Using Landscape Integrity Index to Evaluate the Cumulative Impacts of BLM Resource Management Programs

by

Liling Lee

A Thesis Presented to the
Faculty of the USC Dornsife College of Letters, Arts and Sciences
University of Southern California
In Partial Fulfillment of the
Requirements for the Degree
Master of Science
(Geographic Information Science and Technology)

May 2020

To my parents, Ngawong Ngoon and Yuhain Lee,
for always reminding me to eat and sleep regularly,
and my grandma, Jui Chu Lee,
for constantly cheering me on this journey

Table of Contents

List of Figures

List of Tables

Acknowledgments

I would like to give a big thanks to Professors Jennifer Bernstein and Karen Kemp for their insightful guidance and constructive feedback on narrowing down my research proposal and improving my thesis. I am grateful of my other faculty who offered much needed assistance in advancing my writing and technical skills: Vanessa Osborne and Jennifer Swift. I greatly appreciate my employer, Bureau of Land Management, who supported my work on the thesis and provided excellent research ideas. A very special gratitude goes out to Dario Lunardi for laying the cornerstone of this thesis and Calvin Deal for fostering a great thesis experience with endless encouragement and invaluable field data. I would also like to thank the experts who shared their knowledge with me during the making of this thesis: Tom Chatfield, Karla Rogers, Devin Johnson, Alec Boyd, and Tony Stelle. Finally, this accomplishment would not have been possible without my family and friends, who are always there for me with unwavering support and unlimited trust in my potential. Thank you.

List of Abbreviations

AIM	BLM Assessment, Inventory, and Monitoring Process
APD	Application for Permit to Drill
BLM	Bureau of Land Management
CEA	Cumulative Effects Analysis
CEQ	U.S. Council of Environmental Quality
CFO	BLM Carlsbad Field Office
EIS	Environmental Impact Statement
EVT	Existing Vegetation Type
FLPMA	Federal Land Policy and Management Act of 1976
GAP	Gap Analysis Project
GIS	Geographic information system
GISci	Geographic information science
IEI	Index of Ecological Integrity
IPA	Important Plant Area
LANDFIRE	Landscape Fire and Resource Management Planning Tools Project
LII	Landscape Integrity Index
MRLC	Multi-Resolution Land Characteristics (MRLC) Consortium
NEPA	National Environmental Policy Act of 1969
NLCD	National Land Cover Database
NM	New Mexico
OHV	Off-Highway Vehicle
RMP	Resource Management

SGCN	Species of Greatest Conservation Need
SSI	Spatial Sciences Institute
USC	University of Southern California
USGS	U.S. Geology Survey
VDEP	Vegetation Departure

Abstract

The Bureau of Land Management (BLM) is instrumental in connecting people with public lands by providing and protecting opportunities to enjoy and use our country's resources. Understanding the cumulative effects of resource management programs is crucial for decision makers to develop effective land management practices and appropriate allocation of funding and resources. A comprehensive, standardized, and transparent GIS workflow can help visualize and analyze ecological integrity, landscape patterns and processes, and promote a consistent Cumulative Effects Analysis (CEA) and collaborative management across jurisdiction boundaries.

This research evaluates the cumulative impacts of resource management programs in the BLM Carlsbad Field Office (CFO), New Mexico by incorporating ecological integrity indicators, resource- and stressor-based metrics, and landscape metrics to create a Landscape Integrity Index (LII). Two resource management programs, Vegetative Communities and Minerals – Leasables – Oil and Gas, were selected as the programs of interest for this study. The *LII* model considers the management goals and objectives in the Draft BLM CFO Resource Management Plan (RMP) to identify the necessary indicators and metrics. These indicators and metrics were each scored for their site impact, distance decay function, or landscape metrics through the use of a Composite Scoring System, and then combined into a single map. The resulting map with the *LII* values shows areas of low landscape integrity near the urban and agricultural areas in CFO planning area and high landscape integrity near central and southwest corner of CFO. CEA practitioners and land managers will be able to address management goals and objectives, conduct a more systematic and consistent analysis with relevant indicators and metrics, and visualize landscape integrity using the *LII* framework.

Chapter 1 Introduction

As the largest land management agency in the nation, the Bureau of Land Management (BLM) has a tremendous impact on how people interact with public lands with its dual responsibility to manage public lands for multiple-use and conserve resources for the benefit of present and future generations. The BLM is a federal agency within the Department of the Interior that manages 246 million surface acres of public lands under the principles of multiple-use and sustained yield. Multiple-use is defined as managing public lands and resource uses collectively to best meet the needs of the present and future generations (U.S. Department of the Interior 2001). Sustained yield is defined as the continuous high-level production of various renewable natural resources via multiple-use in the public lands (U.S. Department of the Interior 2001). The BLM promotes multiple-use on public lands by supporting a variety of resource management programs such as energy development, conservation stewardship, and recreation, which can affect the ecological integrity of the lands in different ways. Ecological integrity refers to the condition and ability of the ecological system to support biological communities with abiotic components and provide ecological services (Hobbs et al. 2010, Wurtzebach and Schultz 2016, Carter et al. 2017).

Resource management programs can affect ecological integrity in both positive and negative ways through surface disturbance, ecological function depletion or alteration, habitat restoration, and other ecological processes. For example, energy developments including both conventional (e.g. oil and gas, coal, or minerals) and renewable (e.g. wind, solar, and geothermal) can disturb surface landscapes and negatively impact soil and water resources (surface water and groundwater), wildlife habitat, and avian and bat species (Bureau of Land Management 2018b). On the other hand, conservation stewardship activities such as vegetation and noxious weed management and riparian and wetland actions promote long-term beneficial impacts by restoring vegetation that meets ecological objectives, preventing soil erosion and runoff, and ensuring water and vegetation quality (Bureau of Land Management 2018b). The effects of a single resource management program are more straightforward to understand; but when the area comprises multiple programs with potential contrasting management goals and impacts, the cumulative effects of these programs are often difficult to assess.

Cumulative effects analysis (CEA), also referred to as cumulative impact assessment, analyzes the cumulative effects of the actions on ecosystems. As defined by the Council of Environmental Quality (CEQ), cumulative effects are "the impact on the environment which results from the incremental impact of the action when added to other past, present, and reasonably foreseeable future action". In this study, these actions are from the resource management programs of BLM Carlsbad Field Office, including the development of oil and gas drilling wells and vegetative treatment, which affect the structure, function, or well-being of various environments.

To better assess the cumulative effects of BLM resource management programs, my research developed a Landscape Integrity Index (LII) for BLM Carlsbad Field Office, New Mexico. The *LII* model serves as a landscape perspective of ecological integrity and land health, incorporating ecological integrity indicators, resource- and stressor-based metrics, and landscape metrics. Evaluating the cumulative impacts of different BLM resource management programs helps us better comprehend how BLM Carlsbad Field Office is achieving its mission of multiple-use and sustained yield of resources and resource uses.

1.1. Study Area

The BLM Carlsbad Field Office (CFO) in New Mexico was selected as the study region (Figure 1) because the planning area manages multiple resources and resource uses with contrasting management goals and objectives. The primary resource uses in BLM-administered lands of the planning area are oil and gas extraction, potash mining, caliche mining, livestock grazing, and off-highway vehicle (OHV) recreation. The combination of these resource uses modifies the landscape in a variety of different ways, which warrants a thorough investigation of how the cumulative effects affect the ecological integrity and landscape health of the land. The CFO also provides extensive field datasets that are parameterized as indicators and metrics for the Landscape Integrity Index.

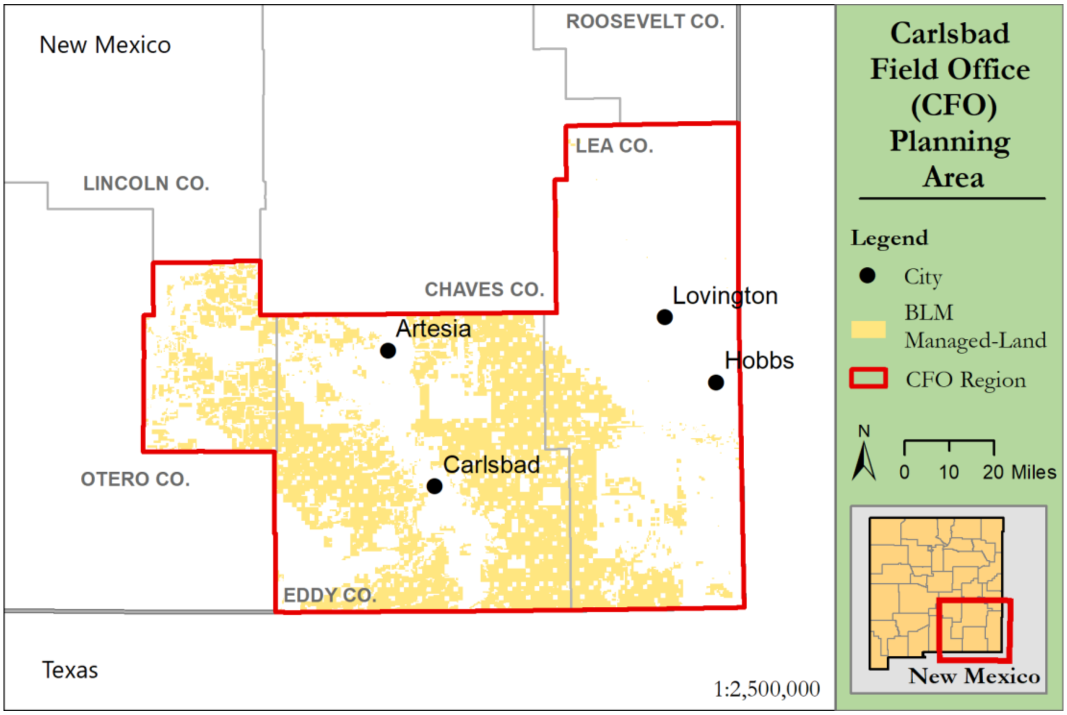


Figure 1. Map of BLM Carlsbad Field Office Planning Area

1.2. Motivation

1.2.1. A Comprehensive, Standardized, and Transparent GIS Approach

With the challenge of defining the geographic (spatial) and time (temporal) boundaries of the cumulative effects, there is a need to establish a comprehensive, standardized, and transparent Geography Information System (GIS) approach. Comprehensive means including relevant and scientifically sound data and analysis, standardized means using consistent and repeatable measures, and transparent means providing clear and documented workflows. The GIS approach can help the subject area experts and decision makers understand the ecological integrity of BLM managed lands at a landscape level (McGarigal and Marks 1995) and provide a framework for continual awareness, communication, and coordination of effective resource management (Atkinson and Canter 2011). This research utilizes standalone python scripts and R Markdown that can be shared with other BLM offices. With a shareable GIS workflow, other field offices can customize it according to their management and data needs and share their findings with other offices. The GIS workflow will promote standardized CEA measures and collaborative management across administrative boundaries.

1.2.2. Evaluation of Ecological Integrity in CEA

The ability to quantify and evaluate ecological integrity helps establish a holistic framework for measuring the effects of the resource programs and communicating the progress of the multiple-use and sustained yield mission to managers and stakeholders (Wurtzebach and Schultz 2016). Identifying indicators to measure elements of ecological integrity is key to evaluating the effects of the past, present, and future resource management programs. Using indicators and indices to evaluate cumulative effects of multiple actions has started to gain traction (Canter and Atkinson 2011), and land-management agencies are using indicators to evaluate ecological integrity (Carter et al. 2019). That said, no formalized *LII* has been developed to evaluate cumulative effects of BLM resource management programs on ecological integrity. This research will bridge the two frameworks – cumulative effects analysis and evaluation of ecological integrity – together through the creation of *LII*. Three components incorporating ecological integrity, management, and landscape will form the *LII*: (1) ecological indicators of ecosystem composition, structure, and function, (2) resource- metrics and stressor-based metrics, and (3) landscape metrics.

1.2.3. Landscape Metrics

Incorporating landscape metrics in the *LII* can help us capture the complex spatial patterns and interactions influenced by the multiple-use resource management programs over time (McGarigal and Marks 1994). The landscape metrics represent landscape structure, one of the three characteristics of the landscape, and define the spatial relationships between diverse ecosystems. Landscape structure is portrayed by the spatial pattern characterized by landscape composition (the variety and abundance of patch types within a landscape) and configuration (spatial characteristics of patches within the landscape), with patches being the basic elements or units that make up a landscape (McGarigal and Marks 1994, Uuemaa et al. 2009). Being able to quantify landscape structure through ecological similarity and connectedness with landscape metrics allow us to incorporate the interactions between ecological processes and landscape dynamics (McGarigal and Marks 1994).

Moreover, landscape metrics can also help us examine landscape fragmentation and diversity as effects from the resource management programs. Landscape metrics quantify landscape structure at the patch-, class-, and landscape-levels, meaning measurements are performed for each individual patch, all patches belonging to the same land cover class type, and all patches in the landscape (regardless of land cover type), respectively (Frazier 2019). Many of the class-level metrics can provide information on landscape fragmentation while the landscape-level metrics can provide information on landscape diversity. Landscape fragmentation occurs when the resource use activities subdivide the ecosystems into smaller and isolated fragments that can reduce biodiversity (McGarigal and Marks 1994). This process transforms the landscape through changes in landscape composition, structure, and function, and can negatively affect ecological processes and habitat patches. Another aspect of this study is landscape diversity, in which the resource use activities improve landscape health by generating more diverse landscapes and promoting biodiversity. The inclusion of landscape metrics as part of the *LII* provides a landscape perspective as to how resource use activities affect the ecological processes spatially and temporally.

1.2.4. Multiscale Data

The framework of the Landscape Integrity Index can utilize multiscale data, which is crucial for implementing a landscape approach in managing public lands. To understand the effects of scale-specific ecological processes and interactions, a multiscale view of landscape is necessary to apply multiscale approaches for ecosystem modeling. In addition to spatial scale (i.e. grain: resolution of the data; and extent: size of the landscape), temporal scale is also an important consideration in assessing changes in the landscape over time. Furthermore, field data have localized details that can help management at the field office level, while national data provides a standardized assessment that can help management at the landscape level. The BLM Assessment, Inventory, and Monitoring (AIM) process is a national monitoring effort that integrates local- and broad-scale data collection and provides the status and condition of natural resources (Carter et al. 2017). Since *LII* can be developed using multiscale data, if some of the field offices do not have the data or no AIM data exists within the field office boundary, the *LII* can still be developed using existing field or national datasets, whichever is available.

1.2.5. Court Challenges

Given the complex and unanticipated nature of cumulative effects, aggregate impacts are not consistently translated into clear and transparent guidance for CEA professionals to apply in practice (Foley et al. 2017). Court challenges relating to CEA against federal agencies have been raised due to the lack of cumulative impact analysis, lack of past, present, or reasonably foreseeable future actions, lack of data and/or credible justification for selection of data, and unsubstantiated assertions that there are no cumulative impacts from the projects (Smith 2006). Federal agencies have lost many of those challenges because of the difficulties in conducting a comprehensive, systematic, and transparent cumulative effects analysis. Smith (2006) found that the Bureau of Land Management had lost all three of their cases from the Ninth Circuit Court of Appeals from 1995 to 2004. In *Klamath-Siskiyou Wildlands vs. BLM* (2004), for example, the court ruled that the CEA was inadequate for the two timber sales in the Cascade Mountains of southern Oregon because there was not enough analysis of other timber sales in the same watershed, CEA lacked data and justification, and analysis cannot be tied to a RMP with no site-specific analysis nor to a non-NEPA document. This case demonstrates the importance of data and the need for a reliable rationale for the selection of data. The standardized *LII* framework and transparent GIS workflow from this research can be used by land managers and CEA practitioners to improve the CEA process.

1.3. Research Purpose, Goals, and Objectives

The purpose of this thesis was to develop a Landscape Integrity Index (LII) with ecological integrity indicators, resource- and stressor-based metrics, and landscape metrics

(Figure 2) to evaluate the cumulative effects of BLM resource management programs. The research aims to improve the Cumulative Effects Analysis in the Resource Management Plans by providing a shareable GIS workflow that is comprehensive, systematic, and transparent. The case study is demonstrated in the BLM Carlsbad Field Office, New Mexico by analyzing just two of the resource management programs, Vegetative Communities and Minerals – Leasables – Oil and Gas. Both of these programs have various management plans and actions that are cast at different spatial and temporal scales within the CFO planning area.

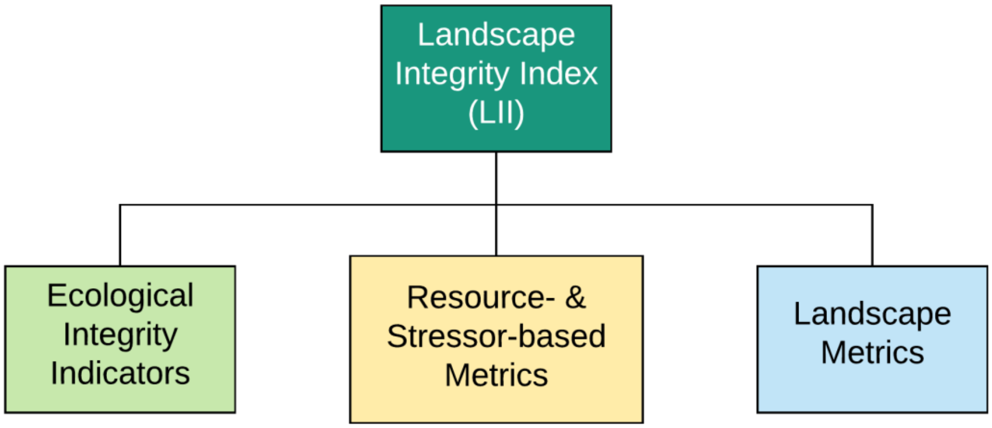


Figure 2. Landscape Integrity Index (LII) Framework

The goals of this research project were as follows:

(1) To create a comprehensive and shareable GIS model that evaluates the cumulative impacts of several programs in the BLM Carlsbad Field Office, New Mexico.

(2) To incorporate ecological integrity indicators, resource- and stressor-based metrics, and landscape metrics to create a Landscape Integrity Index (LII).

(3) To assess areas of high and low landscape integrity in BLM Carlsbad Field Office.

In order to accomplish these research goals, the objectives of this research were listed as follows:

(1) Research historical and current methods for cumulative effect analysis in the BLM to identify the components needed in the analysis.

(2) Apply field data in the *LII* model as indicators and metrics according to the resource management plan in BLM Carlsbad Field Office.

(3) Conduct the moving window analysis to depict the Landscape Integrity Index and use the *LII* values to assess landscape integrity.

1.4. Research Questions

The research questions that drove this study were as follows.

(1) How can spatial data and standardized measures of ecological integrity and landscape health be used to evaluate the cumulative impacts of Vegetative Communities and Minerals – Oil and Gas?

(2) What elements of ecological integrity and landscape health should be included in the BLM's cumulative effects analysis to provide a more comprehensive, standardized, and transparent assessment?

(3) How does this assessment reveal the cumulative impacts the BLM resource management programs (specifically Vegetative Communities and Minerals – Oil and Gas) have on the public lands in BLM Carlsbad Field Office, New Mexico?

(4) Where are the areas of low and high landscape integrity in the BLM Carlsbad Field Office?

1.5. Thesis Structure

The remainder of this thesis consists of four chapters. Chapter 2 explores the BLM's mission and history of cumulative effects analyses, identifies the challenges in conducting a cumulative effects analysis, and defines the indicators and metrics for the Landscape Integrity

Index (LII). Chapter 3 presents the study area, data sources and selection of indicators and metrics, the three-stage workflow, and procedures of designing and developing the *LII* model. Chapter 4 describes the results and Chapter 5 discusses the landscape integrity of CFO Planning Area, applications of *LII*, research limitations, and future research opportunities.

Chapter 2 Related Work

The presence of the BLM can be felt in the majestic mountains towering in wilderness areas, sheep and cattle grazing in the distance, the busy hum of drilling machines extracting oil and gas, and people creating memorable experiences on public lands. Protecting these multiple natural, cultural, and historic resources is an incredible and challenging undertaking for the BLM. To appropriately manage the multiple and often competing resource management programs, the BLM needs to understand the impacts of all of these programs by conducting the cumulative effects analysis (CEA) during the National Environmental Policy Act (NEPA) process. The hurdles of conducting the cumulative effects are also multifaceted, as the intricacies of identifying spatial and temporal scale and analyzing indirect and future effects pose quite a dilemma for CEA practitioners and land managers.

