2005). Jaarsma and Willems (2002 as cited by Hawbaker et al. 2005 p. 1235) point out, "that traffic calming or concentrating diffuse rural traffic onto a smaller number of roads can limit the fragmenting effects of roads."

Regulating land uses on private lands and preserving forests and open spaces are some of the attempts to lessen landscape fragmentation (Nassauer 1997).The current practice in the United States is to combat landscape fragmentation by controlling the type and location of land uses through planning and zoning regulation (Razin 1998). Munroe and York (2005) find zoning ordinance as a primary tool to lessen landscape fragmentation. This regulates land uses and helps prevent human disturbance in the conservation of reserve lands.

Jacquet (2009) suggests having remedial strategies to minimize impact and maximize the restoration of land associated with shale gas production. Regulatory frameworks are required to mitigate the impact of natural gas extraction while continuing the growth of the industry (The Horinko Group 2012.) One of the methods suggested by (Jordaan, Keith, and Stelfox 2009) to reduce development impact is to construct natural well pads in an urban environment. The new drilling sites can use existing roads and infrastructure. This reduces the need to clear the site and add new roads and pipeline easement can be created to accommodate the need of the drilling sites. Such intensification and concentration of gas well sites can reduce fragmentation (Jordaan, Keith, and Stelfox 2009).

Chapter 3

Research Methods

3.1. Introduction

Chapter three discusses the methods used to carry out this research including a discussion of the methodology for identifying components of shale gas drilling responsible for landscape fragmentation. This chapter also outlines the research design, discusses the data used for GIS analysis, and describes the tool used to quantify landscape fragmentation.

This study employs quantitative research techniques to conduct longitudinal studies of three sample sites during pre-drilling and post-drilling conditions. The sample sites are selected through a deductive approach (Harwell 2011) and the variables for this study are identified through literature review. Well pads, roads, and impoundment areas are used as variables. These variables are the primary data prepared in ArcGIS 10.1 (Esri 2014) using aerial images of the sample sites for study timeframes 1995, 2005, and 2010. The Landscape Fragmentation Tool (LFT) is used to quantify landscape fragmentation as an impact of shale gas drilling.

3.2. Identification of Components of Shale Gas Drilling Contributing to Landscape Fragmentation

A goal of this study is to determine the degree to which shale gas drilling contributes to landscape fragmentation. Chapter 2 identifies components required for shale gas drilling, such as well pads, roads, and impoundment areas, which contribute to landscape fragmentation. The literature review focuses on shale gas drilling in Texas and other parts of the United States (for example: Slonecker et al. 2012), on landscape fragmentation (for example: Gulinck and Wagendorp 2002, Serrano et al. 2002, and Dramstad et al. 1996), and on landscape ecology (Forman 1995 and Forman and

Collinege 1996). The literature review identifies well pads, roads, pipelines, and impoundment areas as the primary causalities of landscape fragmentation (See section Chapter 2 page 20).

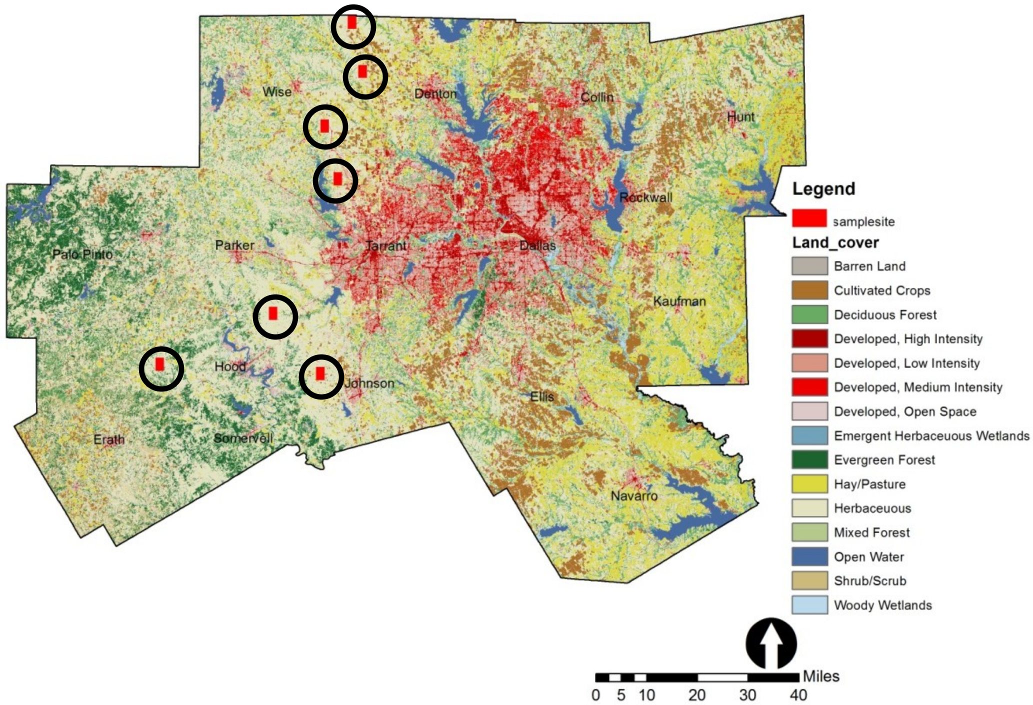
3.3. Research Design

3.3.1 Sample Site Selection

To study the pre-drilling and post-drilling conditions of landscapes, this research is conducted on three sample sites using three study timeframes: 1995, 2005, and 2010. Sample site selection is done in two steps. In the first step, seven sample sites are chosen as shown in Figure 3-1.

Because the aim of this research is to study landscape fragmentation as an impact of shale gas drilling, these seven sample sites are selected in the areas where there is a paucity of pre-existing fragmented landscape conditions caused by human activities other than shale gas drilling. In the second step, through a deductive approach, three sample sites are selected that meet the following criteria (Figure 3-2).

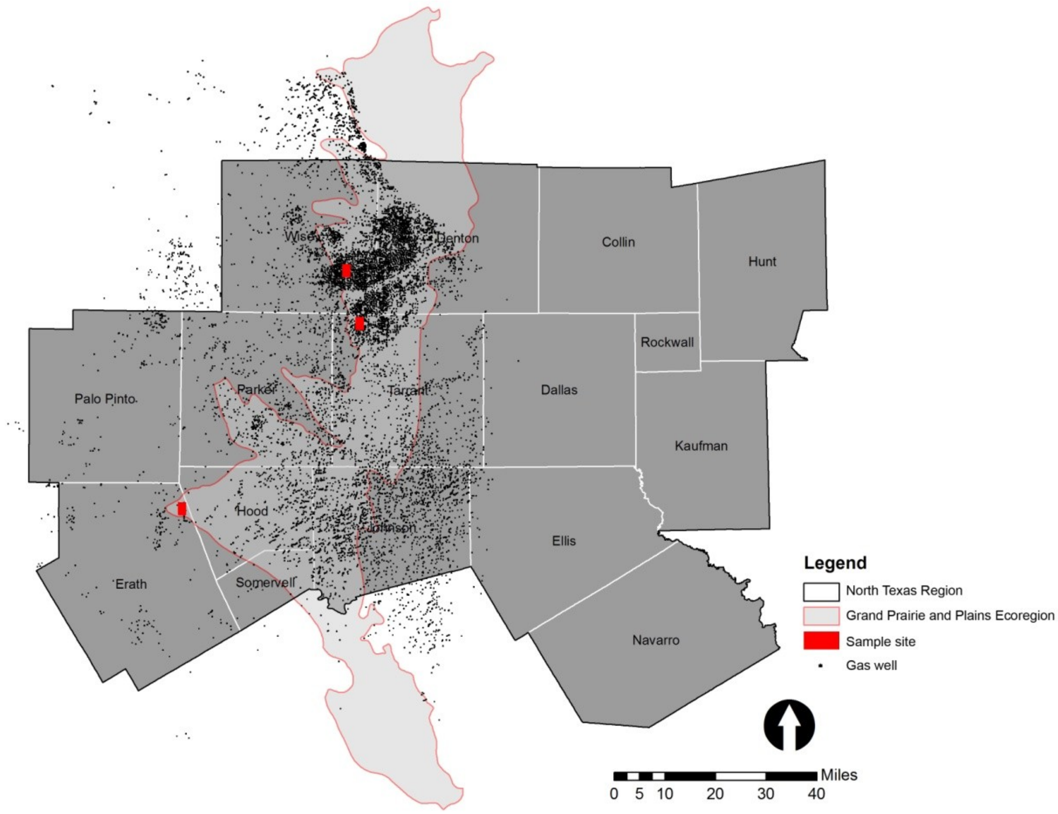
- Selected region: North Texas
- Selected activity: Barnett Shale drilling
- Selected ecoregion: Grand Prairie and Plains Ecoregion
- Selected land cover: Mostly grassland
- Pre-drilling landscape condition: Less than 20% of the land is developed (for example, through urbanization, agriculture, and so on)
- Vegetative cover: Prairie grasses (such as bluestem, silver wintergrass, and so on)



(Data source: USDA Geospatial Data Gateway 2005, NCTCOG 2007)

Figure 3-1: Initial sample site selection

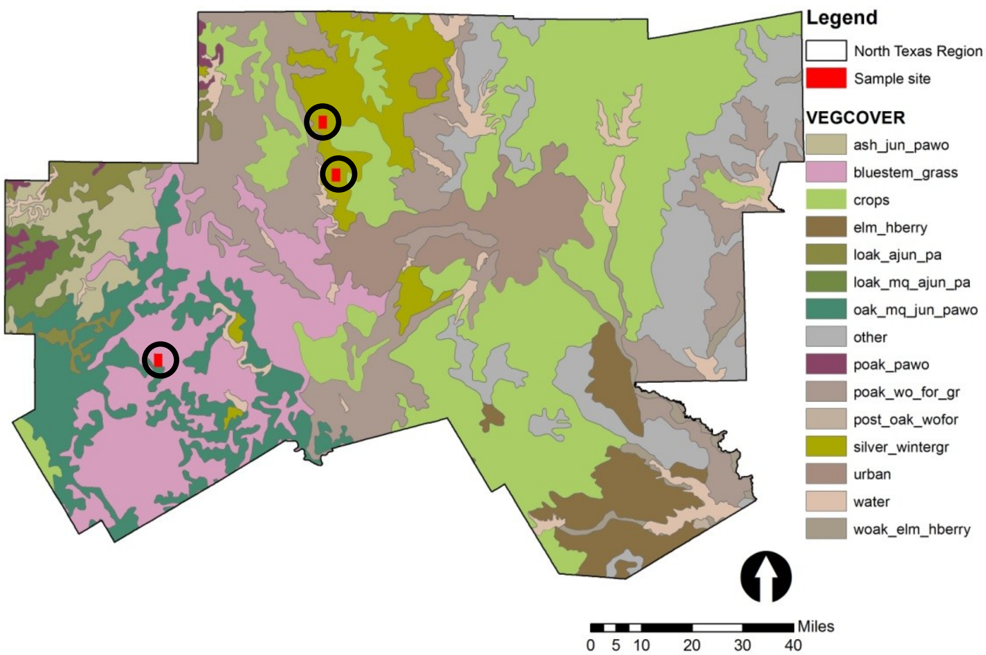
The final three sample sites are located in the Grand Prairie and Plains Ecoregion in North Texas because it is the area where most of the Barnett Shale drilling is taking place. The Grand Prairie and Plains is a Level IV ecoregion and falls under the Cross Timbers Ecoregion. The vegetation in this ecoregion includes tall to midgrass prairie grasses such as big bluestem, yellow Indian grass, sideoats grama, little bluestem, switchgrass, tall dropseed, Texas cupgrass, silver bluestem, grama grasses, Texas wintergrass, purple threeawn, seep muhly, buffalograss, mesquite, and introduced bermudagrass and Kleingrass (Griffith et al. 2007).