This research addresses the challenges in conducting the CEA by examining how the resource management programs affect the landscape health and the ecosystem through the creation of a Landscape Integrity Index. The different components in the *LII* framework – ecological integrity indicators, resource- and stressor-based metrics, and landscape metrics – provide a systematic and transparent way for evaluating the cumulative effects of resource management programs.

2.1. BLM’s Mission

As mandated by the Federal Land Policy and Management Act of 1976 (FLPMA), the BLM manages the public land under the principles of multiple-use and sustained yield, while protecting the scientific, scenic, historical, ecological, environmental, air and atmospheric, water resource, and archeological values of the lands (U.S. Department of the Interior 2001). The BLM supports a wide range of resource management programs such as energy development, livestock grazing, timber harvesting, conservation stewardship, and recreation, utilizing a multiple-use approach and striving for a long-term sustainable management of the public lands (Carter et al. 2019). Some of these programs may disrupt landscape patterns and reduce ecologic integrity and landscape health, while others may improve them or mitigate the negative impacts. For instance, conventional energy development such as coal mines and oil and gas drilling modify the structure of surface landscapes and disrupt vital ecological processes, resulting in increased habitat fragmentation and decreased biodiversity with long-term consequences (Copeland et al. 2009, Allred et al. 2015, Wu et al. 2019). On the other hand, habitat restoration activities such as vegetative treatments can improve patch size and connectivity of habitat, ultimately improving the landscape health for that region (Carter et al. 2017). As such, incorporating measurements of ecological integrity and landscape health are essential in management decisions to help sustain and protect resources and resource uses despite competing resource management goals.

2.1.1. Landscape Approach

Effective management of the diverse range of resource management programs throughout the various BLM offices involves collaboration with government agencies and organizations and comprehension of the program effects by managers and stakeholders (Carter et al. 2017). This is currently being addressed by implementing a landscape approach to resource management, in which the BLM engages with diverse stakeholders, considers the resource values and tradeoffs in operating different resource management programs, and incorporates multiscale and broad-scale spatial and temporal perspectives (Carter et al. 2017). Included in the landscape approach effort is the multiscale natural resource monitoring and assessment information, which aligns with the BLM Assessment, Inventory, and Monitoring (AIM) process to inform BLM resource planning and management decisions (Carter et al. 2017). The challenge lies in meeting the objectives of multiple-use resource management programs while protecting the ecological integrity and health of public lands.

2.2. Cumulative Effects Analysis

2.2.1. History of Cumulative Effects Analysis

The National Environmental Policy Act (NEPA) of 1969 requires the BLM to conduct cumulative effects analysis of a proposed action to assess the incremental impact of past, present, and reasonably foreseeable future actions on the environment (Bureau of Land Management 2008). But throughout the 15 years following the inception of NEPA, many agencies have failed to include CEA or submit a well-written CEA in the NEPA documents, leading to an increase in the court cases challenging cumulative effects analyses (Smith 2006). The main problem arose from the lack of clear guidelines, scopes, and proper procedures for preparing a cumulative effect analysis (Canter and Kamath 1995). In 1997, the Council of Environmental Quality published the "Considering Cumulative Effects Under the National Environmental Policy Act", which is a handbook that provides a framework and process of analyzing cumulative effects (U.S. Council of Environmental Quality 1997). However, cumulative effects analysis still remains confusing for NEPA practitioners even with the publication of CEQ's handbook (Smith 2006).

2.2.2. Defining Cumulative Effects

Analyzing the cumulative effects of BLM program actions is complex and challenging because it is difficult to keep track of cumulative effects when they can be produced and interact in multiple ways (Foley et al. 2017). For example, a single activity can repeatedly produce a single stressor or multiple stressors, and multiple activities can produce a single stressor or multiple stressors. A stressor is the environmental and biotic factor created from human activities that causes stress to an ecosystem. Response to the stressor can be affected by additional stressors. For instance, a species can respond differently to invasive species under different nutrient conditions (Crain et al. 2008). In cases where stressor A reduces the response by ‘a’ and stressor B by ‘b’, the cumulative effects of multiple stressors can then interact in multiple ways: additively (cumulative effects = a + b), synergistically (cumulative effects < a + b), or antagonistically (cumulative effects > a + b). Figure 3a shows how cumulative effects are produced by multiple stressors from multiple activities and can interact with each other (dashed lines between effects arrows). Figure 3b shows that the impact is characterized by activity, stressor, and/or by ecological components (dashed lines). The terms “effects” and “impacts” are synonymous according to the CEQ regulations. Effects are changes that result from action(s) and can be ecological, aesthetic, historic, cultural, economic, social, or health (Bureau of Land Management 2008). Effects can also be beneficial or detrimental, and short-term or long-term. To evaluate the cumulative effects of BLM resource management programs, this research considers and scores each indicator and metric, then combines these scores into a Landscape Integrity Index to produce a value for the cumulative effects.

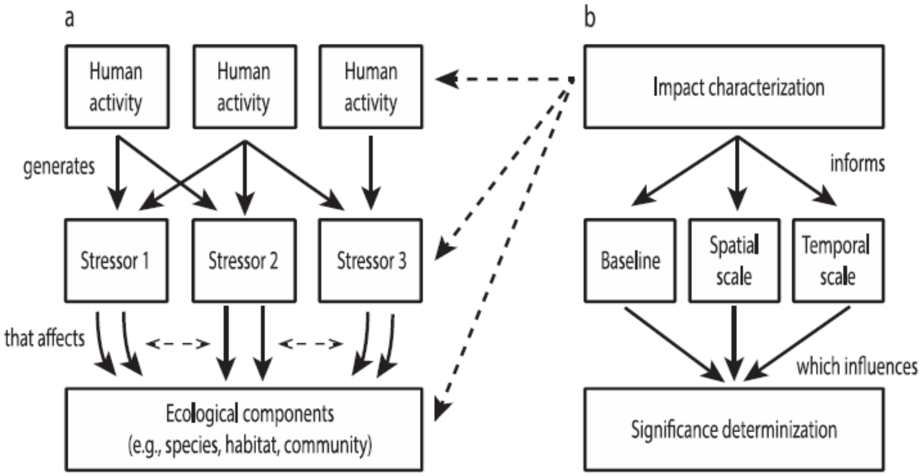


Figure 3. (a) Relationships between activities (from resource management programs), stressors, and ecological components; (b) relationships between impact characterization and activity, stressor, and/or ecological components. Source: Foley et al. (2017)

2.2.3. Evaluating Cumulative Effects

In order to improve CEA, definition of impact and relationship between activities, stressors, and ecosystem effects need to be consistently established with the best available science (Foley et al. 2017). Foley et al. (2017) evaluated how CEA practitioners conduct CEA, specifically examining key gaps in and relationships between impacts, baseline, scale, and significance in a comparative case analyses in California, Canada, Australia, and New Zealand. Baseline condition is the condition of the ecosystem prior to human impact and is used to compare ecosystem effects with and without the resource management programs. Some of their recommendations to improve CEA include mapping overlapping and potentially interactive effects to assess impacts; increasing access to data and details of past, present, and future projects across jurisdictional boundaries to define baseline; improving understanding of threshold dynamics and feedback loops and incorporating chronic impacts that act over long temporal scales to define spatial and temporal scale; and developing ecological indicators that signify wide-ranging ecosystem change to determine significance.

In my study, impacts, spatial and temporal scale, and significance are incorporated in the data and methodology of developing the *LII*. Impacts consider both the activity (i.e. oil and gas wells drilling) and impact type (i.e. habitat disturbance). Spatial and temporal scales are determined by the jurisdiction boundary of the BLM Carlsbad Field Office, distance of influence from BLM staffs and research literature, fiscal year of operation, and availability of data. These scales are further addressed in the methodology (Section 3.3.2). Significance is defined as “effects of sufficient context and intensity that an environmental impact statement is required” in the NEPA Handbook. In other words, the action is significant in context to society as a whole, the affected region, the affected interests, and locality, and the severity of effect is significant. Areas with *LII* value higher than 0.8 are be referred to as significant areas of high landscape integrity, and areas with *LII* value lower than 0.3 are referred to as significant areas of low landscape integrity.

Carter et al. (2019) proposed a method of using indicators that consider the ecological health (structure, composition, and function) and management objectives and policies (resource- and stressor-based) to evaluate ecological integrity. This method sets the foundation for selecting the ecological and management indicators for my research. In addition to those indicators, my research also comprises landscape metrics to account for spatial patterns and processes to create a Landscape Integrity Index.

2.3. Challenges to Cumulative Effects Analysis

2.3.1. Spatial and Temporal Scale

The implementation of GIS in cumulative effect analysis is largely focused on establishing spatial and temporal boundaries and identifying vulnerable resources and areas where the greatest effects occur (Atkinson and Canter 2011). Generally, the natural boundaries of the resource affected defines the geographic scope, not the jurisdictional boundaries (Bureau of Land Management 2008). Some challenges with the CEA involving spatial scale include having too small of a geographic area for the analysis (Smith 2006) or using jurisdiction as the spatial extent (Foley et al. 2017), which has resulted in missing potential important contributing factors that affect ecological components. Moreover, determining the geographic scope of the CEA can be difficult when there are multiple land use activities across the landscape.

The timeframe for each cumulative effect should be established by defining the long- and short-term effects and incorporating the duration of the effects anticipated (Bureau of Land Management 2008). However there are several challenges in selecting the appropriate temporal scale. One of the issues from past CEA is having too short of a timeframe (Smith 2006). Other issues include using the operational period of the project or the duration of the action (Foley et al. 2017), limited availability of long-term data, or a temporal lag between the action and its effect until triggered by rare events such as extreme weather (Harvey and Railsback, 2007). The *LII* model in my research is also confined by the fiscal year of the project and the available data, but future attempts in advancing the *LII* model should include additional background research on the duration of the effects and how long the effects affect ecological components.

2.3.2. Indirect and Future Effects

There is also a gap in identifying indirect and cumulative effects from multiple past, present, and future actions. Indirect effects are effects caused by actions that occur later in time or further in distance that can induce changes in the pattern of land use and other ecological processes (Bureau of Land Management 2008). Interactions among the past, present, and future actions include additive (sum of the effects make up the cumulative effect), countervailing (effects of some actions balance the effects of other actions), and synergistic (the total effect is greater than sum of the individual effects) (Bureau of Land Management 2008). The GIS workflow in this research project considers these indirect effects and interactions in the past, present, and future by examining the spatial and temporal changes in the landscape structure and how these changes are reflected in the spatial patterns. While it may be difficult to distinguish between different interactions, determining the impact scores and distance of influence for the resource management activities and the stressors will help identify the magnitude and the areal extent of the effects. For example, identifying that oil and gas wells have an impact score of 0.2 (from previous landscape models) and calculating its Euclidean Distance with distance decay function can help quantify the amount and distance of the impact have on the environment.

2.4. Ecological Integrity and Its Indicators

The scientific community and land management agencies have an increased awareness of the concept of ecological integrity and the need to assess it as a way to manage natural systems (Hobbs et al. 2010, Carter et al. 2019). However, most ecological indicators, including environmental indices, and habitat suitability models have been identified for assessing the ecological integrity of aquatic habitats, rather than terrestrial habitats (Canter and Atkinson 2011, Carter et al. 2019). By contrast, this research considers a variety of terrestrial ecosystems by incorporating landscape metrics and patch analysis, which can lead us to a better understanding of the ecological integrity of different landscapes and how to better manage resource management programs.

2.4.1. Composition, Structure, and Function

Quantifying ecological integrity and landscape health is one way to evaluate the cumulative effects of the BLM resource management programs. The characterization of ecological integrity at a landscape-level is described by the elements of composition, structure, and function (Andreasen et al. 2001, Dale and Beyeler 2001), in which the health level of an ecological system is determined by its endurance and recovery dynamics against environmental processes or human disturbances (Parrish et al. 2003). Composition emphasizes the biological elements that influence ecosystem processes, such as focal or indicator species, species richness or evenness, or richness of patch size (Andreasen et al. 2001, Dale and Beyeler 2001). Structure comprises of landscape-level elements such as physical features, habitat fragmentation, or landscape connectivity. Function incorporates biotic and abiotic processes and interactions such as productivity, predation, weather, or disturbance. The inclusion of these components of ecological integrity in a cumulative effects analysis can better help identify the incremental effects of BLM resource management programs have on the managed lands.

2.4.2. BLM Management Indicator Species

To identify the appropriate ecosystems and weights of ecological integrity variables for the *LII* model, BLM management indicator species and their habitats were examined to determine the general habitats (i.e. vegetation areas) and associated habitat requirements. BLM New Mexico manages Bureau Sensitive Species (i.e. at-risk native species) and their habitats in BLM lands by planning and implementing conservation actions to prevent species listing and eventually remove them from the sensitive species list (Bureau of Land Management 2019). Three amphibians, two arthropods, twenty birds, five mammals, and two reptiles species were selected from the 2018 BLM NM Sensitive Species list, with existence verified in Carlsbad Field Office (Appendix A). Most of these species are either Endangered, Threatened, or Species of Greatest Conservation Need (SGCN) under the NM Status; or Watch (species of concern with the potential to become problematic), Watch New, BLM Sensitive (BLM determined priority species), or BLM Sensitive New under BLM Status. These species act as the BLM management indicator species for Carlsbad Field Office, and their habitats help identify the which vegetation area to include in the *LII* model (Appendix A). Additionally, given that patch size and structural connectivity vary amongst species, Lesser Prairie Chicken was selected as the species of concern since this species was given management actions and habitat restoration plans in the Draft BLM CFO RMP. The habitat requirements of Lesser Prairie Chicken are used to identify specific acres and distance to be used in the *LII* model. Other BLM management indicator species can be selected in future developments of *LII* model to represent the needs of other species.

2.5. Use of Landscape Metrics

Landscape metrics are emphasized in this study as a separate landscape indicator to characterize landscape patterns, changes, fragmentation, and diversity. Although there are several metrics for quantifying the structural components of ecological integrity in Carter et al. (2019), these metrics are not class-level pattern metrics used for analyzing landscape fragmentation or landscape diversity. Wang et al. (2014) considered 9 out of 64 class-level landscape pattern metrics to be robust for fragmentation measurements, including core area, shape, proximity/isolation, contrast, and contagion/interspersion. They compared numerous metrics including the ones available in FRAGSTATS to assess how aggregation affects pattern metrics and how habitat abundance dependency affects metrics, which can influence the selection of landscape metrics. FRAGSTATS is a program that quantifies landscape structure for vector and raster images by generating a variety of landscape metrics for 3 groups of metrics (patch, class, landscape mosaic), including area metrics, patch density, size and variability metrics, edge metrics, shape metrics, core area metrics, diversity metrics, and contagion and interspersion metrics. It is more advantageous to use the *landscapemetrics* package in R for calculating landscape metrics since it provides a reproducible workflow, and uses the most common metrics from FRAGSTATS and new metrics from the current literature on landscape metrics (Hesselbarth 2019). Table 1 shows the major subject areas for landscape metrics introduced from Wang et al. (2014), definitions, and how they provide information on landscape fragmentation or diversity. Since the prevention of habitat fragmentation, loss of habitat, and improving habitat diversity are key management goals at the BLM, landscape metrics that assess habitat fragmentation and diversity are included in this study.

Table 1. Subject Area for Landscape Metrics, Definitions, and Information Relevant to Landscape Fragmentation or Landscape Diversity

Subject Area for Landscape Metrics	Definition	Landscape Fragmentation / Landscape Diversity
Shape Metrics	Quantifies landscape configuration in terms of the complexity of patch shape.	Simple patch shape may be a result of human-induced fragmentation. Generally, patch shape should be geometrically complex in natural, unaltered landscape.
Core Area Metrics	Quantifies landscape composition and landscape configuration in terms of the core area of a patch.	Core area can serve as habitat area, in which the values from the core area metrics can show if landscape is a more fragmented configuration of habitat and contains less suitable habitat.
Proximity/Isolation Metrics	Quantifies landscape configuration through the placement of patch types relative to the same patch type within a specified distance.	Lox proximity/high isolation means that the habitat is far away from the same patch type, which can characterize fragmented habitats. As habitat diminishes and becomes fragmented, the remaining habitat becomes more isolated from each other in space and time.
Contrast Metrics (see edge metrics in 1995)	Quantifies landscape configuration through the degree of contrast among patch types	High degree of contrast between patches can indicate fragmentated habitat with boundaries between different patch types.
Contagion/Interspersion Metrics	Quantifies landscape configuration through patch type interspersion (i.e. the intermixing of units of different patch types) and patch dispersion (i.e. the spatial distribution of a patch type). In other words, contagion measures the extent to which patch types are aggregated or clumped.	Higher values of contagion characterize landscapes with a few large, contiguous patches (low fragmentation), whereas lower values generally characterize landscapes with many small and dispersed patches (high fragmentation).
Diversity Metrics	Quantifies landscape composition through 2 components: richness (number of patch types present) and evenness (distribution of area among different types).	Higher values from diversity metrics suggest more number of patch types and even area distribution among patch types, which can indicate greater landscape diversity.

Source: McGarigal and Marks (1995, McGarigal (2015)

2.6. Landscape Integrity Index

Several studies have been done to develop a landscape index of ecological integrity using measures of human footprint (i.e. human modification in the environment), indicators of ecological integrity, and intactness and resiliency metrics (Andreasen et al. 2001, McGarigal et al. 2018, Walston et al. 2018), but none of them has been applied to cumulative effects analysis. For instance, McGarigal et al. (2018) created the index of ecological integrity (IEI) by combining anthropogenic stressor metrics representing intactness and resiliency in a weighted linear model, in which the change in IEI over time computed the index of ecological impact. Walston et al. (2018) developed a Landscape Integrity Index as a landscape indicator of ecological integrity using measures of human modification on the environment (e.g. human footprint), and indicators of ecological integrity including biodiversity (e.g. species richness) and landscape change (e.g. vegetation departure). His paper introduced the methodology of moving window analysis to compute *LII*, which will be used in my research and further explained in Section 3.4.4.

The qualities of the ideal characteristics of a Landscape Integrity Index should include comprehensiveness, multi-scale, naturalness, relevancy, helpfulness, integration of aquatic and terrestrial ecology, flexibility, and measurability (Andreasen et al. 2001). These qualities go in tandem with the qualities of scientifically sound, transparent, comprehensive methods of conducting CEA. Using *LII* to evaluate the resource management programs at BLM offices will provide a standardized and comprehensive measure of ecological integrity and landscape patterns, which will help inform management and conservation decision making.

The use of a composite index of ecological integrity has been criticized in studies due to the loss of information, the inability to explore individual factors that affect ecological integrity, statistical problems, and the masking of variation in the direction and magnitude of effects of individual metrics to stressors (Carter et al. 2019). These authors suggested presenting individual metrics to managers and not combining the metrics. This study advocates the use of Landscape Integrity Index in cumulative effects analysis because the combination of the indicators and metrics better represents the cumulative effects on land disturbance and health.

Chapter 3 Methodology

The purpose of this study was to develop a Landscape Integrity Index (LII) to evaluate the cumulative effects of BLM resource management programs, specifically Vegetative Communities and Minerals – Leasables – Oil and Gas. This chapter first describes the study area, then the data sources, parameters, and the selection of indicators and metrics for the *LII* model. The next section applies the three-stage workflow developed by Carter et al. (2019): 1) Understand the management context of BLM Carlsbad Field Office; 2) Design the *LII* model using target resources, key stressors, spatial and temporal scales, and landscape metrics of *LII* model; and 3) Implement the *LII* model. The procedures for conducting the data preparation, landscape metrics in R, composite scoring system, moving window analysis, and model validation are explained further in the chapter.

3.1. Study Area

The study area was the BLM Carlsbad Field Office (CFO) in New Mexico (Figure 1), in which the *LII* model was applied. The CFO planning area is in southeastern New Mexico, within the Eddy, Lea, and a portion of Chaves County (Bureau of Land Management 2018b). The landscape of the planning area is predominantly desert with parts of three ecoregions including the Chihuahua Desert, Arizona/New Mexico Mountains, and High Plains. Approximately 2.1 million surface acres of federal land out of the estimated 6.2 million acres in the planning area will be affected by the decisions in the approved resource management plan (RMP). Neighboring BLM field offices can use this study area as a starting template for identifying indicator species and ecological indicators.

3.2. Data Sources and Selection of Indicators & Metrics

The BLM Carlsbad Field office provided the main datasets for the two resource management programs as they are the office responsible for the Draft RMP. Table 2 summarizes the spatial data inputs for the management actions and measures in Vegetative Communities and Minerals – Oil and Gas. Each of the management actions and measures was categorized into an ecological indicator, resource-based metric, stressor-based metric, or landscape metric.

Table 2. Spatial data inputs of management action and measure for Ecological Indicators and Resource- and Stressor-based Metrics

Management Action/Measure	Indicator/Metric	Data/Sources
	Vegetative Communities	
Vegetation area (2001, 2008, 2010, 2012, 2014)	Ecological Integrity Indicator	Existing vegetation type (LANDFIRE 2016b)
Vegetation alteration (2001, 2008, 2010, 2012, 2014)	Ecological Integrity Indicator	Vegetation departure (LANDFIRE 2016a)
Patch size (2001, 2008, 2010, 2012, 2014)	Ecological Integrity Indicator	Existing vegetation type (LANDFIRE 2016b)
Structural connectivity (2001, 2008, 2010, 2012, 2014)	Ecological Integrity Indicator	Existing vegetation type (LANDFIRE 2016b)
Important plant areas (2017)	Ecological Integrity Indicator	Important plant areas of New Mexico (EMNRD 2017)
Noxious weed treatment areas (2001-2016)	Resource-based Metric	Noxious Weed Treatment Areas (BLM 2018b)
Vegetative Treatment (2002-2018)	Resource-based Metric	CFO VTRT Data (BLM 2018b)
	Oil and Gas Wells	
Oil and gas wells (2001-2014)	Stressor-based Metric	Existing oil and gas wells (BLM 2018b)
Applications for Permit to Drill (APDs) (2001-2018)	Stressor-based Metric	apd point (BLM 2018b)
Flowline (2011-2018)	Stressor-based Metric	apd line (BLM 2018b)
Pipeline (2011-2018)	Stressor-based Metric	apd line (BLM 2018b)
Powerline (2011-2018)	Stressor-based Metric	apd line (BLM 2018b)
Road (2011-2018)	Stressor-based Metric	apd line (BLM 2018b)

Frac pond (2009-2018)	Stressor-based Metric	apd polygon (BLM 2018b)
Well pad (2009-2018)	Stressor-based Metric	apd polygon (BLM 2018b)

3.2.1. Ecological Integrity Indicators

As indicators of land health and ecological integrity, vegetation area, vegetation alteration, patch size, and structural connectivity were selected as ecological integrity indicators to quantify the compositional, structural, and function components of ecological integrity (Carter et al. 2019). Important Plant Areas was also included as an ecological integrity indicator in this analysis.

Existing Vegetation Type (EVT) and Vegetation Departure (VDEP) datasets (both 30 m resolution) were from the Landscape Fire and Resource Management Planning Tools Project (LANDFIRE). Existing Vegetation Type represented the plant community types that occurred in the location (LANDFIRE 2016b). Vegetation area was categorized by the EVT_PHYS and SYSTMGRPPH fields (depending on the year) from the EVT dataset, in which “Conifer”, “Conifer-Hardwood”, “Grassland”, “Riparian”, and “Shrubland” were selected to represent the general habitats of the BLM management indicator species and ultimately the different ecosystems within CFO. Vegetation alteration was from the VDEP dataset, depicting the changes in species composition, structural stage, and canopy closure between current vegetation conditions and reference vegetation conditions (pre-EuroAmerican settlement) (LANDFIRE 2016a).

Patch size (acres) and structural connectivity (meters) were calculated for each vegetation area. Patch size refers to the amount of vegetation area, and it is a measure of landscape configuration (McGarigal and Marks 1995). Patch size could affect the ecological properties of a patch via the surrounding neighborhood (e.g. edge effects). Structural connectivity is the proximity of vegetation area; for instance, grassland connectivity is the distance between individual grassland pixels. Connectivity could affect the permeability of various patch types, movement of organisms, and ecological processes and interactions (McGarigal and Marks 1995). Even though the Lesser Prairie Chicken is a highly mobile species, its broods have limited mobility and their habitats need to be close to nesting habitats (Pelt et al. 2013). Ideal habitat for the species is a mosaic of brood and nesting habitat, with a distinction between the forb and grass cover. However, this distinction requires additional datasets that are not currently available. Therefore, the habitat patch for Lesser Prairie Chicken is generalized and connectivity in this study is limited to linear distance between the habitat patch. Moreover, the RMP identified a minimum patch size of 320 acres without fragmentation from development as habitat requirement. Other research shows that grassland is the habitat of Lesser Prairie Chicken, with a minimum habitat patch size ranges from 4,900 ha (12,108.16 acres) to 20,236 ha (50,004.245 acres) (Spencer et al. 2016), and < 2 miles (3,218.69 m) between habitat patches for connectivity (Pelt et al. 2013). Hence only grassland patch size and connectivity with specific range of acres and meters were used in the analysis.

New Mexico State Forestry was the source of the Important Plant Areas of New Mexico data. Important Plant Areas (IPA) are specific areas that support either a high diversity of sensitive plant species or are the last remaining habitats of rare and endangered plants in New Mexico (Natural Heritage New Mexico n.d.). This variable was included to incorporate habitats of sensitive plant species and highlight the importance of these areas. Note that there was no evaluation of habitat or landscape integrity for this dataset, and some of the polygons include towns, mines, roads, and other heavily impacted areas.

3.2.2. Resource- and Stressor-based Metrics

Resource-based metric measures resources and resource uses, often those that are managed by the agency (e.g. vegetation, soils, and etc.). In this study, noxious weed treatment areas and vegetative treatment data layers were selected as resource-based metrics to assess how these management actions affect the Vegetative Communities. The noxious weed treatment areas are transect lines where the herbicide is applied. The vegetative treatment includes areas of different treatment such as removal of invasive species, the use of fertilizer, pesticide, and other treatments.

Stressor-based metrics measure anthropogenic drivers that affect the ecosystem (e.g. oil and gas operations, grazing, etc.). Oil and gas wells, applications for permit to drill (APDs) points, linear features of approved APD (i.e. flowline, pipeline, powerline, road), and polygon features of approved APD (i.e. frac pond and well pond) were selected as stressor-based metrics to assess how these management actions affect the landscape.

3.2.3. Landscape Metrics

Landscape metrics quantify the landscape structure and assess the changes in the landscape over time (McGarigal and Marks 1995). The dataset for the landscape metrics was the National Land Cover Database (NLCD), a 30 m resolution land cover raster dataset from the Multi-Resolution Land Characteristics (MRLC) Consortium (Homer 2015). Appendix B lists the NLCD land cover classes. Table 3 shows the FRAGSTATS metrics, the counterpart R-function, definition of the metric, and interpretation of the output values from 2001, 2004, 2006, 2008, 2011, 2013, 2016, which are the years of the available NLCD data. Shape metrics, core area metrics, contagion/interspersion metrics, and diversity metrics were selected as the final landscape metrics in this study to analyze landscape fragmentation and diversity.

Proximity/isolation metrics and contrast metrics were not included because the *landscapemetrics* package in R did not include functions to calculate those variables from Wang et al. (2014) (R-function = NA in Table 3). And since some of the landscape metrics presented redundant information insofar as they measured a similar or identical feature of landscape pattern, only a handful (landscape metrics with a * in Table 3) were used in the development of *LII*. The CAI_CV variable was used instead of CAI_SD as the measure of variability because coefficient of variation (CV) was a relative measurement (i.e. variability expressed as a percentage of the mean) and easier to interpret compared to standard deviation (SD), which was an absolute measurement and interpretation was dependent on the mean (McGarigal and Marks 1995). Landscape diversity metrics were not used in the development of *LII* because they were landscape-level metrics, meaning that the output value was for the entire study area instead of for each land cover class and would be used for comparing the landscape between different years. The results would be discussed more in Section 4.2.

Table 3. Landscape Metrics from FRAGSTATS and R with Definition and Interpretation (2001, 2004, 2006, 2008, 2011, 2013, 2016)

FRAGSTATS Metrics	**R-function**	**Definition**	**Interpretation**
		Shape Metrics	
Perimeter-Area Fractal Dimension (PAFRAC)*	lsm_c_pafrac	Describes the patch complexity of the class while being scale independent.	1 = simple perimeter, 2 = complex shape
		Core Area Metrics	
Area Weighted Mean Core Area Index (CAI_AM)	NA	Quantifies core area for the entire class or landscape as a percentage of total class or landscape area, respectively, by weighting patches according to their size.	0 = patch contains no core area, 100 = patch contains mostly core area

		Core Area Index quantifies the percentage of the patch that is comprised of core area.	
Coefficient of Variation of Core Area Index (CAI_CV)*	lsm_c_cai_cv	Summarizes each class as the coefficient of variation of the core area index of all patches belonging to the class.	Higher CV = larger relative variation in CAI
Standard Deviation of Core Area Index (CAI_SD)	lsm_c_cai_sd	Summarizes each class as the standard deviation of the core area index of all patches belonging to the class.	Higher SD = larger absolute variation in CAI
Coefficient of Variation of Core Area (CORE_CV)*	lsm_c_core_cv	Equals the coefficient of variation of the core area of each patch in the landscape. Core Area is the interior area of patches beyond some specified edge distance or buffer width.	Higher CV = larger relative variation of patch core areas
Proximity/Isolation Metrics			
Coefficient of Variation of Proximity Index (PROX_CV)	NA	Summarizes each class as the coefficient of variation of the proximity index of all patches belonging to the class. Proximity Index considers the size and proximity of all patches whose edges are within a specified search radius of the focal patch and measures both the degree of patch isolation and the degree of fragmentation of the corresponding patch type within the specified neighborhood of the focal patch.	Higher CV = larger relative variation in PROX
Contrast Metrics			
Area Weighted Mean Euclidian Nearest Neighbor Index (ECON_AM)	NA	Calculates the Euclidean Nearest Neighbor Index by weighting patches according to their size. Nearest neighbor distance is defined as the shortest straight-line distance from a patch to the nearest neighbor of the same class.	Mean distance to the nearest neighbor patch of the same class weighted by area

Total Edge Contrast Index (TECI)	NA	Quantifies edge contrast as a percentage of maximum possible (landscape as a whole). Edge contrast is the degree of contrast a patch has compared to its neighbor.	0 = no edge in the landscape (entire landscape and landscape borders is one patch), 100 = edge is maximum contrast
Contagion and Interspersion Metrics			
Clumpy Index (CLUMPY)*	lsm_c_clumpy	Equals the proportional deviation of the proportion of like adjacencies involving the corresponding class from that expected under a spatially random distribution.	-1 = patch is maximally disaggregated, 0 = patch is distributed randomly, approaches 1 = patch is maximally aggregated
Diversity Metrics			
Shannon's Diversity Index (SHDI)	lsm_l_shdi	Characterizes diversity for the class and accounts for both the number of classes and the abundance of each class. Sensitive to rare classes.	Higher = greater number of classes; greater diversity
Simpson's Diversity Index (SIDI)	lsm_l_sidi	Characterizes diversity for the class and is less sensitive to rare class types than SHDI. Calculates the probability that two randomly selected cells belong to the same class. Responsive to dominant classes.	0 = only one patch is present, approaches 1 = greater number of classes; greater diversity
Patch Richness (PR)	lsm_l_pr	Measures the number of patch types present; not affected by the relative abundance of each patch type (rare or common patch types contribute equally to richness) or the spatial arrangement of patches.	Higher = more different patch types
Patch Richness Density (PRD)	lsm_l_prd	Measures the number of patch types per area.	Higher = more different patch types per area
Shannon's evenness index (SHEI)	lsm_l_shei	Calculates the ratio between SHDI and the maximum of SHDI.	0 = only one patch present; no diversity, approaching 1 = proportion of classes is

		An even distribution of area among patch types results in maximum evenness.	completely equally distributed; greater evenness
Simpson's evenness index (SIEI)	lsm_l_siei	Calculates the ratio between SIDI and the maximum of SIDI.	0 = only one patch present, 1 = proportion of classes is completely equally distributed; greater evenness

* These metrics were used in the development of *LII* model
Source: McGarigal and Marks (1995), McGarigal (2015), Hesselbarth (2019)

3.3. Three-Stage Workflow

My workflow was based on the three-stage method developed by Carter et al. (2019), which assessed ecological integrity for multiple-use systems and helped inform land management. The first stage identifies management policies and actions; the second stage identifies target resources and key stressors to be managed, and spatial and temporal scales; and the third stage conducts the analysis and uses the results to inform planning and management (Figure 4). Not all steps shown in Figure 4 were adopted in my analysis, but they could be included in future research.

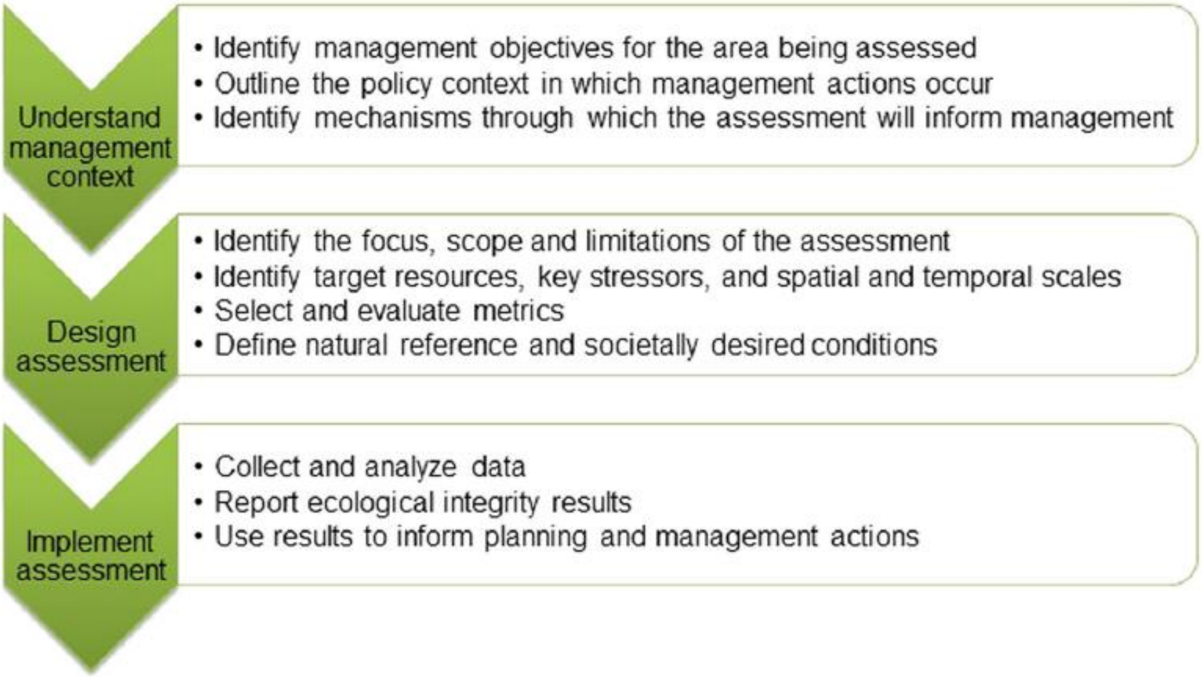


Figure 4. 3-Stage Workflow to Assess Ecological Integrity. Source: Carter et al. (2019)

3.3.1. Understand management context

The first stage of assessing ecological integrity for multiple-use ecosystems is to understand the management context for the assessment area (Carter et al. 2019). The management goals and objectives in the BLM Carlsbad Field Office's Draft Resource Management Plan and Environmental Impact Statement (Draft RMP/EIS) provided guidance as to the management of the CFO planning area. Table 4 showed some of the goals and objectives in Vegetative Communities and Minerals – Leasables – Oil and Gas from the CFO Draft RMP/EIS that were pertinent to this research with available data. By understanding the management context for the assessment area, the Landscape Integrity Index can better incorporate useful variables, capture the influence of management actions on landscape health, and evaluate management effectiveness.

Table 4. Management Goals and Objectives of Vegetative Communities and Minerals – Oil and Gas

Vegetative Communities	
Goals	• "Manage vegetation to restore the resiliency of ecosystem structure and function, reduce fragmentation of habitat for native species, and move toward desired plant communities." • "Manage public lands to prevent, eliminate, or control noxious weeds and invasive plants."
Objectives	• "Manage public lands to prevent, eliminate, or control noxious weeds and invasive plants." • "Manage for vegetation restoration, including control of undesirable and invasive plant infestations (native and non-native species) to achieve healthy, sustainable rangeland ecosystems that support resource values such as, but not limited to, wildlife habitat and functional watersheds." • "Protect special status plant species and their habitats." • "Minimize or halt the spread of noxious, non-native, and invasive plant species." • "Control or eliminate existing populations of noxious, non-native, and invasive plant species. Monitor the spread of noxious, non-native, and invasive plant species." • "Manage uses and treat noxious weeds such that there is no net increase in the number of acres containing noxious weeds and reduce the number of noxious weed species present."
Minerals – Leasables – Oil and Gas	
Goals	• "Promote and support American agriculture and provide jobs and economic development opportunities to the local community. (Executive Order 13790, April 25, 2017)." • "Support the national interest to promote clean and safe development of our Nation's vast energy resources, in a manner that does not unnecessarily encumber energy production, constrain economic growth, and prevent job creation. (Executive Order 13783 March 28, 2017)."
Objectives	• "Allow the oil and gas industries reasonable opportunities to lease and explore, while protecting sensitive areas and various other resources." • "The BLM would seek the input of industry and the public at every opportunity to discuss changes in policy or priorities." • "Facilitate reasonable, economical, and environmentally sound exploration and development of leasable minerals where compatible with resource objectives and as consistent with Secretarial Order 3324."

Source: Bureau of Land Management (2018b)

For example, in Vegetative Communities, the management goals and objectives specify vegetative restoration, the prevention, elimination, and control of noxious weed and invasive plants, and the protection of special status plant species and their habitats. The management actions and field datasets (vegetative treatment and noxious weed treatment), and dataset provided by other organization (Important Plant Areas) could attest to those management goals and objectives. While managing for vegetation restoration is a high priority for CFO, fostering economic opportunities from oil and gas industries is also imperative for the local community. These two contrasting resource management programs create a dichotomy of effects that may or may not balance each other.

3.3.2. Design assessment

The second stage is to design assessment by identifying target resources, key stressors, spatial and temporal scales, and selecting and evaluating the metrics for the Landscape Integrity Index. This research reviews the resource management programs in the Draft RMP and identified the target resource as Vegetative Communities: Upland Vegetation, Noxious Weeds, and Invasive Species, and the key stressor as Minerals – Leasable – Oil and Gas. It is important to note that a landscape is defined as "an interacting mosaic of patches relevant to the phenomenon under consideration (at any scale)" (McGarigal and Marks 1995), and the CEA practitioner or land manager needs to define landscape pertinent to their management endeavor. The landscape for my study was the BLM Carlsbad Field Office. And although patches should also be defined, the NLCD land cover class (e.g. Deciduous Forest, Shrub/Scrub, Woody Wetlands, etc.) defined the patches in this case.

In this study, the spatial and temporal scales were determined by the jurisdiction boundary of the BLM Carlsbad Field Office, fiscal year of operation, and availability of data. The spatial extent is the CFO planning area (Figure 1). Even though the spatial scale should extend to the specific resource or ecosystem being impacted and possible ecosystem impacts may exist outside of the CFO planning area boundary, funding and allocation of resources and available data were determined by the jurisdiction boundary, and therefore the CFO planning area boundary defined the general spatial extent. For future research, it would be ideal to obtain field datasets from other BLM field offices and establish a spatial extent that aligned with ecosystem processes or habitats of species of concerns to define a more natural spatial extent. The temporal scale ranged from 2001 to 2018, depending on data availability. Some of the datasets did not have the whole 18 years, such as the EVT and VDEP datasets (2001, 2004, 2010, 2012, and 2014), IPA data layer (2017), and NLCD data layer (2001, 2004, 2005, 2008, 2011, 2013, and 2016), which might reduce the accuracy and completeness of the *LII* value since the datasets from the missing years were not accounted for. The IPA variable was the only data layer that was used with other ecological indicators that were in different years. This might have increased the *LII* value if no other ecological indicators were present at the IPA. On the other hand, there were also occasions when there was no data in the CFO datasets (e.g. noxious weed treatment or oil and gas wells) for specific years. If it was the case that there was no activity that year, then the *LII* value would reflect the lack of activity. However, if it was the case that there was activity that year but was not captured in the data, then the *LII* value would be affected by the missing data. Moreover, past, present, and future effects were taken into consideration by the nature of the datasets. For example, existing oil and gas wells represented the past and present effects, while APD points represented potential past, present, and future effects.