(Data source: Railroad Commission of Texas 2011 and NCTCOG 2007)

Figure 3-2: Final sample sites selected through deductive approach

In order to select the areas that have a low level of human uses and activities other than shale gas drilling, the sample sites that have more than 20% of their area developed in the form of urbanization or cultivated land are eliminated from the selection of final sample sites. Through this approach, three final sample sites are chosen for this study. Each of the three different sites selected also has a different number of well pads to study the degree of fragmentation in three different scenarios.

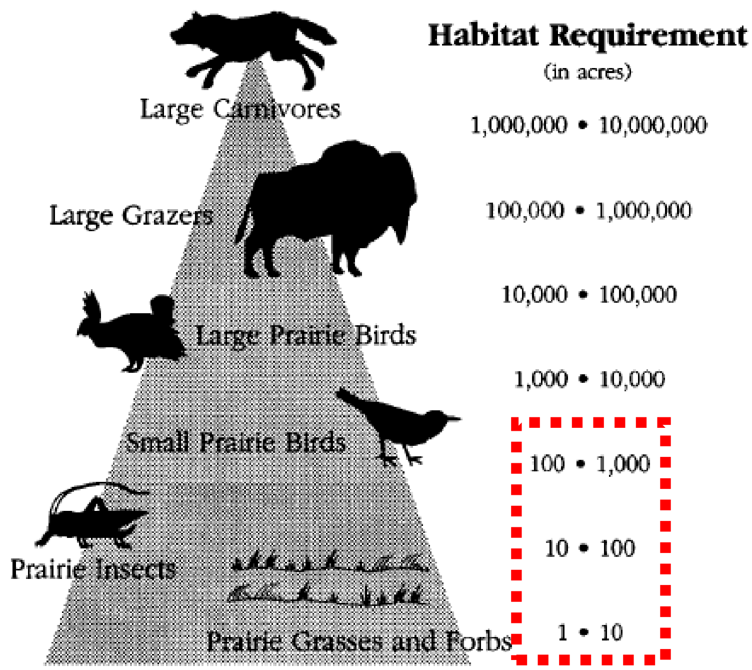


(Data source: NCTCOG 2003 and NCTCOG 2007)

Figure 3-3: The vegetative cover of three sample sites includes prairie grasses such as bluestem and silver wintergrass.

3.3.2 Area of Selected Sample Site

Each sample site area is 1,000 acres. The size of the sample site is decided based on the habitat size of tall grass prairie ecosystems as shown in Figure 3-4.



(Image source: Minnesota Department of Natural Resources 1998)

Figure 3-4: Tallgrass prairie ecosystem: A pyramid of life

According to Figure 3-4, prairie grass requires 1-10 acres of habitat (Minnesota Department of Natural Resources 1998). However, a sample site area of 1,000 acres is utilized for this study in order to have an area large enough to study plant habitats of the tallgrass prairie ecosystems. 1,000 acres is also large enough to include the habitat for prairie insects and small prairie birds. In addition, 1,000 acres is a large enough area for each site to include a different number of well pads, which can be up to 10 acres in size.

3.4. Data Collection

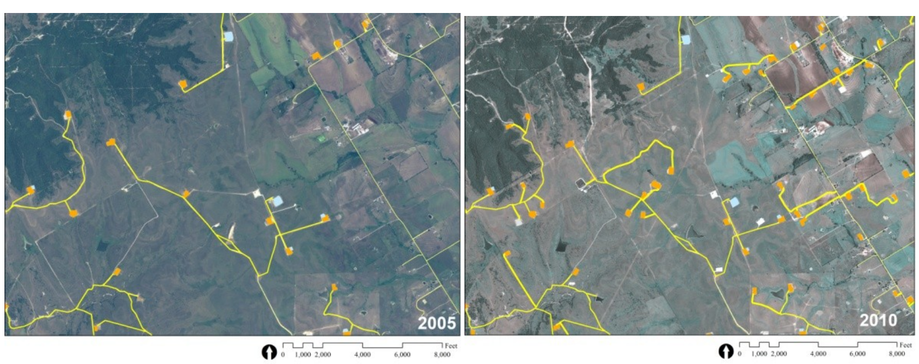
To determine the impact of shale gas drilling, the Landscape Fragmentation Tool (LFT) is used to quantify the degree of fragmentation of landscapes and to study the change in landscape conditions over the chosen timeframes of 1995, 2005, and 2010. LFT was first developed by the Center for Land Use Education and Research (CLEAR) at the University of Connecticut in 2002 (Wilson and Arnold 2009). It was later refined in 2009 based on research done by Vogt et al. in 2007. LFT is a python script that runs in ArcToolbox in ArcGIS. CLEAR researchers used the tool to study the fragmentation of Connecticut's forests over the period of 1985-2005. Though the tool was applied to map forest fragmentation, it can be used for any other land cover type, such as shrub land, grassland, and urban land (Wilson and Arnold 2009).

LFT requires input data with two classes.

Class 1 = Fragmenting elements (well pads, impoundment areas, and roads)

Class 2 = Land cover of interest or fragmented layer (grassland)

Class 1 data are obtained by the digitization of well pads, impoundment areas, and roads using Barnett Shale well data (Railroad Commission of Texas) and high resolution satellite imagery (U.S. Department of Agriculture) for the study timeframes 1995, 2005, and 2010 using ArcGIS 10.1. Figure 3-5 shows an example of the preparation of data by digitizing the well pads, impoundment areas, and roads for years 2005 and 2010.



(Data source: Texas Natural Resources Information System 2005 and 2010)

Figure 3-5: Digitization of well pad, impoundment area, and road data from aerial maps for years 2005 and 2010

Class 2 data are obtained from land cover data downloaded from the US Department of Agriculture, Geospatial Data Gateway. Hence, the input data is a combined layer of the fragmenting elements as class 1 and the fragmented layer as class 2. After obtaining these data, they are imported to ArcGIS and analyzed using LFT.

3.5. Quantification of Landscape Fragmentation

LFT categorizes input data into six types of landscape conditions. These are *patch condition*, *edge condition*, *perforated condition*, *small core condition*, *medium core condition*, and *large core condition* in the order of most to least disturbed landscape conditions as shown in Figure 3-6.

A core condition represents undeveloped land, and LFT divides this land into three categories. A *large core condition* is identified by LFT as an undisturbed area over 500 acres, a *medium core condition* is an undisturbed area of 250 to 500 acres, and a *small core condition* represents an undisturbed area of 250 acres or less. A *perforated condition* represents a hole or perforation in a *core condition*. For example, Figure 3-7 shows a single well pad as a *perforated condition* in the middle of the grassland. An *edge condition* represents the periphery of a *core condition* that meets the fragmenting area. The most disturbed condition, *patch*, is a small fragment of landscape that is completely surrounded by fragmenting elements. This is a condition where the area is completely encompassed by an *edge condition*.

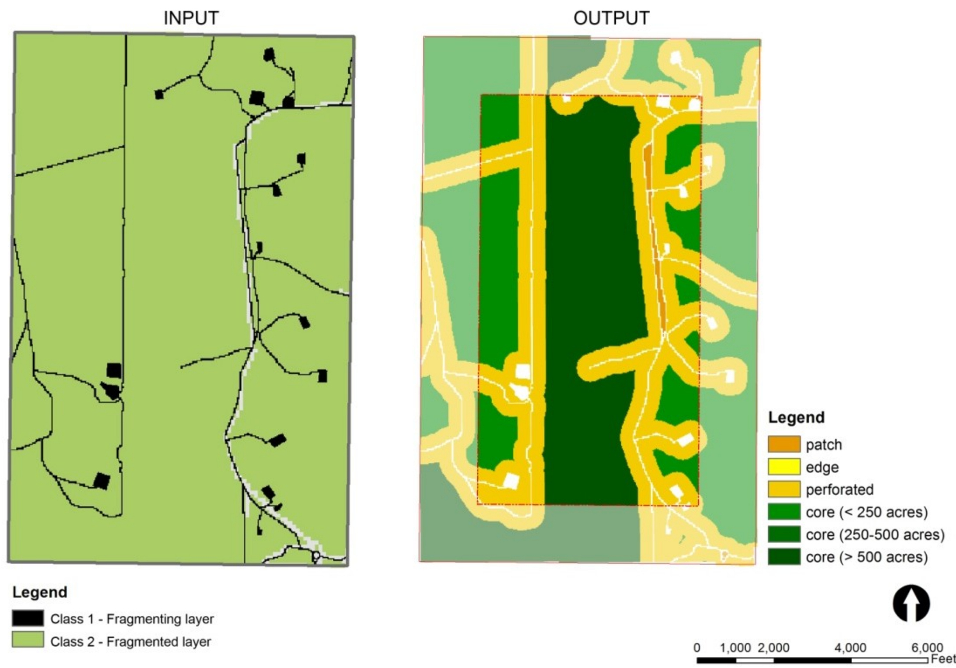
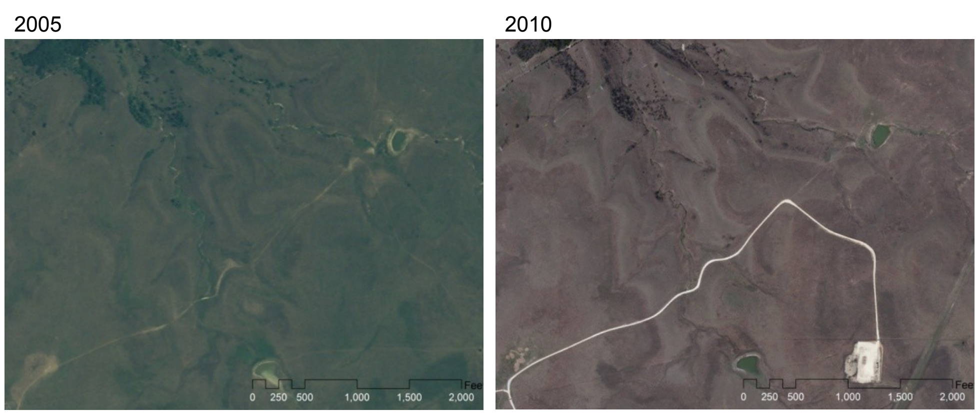


Figure 3-6: Six landscape conditions obtained as output after running LFT.



(Data source: Texas Natural Resources Information System 2005 and 2010)

Figure 3-7: An area in Johnson County showing a core grassland in 2005 and a perforated grassland created by a road and well pad in 2013.