3.3.3. Implement assessment

The third stage implements the Landscape Integrity Index through data collection and analysis and reporting of the *LII* results, thereby improving the CEA process and ultimately helping to inform planning and management actions. Since the datasets were already collected by the CFO and other agencies and organizations, the main tasks were to prepare these datasets for the analysis, perform the analysis, and validate the model. For this analysis, the *LII* results were the map of the Landscape Integrity Index, a raster with *LII* values, and a shareable GIS model with python scripts and R Markdown. Some ways to inform planning and management actions would be for the CEA practitioners to look into specific areas of concerns and identify the *LII* values within those areas to see if improvements can be made in those areas, if the areas should not have future management programs, and predict the effects of potential additional management programs.

The datasets for the ecological indicators, resource- and stressor-based metrics, and landscape metrics were processed using a python script (LII_DataPrep.py), and this process is explained more in Section 3.4.1. The processed NLCD data layers were the input variables to calculate the landscape metrics using an R Markdown (LII_landscapemetrics.Rmd), and this process is explained more in Section 3.4.2. The indicators and metrics were assigned the site impact score or the landscape integrity values using the composite scoring system developed in Walston and Hartmann (2018) and a python script (LII_CompositeScoringSystem.py), which is explained in Section 3.4.3. After all of the ecological indicators, resource- and stressor-based metrics, and landscape metrics were ranged from 0 to 1, they would be averaged into one Landscape Integrity Index ranging from 0 (low landscape integrity) to 1 (high landscape integrity) using the moving window analysis through a python script (LII_MovingWindowAnalysis.py). This process is explained in Section 3.4.4. Additionally, the *LII* model was validated with two comparison methods involving a linear regression model and a Welch’s two sample t-test and using both python script and R Markdown (LII_ModelValidation.py and LII_ModelValidation.Rmd), which is explained in Section 3.4.5.

3.4. Procedure

The diagram below (Figure 5) shows the general workflow, encompassing the three-stage workflow and major steps, processes, inputs, outputs, and tools for creating the Landscape Integrity Index. Most of the steps were performed in standalone python scripts (with ArcMap 10.6 and Python 2.7) and R Markdown (R version 3.5.3).

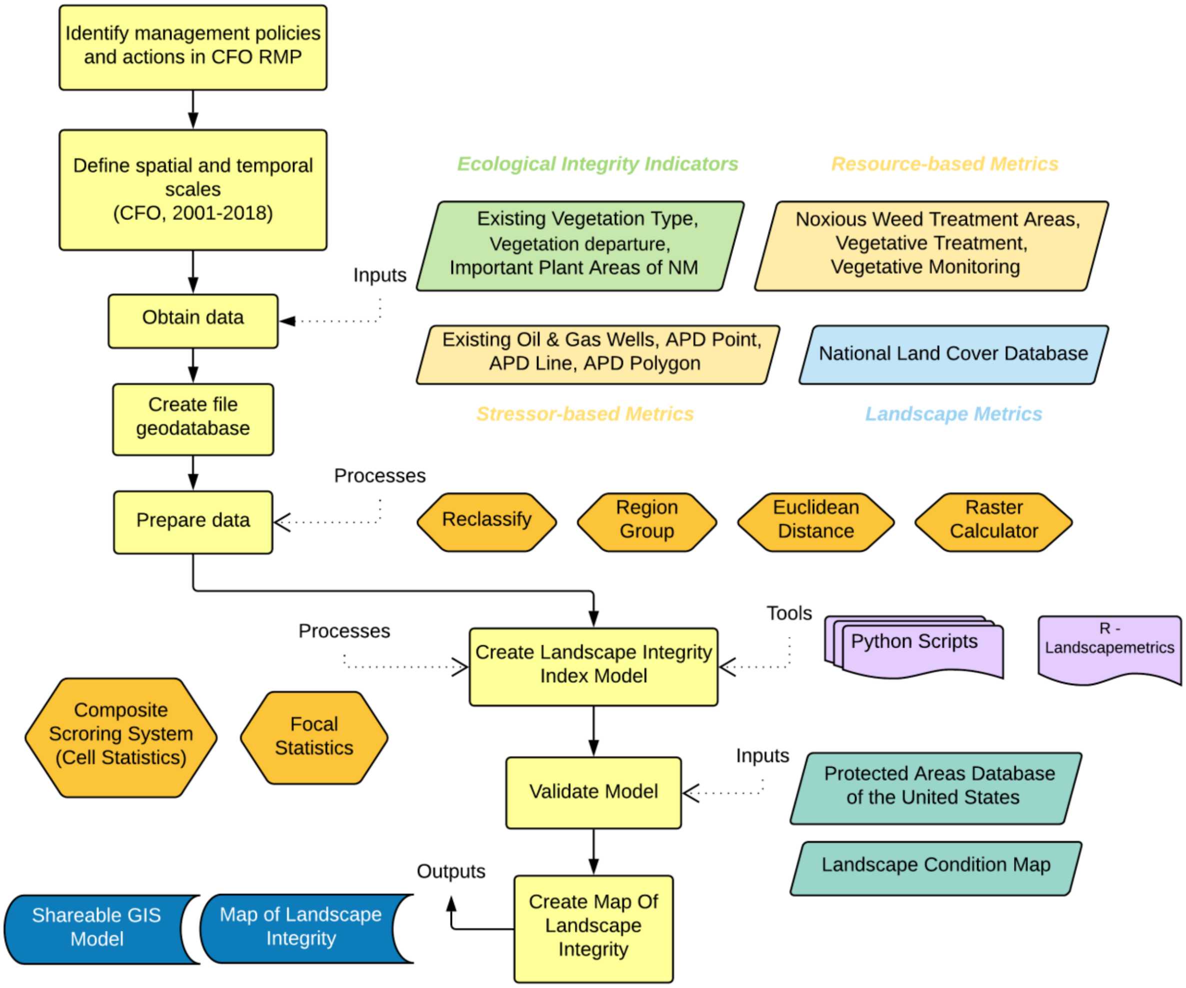


Figure 5. Landscape Integrity Index (LII) Workflow

3.4.1. Data Preparation

A series of steps was performed to prepare the data for the ecological integrity indicators, resource- and stressor-based metrics, and landscape metrics. After going through the first two stages of the three-stage workflow and obtaining the appropriate data, a file geodatabase for the base variables and parameters was created. All of the raster and feature classes were then projected to NAD 1983 UTM Zone 13N and clipped to the CFO boundary. A year text field (Year) was added and the year information from the Last Activity field was extracted for the oil and gas wells variable. Subsequently, raster and feature classes were extracted and selected using different categories (i.e. vegetation area, APD lines, and APD polygons) and the appropriate year.

For ecological integrity indicators, the patch size and structural connectivity variables required additional steps to produce. The patch size variables for each ecosystem were created by the Region Group tool with an eight-cell neighborhood rule. This tool identifies the patch where each cell belongs to using the immediate surrounding cells (the eight-cell neighborhood rule includes diagonals) (Esri 2019b). The Lookup tool was used to create a new patch size raster using the COUNT field, which would show how many pixels were in each group. To get the number of acres of each patch, Map Algebra (e.g. Raster Calculator tool) was used to multiply the new raster with 0.222395 (0.222395 acres = 900 m^2, for 30 m pixels). The structural connectivity variable for each ecosystem was generated by the Euclidean Distance tool, which calculated the distance between individual ecosystem pixels (Esri 2019a).

3.4.2. Landscape Metrics in R

The *landscapemetrics* package in R produced the shape metrics, core area metrics, contagion/interspersion metrics, and diversity metrics to assess landscape fragmentation and diversity. The first step was setting the working directory and installing and loading the necessary packages such as *raster*, *rgdal*, *sp*, *kableExtra*, *knitr*, and *landscapemetrics*. The inputs were the NLCD TIFFs that were prepared in the above section. The *lsm_c_pafrac* function calculated the Perimeter-Area Fractal Dimension (PAFRAC) for shape metrics. The *lsm_c_cai_cv* function calculated the Coefficient of Variation of Core Area Index (CAI_CV); the *lsm_c_cai_sd* function calculated the Standard Deviation of Core Area Index (CAI_SD); and the *lsm_c_core_cv* function calculated the Coefficient of Variation of Core Area (CORE_CV) for core area metrics. The *lsm_c_clumpy* function calculated the Clumpy Index (CLUMPY) for the contagion/interspersion metrics. The *lsm_l_shdi* function calculated the Shannon's Diversity Index (SHDI); the *lsm_l_sidi* function calculated the Simpson's Diversity Index (SIDI); the *lsm_l_pr* function calculated the Patch Richness (PR); the *lsm_l_prd* function calculated the Patch Richness Density (PRD); the *lsm_l_shei* function calculated the Shannon's Evenness Index (SHEI); and the *lsm_l_siei* function calculated the Simpson's Evenness Index (SIEI). Additional parameters were specified in the LII_landscapemetrics.Rmd, and the results could be viewed in Appendix B.

3.4.3. Composite Scoring System

To model the effects each indicator and metric had on the landscape, a modified composite scoring system from Walston and Hartmann (2018) was implemented in this analysis. The ecological integrity indicators were characterized by only the site impact scores. The resource- and stressor-based metrics were characterized by the modeling approach and parameters of site impact score, distance of influence, and distance decay function, which were adopted from previous landscape modeling efforts (Theobald 2013, Hak and Comer 2017, Walston and Hartmann 2018). The site impact score represents the impact of the landscape condition, or the ecological stress caused by the management action, and ranges from 0 (greater site impact) to 1 (lower site impact). This definition differed slightly from Walston and Hartmann (2018)'s definition of site impact score, which was "the assumed intensity of the human land use." Distance of influence is the distance at which the management action presumed to affect ecological integrity, since habitat quality and wildlife use generally declines with proximity to human activities. Distance decay function reveals the relationship between ecological impact and distance from the management action, in which logistic function was used as the distance decay function. On the other hand, the landscape metrics were not assigned any impact score; they were only normalized from 0 (low landscape integrity) to 1 (high landscape integrity) according to the calculated values from the *landscapemetrics* package.

For the ecological integrity indicators, a file geodatabase was created, and the environmental extent was set to the CFO boundary so that the raster cells would cover the entire CFO boundary for all variables. A site impact score double field (IP) was added and assigned a site impact score of 1 to the IPA variable, indicating that the IPA were areas of high ecological integrity. Since the IPA dataset was in vector format, it was converted to 30 m resolution raster using the Feature to Raster tool. An important step was to use the IsNull tool in combination with the Con tool to ensure that cells with Null, NoData, and area with low habitat suitability values were set to -10 (Table 5). This step warranted that those cells would be accounted for when used in Map Algebra or Raster Calculator tool, but the negative value would not be in the final calculation for the *LII* value. Next, the Reclassify tool was used to reclassify the values of the ecosystems to site impact score of 1 and "NoData" to -10, indicating that the vegetation areas were areas of high ecological integrity. The Con tool was used to reassign values of -10 to grassland patch sizes < 320 acres, 0.75 to grassland patch sizes < 12,108.16 acres, 0.95 to grassland patch sizes < 50,004.245 acres, and 1 to grassland patch sizes ≥ 50,004.245 acres. In addition, the Con tool was used to reassign value of 1 to grassland connectivity ≤ 3,218.69 m, and -10 to grassland connectivity > 3,218.69 m. Since the vegetation alteration data layer ranged from 0 to 100, it was inversely normalized to the range of 0 (high vegetation change from reference vegetation condition) and 1 (little vegetation change from reference vegetation condition) with the following equation:

$$\text{Equation 1.} \quad \frac{Maximum - X}{Maximum - Minimum}$$

Raster with cell values < 0 were set to Null using the SetNull tool. The Cell Statistics tool was used to calculate the minimum site impact score out of all of the ecological indicators for the appropriate years.

Table 5. Site Impact Scores of Ecological Integrity Indicators

Management Action or Measure	**Site Impact Score**	**NoData/Null/Area with low habitat suitability**
IPA	1	-10
Conifer	1	-10
Conifer-Hardwood	1	-10
Grassland	1	-10
Riparian	1	-10
Shrubland	1	-10
Grassland Patch Size	0.75, 0.95, 1	-10
Grassland Structural Connectivity	1	-10
Vegetation Alteration	0 - 1	NA

For resource- and stressor-based metrics, a file geodatabase was created for each management program, and the environment extent was set to the CFO boundary. A site impact score double field (IP) was added; and site impact score of 0.7 was assigned for the noxious weed treatment and vegetative treatment variables, 0.2 for the oil and gas wells, APD point, flowline, pipeline, frac pond, and well pad variables, 0.6 for powerline variable, and 0.75 for road variable (Table 6).

Table 6. Site Impact Scores of Resource- and Stressor-based Metrics

Management Action or Measure	**Site Impact Score**	**Null**	**Distance of Influence (m)**	**Distance Decay Function**
Resource-based Metrics				
Noxious weed treatment areas	0.7	-10	500	Logistic
Vegetative Treatment	0.7	-10	500	Logistic
Stressor-based Metrics				
Oil and gas wells	0.2	-10	1000	Logistic
Applications for Permit to Drill (APDs) points	0.2	-10	1000	Logistic
Flowline	0.2	-10	1000	Logistic
Pipeline	0.2	-10	1000	Logistic
Powerline	0.6	-10	200	Logistic
Road	0.75	-10	500	Logistic
Frac pond	0.2	-10	1000	Logistic
Well pad	0.2	-10	1000	Logistic

Source: Modified from Walston and Hartmann (2018)

The site impact scores and distance of influence for resource- and stressor-based metrics were adopted from Walston and Hartmann (2018). Noxious weed and vegetative treatment utilized the site impact score from the “Low agriculture and invasive (ruderal forest, recently burned, recently logged, etc.)” field, and road utilized the site impact score from the “Primitive roads (e.g. dirt roads and trails) field from Walston and Hartmann (2018). All the resource- and stressor-based metrics datasets were in vector format, and they were converted to 30 m resolution raster using the Feature to Raster tool. The IsNull tool in combination with the Con tool were used to ensure that cells with Null were set to -10. The Euclidean Distance tool was used to calculate the Euclidean distance (meters) for each resource- and stressor-based metrics, in which each cell value represented the distance to the closest objects of interest (in this case, management action) (Esri 2019a). A maximum distance of 4,000 m was used in the Euclidean Distance tool to represent the distance of influence human activities have on wildlife (Walston and Hartmann 2018). The distance decay function, more specifically the Logistic 10 tool, was applied on the Euclidean Distance output. Logistic function was selected instead of using both linear and logistic functions. This was because most of the metrics had higher site impacts and the difference between logistic and linear functions were minimal. The IsNull tool in combination with the Con tool were used again to ensure that the Null in the outputs were set to -10. The outputs from the previous step were normalized using the following equation:

$$\text{Equation 2.} \quad \frac{X - Minimum}{Maximum - Minimum}$$

The normalized raster was multiplied with the raster that had the site impact score as the cell value to incorporate the effects from the Euclidean Distance and distance decay function have onto the site impact scores. If there were areas that the two raster data layers did not overlap, then the output raster cell would contain value from either the normalized raster or the raster that had the site impact score. The IsNull tool in combination with the Con tool were used again to ensure that the Null in the outputs were set to -10. Raster with cell values < 0 or = 100 were set to Null using the SetNull tool to exclude Null (-10) and Null overlaps (-10 times -10 = 100). The Cell Statistics tool was used to calculate the minimum site impact score out of all of the resource- and stressor-based metrics for the appropriate years.

For landscape metrics, a file geodatabase was created, and the environment extent was set to the CFO boundary. Reclassify tool was used to reclassify the NLCD values to landscape metric values that were calculated from the *landscapemetrics* package in R (see Appendix B for a complete list of the values). The raster with landscape metric values were then normalized to a range of 0 (high landscape fragmentation) to 1 (low landscape fragmentation) with the range of the landscape metrics or the minimum and maximum landscape metric values if the metric did not have a range of output. For example, PAFRAC was normalized with the range of 1 to 2

(Equation 3), while CAI_CV was normalized with its minimum and maximum values (Equation 4):

Equation 3. $$\frac{(PAFRAC - 1)}{2 - 1}$$ Equation 4. $$\frac{CAI\_CV - Minimum}{Maximum - Minimum}$$

The Cell Statistics tool was used to calculate the minimum landscape integrity value out of all of the landscape metrics for the appropriate years.

3.4.4. Moving Window Analysis

The *LII* was computed by calculating the average of all overlapping 30 m pixel values in the raster models of ecological integrity indicators, resource- and stressor-based metrics, and landscape metrics within 1 km moving windows using the Focal Statistics tool (Walston and Hartmann 2018). To prepare for the moving window analysis step, a file geodatabase was created, and the environment extent was set to the CFO boundary. The Cell Statistics tool was used to overlay the raster models of ecological integrity indicators, resource- and stressor-based metrics, and landscape metrics and calculate the mean of the site impact scores and landscape metric values for each year. The Cell Statistics tool was used once more to overlay the raster models for all of the years into one raster with mean as the statistics type. Circle was selected as the neighborhood, and 1,000 map units (meters), mean, and ignore NoData value were selected as the parameters for the Focal Statistics Tool. Lastly, the output Landscape Integrity Index was clipped to the CFO boundary.

3.4.5. Model Validation

The model was validated by (1) comparing the *LII* values with the values from the Landscape Condition Map (LCM) developed by Hak and Comer (2017) using a linear regression model, and (2) comparing the *LII* values in protected areas to the *LII* values in multiple-use areas using the Protected Areas Database of the United States (PAD-US) data from U.S. Geology Survey (USGS) Gap Analysis Project (GAP) and Welch's two sample t-test. The linear regression would show if there was a relationship between Landscape Integrity Index and Landscape Condition Map. And the Welch's two sample t-test would indicate if the mean *LII* value would be different between protected areas and multiple-use Areas. Both python scripts and R Markdown were used during the model validation process. To prepare the datasets for the model validation, a file geodatabase was created, and the environment extent was set to the CFO boundary. All of the raster and feature classes were then projected to NAD 1983 UTM Zone 13N and clipped to the CFO boundary. The LCM raster was manually projected due to the large size. I then selected the areas that were protected (GAP Status = 1 or 2) and multiple-use (GAP Status = 1 or 3) in the PADUS data and dissolved those areas. I had initially included unprotected areas (Gap Status = 4), but there was no unprotected areas within CFO boundary, and thus it was not included in the final model validation.

For the first model validation process, 100 random points were created within the CFO boundary using the Create Random Points tool, then the *LII* values and LCM values were extracted and recorded in those points using Extract Values to Points tool. Then the *LII* values and LCM values were compared in R using a linear regression to model the relationship between *LII* and LCM. In R, the working directory was set and the necessary packages such as *readxl*, *ggplot2*, *dplyr*, *tidyr*, *magittr*, gridExtra, *e1071*, *kableExtra*, and *knitr* were installed and loaded. The inputs were the tables of *LII* values and LCM values (see Appendix C). The LCM value was the independent/predictor variable (x), and the *LII* value was the dependent/response variable (y). A scatter plot was plotted to visualize the relationship between *LII* and LCM using the *scatter.smooth* function. A density plot was used to check if the response variable was close to normal using the *density* function. The correlation between *LII* value and LCM value was calculated using the *cor* function. Then the linear regression model was built using the *lm* function.

For the second model validation process, 100 random points was created within the protected areas and another 100 random points was created within the multiple-use areas using the Create Random Points tool, then the *LII* values were extracted and recorded in those points using Extract Values to Points tool. The *LII* values in protected areas were compared to the *LII* values in multiple-use areas using Welch's two sample t-test to test the hypothesis that two different areas have equal means. In R, the working directory was set, and the packages were already installed and loaded from model validation process 1. Box plots were plotted to identify any outliers within the two groups of *LII* values. The Welch's two sample t-test was performed using the *t.test* function.

Chapter 4 Results

This chapter presents the key findings of the Landscape Integrity Index model and the two model validation processes. The results of the *LII* model indicate that the overall landscape integrity in Carlsbad Field Office planning area is at a moderate level. The resulting map identifies areas of low and high landscape integrity in CFO, in which low landscape integrity may be attributed by urban and industrial development, and agriculture. Results from the diversity metrics suggest that landscape diversity remained relatively low from the time period of 2001 to 2016, peaking at 2013 and declining in later years. The linear regression results show a moderate positive and significant correlation between the Landscape Integrity Index and Landscape Condition Map. And the Welch's two sample t-test results show that the mean *LII* value in protected areas is slightly higher than the mean *LII* value in multiple-use areas.

4.1. The Landscape Integrity Index Model

The Landscape Integrity Index showed that the overall average of landscape integrity value was 0.48 (SD = 0.05), indicating a moderate level of landscape integrity at the Carlsbad Field Office planning area. The region was mostly characterized by *LII* values of 0.45 to 0.55 (~55% of the region had *LII* values of 0.45 to 0.5 and ~35% of the region had *LII* values of 0.5 to 0.55); less than 5% of the region had high *LII* values (>0.7) or low *LII* values (0.2 to 0.3) (Figure 6).

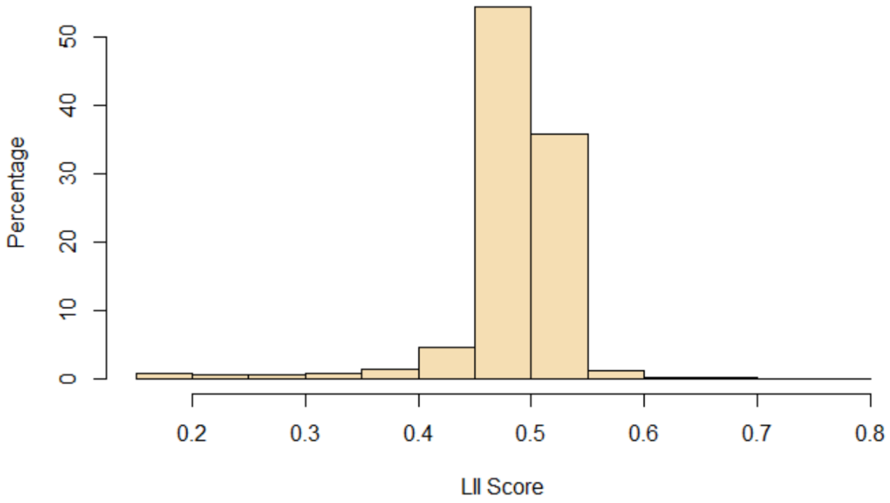


Figure 6. Histogram of LII values at Carlsbad Field Office

The resulting map showed areas of low landscape integrity near the major cities and the northeast corner of CFO planning area; and areas of high landscape integrity were near central and southwest corner of CFO planning area (Figure 7). There were very few areas with the highest landscape integrity (*LII* values of 0.8 to 1), which were scattered throughout the region and located at the CFO boundary, which could have resulted from the issue of using a boundary constraint. Areas of moderately high landscape integrity (*LII* values of 0.5 to 0.7) occurred in Arid Llano Estacado, Chihuahuan Desert Grasslands, Southern New Mexico Dissected Plains, and Madrean Lower Montane Woodlands ecoregions. And areas of lowest landscape integrity (*LII* values of 0 to 0.3) were located at areas of high human influence such as urban areas, development areas, and agricultural areas (cultivated crops).

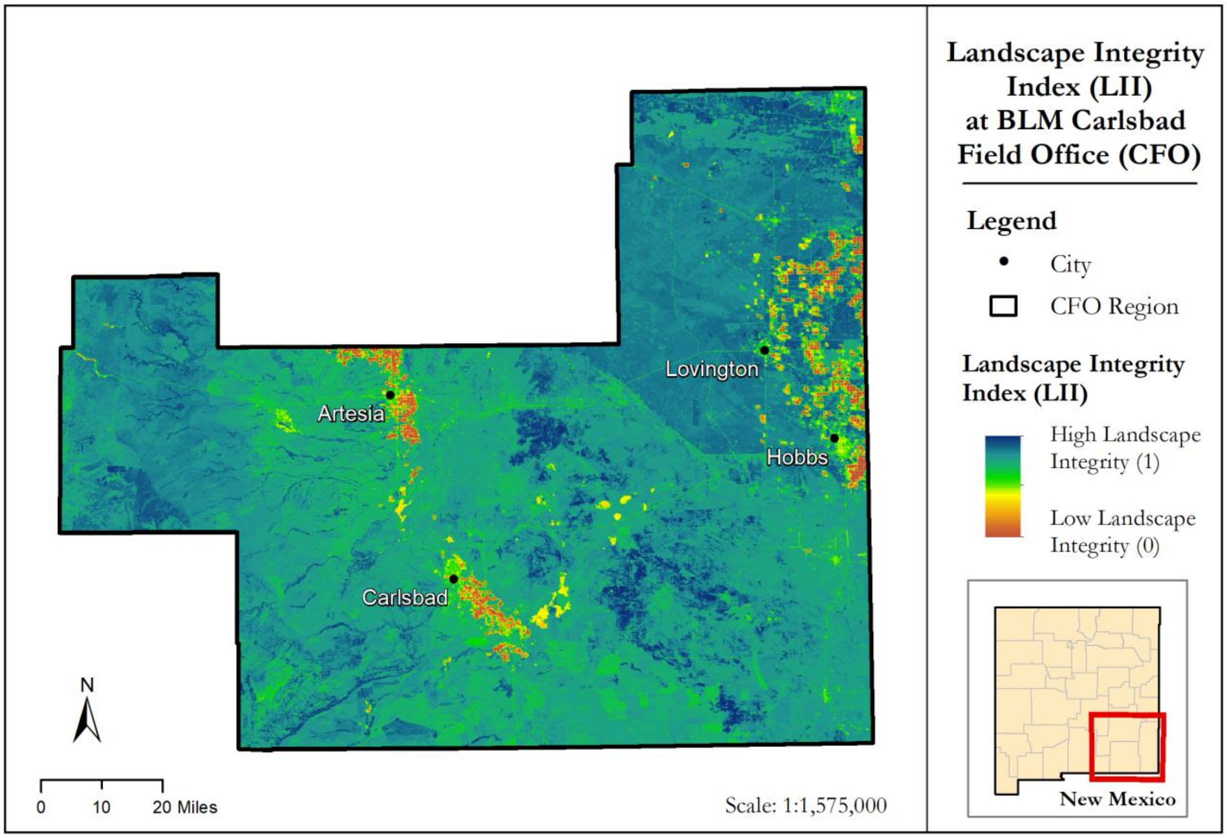


Figure 7. Map of Landscape Integrity Index at Carlsbad Field Office Planning Area (2001-2018). LII values ranged from 0 (low landscape integrity) to 1 (high landscape integrity).

Maps of ecological integrity and landscape metrics showed that areas with low ecological integrity and high landscape fragmentation occurred in high human influence areas (Figure 8). Maps of resource- metrics and stressor-based metrics depicted that management actions for vegetative communities were concentrated on central and southern CFO planning area whereas management actions for oil and gas development were in central-north and central-east (Figure 8).

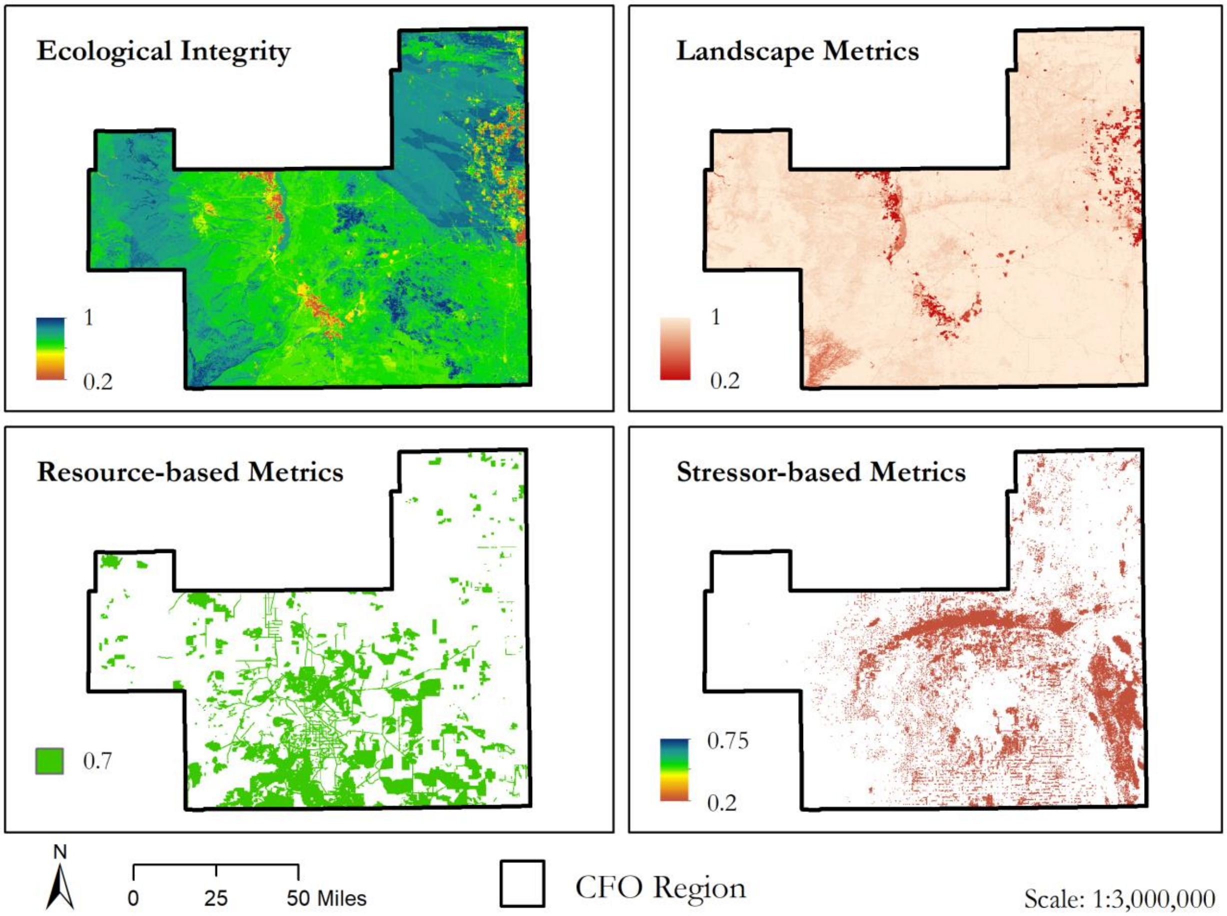
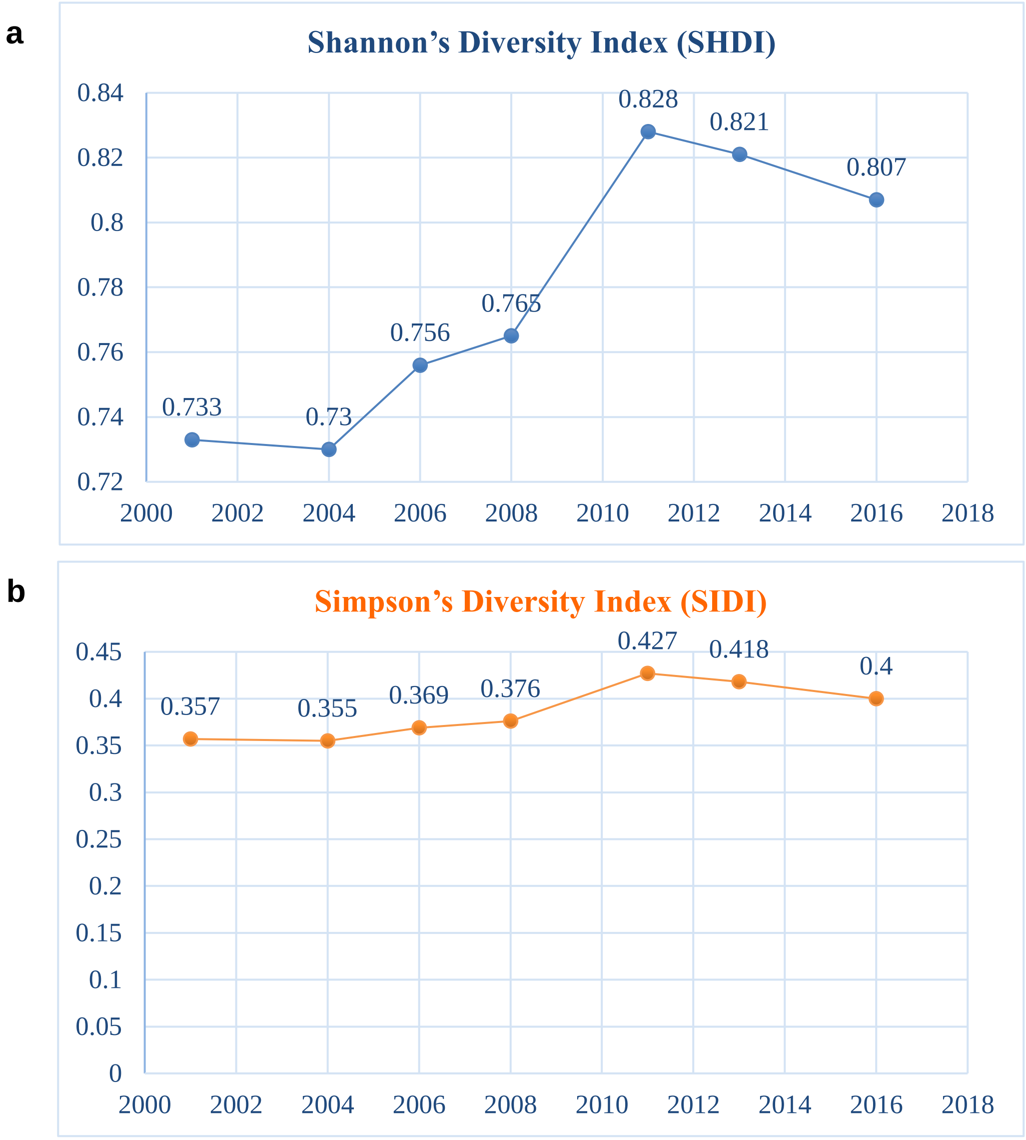


Figure 8. Maps of Ecological Integrity, Landscape Metrics, Resource-based Metrics, and Stressor-based Metrics at Carlsbad Field Office Planning Area (2001-2018)

4.2. Landscape Diversity Metrics

The Diversity Metrics calculated using R suggested that landscape diversity was the highest at 2013 and then declined in later years. Shannon’s Diversity Index and Simpson’s Diversity Index both showed a similar trend of increased diversity from 2004 to 2013 and reduced diversity from 2013 to 2016 (Figures 9a and 9b). The Simpson’s Diversity Index values of 0.3 to 0.4 indicated that landscape diversity remained relatively low from the time period of 2001 to 2016. Values from the Shannon’s Evenness Index and Simpson’s Evenness Index were both low, meaning that there was an uneven distribution of area among patch types (Figures 9c and 9d). There were 14 patch types (i.e. the number of NLCD land cover classes) and 0.00055 as the patch richness density, and these values remained constant throughout the time period.



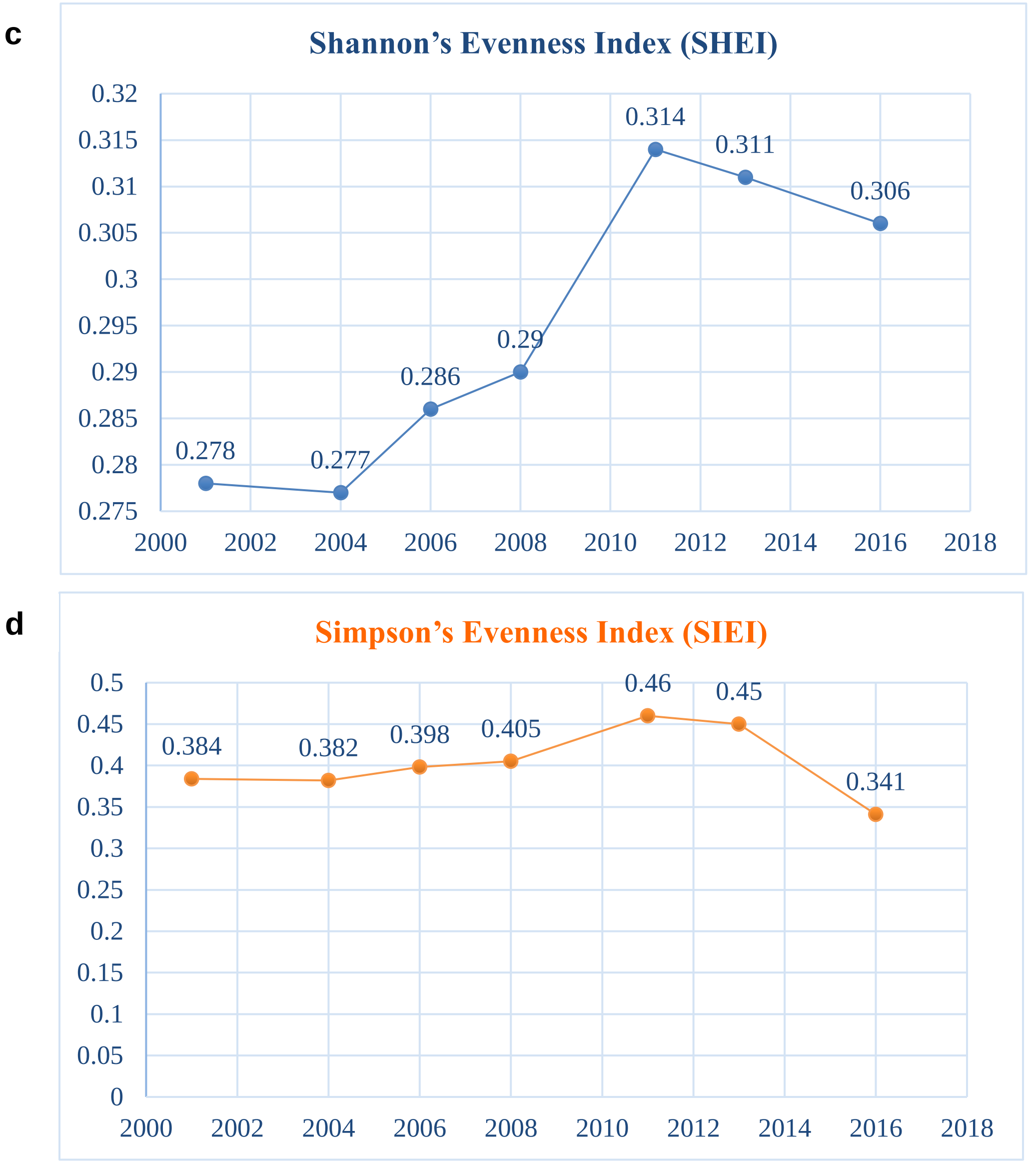


Figure 9. Scatter Plots from 2001, 2004, 2006, 2008, 2011, 2013, and 2016 of (a) Shannon's Diversity Index (SHDI); (b) Simpson's Diversity Index (SIDI); (c) Shannon's Evenness Index (SHEI); (d) Simpson's Evenness Index (SIEI)

4.3. Model Validation Results

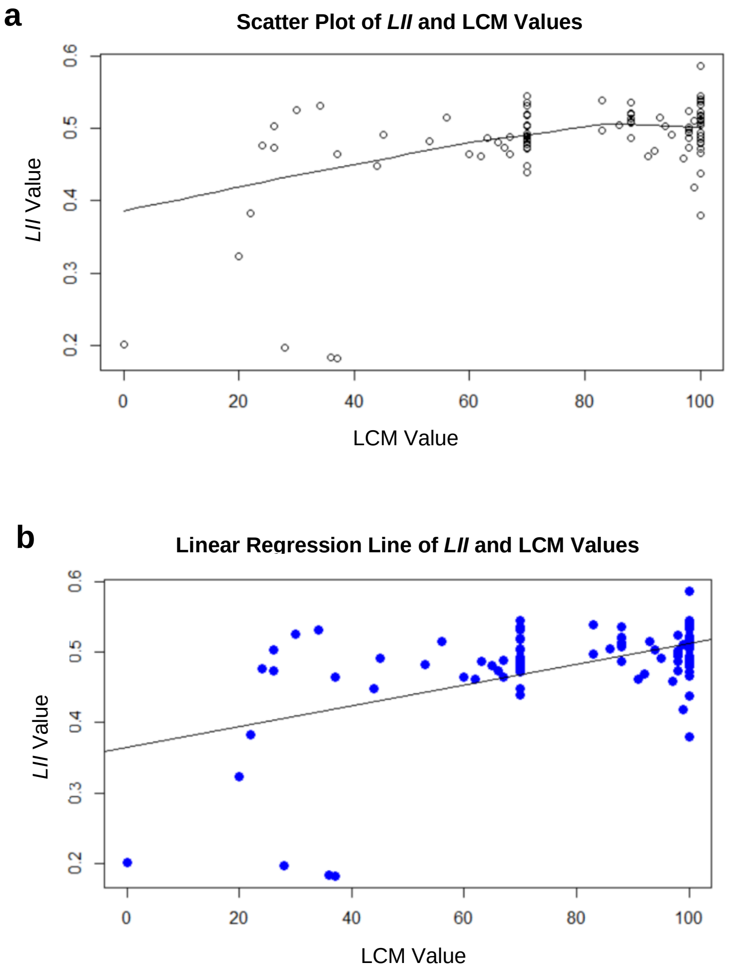
The first model validation process found a moderate positive and significant correlation between 100 randomly selected *LII* values and the Landscape Condition Map (r = 0.5, p-value = 0.0000000189) (Table 7). The scatter plot and linear regression line of *LII* and LCM values visualized the linear and positive relationship between LCM and *LII* (Figures 10a and 10b). The box plot and density plot showed that both LCM and *LII* values contained several outliers, and the distribution of LCM skewed left (towards high values) and *LII* values skewed right (towards low values) (Figures 10c and 10d).