The six landscape conditions obtained after running LFT are the result of edge width. Edge width is the distance over which fragmenting elements can degrade the specified land cover, which for this study is grassland. Edge width varies from one species to another and can range from 50 meters to hundreds of meters. However, an edge width of 100 meters (300 feet) is generally used for any kind of fragmentation (Wilson and Arnold 2009). Hence, assuming an edge width of 300 feet, a *core condition* represents any undisturbed area more than 300 feet from the fragmenting layer. A *perforated* and *edge condition* are the areas within 300 feet of the fragmenting layer. Finally, a *patch condition* represents the fragmented area that is less than 300 feet from the fragmenting layer on all sides. With this definition of *patch condition*, the edge width for this study has been calculated.

As shown in the habitat pyramid of a tallgrass prairie ecosystem Figure 3-4, the smallest patch size for a tallgrass prairie ecosystem is 1 acre. Since patch size represents the largest circle that fits within a patch (Forman 1995), a circular patch of 1 acre is assumed to represent a *patch condition* in this study. A circular patch of 1 acre has a diameter of about 235 feet. Hence, LFT identifies an area of 1 acre or less as a patch if the edge width is 235 feet. In this way, an edge width of 235 feet is used in this study based on the minimum habitat requirement for a tallgrass prairie ecosystem.

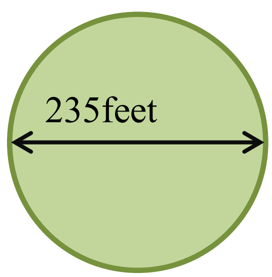


Figure 3-8: Circular patch of 1 acre

Referring to the earlier definitions of the landscape conditions, a *core condition* represents an undisturbed area more than 235 feet from the fragmenting layer. *Perforated* and *edge conditions* represent the areas within 235 feet of the fragmenting layer. A *patch condition* is the area less than 235 feet in all directions and surrounded by fragmenting layers.

In this study, LFT is used in a repetitive manner to quantify landscape fragmentation caused by shale drilling in the three sample sites. LFT is run for each sample site and is repeated for the selected timeframes: 1995, 2005, and 2010.

3.6. Limitations of The Methodology

This study of landscape fragmentation is done by evaluating the changes in land cover at three sample sites for the period of 1995-2010. The land cover analyzed in this study includes mostly prairie grasses. The degree of fragmentation with this land cover might be different than the rest of the Barnett Shale area because of variations in the land cover types and in the spatial distribution of well pads.

In addition, because most data are obtained from aerial imagery, it is not possible to locate pipelines. Therefore, pipelines are not included in this study though they are one of the fragmenting components.

Finally, because LFT identifies the sample site boundary (Boundary A, Figure 3-9) as a physical boundary, which results in errors in identifying landscape conditions, a buffer is created around the sample site (Boundary B, Figure 3-9). To avoid these errors, LFT is run for boundary B; however, the result is analyzed only for boundary A.

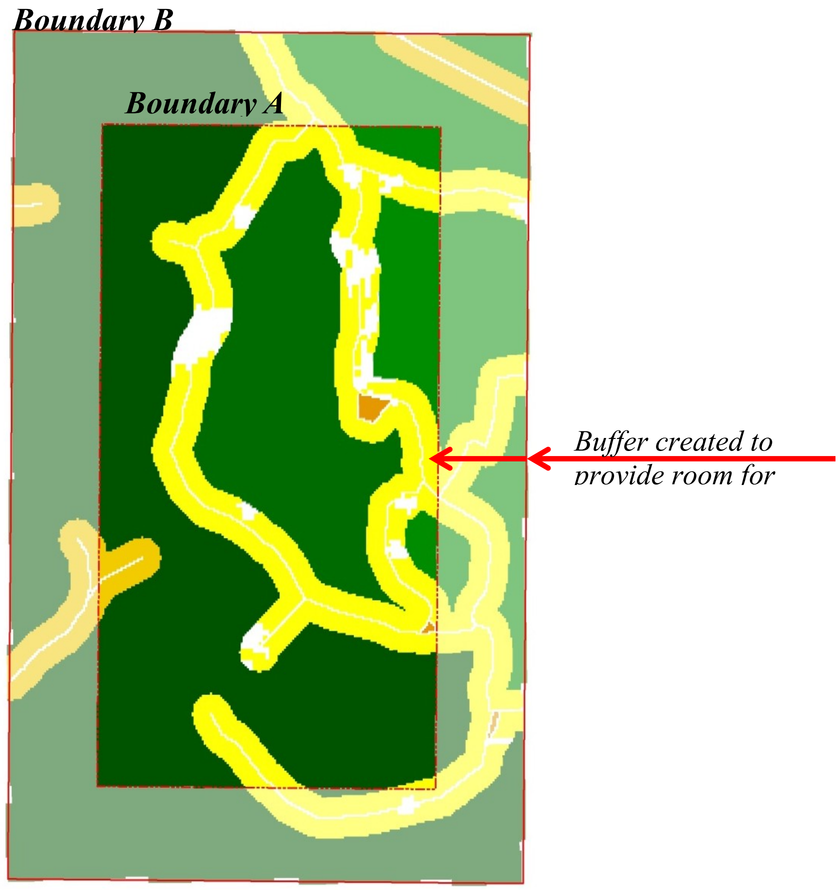


Figure 3-9: A buffer created around the sample site boundary A to avoid error.

Chapter 4

Analysis and Findings

4.1. Introduction

This chapter outlines the analysis and findings of the landscape fragmentation study carried out on the three sample sites. The chapter includes description of all three sample sites in each study timeframe and provides analyses of all scenarios. Each sample site differs from the others in terms of the density of well pads (Figure 4-1). Concluding the chapter is the overall findings of the study.

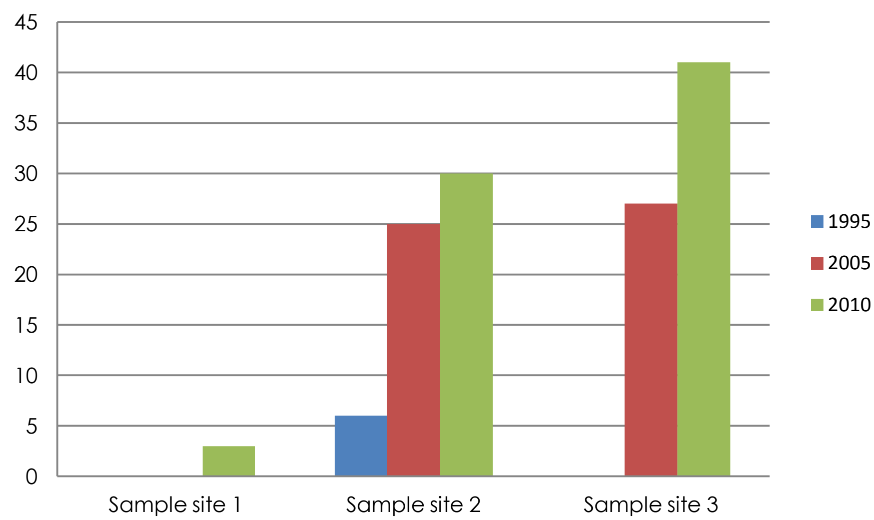


Figure 4-1: Chart showing the number of well pads in three sample sites in the three study timeframes 1995, 2005, and 2010.

As mentioned earlier in section 3.4. , input data for quantification of landscape fragmentation of each sample site requires two classes of data. Class 1 data includes well pads, roads, and impoundment areas and class 2 includes the land cover layer, grassland in this study. For this study, developed areas such as urbanized areas from land cover data are not included for analysis. Thus, this study only quantifies landscape fragmentation by shale gas development and excludes landscape fragmentation from other human activities such as residential developments, agriculture, and others that happen within the sample site. Hence, class 2 data are obtained by isolating the landscape layer of interest, grassland, from land cover data.

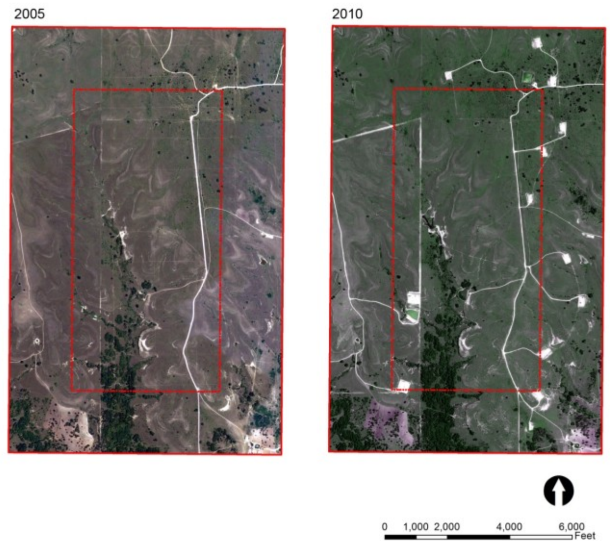
After running the LFT, results were obtained for each study timeframe in terms of six landscape conditions. They were *patch, edge, perforated*, *small core* (<250 acres on undisturbed condition), *medium core (*250-500 acres of undisturbed condition), and *large core (*>500 acres of undisturbed condition).

4.2. Analysis and Findings

4.2.1 *Sample Site 1*

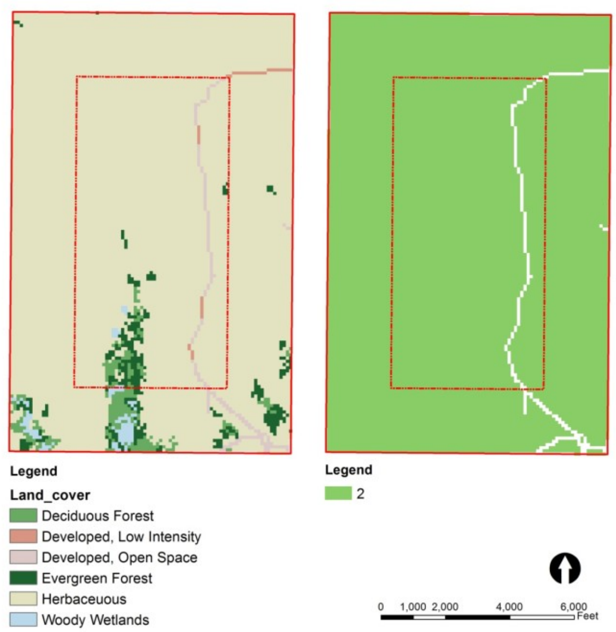
Located in Erath County, this total sample site area is about 1000 acres, the inner boundary in Figure 4-2. Figure 4-2 verifies that shale gas exploration was not started in 2005 in this sample site. By 2010, there were three well pads and one impoundment area within study area, the inner boundary, covering a total area of 7.25 acres and 3.17 acres respectively. Total length of the roads associated with shale gas exploration was 54,344 ft in 2010.

Figure 4-4 shows the input data for sample site 1. Class 1 data were obtained by creating well pad layer, impoundment area layer, and road layer in ArcGIS. Class 2 data were obtained by isolating selected land cover as shown in Figure 4-3. The input data were then used to run the LFT, the results obtained are shown in Figure 4-5.



(Data source: Texas Natural Resources Information System 2005 and 2010)

Figure 4-2: Aerial image of sample site 1 in 2005 and 2010.



(Data source: USDA Geospatial Data Gateway 2005)

Figure 4-3: Isolation of selected land cover types (class 2 data).