Table 7. Model Validation Results for Linear Regression Model

Model	r	r^2	Adjusted r^2	Std. Error of the Estimate	p-value
LII and LCM	0.5261	0.2768	0.2694	0.0002	1.89e-08 *

* indicates significance

The linear regression results showed that the LCM could explain 28% of the correlation with *LII* ($r^2 = 0.28$) (Table 7), which could be attributed to the inclusion of human land use change datasets that reflected urban and industrial development, and managed and modified land cover.



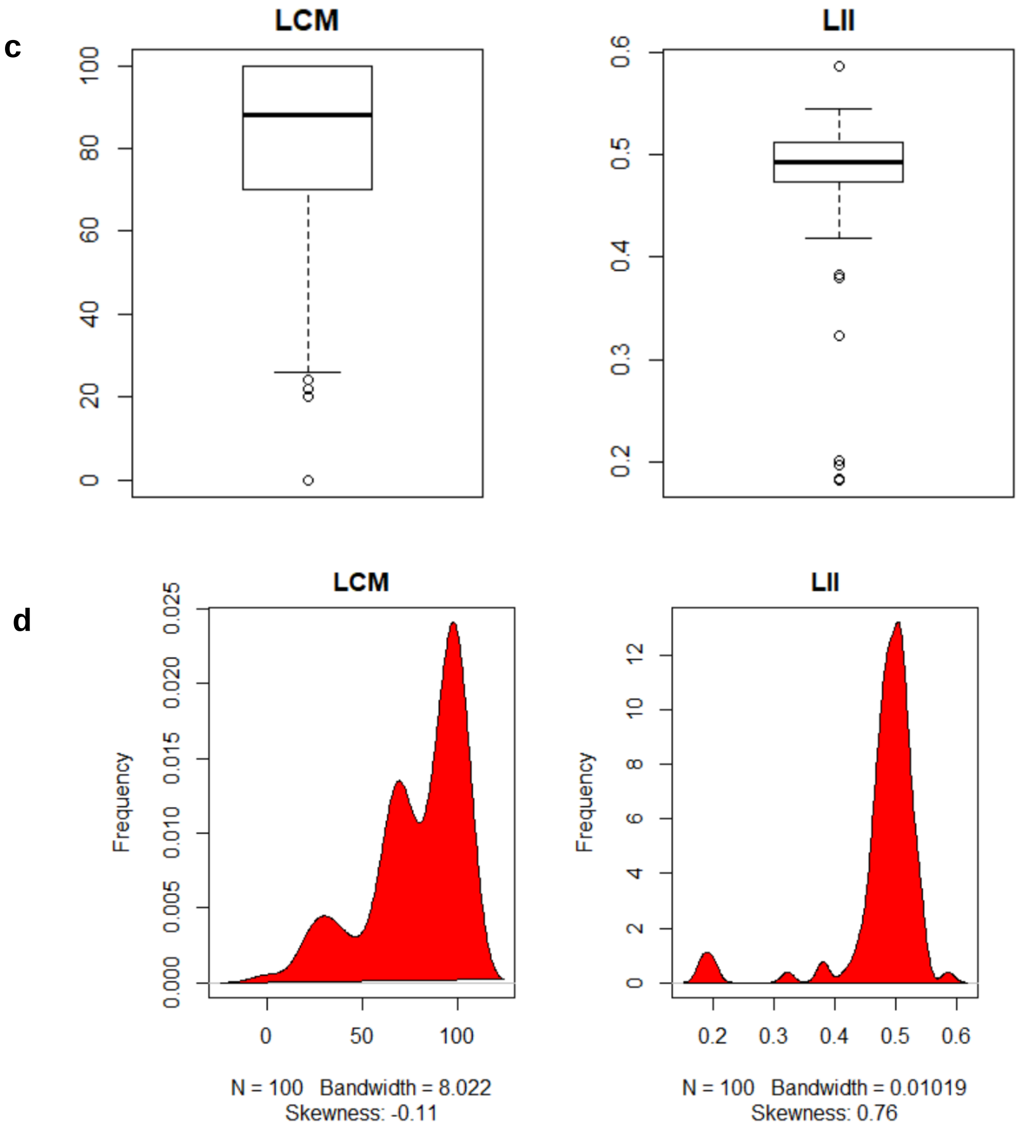


Figure 10. (a) Scatter Plot of LII and LCM Values;
(b) Linear Regression Line of *LII* and LCM Values;
(c) Box Plot of *LII* and LCM Values; (d) Density Plot of *LII* and LCM Values

Visually comparing the *LII* and LCM, the low landscape integrity areas both concentrated on the urban areas, development areas, and agricultural areas (Figure 11).

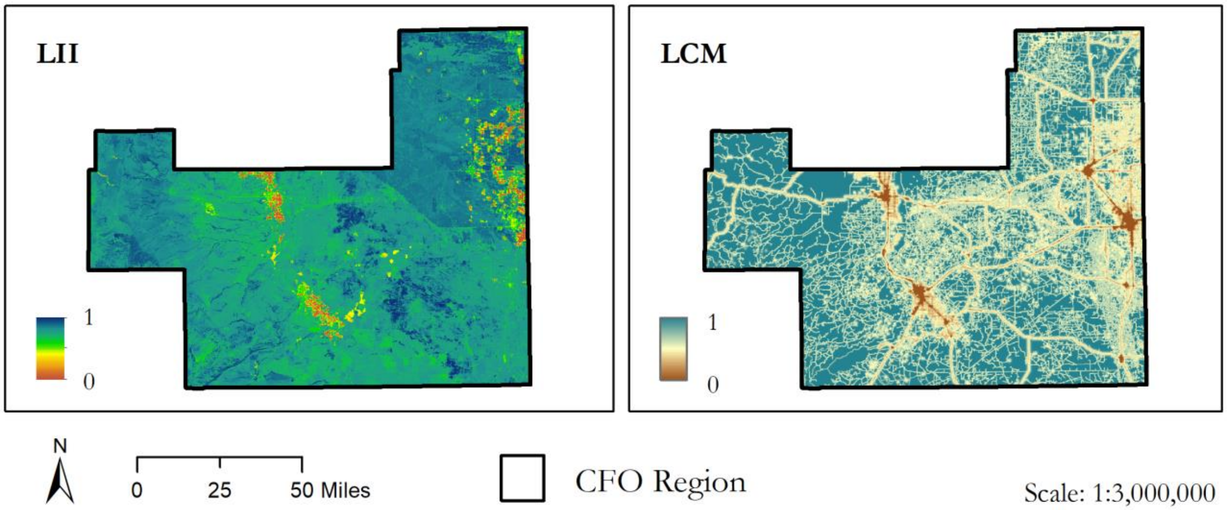


Figure 11. Landscape Integrity Index Map and Landscape Condition Map

The second model validation process found that *LII* values in protected areas were slightly higher than *LII* values in multiple-use areas (Figure 12) At a 95% confidence level, there was a statistically significant difference between *LII* mean value in protected areas and *LII* mean value in multiple-use areas (p-value = 0.03) (Table 8).

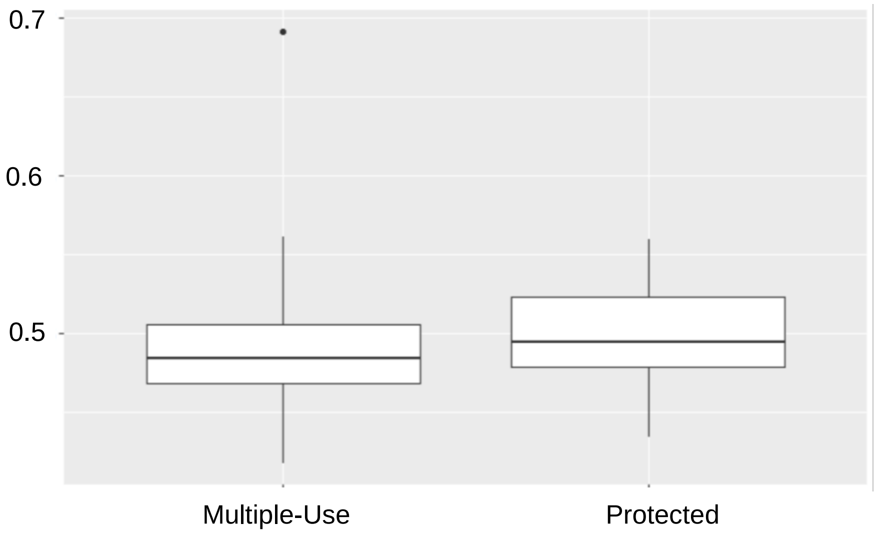


Figure 12. Box Plot of LII Values within Protected Areas and Multiple-Use Areas

On average, the *LII* value within protected areas was 0.5, whereas the *LII* value within multiple-use area was 0.49 (Table 8). Since there was only a small portion of protected areas in CFO planning area and some of protected areas were also part of multiple-use areas, this might explain why the mean values were very similar.

Table 8. Model Validation Results for Welch's Two Sample T-Test

Model	mean	p-value
LII values in protected areas	0.4983	0.03295*
LII values in multiple-use areas	0.4887	0.03295*

* indicates significance under 95% confidence interval

Chapter 5 Discussion and Conclusions

This chapter discusses into the landscape integrity of CFO planning area and how *LII* can be applied in the BLM cumulative effects analysis, including the Assessment, Inventory, and Monitoring Strategy; decision-making process; and public communication and outreach. In this final chapter, research limitations as data, analysis, and processing, as well as future research opportunities to improve the methodology, *LII* approach, and communication and sharing of *LII* model are discussed. Overall, the Landscape Integrity Index offers a comprehensive, standardized, and transparent way to evaluate the cumulative impacts of BLM resource management programs and can be used to improve the cumulative effects analysis.

5.1. Landscape Integrity of CFO Planning Area

The results of the *LII* model suggest that the overall landscape integrity of CFO planning area is moderate, with low landscape integrity in urban and agricultural areas and high landscape integrity near the central and southwest corner of CFO planning area. Low landscape integrity can indicate low ecological integrity, low resources, high resource uses, high stressors, or high landscape fragmentation, or all of the above on the ecosystem. While most of the region harbors moderate levels of landscape integrity, this result represents a simplified view because only two resource management programs were examined in this *LII* model. Nonetheless, the *LII* map reveals valuable information for landscape-level planning even if this model may not have captured all of the spatial complexities and relationships that exist in the region. However, these findings provide direction for appropriate management of the landscape. Areas of substantial human footprints and disturbance can become potential areas of restoration management for the BLM, and/or should be further developed until landscape integrity is improved. Areas of high landscape integrity are important zones for resources and ecosystem services that need active monitoring to maintain their integrity.

To effectively manage multiple-use lands, certain *LII* values can be used as a limiting factors for accepting or restricting proposed actions and as indicators for restoration planning. For instance, land managers need to be vigilant in considering proposed actions that involve stressor(s) on the ecosystem in areas with *LII* value of 0.3 or lower. These areas may require restoration planning and/or extensive studies on resource presence and resources. Considering that the mean *LII* value in protected areas is very similar to the mean *LII* value in multiple-use areas, it may be necessary for land managers to inspect the type of activities that are allowed in protected areas and identify areas of high conservation priority.

5.2. Applications of *LII*

The Bureau of Land Management can apply the Landscape Integrity Index in cumulative effects analysis; Assessment, Inventory, and Monitoring (AIM) Strategy, decision-making process; and communication and outreach to the public. For CEA, the land manager can develop several *LII* models including baseline condition, with proposed actions, and with alternative actions, and compare the *LII* values to evaluate the cumulative effects of the proposed actions and alternatives. The land manager will have to identify thresholds of significance to determine if there is a substantial cumulative impact. More steps are needed to conduct a thorough CEA, but the addition of the *LII* can improve the CEA approach and produce pertinent information and measures regarding the cumulative impacts of BLM resource management programs. Moreover, the improvement of CEA process through the inclusion of scientifically sound data and credible justification for data selection can lead to reduction in court challenges and court case losses.

The measures and metrics produced in the *LII* model will enhance the AIM Strategy by determining ecosystem conditions and identifying potential monitoring locations. The *LII* model can help establish the baseline condition using vegetation and land cover datasets and provide precise values to express change and/or fluctuation in the condition of natural resources on public lands. The *LII* model can also be used to investigate and prioritize specific areas of concerns or areas of low landscape integrity, explore ecological restoration practices, measure the effectiveness of those practices, and suggest potential monitoring locations in those areas.

The *LII* data layers and result values provide a summary of the cumulative impacts of the BLM resource management programs, proposed actions, and alternatives to help inform the decision-making process. The *LII* values and maps can help land managers and decision-makers in examining areas of low and high landscape integrity and understand cumulative effects of the programs and/or proposed actions. The comprehensive, transparent, and standardized GIS approach provides appropriate data and credible justification for selection of data that will help land managers make a better, more informed decision as to how to manag the public lands.

Finally, the *LII* map is a clear medium that can communicate to the public as to the combined effects of BLM resource management programs actions on the environment. It can improve public understanding of the multiple-use mission of the BLM and the landscape condition of public lands.

5.3. Research Limitations

Although the *LII* model includes various ecological indicators, resource- and stressor-based metrics, and landscape metrics, there are several data and analysis limitations imposed by the lack of other field data and the limited R-functions for calculating landscape metrics. There was no terrestrial data from the AIM data in Carlsbad Field Office Planning Area, which meant that terrestrial core field measurements like bare ground, vegetation composition, vegetation height, plant canopy gaps, non-native invasive plant species, and plant species of management concern were not included as ecological indicators in the development of this *LII* model. Field datasets that provide similar measurements from CFO were unable to obtained at this time, but both AIM and field datasets can be used in future development of *LII* models. Some landscape metrics such as proximity/isolation and contrast were not included in the development of this *LII* model because the *landscapemetrics* package in R did not have the functions for calculating those metrics. In the future, the authors of the package may add those functions or more research can be done to use other landscape metrics as alternatives in identifying proximity and contrast.

Another data limitation is the data quality of the field data, in which inaccuracies in data due to measurement error, data collection error, or human error will affect the precision and completeness of the *LII* model. Moreover, missing data, duplicated data, and inaccurate data will modify the cumulative effects at a spatial and temporal level by including or excluding management actions. These problems need to be addressed by the data stewards and recognized by the land managers or CEA practitioners who may use the field data in their analysis.

There was insufficient memory necessary to process complex statements for multiplying multiple rasters and preserving all pixel values, which proved another limitation in the *LII* model. Instead of only using the lowest *LII* value, a more comprehensive way to combine overlapping stressors is to use either the summation approach (i.e. adding the values of the effects) or the product-based approach (i.e. multiplying the values of the effects). The summation approach can be used on additive interactions, and the product-based approach can be used on countervailing and synergistic interactions. Future endeavors of enhancing the *LII* model should include the summation and product-based approach, and identify less complex statements for adding or multiplying multiple rasters or use a more powerful computer to process the complex statements.

5.4. Future Research Opportunities

The methodology presented in this study could benefit from expert opinions and research on spatial and temporal scales, indicator species, site impact scores, and buffer distance for resource- and stressor-based metrics. As mentioned earlier, the determination of spatial and temporal scope should be based on the specific resource or ecosystem being impacted and the duration of the effects. For example, a future development of the *LII* model to determine the cumulative effects of a proposed oil and gas well should consider the resource(s) being impacted by the proposed action and the duration of the effect (e.g. clearing the land, drilling the well, extracting oil or gas from the well, and burying the well) to define the spatial and temporal scopes of this project. With additional expert opinions from BLM staff, the selection of indicator species can be expanded to include more pertinent BLM management species and identify acres and distance measurements for assigning weights to the patch size and structural connectivity variables. With the inclusion of other species, the connectivity variable requires additional review and potentially new representation because it is fluid and varies amongst species. Adjusting the site impact scores of ecological integrity indicators and resource- and stressor-based metrics though expert opinions can be another future progression of the LII model, adding more credible justification for selection of data and exploring the range of *LII* values. A future addition to enhance the *LII* model is identifying the impact radius and creating buffers for resource- and stressor-based metrics. For instance, the existing oil and gas wells can be buffered using a distance of 49.47 m to create a zone of 7689.03 m^2 to simulate the approximate area of surface disturbance caused by the wells.

Future directions to strengthen the *LII* approach include integrating additional steps into the three-stage workflow, refining the indicators and metrics, and investigating other ways to weight the landscape metrics and examine landscape diversity metrics. In the first stage of the workflow, mechanisms such as target resources, key stressors, societally desired conditions, and thresholds of significance can be included in the assessment report to inform management. In the second stage of the workflow, BLM staff can define the natural reference and societally desired conditions and analyze the deviation of the *LII* value resulted from the management action or proposed action. In the third stage of the workflow, establishing thresholds of significance will help with informing management by delineating what management actions to take if the *LII* value reaches a certain number or what it means to have a low or high landscape integrity. Future assessments should consider a wide range of indicators and metrics that would encompass priority resources, ecosystem services, and sub-surface disturbance, depending on the mission and region of the BLM office conducting the *LII* analysis. In this analysis, the landscape metrics were normalized from 0 to 1 given the range or the minimum and maximum of the results. To better represent the significance of the landscape metrics, there should be a deeper look at other classification or weighting options for ranking the landscape metrics from 0 to 1. And even though landscape diversity metrics could not be included in the development of the *LII* model, its decreasing trend revealed landscape patterns that could be worthwhile to examine. Future research direction can tackle the complex question of which management decisions could have caused the reduction in landscape diversity.

Future efforts in communication and sharing of the *LII* model could create ArcGIS StoryMaps as a public relations outreach medium, convert the python code from Python 2.7 to Python 3 for ArcGIS Pro use, and collaborate with other BLM offices to compare the selection of data and weighting options for indicators and metrics. In addition to Resource Management Plans, ArcGIS StoryMaps can illustrate the cumulative effects of BLM resource management programs or proposed actions via interactive visuals of the indicators, metrics, and the *LII* map. Incorporating *LII* StoryMaps in the BLM website may help the public gain a better understanding of what is happening on public lands and create awareness for the multiple-use and sustained yield mission of BLM. With the migration of ArcMap to ArcGIS Pro, the python script will need to be upgraded to Python 3 to access the ArcGIS Pro functionalities and geoprocessing tools. The advancement of *LII* model also relies on the coordination between BLM offices, where neighboring offices can share field data, expert opinions on selection of data and composite scoring system, and *LII* results for comparison.

5.5. Conclusion

The Bureau of Land Management is constantly striving to balance the complex multiple-use and sustained yield mission of protecting the resources of our public lands and generating revenue through development. The short- and long-term impacts of the diverse range of BLM resource management programs and proposed actions are affecting the landscape in various ways, and it is essential to understand and analyze these cumulative impacts so that we can manage the public lands in a sustainable manner. The Landscape Integrity Index evaluates the cumulative effects of these programs by using indicators and metrics to examine the ecological integrity, resources, resource uses, stressors, and landscape patterns and relationships. The GIS approach proposed in this study builds on the cumulative effects analysis and evaluation of ecological integrity to assess the landscape condition in a comprehensive, standardized, and transparent process. The GIS model of *LII* with python scripts and R Markdown will be available to download at https://github.com/liling2lee/Landscape_Integrity_Index. With future improvements made to the *LII* model, it will address management goals and objectives, incorporate relevant and pertinent indicators and metrics, and facilitate planning and management across BLM offices.

References

Allred, Brady W., W. Kolby Smith, Dirac Twidwell, Julia H. Haggerty, Steven W. Running, David E. Naugle, and Samuel D. Fuhlendorf. 2015. “Ecosystem Services Lost to Oil and Gas in North America.” *Science* 348 (6233): 401–2. https://doi.org/10.1126/science.aaa4785.

AmphibiaWeb. 2019. University of California, Berkeley, CA, USA. Accessed October 13, 2019. http://amphibiaweb.org.

Andreasen, James K, Robert V O’Neill, Reed Noss, and Nicholas C Slosser. 2001. “Considerations for the Development of a Terrestrial Index of Ecological Integrity.” *Ecological Indicators* 1 (1): 21–35. https://doi.org/10.1016/S1470-160X(01)00007-3.

Animal Diversity Web. 2014. University of Michigan, Museum of Zoology, Ann Arbor, MI, USA. Accessed October 13, 2019. https://animaldiversity.org/.

Atkinson, Samuel F., and Larry W. Canter. 2011. “Assessing the Cumulative Effects of Projects Using Geographic Information Systems.” *Environmental Impact Assessment Review*, SPECIAL ISSUE on Cumulative Effects Assessment, 31 (5): 457–64. https://doi.org/10.1016/j.eiar.2011.01.008.

Bureau of Land Management, Office of the Assistant Director, Renewable Resources and Planning. “BLM NEPA Handbook H-1790-1.” U.S. Washington, D.C.: Bureau of Land Management Office of the Assistant Director, Renewable Resources and Planning, 2008. https://www.ntc.blm.gov/krc/uploads/366/NEPAHandbook_H-1790_508.pdf.

Bureau of Land Management. 2018a. “NM Sensitive Update: Amphibians, arthropods, birds, crustaceans, fish, mammals, mollucks, and reptiles.” Accessed October 13, 2019. https://www.blm.gov/sites/blm.gov/files/IB%20NM-2019-002_Attachment%201%20Animal.pdf

Bureau of Land Management, New Mexico State Office. “Draft Resource Management Plan and Environmental Impact Statement.” New Mexico: Bureau of Land Management, New Mexico State Office, 2018b. https://eplanning.blm.gov/epl-front-office/projects/lup/64444/153042/187358/BLM_CFO_Draft_RMP_-_Volume_I_-_EIS_-_August_2018_(1).pdf.

Canter, Larry W., and J. Kamath. 1995. “Questionnaire Checklist for Cumulative Impacts.” *Environmental Impact Assessment Review* 15 (4): 311–39. https://doi.org/10.1016/0195-9255(95)00010-C.

Canter, Larry W., and S. F. Atkinson. 2011. “Multiple-uses of Indicators and Indices in Cumulative Effects Assessment and Management.” *Environmental Impact Assessment Review* 31 (5): 491–501. https://doi.org/10.1016/j.eiar.2011.01.012.

Carter, Sarah K., Erica Fleishman, Ian I. F. Leinwand, Curtis H. Flather, Natasha B. Carr, Frank A. Fogarty, Matthias Leu, Barry R. Noon, Martha E. Wohlfeil, and David J. A. Wood. 2019. "Quantifying Ecological Integrity of Terrestrial Systems to Inform Management of Multiple-Use Public Lands in the United States." *Environmental Management*, April. https://doi.org/10.1007/s00267-019-01163-w.

Copeland, Holly E., Kevin E. Doherty, David E. Naugle, Amy Pocewicz, and Joseph M. Kiesecker. 2009. "Mapping Oil and Gas Development Potential in the US Intermountain West and Estimating Impacts to Species." *PLOS ONE* 4 (10): e7400. https://doi.org/10.1371/journal.pone.0007400.

Crain, Caitlin Mullan, Kristy Kroeker, and Benjamin S. Halpern. 2008. "Interactive and Cumulative Effects of Multiple Human Stressors in Marine Systems." *Ecology Letters* 11 (12): 1304–15. https://doi.org/10.1111/j.1461-0248.2008.01253.x.

Dale, Virginia H., and Suzanne C. Beyeler. 2001. "Challenges in the Development and Use of Ecological Indicators." *Ecological Indicators* 1 (1): 3–10. https://doi.org/10.1016/S1470-160X(01)00003-6.

Esri. 2019a. "Euclidean distance." Environmental Systems Research Institute. Accessed August 25, 2019. http://desktop.arcgis.com/ja/arcmap/10.6/tools/spatial-analyst-toolbox/euclidean-distance.htm.

____. 2019b. "Region Group." Environmental Systems Research Institute. Accessed August 25, 2019. http://desktop.arcgis.com/ja/arcmap/10.6/tools/spatial-analyst-toolbox/region-group.htm.

Foley, Melissa M., Lindley A. Mease, Rebecca G. Martone, Erin E. Prahler, Tiffany H. Morrison, Cathryn Clarke Murray, and Deborah Wojcik. 2017. "The Challenges and Opportunities in Cumulative Effects Assessment." *Environmental Impact Assessment Review* 62: 122–34. https://doi.org/10.1016/j.eiar.2016.06.008.

Frazier, A. 2019. Landscape Metrics. *The Geographic Information Science & Technology Body of Knowledge*. Edited by John P. Wilson. 2nd ed. DOI: 10.22224/gistbok/2019.2.3.

Hak, John C., and Patrick J. Comer. 2017. "Modeling Landscape Condition for Biodiversity Assessment—Application in Temperate North America." *Ecological Indicators* 82: 206–16. https://doi.org/10.1016/j.ecolind.2017.06.049.

Harvey, Bret C., and Steven F. Railsback. 2007. "Estimating Multi-Factor Cumulative Watershed Effects on Fish Populations with an Individual-Based Model." *Fisheries* 32 (6): 292–98. https://doi.org/10.1577/1548-8446(2007)32[292:EFCWEO]2.0.CO;2.

Hobbs, Richard J., David N. Cole, Laurie Yung, Erika S. Zavaleta, Gregory H. Aplet, F. Stuart Chapin, Peter B. Landres, et al. 2010. "Guiding Concepts for Park and Wilderness Stewardship in an Era of Global Environmental Change." *Frontiers in Ecology and the Environment. 8(9): 483-490* 8 (9): 483–90.

Homer, C.G., J.A. Dewitz, L. Yang, S. Jin, P. Danielson, G. Xian, J. Coulston, N.D. Herold, J.D. Wickham, and K. Megown. 2015. "Completion of the 2011 National Land Cover Database for the conterminous United States-Representing a decade of land cover change information." *Photogrammetric Engineering and Remote Sensing* 81 (5): 345-354. https://cran.r-project.org/web/packages/landscapemetrics/landscapemetrics.pdf.

IUCN. 2019. The IUCN Red List of Threatened Species. Accessed October 13, 2019. https://www.iucnredlist.org.

Landscape Fire and Resource Management Planning Tools (LANDFIRE). 2016a. "LANDFIRE Program: Data Products - Fire Regime - Vegetation Departure." U.S. Geologic Survey. Accessed July 21, 2019. https://www.landfire.gov/vdep.php.

_______. 2016b. "LANDFIRE Program: Data Products - Vegetation - Existing Vegetation Type." U.S. Geologic Survey. Accessed July 21, 2019. https://www.landfire.gov/evt.php.

McGarigal, Kevin, and Barbara J. Marks. 1995. "FRAGSTATS: Spatial Pattern Analysis Program for Quantifying Landscape Structure." Gen. Tech. Rep. PNW-GTR-351. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. https://doi.org/10.2737/PNW-GTR-351.

McGarigal, Kevin. 2015. "FRAGSTATS HELP." LandEco Consulting. https://www.umass.edu/landeco/research/fragstats/documents/fragstats.help.4.2.pdf

McGarigal, Kevin, Bradley W. Compton, Ethan B. Plunkett, William V. DeLuca, Joanna Grand, Eduard Ene, and Scott D. Jackson. 2018. "A Landscape Index of Ecological Integrity to Inform Landscape Conservation." *Landscape Ecology* 33 (7): 1029–48. https://doi.org/10.1007/s10980-018-0653-9.

Natural Heritage New Mexico. n.d. "New Mexico Rare Plant Conservation Strategy | NHNM." Natural Heritage New Mexico. Accessed July 21, 2019. https://nhnm.unm.edu/botany/nm_rare_plant_conservation_strategy.

New Mexico Energy, Minerals, and Natural Resources Department (EMNRD) Forestry Division. New Mexico Rare Plant Conservation Strategy Partnership. *New Mexico Rare Plant Conservation Strategy*. Open-file report. Santa Fe, New Mexico, 2017. http://www.emnrd.state.nm.us/SFD/documents/NM%20Rare%20Plant%20Conservation%20Strategy_03202019.pdf.

Parrish, Jeffrey D., David P. Braun, and Robert S. Unnasch. 2003. "Are We Conserving What We Say We Are? Measuring Ecological Integrity within Protected Areas." *BioScience* 53 (9): 851–60. https://doi.org/10.1641/0006-3568(2003)053[0851:AWCWWS]2.0.CO;2.

Richardson, Leif L., Kent P. McFarland, Sara Zahendra, and Spencer Hardy. 2019. "Bumble bee (*Bombus*) distribution and diversity in Vermont, USA: a century of change. *Journal of Insect Conservation*, 23 (1): 45-62. https://doi.org/10.1007/s10841-018-0113-5.

Smith, Michael D. 2006. “Research Article: Cumulative Impact Assessment under the National Environmental Policy Act: An Analysis of Recent Case Law.” *Environmental Practice* 8 (4): 228–40. https://doi.org/10.1017/S1466046606060467.

Smithsonian. 2019. “Animals.” Smithsonian’s National Zoo & Conservation Biology Institute, Washington, DC, USA. Accessed October 13, 2019. https://nationalzoo.si.edu/animals.

The Cornell Lab of Ornithology. 2019a. “All About Birds.” Cornell University, Ithaca, NY, USA. Accessed October 13, 2019. https://www.allaboutbirds.org/guide/.

The Cornell Lab of Ornithology. 2019b. “Birds of North America.” Cornell University, Ithaca, NY, USA. Accessed October 13, 2019. https://birdsna.org/Species-Account/bna/home.

Spencer, David, David Haukos, Christian Hagen, Melinda Daniels, and Doug Goodin. 2017. “Conservation Reserve Program Mitigates Grassland Loss in the Lesser Prairie-Chicken Range of Kansas.” *Global Ecology and Conservation* 9: 21–38. https://doi.org/10.1016/j.gecco.2016.11.004.

Theobald, David M. 2013. “A General Model to Quantify Ecological Integrity for Landscape Assessments and US Application.” *Landscape Ecology; Dordrecht* 28 (10): 1859–74. http://dx.doi.org.libproxy2.usc.edu/10.1007/s10980-013-9941-6.

U.S. Council of Environmental Quality. *Considering Cumulative Effects Under the National Environmental Policy Act*. U.S. Washington, D.C.: U.S. Council of Environmental Quality, 1997. https://www.energy.gov/sites/prod/files/nepapub/nepa_documents/RedDont/G-CEQ-ConsidCumulEffects.pdf.

U.S. Department of the Interior. Bureau of Land Management, Office of the Solicitor (editors). *The Federal Land Policy and Management Act, as amended*. U.S. Washington, D.C.: Department of the Interior, Bureau of Land Management Office of Public Affairs, 2001. https://www.blm.gov/or/regulations/files/FLPMA.pdf.

U.S. Department of the Interior. U.S. Geologic Survey. *Multiscale Guidance and Tools for Implementing a Landscape Approach to Resource Management in the Bureau of Land Management*, by Carter, Sarah K., Natasha B. Carr, Kevin H. Miller, and David J.A. Wood. Open-file report 2016–1207. Reston, Virginia, 2017. http://pubs.er.usgs.gov/publication/ofr20161207.

U.S. Fish & Wildlife Service. 2019. “Featured Pollinator.” Accessed October 13, 2019. https://www.fws.gov/pollinators/features/Monarch_Butterfly.html.

Walston, Leroy J., and Heidi M. Hartmann. 2018. “Development of a Landscape Integrity Model Framework to Support Regional Conservation Planning.” *PLOS ONE* 13 (4): e0195115. https://doi.org/10.1371/journal.pone.0195115.

Wang, Xianli, F. Guillaume Blanchet, and Nicola Koper. 2014. “Measuring Habitat Fragmentation: An Evaluation of Landscape Pattern Metrics.” *Methods in Ecology and Evolution* 5 (7): 634–46. https://doi-org.libproxy1.usc.edu/10.1111/2041-210X.12198.

Western Association of Fish and Wildlife Agencies. *The Lesser Prairie-Chicken Range-wide Conservation Plan*, by Van Pelt, William E., S. Kyle, J. Pitman, D. Klute, G. Beauprez, D. Schoeling, A. Janus, and J. Haufler. Open-file report. Cheyenne, Wyoming, 2013. https://www.wafwa.org/Documents%20and%20Settings/37/Site%20Documents/Initiatives/Lesser%20Prairie%20Chicken/2013LPCRWPfinalfor4drule12092013.pdf.

Wu, Zhenhua, Shaogang Lei, Bao-Jie He, Zhengfu Bian, Yinghong Wang, Qingqing Lu, Shangui Peng, and Linghua Duo. 2019. “Assessment of Landscape Ecological Health: A Case Study of a Mining City in a Semi-Arid Steppe.” *International Journal of Environmental Research and Public Health* 16 (5). https://doi.org/10.3390/ijerph16050752.

Wurtzebach, Zachary, and Courtney Schultz. 2016. “Measuring Ecological Integrity: History, Practical Applications, and Research Opportunities.” BioScience 66 (6): 446–57. https://doi.org/10.1093/biosci/biw037.

Appendix A Management Indicator Species for Carlsbad Field Office, NM

Species	**Common Name**	**Taxonomic Group**	**NM Status**	**BLM Status**	**Habitat (Vegetation Area)**
Craugastor (Eleutherodactylus) augustilatrans	Eastern barking frog	Amphibian	SGCN	Watch	Scrub (Shrubland)
Gastrophryne olivacea	Western narrowmouth toad	Amphibian	Endangered, SGCN	Watch	Grasslands
Lithobates (Rana) blairi	Plains leopard frog	Amphibian	SGCN	Watch	Grasslands
Danaus plexippus plexippus	Monarch Butterfly	Arthropods	SGCN	Watch *New*	Shrubland
Bombus occidentalis	Western Bumble Bee	Arthropods	None	Watch *New*	Shrubland
Athene cunicularia	Western Burrowing Owl	Birds	SGCN	BLM Sensitive	Grasslands
Anthus spragueii	Sprague's Pipit	Birds	SGCN	BLM Sensitive	Grasslands
Calcarius mccownii	McCown's Longspur	Birds	SGCN	BLM Sensitive *New*	Grasslands
Calcarius ornatus	Chestnut-collared Longspur	Birds	SGCN	BLM Sensitive	Grasslands
Tympanuchus pallidicinctus	Lesser Prairie-chicken	Birds	SGCN	BLM Sensitive	Grasslands
Vireo bel*LII* arizonae	Bell's Vireo	Birds	Threatened, SGCN	BLM Sensitive	Scrub (Shrubland)
Vermivora virginiae	Virginia's Warbler	Birds	SGCN	BLM Sensitive *New*	Open Woodlands (Conifer-Hardwood)
Aphelocoma woodhouseii	Woodhouse's Scrub- Jay	Birds	None	Watch *New*	Scrub (Shrubland)
Aquila chrysaetos	Golden Eagle	Birds	None	Watch	Grasslands
Botaurus lentiginosus	American Bittern	Birds	SGCN	Watch	Marshes (Riparian)
Buteogallus anthracinus	Common Black-Hawk	Birds	Threatened, SGCN	Watch	Riparian

Callipepla squamata	Scaled Quail	Birds	None	Watch *New*	Grasslands
Carpodacus cassinii	Cassin's Finch	Birds	SGCN	Watch	Forests (Conifer)
Lanius ludovicianus	Loggerhead Shrike	Birds	SGCN	Watch	Open Woodlands (Shrubland)
Melanerpes lewis	Lewis's Woodpecker	Birds	SGCN	Watch *New*	Open Woodlands (Conifer)
Numenius americanus	Long- billed Curlew	Birds	SGCN	Watch	Grasslands
Oreoscoptes montanus	Sage Thrasher	Birds	None	Watch	Scrub (Shrubland)
Passerina ciris	Painted Bunting	Birds	None	Watch	Scrub (Shrubland)
Spizella atrogularis evura	Black-chinned Sparrow	Birds	SGCN	Watch	Scrub (Shrubland)
Vireo vicinior	Gray Vireo	Birds	Threatened, SGCN	Watch	Scrub (Shrubland)
Corynorhinus townsendii	Townsend's big-eared bat	Mammals	SGCN	BLM Sensitive	Forest (Conifer)
Cynomys ludovicianus	Black-tailed prairie dog	Mammals	SGCN	BLM Sensitive	Grasslands
Cratogeomys castanops	Yellow-faced pocket gopher	Mammals	None	Watch	Grasslands
Cryptotis parva	Least shrew	Mammals	Threatened, SGCN	Watch *New*	Grasslands
Nyctinomops femorosaccus	Pocketed free-tailed bat	Mammals	None	Watch	Desertlands (Shrubland)
Sistrurus tergeminus	Desert massasauga	Reptiles	SGCN	BLM Sensitive *New*	Desert grasslands (Grasslands)
Crotalus lepidus lepidus	Mottled Rock Rattlesnake	Reptiles	Threatened, SGCN	Watch	Grasslands

Source: AmphibiaWeb (2019), Animal Diversity Web (2014), Bureau of Land Management (2018a), IUCN 2019, Richardson et al. (2019), Smithsonian (2019), The Cornell Lab of Ornithology (2019a), The Cornell Lab of Ornithology (2019b), and USFWS (2019)

Appendix B Landscape Metrics Results

Shape Metrics: Perimeter-Area Fractal Dimension (PAFRAC) – 2001

NLCD Class	NLCD Class	Value	Range
11	Open Water	1.35	1 ≤ PAFRAC ≤ 2
21	Developed, Open Space	1.60	1 ≤ PAFRAC ≤ 2
22	Developed, Low Intensity	1.58	1 ≤ PAFRAC ≤ 2
23	Developed, Medium Intensity	1.60	1 ≤ PAFRAC ≤ 2
24	Developed, High Intensity	1.50	1 ≤ PAFRAC ≤ 2
31	Barren Land	1.39	1 ≤ PAFRAC ≤ 2
41	Deciduous Forest	1.76	1 ≤ PAFRAC ≤ 2
42	Evergreen Forest	1.52	1 ≤ PAFRAC ≤ 2
52	Shrub/Scrub	1.55	1 ≤ PAFRAC ≤ 2
71	Herbaceous	1.63	1 ≤ PAFRAC ≤ 2
81	Hay/Pasture	1.38	1 ≤ PAFRAC ≤ 2
82	Cultivated Crops	1.27	1 ≤ PAFRAC ≤ 2
90	Woody Wetlands	1.51	1 ≤ PAFRAC ≤ 2
95	Emergent Herbaceous Wetlands	1.50	1 ≤ PAFRAC ≤ 2