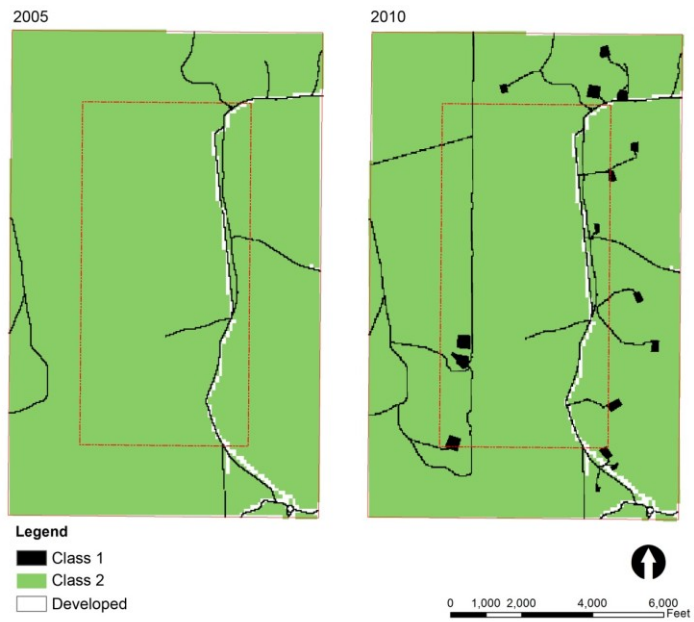


Figure 4-4: Map showing input data for sample site 1.

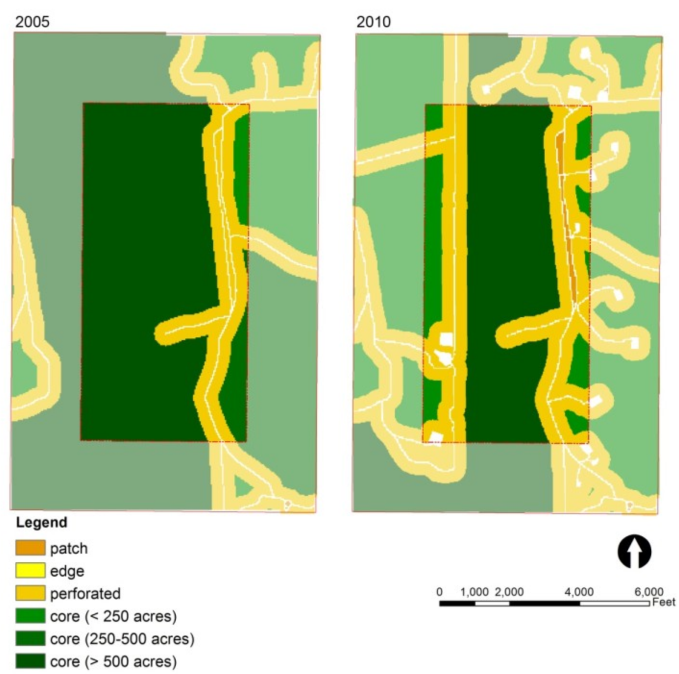


Figure 4-5: Six landscape conditions for sample site 1 in 2005 and 2010.

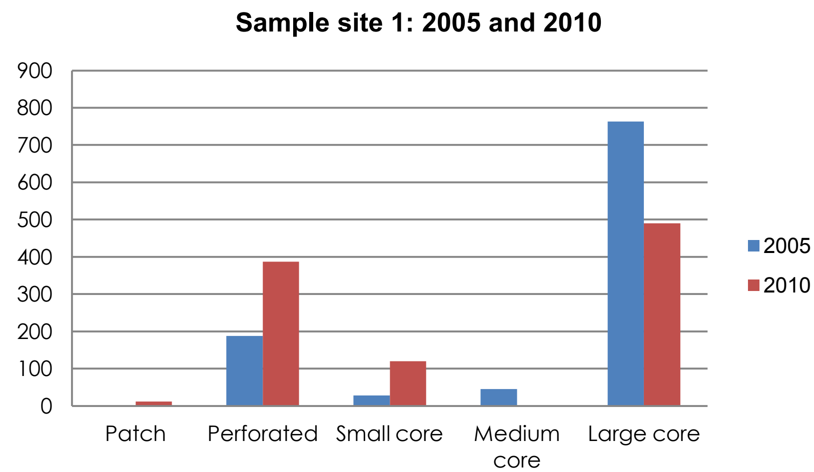


Figure 4-6: Chart showing landscape conditions in sample site 1 in the study timeframes 2005 and 2010.

Figure 4-6 shows that between 2005 and 2010, there were increase in patch, perforated and small core conditions, and decrease in medium core and large core conditions as a result of shale gas drilling. Edge conditions were not found in sample site 1 within this time period. Figure 4-1 provides the area covered by each landscape condition in 2005 to 2010 in sample site 1.

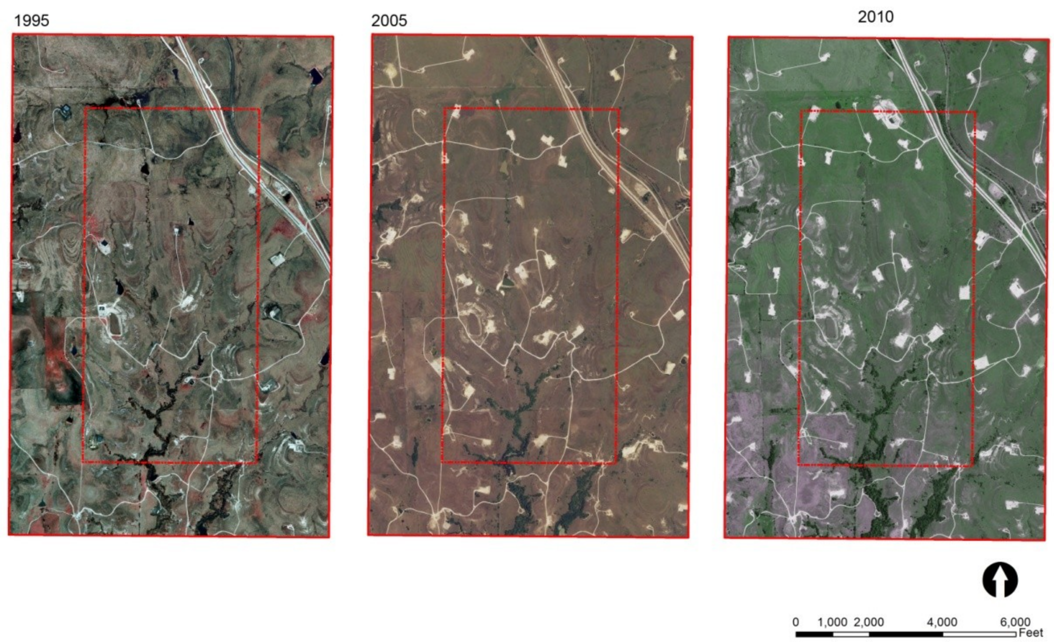
Table 4-1: Table showing total area of each landscape condition in 2005 and 2010.

Year	Patch	Edge	Perforated	Small core	Medium core	Large core
2005	-	-	188	28	45	763
2010	12	-	387	120	-	490

**Note: Areas are in acres.*

Large core conditions covering about 73% of the total area in pre-drilling condition (in the year 2005) were divided into *small core conditions* and *perforated conditions* after shale gas exploration took place in the sample site. As a result, the total amount of *large core conditions* were reduced and fragmented conditions such as *small core conditions*, *perforated conditions* and *patch conditions* were created by shale gas activity. Hence, it is concluded that sample site 1 is in the early phase of fragmentation characterized by dominance of *perforated condition*s (an initial stage of landscape fragmentation).

4.2.2 Sample Site 2



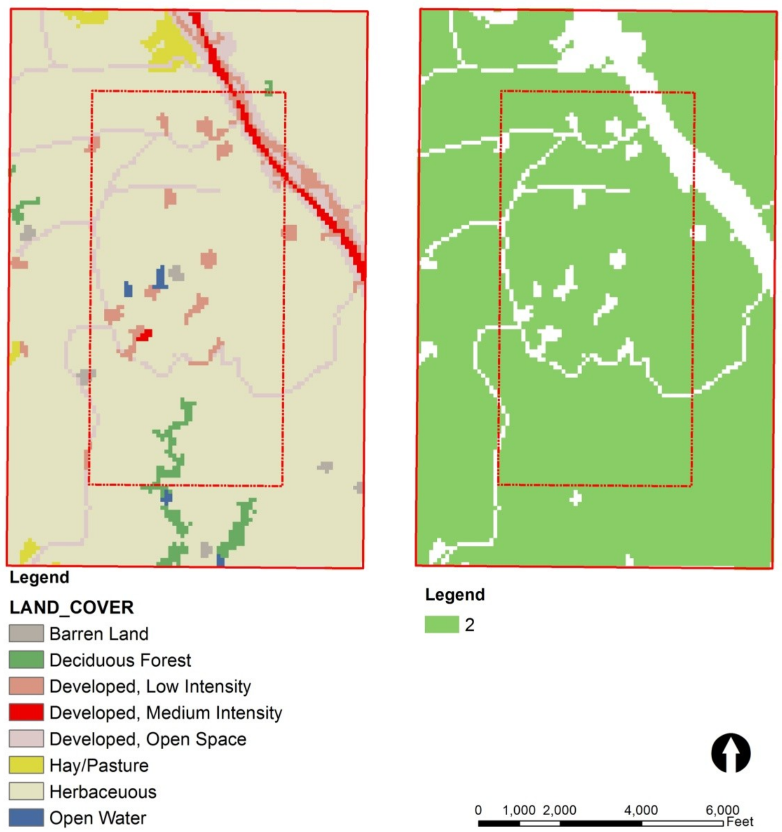
(Data source: Texas Natural Resources Information System 1995, 2005 and 2010)

Figure 4-7: Aerial image of sample site 2 in 1995, 2005, and 2010.

Sample site 2 is located in Wise County. In 1995, there were six well pads and four impoundment areas covering about 7.25 acres and 2.14 acres of land respectively. The maximum size of well pad in sample site 2 was 1.9 acres in 1995. The length of roads serving the well pads in the site was 36,436 feet.

In 2005, there were twenty-five well pads covering 28.63 acres of land and the total length of roads serving the well pads was 46,701 feet. There were no impoundment areas. The maximum area of each well pad was about 2.8 acres.

In 2010, there were 30 well pads covering 52 acres of the sample site. The total length of roads serving the well pads was 47,834 feet. The maximum area of a single well pad was 10 acres.



(Data source: USDA Geospatial Data Gateway 2005)

Figure 4-8: Isolation of selected land cover (class 2 data) of sample site 2 to study fragmentation.

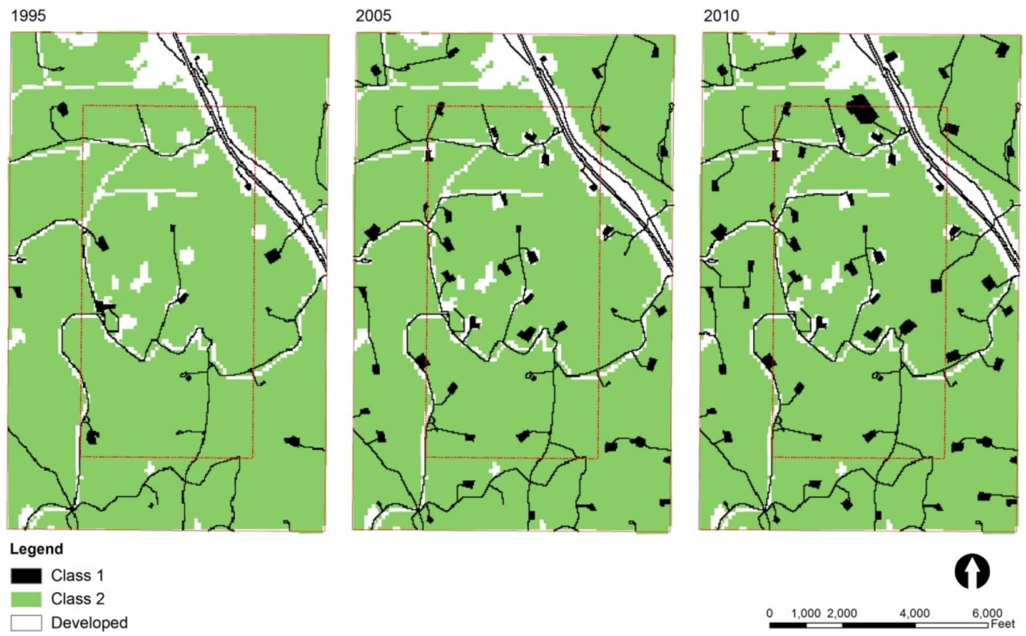


Figure 4-9: Maps showing input data for sample site 2 for study timeframes 1995, 2005, and 2010.

Well pad data, impoundment area data, and road data are prepared in ArcGIS. These data along with selected land cover layer data are combined to prepare input dataset that have two classes, class 1 as well pads, impoundment areas and roads and class 2 as the area where the degree of fragmentation is being measured. Figure 4-9 shows the input dataset for sample site 2 for three study timeframes 1995, 2005, and 2010. Figure 4-10 shows the results obtained after running the LFT for selected study timeframes.

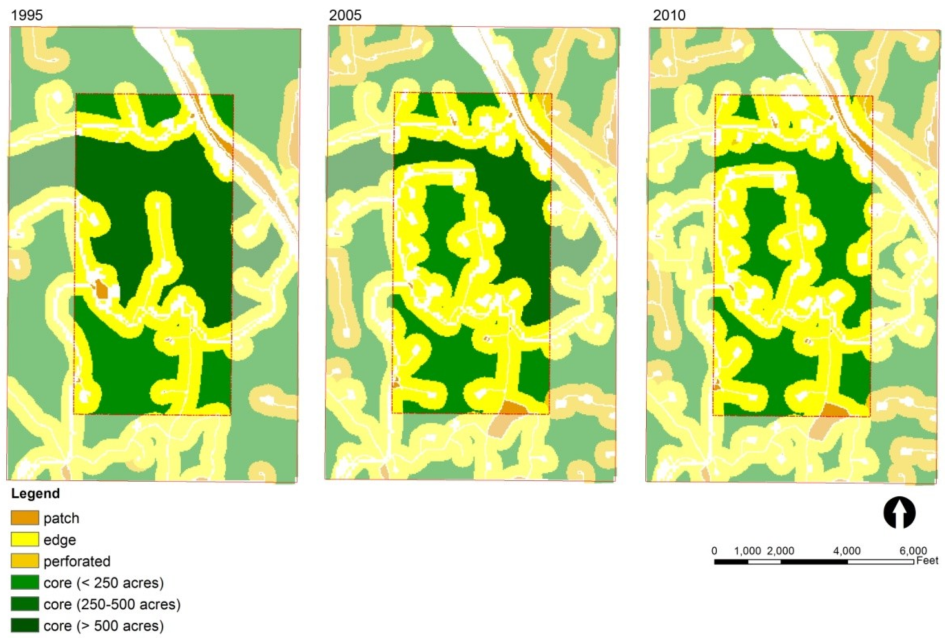


Figure 4-10: Six landscape conditions (patch, edge, perforated, small core, medium core, and large core) in sample site 2 as an impact of shale gas drilling.

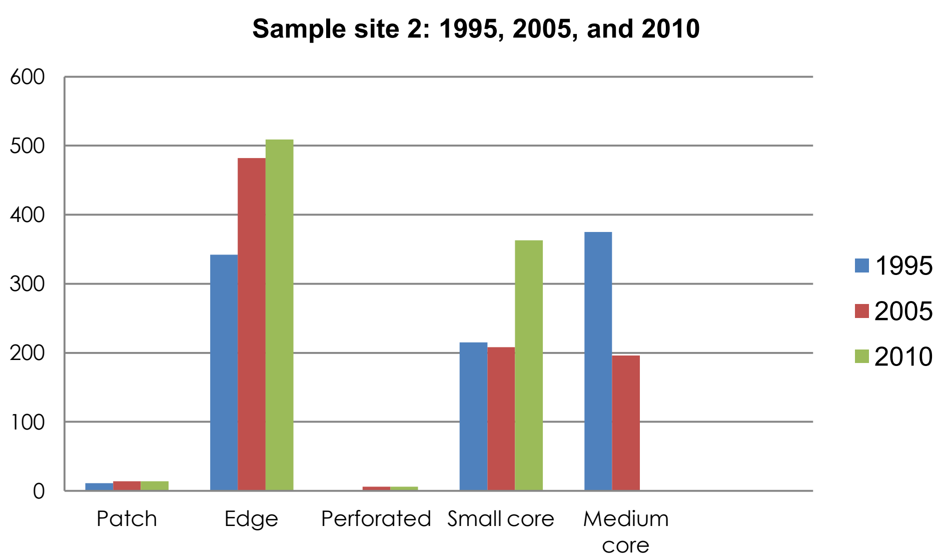


Figure 4-11: Chart showing landscape conditions in sample site 2 in the years 1995, 2005, and 2010.

Between 1995 and 2010, number of well pads increased from 6 to 30 and length of the roads associated with drilling increased from 36,436 feet to 47,834 feet. Figure 4-11 shows that *edge conditions, perforated conditions, and small core conditions* increased in sample site 2. *Core conditions* (*medium core conditions* and *small core conditions*) covered 68% of the total area in 1995 which decreased to 35% of the total area in 2010. Some acreage of core area was taken by well pads and associated roads, while the rest of the core areas were converted to edge. The changes in the landscape conditions from 1995 to 2010 are summarized in Table 4-2.

Table 4-2: Table showing the changes in landscape condition in sample site 2 from 1995 to 2010 as an impact of drilling.

Year	**Patch**	**Edge**	**Perforated**	**Small core**	**Medium core**	**Large core**
1995	11	342	-	215	375	-
2005	14	482	6	208	196	-
2010	14	509	6	363	-	-

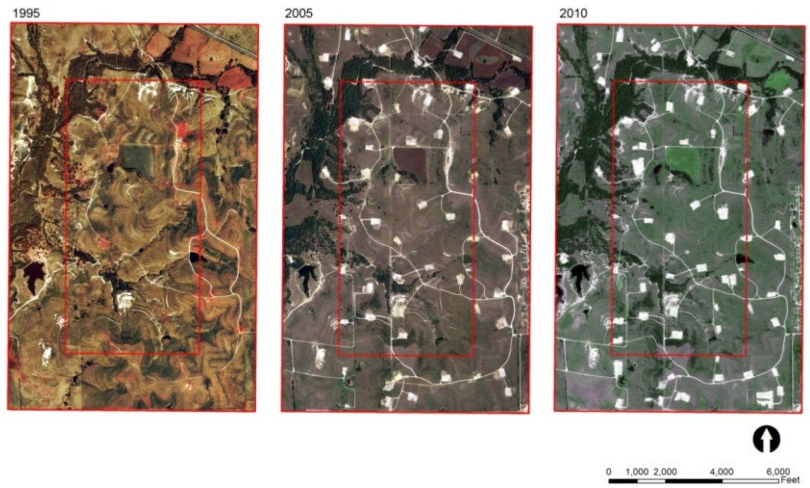
**Note: Areas are in acres*

Hence, the degree of fragmentation is more in sample site 2 as compared to sample site 1 because sample site 1 is in the initial stage of fragmentation characterized by *perforated conditions.* However, dominance *of edge conditions* was observed in sample site 2, signifying higher degree of fragmented conditions.

4.2.3 Sample Site 3

Sample site 3 is located in Tarrant County. This sample site has the most intense drilling situation among the three chosen sample sites. In 1995, there were not any well pads on this site. In 2005, there were 27 well pads covering about 38 acres of the site area. The maximum size of the well pad was 3.3 acres and the length of roads serving the roads was 47,700 feet. In 2010, there were 41 well pads covering a total area of about 64 acres. The maximum size of the well pad was about 4.2acres and the total length of the roads was about 52,010 feet.

Figure 4-13 shows the input data for sample site 3 for study timeframes 1995, 2005, and 2010. The output obtained after running the LFT is shown in Figure 4-15. Figure 4-16 shows the six landscape conditions in 1995, 2005, and 2010.



(Data source: Texas Natural Resources Information System 1995, 2005, and 2010)

Figure 4-12: Aerial images of sample site 3 in 1995, 2005, and 2010.

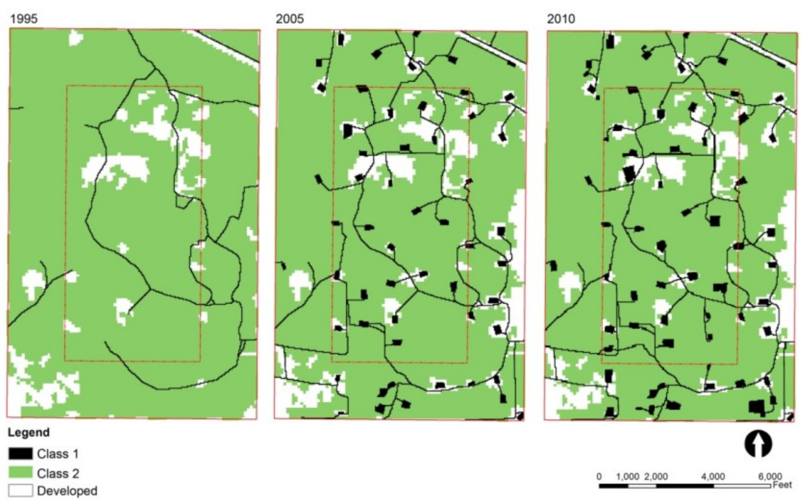
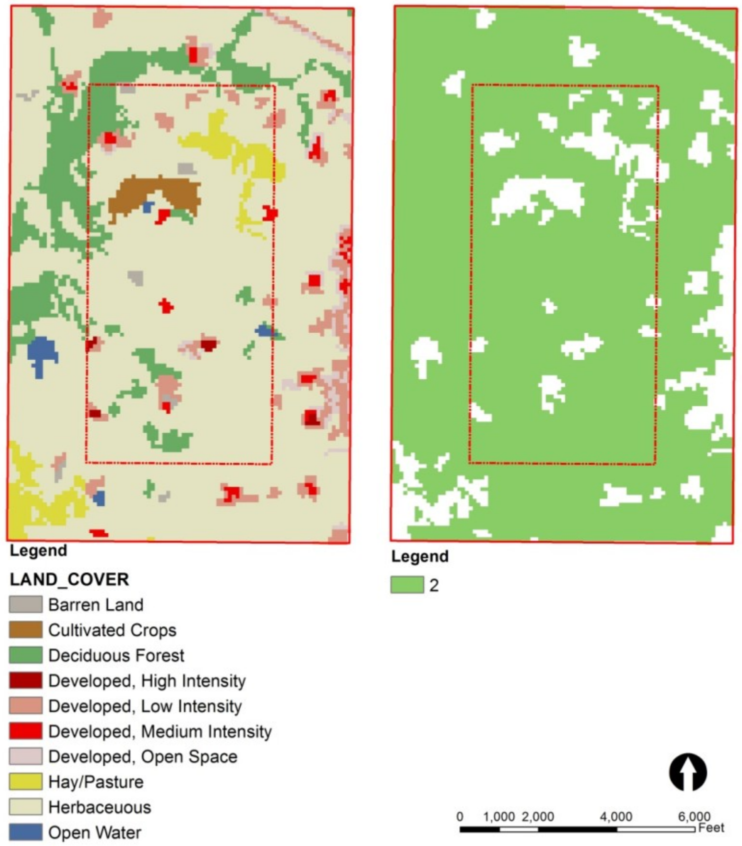


Figure 4-13: Maps showing input data classified as class 1 and class 2.



(Data source: USDA Geospatial Data Gateway 2005)

Figure 4-14: Isolation of selected land cover types (class 2 data) in sample site 3.

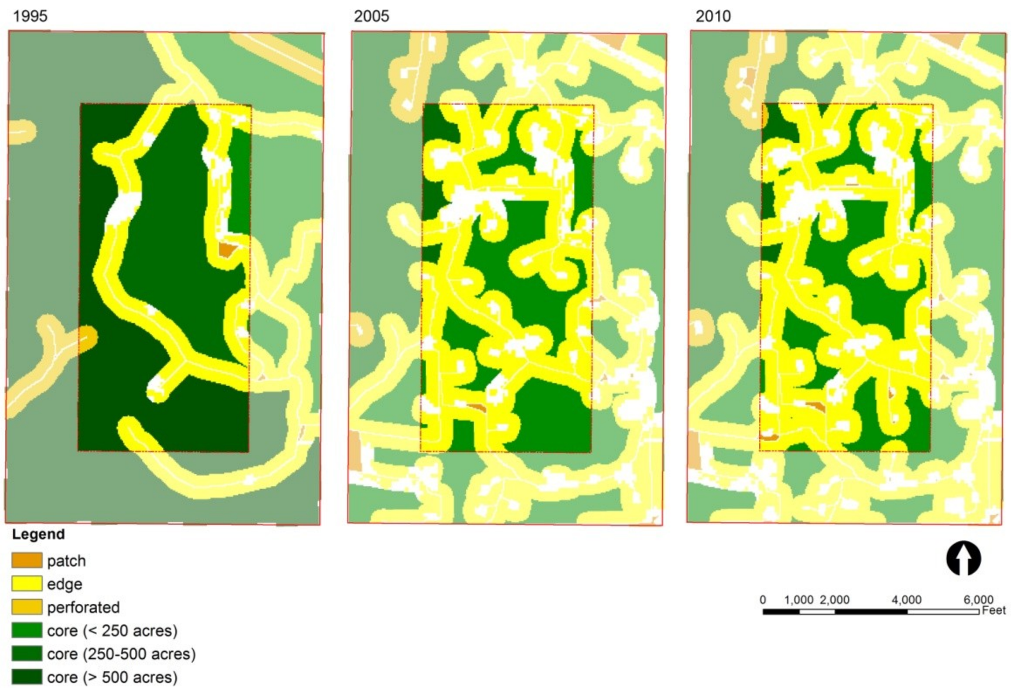


Figure 4-15: Six landscape conditions (patch, edge, perforated, small core, medium core, and large core) in sample site 3 as an impact of shale gas drilling.

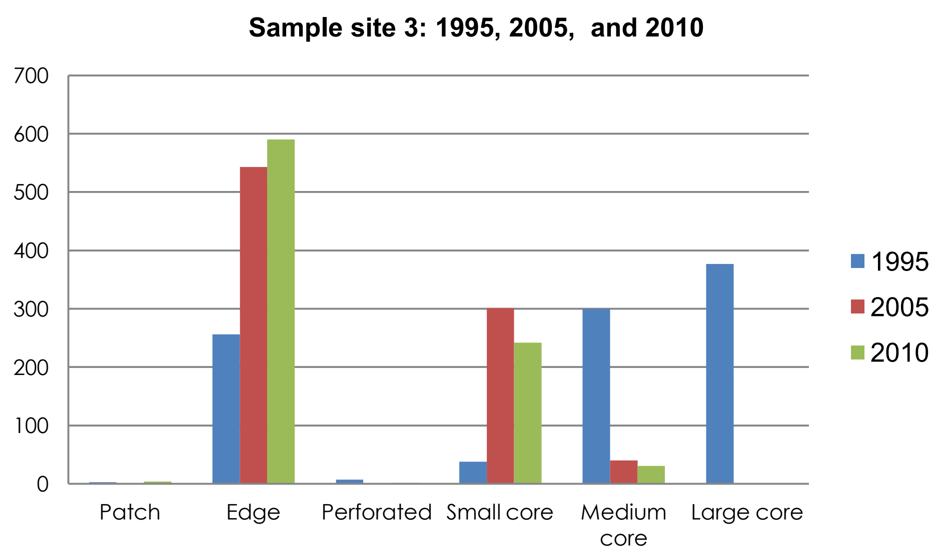


Figure 4-16: Charts showing six landscape conditions in sample site 3 in 1995, 2005, and 2010.

Between 1995 and 2010, the number of well pads increased from 0 to 47 and the total length of roads increased from 27,714 feet to 52,010 feet. Increase in drilling activity between 1995 and 2010 increase *patch* and *edge conditions*. Total *core conditions* (*large core conditions, medium core conditions, and small core conditions*) covering about 68% of the total area in 1995 was reduced to 26% in 2010. The summary of changes in landscape conditions over the period of 1995-2010 for sample site 3 is shown in Table 4-3.

Table 4-3: Table showing the changes in landscape conditions from 1995 to 2010 as an impact of drilling in sample site 3.

Year	Patch	Edge	Perforated	Small core	Medium core	Large core
1995	3	256	7	38	300	377
2005	1.5	543	0.1	301	40	31
2010	4	590	2	242	31	-

**Note: Areas are in acres.*

4.3. <u>Review of The Findings</u>

Findings from this study suggest that shale gas exploration contributes to fragmentation of landscapes, and the degree of fragmentation is highly dependent on variables such as well pads, roads, and impoundment areas. Findings also suggest that low intensity of shale gas drilling creates perforation, the earliest stage of fragmentation, on landscapes such as are found in sample site 1. But, as exploration progresses, more well pads and roads are constructed resulting in more fragmented conditions such as *edge conditions* and *patch conditions* as seen in sample sites 2 and 3. *Patch conditions* are mostly observed where the roads crisscross each other as are seen in sample site 3.

Table 4-4: Comparison of changes in landscape conditions in the three sample sites.

Site	Patch	Edge	Perforated	Small core	Medium core	Large core
1	+12	0	+199	+92	-45	-273
2	+3	+167	+6	+148	-375	0
3	+1	+334	-5	+204	-269	-377

**Note: "+" means increase, "-" means decrease, and "0" means not found.*

Analysis of the three sample sites reveal that *patch conditions*, *edge conditions* and *small core conditions* increase as a result of shale gas drilling. Change in *perforated conditions* varies depending on the intensity of drilling and also in pre-existing landscape condition. In more intense drilling situations, *perforated conditions* change to more fragmented landscape conditions such as *edge conditions* and *patch conditions. Medium core conditions* and *large core conditions*, the least disturbed conditions, decrease with the increase in drilling activity. These findings are summarized in Table 4-5.

Table 4-5: Table showing generalized direction of changes in landscape conditions as a result of shall gas drilling from pre-drilling to post-drilling situation

Patch	Edge	Perforated	Small core	Medium core	Large core
+	+	+/-	+/-	-	-

**Note: "+" means increase, "-" means decrease, "0" means not found, and "=" means no change.*

4.4. Changes From 1995 to 2010

About 3% of vegetative cover of sample site 1 was converted into well pads, impoundment areas, and roads from 2005-2010. In sample site 2 and 3, about 5.2% and

8% of the vegetative cover was converted into well pads and roads respectively. Following primary data collection, a decrease in the use of impoundment areas was noticed in recent years which eliminated one of the variables, impoundment areas, in the study as shown in Figure 4-17. Hence, in most of the cases, there are no impoundments areas on the sample sites. It was also noticed that some well pad sizes changed, increased, or even decreased in some cases, with the increase in drilling activity. Though the length of the total roads increased over time, close examining of each road showed that some roads were abandoned over time as shown in Figure 4-17. In all three cases, loss of *core conditions* (*large core conditions, medium core conditions*, and *small core conditions*) during the study timeframe is about 210 acres, 210 acres, and 420 acres in three sample sites 1, 2, and 3, respectively. Within the *core conditions*, there is degradation of *large core conditions* and *medium core conditions* to *small core conditions* as discussed in earlier sections of this chapter.

While certain amounts of core landscapes are converted into well pads, roads, and impoundment areas, most landscape conditions are converted to *edge conditions* as an impact of shale gas development. In other words, *edge conditions* emerge as the dominating landscape conditions from shale gas development while *perforated* and *patch conditions* are the minor components. In addition, *core conditions* are in decreasing trend with the increase of shale gas exploration. Though there are very few *patch conditions,* the highest degree of fragmented condition, observed in these three sample sites, procedures and steps should be taken to ameliorate the situation.

2005 2010

(Data source: Texas Natural Resources Information System 2005 and 2010)

Figure 4-17: Images show that impoundment areas that existed in 2005 were removed in year 2010, well pads were smaller in 2010, and some roads that were serving well pads in 2005 had disappeared by 2010.

Chapter 5

Conclusion

5.1. Introduction

This chapter includes the discussion of findings from the quantitative research carried out to map landscape fragmentation as an impact of shale gas drilling in North Texas. This study mainly focuses on the fragmentation of prairies in North Texas. The study is carried out on three sample sites in the Grand Prairie and Plains Ecoregion of North Texas where most Barnett Shale gas exploration occurs (Figure 3-2). The dominant vegetative cover on these sample sites is the tall grass prairie which features bluestem and silver wintergrass. The sites differ from each other in that they have different intensities of shale gas drilling.

The chapter also includes relevance of this study to the field of landscape architecture. Concluding the chapter are the suggestions for future research.

5.2. Landscape Fragmentation As An Impact of Shale Gas Drilling

This study employs a quantitative research method that uses the Landscape Fragmentation Tool (LFT) in ArcGIS to quantify fragmentation on the three sample sites. To compare pre-drilling and post-drilling conditions, longitudinal studies of three sample sites are carried out using the three study timeframes of 1995, 2005 and 2010. This section describes how these analyses apply to the study's research questions:

- What are the components of shale gas drilling that result in landscape fragmentation?
- What is the degree of landscape fragmentation caused by shale gas exploration on the three sample sites and how has this changed over time?
- How is LFT used in this study to analyze the three sample sites?

- What are the procedures and steps that landscape architects, planners, and policy makers can follow to lessen surface impacts from shale gas drilling in the future?

5.2.1 Research question: What are the components of shale gas drilling that result in landscape fragmentation?

Shale gas exploration includes significant removal of vegetation for construction of well pads, impoundment areas, roads, and pipelines (Drohan et al. 2012a and Slonecker et al. 2012). This removal process increases the *edge conditions* which in turn eliminates the ecological values of the *core conditions* and thus degrading the pre-development landscapes (Forman 1995). Undisturbed *large core conditions* maintain a larger volume of plant and animal habitats than smaller *patch conditions* do. This result in a lower probability of extinction of native plant and animal habitats on and around drilling sites (Dramstad et al. 1996).

Literature on shale gas exploration and landscape ecology suggests that well pads, impoundment areas, roads, and pipelines cause landscape fragmentation (Drohan et al. 2012a, Forman 1995, Forman et al. 1996, Dramstad et al. 1996, and Slonecker et al. 2012). In the three analyzed sample sites, well pads are relatively small varying from 0.4 acres to 10 acres. The cumulative length of new roads branching from existing roads to provide access to the well pads is thousands of feet. Apart from areas directly developed as well pads and roads, the created *edge conditions* convert *core conditions* to *perforated conditions* and *patch conditions*. This means that besides direct removal of vegetation, the construction of well pads, impoundment areas, and roads have significant ecological impact on the landscapes on and near drilling sites.

Crisscrossing roads and pipelines cause further small patches resulting in fragmented landscape conditions. Therefore, well pads, impoundment areas, roads and pilepines are identified in this study as the causalities of landscape fragmentation.

5.2.2 Research question: What is the degree of landscape fragmentation caused by shale gas exploration on the three sample sites and how has this changed over time?

This research quantifies landscape fragmentation by dividing landscapes into six landscape conditions. They are *patch*, *edge*, *perforated*, *small core*, *medium core*, and *large core*. As mentioned earlier, these conditions are in the order of the most fragmented to the least fragmented. The studies carried out in the three sample sites reveal that the degree of fragmentation differs with the intensity of shale gas drilling. For example, in sample site 1, where shale gas exploration is less intense than sample site 2 and 3, *perforated conditions* are dominant, signifying the early stage of landscape fragmentation. While in sample site 2, where shale gas exploration started before 1995, the prevailing landscape condition is *edge*, formed by well pads and roads. Similarly, in sample 3, which has the most intense drilling activity among the three sample sites, a significant amount of *edge conditions* are observed. Hence, it is concluded from these three studies that the degree of fragmentation caused by well pads, impoundment areas, and roads is dependent on the density of the shale gas exploration in the area.

Longitudinal studies of the three sample sites show the changes in landscapes as a result of shale gas drilling over time. It is noted that with the increase in well pads and roads in successive timeframes, the *core conditions* are decreasing and are being transformed to *perforated*, *edge* and *patch conditions* signifying a higher degree of landscape fragmentation over time. Where there is less intense drilling activity, the amount of *perforated conditions* increases because of the increase of well pads and roads. In areas with more intense drilling, edge conditions increase over time. Where new roads crisscross existing roads, *patch conditions* are noted on all three sites.

In some shale gas exploration sites (other than these sample sites studied) it is noted that well pads, impoundment areas, and the roads are abandoned over time once shale gas exploration is complete as shown in Figure 4-17. In such cases, the landscape conditions can change differently than changes observed in the selected sample sites. This difference implies if the rate of abandonment of drilling sites increases faster than the rate of the addition of new drilling sites, the degree of landscape fragmentation will decrease. Thus, if drilling slows down for any reason, and the site and associated roads are abandoned for years, the landscapes might recover to the pre-drilling state over time, although the time required is unknown.

5.2.3 Research question: How is LFT used in this study to analyze the three sample sites?

In this research, three sample sites are studied for an extended period of time, from 1995 to 2010, within which a noticeable change on the landscapes of the sample sites occurred as a result of shale gas exploration. Rajulton (2001) describes such study as longitudinal study. A longitudinal study is a repetitive study of the same individuals or data over an extended period of time, long enough to include a noticeable change in their developmental status (Cherry 2012 and Rajulton 2001). This study uses LFT in a repetitive manner to conduct longitudinal study of the three sample sites.

To conduct this longitudinal study, data collection was done for the three sample sites for each study timeframe. The collected data were analyzed with the help of the LFT, which provides results in the form of six landscape conditions: *patch; edge; perforated; small core; medium core;* and *large core,* in the order of the most to the least disturbed landscape condition. LFT was used in a repetitively for each sample site for the selected timeframes. This provided results for pre-drilling and post-drilling situations and allowed for the study of changes in landscapes as an impact of shale gas drilling. In this way, LFT has facilitated the longitudinal study of the three sample sites.

5.2.4 Research question: What are the procedures and steps that landscape architects, planners, and policy makers can follow to lessen surface impacts from shale gas drilling in the future?

Procedures and steps to ameliorate surface impacts from shale gas drilling include various measures and practices. For example:

- Adoption of best management practices (BMPs) by landscape architects, planners, and policy makers is one of the essential steps to lessen the impacts of shale gas exploration in the future. One research (Bearer et al. 2012) concluded that the most supported BMPs are landscape-level planning and shared infrastructures; avoidance of sensitive areas, aquatic habitats and core landscapes; and road design, location and maintenance. The research also emphasized having a strong scientific foundation for BMPs.
- Some BMPs to reduce fragmentation (Bearer et al. 2012) include:
    - Reclaiming roads that are no longer in use for regular well-access; such rights-of-way should be designed for retirement (minimum compaction);
    - Providing an adequate buffer for endangered species;
    - Avoiding crossings of wetland and riparian areas that bisect movement pathways; and
    - Co-locating infrastructure and landscape-level planning to minimize overall landscape impacts.
- In addition to the technologies (used by shale gas operators and energy companies) such as directional drilling, closed-loop drilling, modular rigs, fit-for-purpose rigs that

help in reducing pad size, developing more wells per pad could result in fewer well pads throughout the region with fewer roads and less associated infrastructure. Specifically, this strategy can lessen land disturbance and fragmentation caused by roads and pipelines (Drohan et al. 2012a). This knowledge can help policy makers and planners to influence shale gas companies in the location of new well pads.

- *Edge conditions* created by well pads, impoundment areas, and roads are human induced. Human induced edges differ from those created by non-human disturbances. Fortunately, the shape of patches, as defined by edge boundaries, can be manipulated by land use planners for ecological objectives. Edges have diverse ecological significance which designers and planners can use to create environmental condition that transition between two types of habitat.
- Reclamation is a BMP that addresses certain key ecological issues by providing habitat for some species of concern.
- Well pads can have decades-long life spans. Findings from this study suggest that more intense drilling activity results in a greater degree of fragmentation. Therefore, multiple well pads that share infrastructure can limit landscape disturbance and hence help to lessen fragmentation (Drohan et al. 2012a).
- Given that shale gas exploration occurs mostly on privately owned land in Texas, state and federal agencies, private citizens with leases, and gas companies could work with communities to identify landscape restoration principles and practices (Drohan at al. 2012a).
- As mentioned earlier, prairies are susceptible to fragmentation, invasion of exotic species, habitat destruction, and degradation. Since most shale gas explorations in North Texas take place on prairies, protection of prairie habitat is an essential BMP for landscape architects, planners, and policy makers. For example, land acquisition

and easements can be used to maintain and restore prairies. Statewide programs such as allowing selected agricultural uses of prairies (like grazing and hay cutting) and managing prairies merely for scientific purpose and habitat value are useful tools in this process. Also, local programs allowing landowners to sell easements on prairie acres to various governmental entities can help protect prairies (Minnesota Department of Natural Resources, 1998).

5.3. Relevance To The Field of Landscape Architecture

This research is a valuable topic in landscape research as it expands the body of knowledge in shale gas drilling with a particular focus on landscape impacts and fragmentation in North Texas. While other studies have been conducted on health and water issues and economic benefits, only a few have been carried out on the impacts on landscapes, specifically on prairie habitats. This opportunity is where landscape architects can contribute to amelioration of situations caused by shale gas exploration.

From site design to remediation and restoration, landscape architects can play an important role by becoming involved as consultants to gas operators and energy companies as well as to local and regional governments. By engaging landscape architects early-on, certain impacts can be reduced. Landscape architects can contribute to well pad design, road design and construction, the selective removal of vegetation, and to minimizing infrastructures development. In addition, after the completion of shale gas exploration landscape architects can lead in habitat restoration and management strategies.

Habitat restoration is one of the tools to ameliorate human impacts on natural ecosystem. Habitat restoration can be defined as the purposeful assembly of plant and animal communities with the aim of reconstructing a stable ecosystem that functions similarly to the original condition (Robertson 2008). Landscape architects can engage in implementation of best management practices and the preservation of remaining prairie habitats as goals in habitat restoration.

5.4. Areas of Future Study

- Assessment of a larger area can be done to include larger habitats in the study of landscape fragmentation.
- This study includes fragmentation by shale gas exploration only. The future study could include the cumulative fragmentation caused by shale gas exploration along with other human uses and activities such as residential development, agriculture, industrialization and so on.
- This study includes analysis of collective impacts of the variables (well pads, impoundment areas, and roads). Assessment of each of the variables separately can be done to find out the degree of impact of each of the variables.
- Future study can include analyses of more than three sample sites and propose tools (such as Agent Based Modeling) to project the future scenario.
- A similar study can be done using other tools such as FRAGSTAT to map fragmentation and compare the results to determine the appropriate tool to measure fragmentation by shale gas exploration.
- Building on this research, research on best management practices to restore sites to pre-drilling condition can be done.

References

Anderson M., Biasi F., and Buttrick S. (1998). "Conservation site selection: Ecoregional planning for biodiversity". The Nature Conservancy, Boston, MA. Retrieved on January 12, 2014 from http://proceedings.esri.com/library/userconf/proc98/PROCEED/TO500/PAP465/P465.HTM

Arthur D. and Cornue D. (2010). "Technologies reduced pad size, waste". The American oil and gas reporter. August 2010.

Arthur J., Langhus B., and Alleman D. (2008). "An overview of modern shale gas development in the United States". ALL Consulting 2008. Retrieved from http://www.all-llc.com/publicdownloads/ALLShaleOverviewFINAL.pdf on October 20, 2013

Barnes T.G. (2000). "Landscape ecology and ecosystem managements". Kentucky Cooperative Extension Service. Retrieved from http://www2.ca.uky.edu/agc/pubs/for/for76/for76.pdf on December 28, 2013.

Bearer S., Nicholas E., Gagnolet T., DePhilip M., Moberg T., and Nels J., "Evaluating the scientific support of conservation best management practices for shale gas extraction in the Appalachian Basin," Environmental Practice 14 (2012): 308-319.

Brown D. G. (2001). "Characterizing the human imprint on landscapes for ecological assessment". A guidebook for integrated ecological assessments 2001, pp 404-415.

Bogaert J., Farina A., and and Ceulemans, R. (2005). "Entropy increase of fragmented habitats: a sign of human impact?" Ecological indicators, 207-212.

Cherry, K. (2012). What is longitudinal research. Retrieved from about.com: http://psychology.about.com/od/lindex/g/longitudinal.htm

Clark W. (2010). "Principles of Landscape Ecology". Nature Education Knowlege 3(10):34

Comber A., Fisher P., and Wadsworth R. (2005). "What is Land Cover?" Environmenta nd Planning, pp199-209.

Cooley H., and Donnelly K. (June 2012). "Hydraulic fracturing and water resources: Spearating the frack from the fiction". Pacific Institute. Retrieved from http://www.pacinst.org/wp-content/uploads/sites/21/2013/02/full_report35.pdf on August 30, 2013.

Directional and Horizontal Drilling (2012). Retrieved from NaturalGas.org: http://www.naturalgas.org/naturalgas/extraction_directional.asp

Dramstad W. E., Olson J. D., and Forman R.T.T (1996). "Landscape ecology principles in landscape architecture and land-use planning", Washington D.C., Island Press.

Drohan P. J., Brittingham M., Bishop J. and Yoder K. (2012a). "Early trends in landcover change and forest fragmentation due to shale-gas deelopment in Pennsylvania: A potential outcome for the Northcentral Appalachians". Environmental management 49, 1061-1075.

Drohan P. J., Finley J. C., Roth P., Schiler T.M., Stout S. L., Brittinghan M. C., and Johnson N.C. (2012b). "Perspective from field: Oil and gas impacts on forest ecosystems: Findings gleaned from the 2012 Goddard Forum at Penn State University". Environmental Practice, December 2012, pp 394-399.

Esri (2014). "What is GIS?". Retrieved from http://www.esri.com/what-is-gis

Forman R. T. (1995). "Land mosaics: The ecology of landscapes and regions". The Press Syndicate of The University of Cambridge.

Forman R. T., and Alexander L. E. (1998). "Roads and their major ecological effects". Annual review of ecology and systematics , 207-C2.

Forman R. T., and Collinege S. K. (1996). "The 'spatial solution' to conserving biodiversity in landscapes and regions". Conservation of faunal diversity in forested landscapes conservation biology, 537-568.

Girveta E., Thorne J., Berry A. M., and Jaeger J. (2008). "Integration of landscape fragmentation analysis into regional planning: A statewide multi-scale case study from California, USA". Landscape and Urban Planning, 205-218.

Griffith G., Bryce S., Omernik J., and Rogers A. (2007). "Ecoregions of Texas". Project report to Texas Commission on Environmental Quality, December 27,2007.

Gulinck H., and Wagendorp T. (2002). "References for fragmentation analysis of the rural matrix in cultural landscapes". Landscape and Urban Planning , 137–146.

Harwell M. R. (2011). " Research design in qalitative/quantitative/mixed methods." The Sage handbook for research in education. 2nd ed, Los Angeles, CA: Sage (2011): 147.

Hawbaker T., Radeloff V., Clayton M., Hammer R., and Gonzalez-Abraham (2005). "Road development, housing growth, and landscape fragmentation in northern Wisconsin". Ecological Applications, 1222-1237.

Huntington G and Khaled K., "Method for Assessing Heavy Traffic Impacts on Gravel Roads Serving Oil- and Gas-Drilling Operations". Journal of the Transportation Research Board, 2101 (2009): 17-24, Retrieved from http://trb.metapress.com/content/p2x287tw6k043753/fulltext.pdf on December 18, 2012.

Jordaan S., Keith D. W., and Stelfox B. (2009). "Quantifying land use of oil sands production: a life cycle perspective". Environmental Research Letters 4 024004. Retrieved from http://iopscience.iop.org/1748-9326/4/2/024004/pdf/1748-9326_4_2_024004.pdf

Kargbo D. M., Wilhelm R. G., and Campbell D. J. (2010). "Natural Gas Plays in the Marcellus Shale: Challenges and Potential Opportunities". Environmental Science and Technology, 5679–5684.

Kuehn S. (2011)."Landscape practices on gas well sites in North Texas: Perceptions of selected industry representatives and regulators". Unpublished master's thesis.

LandScope America (2014). "Tallgrass Prairie Ecosystem". Retrieved from http://www.landscope.org/explore/ecosystems/disappearing_landscapes/tallgrass_prairie/

Llausàs A., and Nogu, J. (2012). "Indicators of landscape fragmentation: The case for combining ecological indices and the perceptive approach". Ecological indicators, 85-91.

Minnesota Department of Natural Resources (1998). "Prairies: The environmental indicators initiative". Legislative Commission on Minnesota Resources, State of Minnesota.

Nagendra H., Munroe D., and Southworth J. (2004). "From pattern to process: landscape freagmentation and the analysis of land use/ land cover change". Agriculture, Ecosystems and Environment, 111-115.

Nassauer J. (1997). "Placing nature: culture and landscape ecology". Island Press.

Native Prairies Association of Texas (2014). "Save tallgrass prairies". Retrieved from file:///E:/Spring2014/JUST%20Thesis_Fall%202013/new%20search/prairie/Native%20Prairies%20Association%20of%20Texaslkkj.htm

Ndubisi F. (2002). "Managing Change in the Landscape:A Synthesis of Approaches for Ecological Planning". Landscape Journal, pp138-155.

Ndubisi F. (2008). "Sustainable Regionalism-Evolutionary Framework and Prospects for managing metropolitan landscapes". Landscape Journal, pp 51-68.

North Central Texas Council of Governments (March 2012), "Development of Associative Truck Emissions Inventory, " Natural Gas Transportation Workshop, NCTCOG, March 8, 2012. Retrieved from http://www.nctcog.org/trans/air/DevEmisInventory.pdf on December 17, 2012.

O'Neill R.V., Hunsaker C.T., Jones K.B., Riitters K.H., Wickham J.D., Schwartz P. M., Goodman I.A., Jackson B.L. and Baillargeon W. S. (1997). "Monitoring environmental quality at the andscape scale-Using landscape indicators to assess biotic diversity, watershed integrity, and landscape stability" Bioscience Vol 47 No. 8, pp513-519.

Orland B., "Impacts of Marcellus Shale activities on environmental and human health," proposal to the Stuckeman School from the Department of Landscape Architecture, Pennsylvania State University (2010), http://stuckeman.psu.edu/sites/stuckeman.psu.edu/files/marcellusproposalp110.pdf.

Paleontological Research Institute, "Beyond water: A Discussion of the Non-Water Related Environmental Issues Associated with Drilling for Natural Gas in Marcellus Shale". Retrieved from http://www.museumoftheearth.org/files/marcellus/Marcellus_issue9.pdf on May 25, 2012.

Pradhananga A., Taylor P., and Ozdil T. R. (2013). "Study of Landscape Fragmentation as an Impact of Natural Gas Drilling in North Texas". Council of Educators in Landscape Architecture (CELA-2013), Austin, Texas, USA

Railroad Commission of Texas (January 2014). "Barnett Shale Infromation". Retrieved January 21, 2014, from http://www.rrc.state.tx.us/barnettshale/index.php#jurisdiction

Rajulton F. (2001). "The fundamentals of longitudinal research: An overview". Special issue on longitudinal methodology, Canadian studies in population. Vol. 28 (2), 2001, pp 169-185.

Razin E. (1998). "Policies to control urban sprawl: Planning regulations or changes in the'rules of the game?". Urban studies, 321-340.

Robertson K. R. (2008). "The tallgrass prairie". Illinois National History Survey.

Serrano M., Sanz L., Puig J., and Pons J. (2002). "Landscape fragmentation caused by the transport network in Navarra (Spain) Two-scale analysis and landscape integration assessment". Landscape and urban planning, 113-123.

Slonecker E., Milheim L., Roig-Silva C., Malizia A., Marr D., and Fisher G. (2012). "Landscape consequences of natural gas extraction in Bradford and Washington Counties, Pennsylvania, 2004-2010". Retrieved March 13, 2013, from http://pubs.usgs.gov/of/2012/1154/of2012-1154.pdf

Taylor, Pat D. (2000). “Fragmentation and Cultural Landscapes: Tightening the coupling between human beings and nature.” Proceedings, ISOMUL Conference, Wageningen University and Research Institute, 2000.

Taylor P.D. (2002). "Fragmentation and cultural landscapes: tightening the relationship between human beings and the environment". Landscape and urban planning 25 (2002), 93-99

Taylor P.D., Ozdil T.R. and Hopman D. D. (2014), "Environmental and related impacts of shale gas development: Case study of The Barnett Shale: Landscape and related impacts". Unpublished white paper, The Energy Institute, The University of Texas at Austin.

The Energy Institute (2012). "Environmental and related impacts of shale gas development: Case study of Barnett Shale, Project Plan".

The Horinko Group (2012). "Hydraulic Fracturing: Guidebook on the Current and Future". The Horinko Group. Retrieved from http://www.thehorinkogroup.org/wp-content/uploads/2012/10/THG-Hydraulic-Fracturing-Guidebook_WEB_20121008.pdf on March 15, 2013.

Trembath A., Jenkins J., Nordhaus T., and Shellenberger M. (May 2012). "Where the shale gas revolution came from - Governments role in the development of hydraulic fracturing in shale". Retrieved from http://thebreakthrough.org/blog/Where_the_Shale_Gas_Revolution_Came_From.pdf

U.S. Energy Information Administration (2012). "Natural gas". Retrieved from http://www.eia.gov/pub/oil_gas/natural_gas/analysis_publications/maps/maps.htmVogt, P., Riitters, K., Estreguil, C., Kozak, J., Wade, T., and Wickham, J. (2007). Mapping spatial pattens with morphological image processing. Landscape Ecology, 171-177.

Vogt P., Riitters K., Estreguil C., Kozak J., Wade T., and Wickham J. (2007). "Mapping spatial patterns with morphological image processing". Landscape Ecology, pp 171-177.

Williams S. (February 2012). "Discovering Shale Gas: An investor guide to hydraulic fracturing". Retrieved January 21, 2014, from http://si2news.files.wordpress.com/2012/03/discovering-shale-gas-an-investor-guide-to-hydraulic-fracturing.pdf

Wynveen B (2011). "A thematic analysis of local respondents' perceptions of Barnett shale energy development". Journal of rural sciences, 8-31.

Biographical Information

Anjana Pradhananga is from Kathmandu, Nepal. She did her undergraduate in Architecture from the Institute of Engineering, Pulchowk Campus, Nepal. She joined Program in Landscape Architecture at The University of Texas at Arlington in August 2011 and was appointed Enhanced Graduate Teaching Assistant (EGTA). As an EGTA, she assisted professors in few courses and was also involved in a research titled "Environmental and related impacts of shale gas development: Case study of The Barnett Shale: Landscape and related impacts." Professionally, Anjana has worked as an architect in an architectural firm for two years in Nepal. She has also interned in Parks and Recreation, City of Arlington, Texas, where she was involved in landscape design for parks, design and preparation graphics for signs and preparation of GIS maps. Anjana plans to do a doctoral degree in Landscape Architecture in near future focusing on landscape ecology.