Shape Metrics: Perimeter-Area Fractal Dimension (PAFRAC) – 2004

NLCD Class	NLCD Class	Value	Range
11	Open Water	1.37	1 ≤ PAFRAC ≤ 2
21	Developed, Open Space	1.60	1 ≤ PAFRAC ≤ 2
22	Developed, Low Intensity	1.58	1 ≤ PAFRAC ≤ 2
23	Developed, Medium Intensity	1.60	1 ≤ PAFRAC ≤ 2
24	Developed, High Intensity	1.50	1 ≤ PAFRAC ≤ 2
31	Barren Land	1.40	1 ≤ PAFRAC ≤ 2
41	Deciduous Forest	1.75	1 ≤ PAFRAC ≤ 2
42	Evergreen Forest	1.52	1 ≤ PAFRAC ≤ 2
52	Shrub/Scrub	1.55	1 ≤ PAFRAC ≤ 2
71	Herbaceous	1.63	1 ≤ PAFRAC ≤ 2
81	Hay/Pasture	1.40	1 ≤ PAFRAC ≤ 2
82	Cultivated Crops	1.26	1 ≤ PAFRAC ≤ 2
90	Woody Wetlands	1.51	1 ≤ PAFRAC ≤ 2
95	Emergent Herbaceous Wetlands	1.50	1 ≤ PAFRAC ≤ 2

Shape Metrics: Perimeter-Area Fractal Dimension (PAFRAC) – 2006

NLCD Class	NLCD Class	Value	Range
11	Open Water	1.37	1 ≤ PAFRAC ≤ 2
21	Developed, Open Space	1.58	1 ≤ PAFRAC ≤ 2
22	Developed, Low Intensity	1.58	1 ≤ PAFRAC ≤ 2
23	Developed, Medium Intensity	1.60	1 ≤ PAFRAC ≤ 2
24	Developed, High Intensity	1.50	1 ≤ PAFRAC ≤ 2
31	Barren Land	1.40	1 ≤ PAFRAC ≤ 2
41	Deciduous Forest	1.72	1 ≤ PAFRAC ≤ 2
42	Evergreen Forest	1.52	1 ≤ PAFRAC ≤ 2
52	Shrub/Scrub	1.55	1 ≤ PAFRAC ≤ 2
71	Herbaceous	1.63	1 ≤ PAFRAC ≤ 2
81	Hay/Pasture	1.37	1 ≤ PAFRAC ≤ 2
82	Cultivated Crops	1.26	1 ≤ PAFRAC ≤ 2
90	Woody Wetlands	1.51	1 ≤ PAFRAC ≤ 2
95	Emergent Herbaceous Wetlands	1.51	1 ≤ PAFRAC ≤ 2

Shape Metrics: Perimeter-Area Fractal Dimension (PAFRAC) – 2008

NLCD Class	NLCD Class	Value	Range
11	Open Water	1.38	1 ≤ PAFRAC ≤ 2
21	Developed, Open Space	1.58	1 ≤ PAFRAC ≤ 2
22	Developed, Low Intensity	1.58	1 ≤ PAFRAC ≤ 2
23	Developed, Medium Intensity	1.60	1 ≤ PAFRAC ≤ 2
24	Developed, High Intensity	1.50	1 ≤ PAFRAC ≤ 2
31	Barren Land	1.40	1 ≤ PAFRAC ≤ 2
41	Deciduous Forest	1.69	1 ≤ PAFRAC ≤ 2
42	Evergreen Forest	1.52	1 ≤ PAFRAC ≤ 2
52	Shrub/Scrub	1.54	1 ≤ PAFRAC ≤ 2
71	Herbaceous	1.63	1 ≤ PAFRAC ≤ 2
81	Hay/Pasture	1.37	1 ≤ PAFRAC ≤ 2
82	Cultivated Crops	1.26	1 ≤ PAFRAC ≤ 2
90	Woody Wetlands	1.51	1 ≤ PAFRAC ≤ 2
95	Emergent Herbaceous Wetlands	1.50	1 ≤ PAFRAC ≤ 2

Shape Metrics: Perimeter-Area Fractal Dimension (PAFRAC) – 2011

NLCD Class	NLCD Class	Value	Range
11	Open Water	1.38	1 ≤ PAFRAC ≤ 2
21	Developed, Open Space	1.55	1 ≤ PAFRAC ≤ 2

22	Developed, Low Intensity	1.57	1 ≤ PAFRAC ≤ 2
23	Developed, Medium Intensity	1.60	1 ≤ PAFRAC ≤ 2
24	Developed, High Intensity	1.49	1 ≤ PAFRAC ≤ 2
31	Barren Land	1.41	1 ≤ PAFRAC ≤ 2
41	Deciduous Forest	1.66	1 ≤ PAFRAC ≤ 2
42	Evergreen Forest	1.52	1 ≤ PAFRAC ≤ 2
52	Shrub/Scrub	1.54	1 ≤ PAFRAC ≤ 2
71	Herbaceous	1.62	1 ≤ PAFRAC ≤ 2
81	Hay/Pasture	1.42	1 ≤ PAFRAC ≤ 2
82	Cultivated Crops	1.26	1 ≤ PAFRAC ≤ 2
90	Woody Wetlands	1.51	1 ≤ PAFRAC ≤ 2
95	Emergent Herbaceous Wetlands	1.50	1 ≤ PAFRAC ≤ 2

Shape Metrics: Perimeter-Area Fractal Dimension (PAFRAC) – 2013

NLCD Class	**NLCD Class**	**Value**	**Range**
11	Open Water	1.40	1 ≤ PAFRAC ≤ 2
21	Developed, Open Space	1.55	1 ≤ PAFRAC ≤ 2
22	Developed, Low Intensity	1.57	1 ≤ PAFRAC ≤ 2
23	Developed, Medium Intensity	1.60	1 ≤ PAFRAC ≤ 2
24	Developed, High Intensity	1.49	1 ≤ PAFRAC ≤ 2
31	Barren Land	1.40	1 ≤ PAFRAC ≤ 2
41	Deciduous Forest	1.76	1 ≤ PAFRAC ≤ 2
42	Evergreen Forest	1.52	1 ≤ PAFRAC ≤ 2
52	Shrub/Scrub	1.54	1 ≤ PAFRAC ≤ 2
71	Herbaceous	1.62	1 ≤ PAFRAC ≤ 2
81	Hay/Pasture	1.39	1 ≤ PAFRAC ≤ 2
82	Cultivated Crops	1.26	1 ≤ PAFRAC ≤ 2
90	Woody Wetlands	1.51	1 ≤ PAFRAC ≤ 2
95	Emergent Herbaceous Wetlands	1.50	1 ≤ PAFRAC ≤ 2

Shape Metrics: Perimeter-Area Fractal Dimension (PAFRAC) – 2016

NLCD Class	**NLCD Class**	**Value**	**Range**
11	Open Water	1.38	1 ≤ PAFRAC ≤ 2
21	Developed, Open Space	1.55	1 ≤ PAFRAC ≤ 2
22	Developed, Low Intensity	1.57	1 ≤ PAFRAC ≤ 2
23	Developed, Medium Intensity	1.59	1 ≤ PAFRAC ≤ 2
24	Developed, High Intensity	1.47	1 ≤ PAFRAC ≤ 2
31	Barren Land	1.43	1 ≤ PAFRAC ≤ 2

41	Deciduous Forest	1.67	1 ≤ PAFRAC ≤ 2
42	Evergreen Forest	1.52	1 ≤ PAFRAC ≤ 2
52	Shrub/Scrub	1.54	1 ≤ PAFRAC ≤ 2
71	Herbaceous	1.62	1 ≤ PAFRAC ≤ 2
81	Hay/Pasture	1.38	1 ≤ PAFRAC ≤ 2
82	Cultivated Crops	1.27	1 ≤ PAFRAC ≤ 2
90	Woody Wetlands	1.52	1 ≤ PAFRAC ≤ 2
95	Emergent Herbaceous Wetlands	1.51	1 ≤ PAFRAC ≤ 2

Core Area Metrics: Coefficient of Variation of Core Area Index (CAI_CV) – 2001

NLCD Class	**NLCD Class**	**Value**	**Range**
11	Open Water	200	CAI_CV ≥ 0
21	Developed, Open Space	383	CAI_CV ≥ 0
22	Developed, Low Intensity	652	CAI_CV ≥ 0
23	Developed, Medium Intensity	560	CAI_CV ≥ 0
24	Developed, High Intensity	442	CAI_CV ≥ 0
31	Barren Land	215	CAI_CV ≥ 0
41	Deciduous Forest	332	CAI_CV ≥ 0
42	Evergreen Forest	162	CAI_CV ≥ 0
52	Shrub/Scrub	238	CAI_CV ≥ 0
71	Herbaceous	219	CAI_CV ≥ 0
81	Hay/Pasture	107	CAI_CV ≥ 0
82	Cultivated Crops	96	CAI_CV ≥ 0
90	Woody Wetlands	230	CAI_CV ≥ 0
95	Emergent Herbaceous Wetlands	246	CAI_CV ≥ 0

Core Area Metrics: Coefficient of Variation of Core Area Index (CAI_CV) – 2004

NLCD Class	**NLCD Class**	**Value**	**Range**
11	Open Water	238	CAI_CV ≥ 0
21	Developed, Open Space	383	CAI_CV ≥ 0
22	Developed, Low Intensity	652	CAI_CV ≥ 0
23	Developed, Medium Intensity	560	CAI_CV ≥ 0
24	Developed, High Intensity	442	CAI_CV ≥ 0
31	Barren Land	216	CAI_CV ≥ 0
41	Deciduous Forest	336	CAI_CV ≥ 0
42	Evergreen Forest	162	CAI_CV ≥ 0
52	Shrub/Scrub	238	CAI_CV ≥ 0
71	Herbaceous	220	CAI_CV ≥ 0

81	Hay/Pasture	106	CAI_CV ≥ 0
82	Cultivated Crops	93	CAI_CV ≥ 0
90	Woody Wetlands	234	CAI_CV ≥ 0
95	Emergent Herbaceous Wetlands	270	CAI_CV ≥ 0

Core Area Metrics: Coefficient of Variation of Core Area Index (CAI_CV) – 2006

NLCD Class	**NLCD Class**	**Value**	**Range**
11	Open Water	239	CAI_CV ≥ 0
21	Developed, Open Space	317	CAI_CV ≥ 0
22	Developed, Low Intensity	663	CAI_CV ≥ 0
23	Developed, Medium Intensity	582	CAI_CV ≥ 0
24	Developed, High Intensity	465	CAI_CV ≥ 0
31	Barren Land	213	CAI_CV ≥ 0
41	Deciduous Forest	336	CAI_CV ≥ 0
42	Evergreen Forest	162	CAI_CV ≥ 0
52	Shrub/Scrub	240	CAI_CV ≥ 0
71	Herbaceous	220	CAI_CV ≥ 0
81	Hay/Pasture	121	CAI_CV ≥ 0
82	Cultivated Crops	93	CAI_CV ≥ 0
90	Woody Wetlands	252	CAI_CV ≥ 0
95	Emergent Herbaceous Wetlands	277	CAI_CV ≥ 0

Core Area Metrics: Coefficient of Variation of Core Area Index (CAI_CV) – 2008

NLCD Class	**NLCD Class**	**Value**	**Range**
11	Open Water	257	CAI_CV ≥ 0
21	Developed, Open Space	317	CAI_CV ≥ 0
22	Developed, Low Intensity	663	CAI_CV ≥ 0
23	Developed, Medium Intensity	582	CAI_CV ≥ 0
24	Developed, High Intensity	465	CAI_CV ≥ 0
31	Barren Land	212	CAI_CV ≥ 0
41	Deciduous Forest	340	CAI_CV ≥ 0
42	Evergreen Forest	162	CAI_CV ≥ 0
52	Shrub/Scrub	241	CAI_CV ≥ 0
71	Herbaceous	220	CAI_CV ≥ 0
81	Hay/Pasture	129	CAI_CV ≥ 0
82	Cultivated Crops	91	CAI_CV ≥ 0
90	Woody Wetlands	235	CAI_CV ≥ 0
95	Emergent Herbaceous Wetlands	285	CAI_CV ≥ 0

Core Area Metrics: Coefficient of Variation of Core Area Index (CAI_CV) – 2011

NLCD Class	**NLCD Class**	**Value**	**Range**
11	Open Water	238	CAI_CV ≥ 0
21	Developed, Open Space	288	CAI_CV ≥ 0
22	Developed, Low Intensity	682	CAI_CV ≥ 0
23	Developed, Medium Intensity	561	CAI_CV ≥ 0
24	Developed, High Intensity	457	CAI_CV ≥ 0
31	Barren Land	215	CAI_CV ≥ 0
41	Deciduous Forest	355	CAI_CV ≥ 0
42	Evergreen Forest	165	CAI_CV ≥ 0
52	Shrub/Scrub	238	CAI_CV ≥ 0
71	Herbaceous	224	CAI_CV ≥ 0
81	Hay/Pasture	126	CAI_CV ≥ 0
82	Cultivated Crops	91	CAI_CV ≥ 0
90	Woody Wetlands	241	CAI_CV ≥ 0
95	Emergent Herbaceous Wetlands	274	CAI_CV ≥ 0

Core Area Metrics: Coefficient of Variation of Core Area Index (CAI_CV) – 2013

NLCD Class	**NLCD Class**	**Value**	**Range**
11	Open Water	237	CAI_CV ≥ 0
21	Developed, Open Space	288	CAI_CV ≥ 0
22	Developed, Low Intensity	682	CAI_CV ≥ 0
23	Developed, Medium Intensity	561	CAI_CV ≥ 0
24	Developed, High Intensity	457	CAI_CV ≥ 0
31	Barren Land	212	CAI_CV ≥ 0
41	Deciduous Forest	332	CAI_CV ≥ 0
42	Evergreen Forest	165	CAI_CV ≥ 0
52	Shrub/Scrub	239	CAI_CV ≥ 0
71	Herbaceous	224	CAI_CV ≥ 0
81	Hay/Pasture	155	CAI_CV ≥ 0
82	Cultivated Crops	91	CAI_CV ≥ 0
90	Woody Wetlands	235	CAI_CV ≥ 0
95	Emergent Herbaceous Wetlands	264	CAI_CV ≥ 0

Core Area Metrics: Coefficient of Variation of Core Area Index (CAI_CV) – 2016

NLCD Class	**NLCD Class**	**Value**	**Range**
11	Open Water	236	CAI_CV ≥ 0

21	Developed, Open Space	278	CAI_CV ≥ 0
22	Developed, Low Intensity	713	CAI_CV ≥ 0
23	Developed, Medium Intensity	620	CAI_CV ≥ 0
24	Developed, High Intensity	418	CAI_CV ≥ 0
31	Barren Land	300	CAI_CV ≥ 0
41	Deciduous Forest	316	CAI_CV ≥ 0
42	Evergreen Forest	165	CAI_CV ≥ 0
52	Shrub/Scrub	237	CAI_CV ≥ 0
71	Herbaceous	229	CAI_CV ≥ 0
81	Hay/Pasture	151	CAI_CV ≥ 0
82	Cultivated Crops	92	CAI_CV ≥ 0
90	Woody Wetlands	242	CAI_CV ≥ 0
95	Emergent Herbaceous Wetlands	264	CAI_CV ≥ 0

Core Area Metrics: Standard Deviation of Core Area Index (CAI_SD) – 2001

NLCD Class	**NLCD Class**	**Value**	**Range**
11	Open Water	18.40	CAI_SD ≥ 0
21	Developed, Open Space	4.95	CAI_SD ≥ 0
22	Developed, Low Intensity	2.10	CAI_SD ≥ 0
23	Developed, Medium Intensity	2.16	CAI_SD ≥ 0
24	Developed, High Intensity	4.24	CAI_SD ≥ 0
31	Barren Land	10.70	CAI_SD ≥ 0
41	Deciduous Forest	4.17	CAI_SD ≥ 0
42	Evergreen Forest	13.90	CAI_SD ≥ 0
52	Shrub/Scrub	9.98	CAI_SD ≥ 0
71	Herbaceous	9.47	CAI_SD ≥ 0
81	Hay/Pasture	19.40	CAI_SD ≥ 0
82	Cultivated Crops	33.40	CAI_SD ≥ 0
90	Woody Wetlands	10.20	CAI_SD ≥ 0
95	Emergent Herbaceous Wetlands	10.10	CAI_SD ≥ 0

Core Area Metrics: Standard Deviation of Core Area Index (CAI_SD) – 2004

NLCD Class	**NLCD Class**	**Value**	**Range**
11	Open Water	16.30	CAI_SD ≥ 0
21	Developed, Open Space	4.95	CAI_SD ≥ 0
22	Developed, Low Intensity	2.10	CAI_SD ≥ 0
23	Developed, Medium Intensity	2.16	CAI_SD ≥ 0
24	Developed, High Intensity	4.24	CAI_SD ≥ 0

31	Barren Land	10.60	CAI_SD ≥ 0
41	Deciduous Forest	4.13	CAI_SD ≥ 0
42	Evergreen Forest	13.90	CAI_SD ≥ 0
52	Shrub/Scrub	10.00	CAI_SD ≥ 0
71	Herbaceous	9.46	CAI_SD ≥ 0
81	Hay/Pasture	19.40	CAI_SD ≥ 0
82	Cultivated Crops	33.80	CAI_SD ≥ 0
90	Woody Wetlands	10.80	CAI_SD ≥ 0
95	Emergent Herbaceous Wetlands	9.42	CAI_SD ≥ 0

Core Area Metrics: Standard Deviation of Core Area Index (CAI_SD) – 2006

NLCD Class	**NLCD Class**	**Value**	**Range**
11	Open Water	17.00	CAI_SD ≥ 0
21	Developed, Open Space	5.66	CAI_SD ≥ 0
22	Developed, Low Intensity	2.11	CAI_SD ≥ 0
23	Developed, Medium Intensity	2.06	CAI_SD ≥ 0
24	Developed, High Intensity	4.59	CAI_SD ≥ 0
31	Barren Land	10.90	CAI_SD ≥ 0
41	Deciduous Forest	4.13	CAI_SD ≥ 0
42	Evergreen Forest	13.80	CAI_SD ≥ 0
52	Shrub/Scrub	10.20	CAI_SD ≥ 0
71	Herbaceous	9.32	CAI_SD ≥ 0
81	Hay/Pasture	20.50	CAI_SD ≥ 0
82	Cultivated Crops	33.80	CAI_SD ≥ 0
90	Woody Wetlands	9.80	CAI_SD ≥ 0
95	Emergent Herbaceous Wetlands	8.78	CAI_SD ≥ 0

Core Area Metrics: Standard Deviation of Core Area Index (CAI_SD) – 2008

NLCD Class	**NLCD Class**	**Value**	**Range**
11	Open Water	16.10	CAI_SD ≥ 0
21	Developed, Open Space	5.66	CAI_SD ≥ 0
22	Developed, Low Intensity	2.11	CAI_SD ≥ 0
23	Developed, Medium Intensity	2.06	CAI_SD ≥ 0
24	Developed, High Intensity	4.59	CAI_SD ≥ 0
31	Barren Land	10.70	CAI_SD ≥ 0
41	Deciduous Forest	4.09	CAI_SD ≥ 0
42	Evergreen Forest	13.90	CAI_SD ≥ 0
52	Shrub/Scrub	10.30	CAI_SD ≥ 0

71	Herbaceous	9.36	CAI_SD ≥ 0
81	Hay/Pasture	18.70	CAI_SD ≥ 0
82	Cultivated Crops	34.00	CAI_SD ≥ 0
90	Woody Wetlands	9.95	CAI_SD ≥ 0
95	Emergent Herbaceous Wetlands	9.34	CAI_SD ≥ 0

Core Area Metrics: Standard Deviation of Core Area Index (CAI_SD) – 2011

NLCD Class	**NLCD Class**	**Value**	**Range**
11	Open Water	16.20	CAI_SD ≥ 0
21	Developed, Open Space	6.02	CAI_SD ≥ 0
22	Developed, Low Intensity	2.11	CAI_SD ≥ 0
23	Developed, Medium Intensity	2.25	CAI_SD ≥ 0
24	Developed, High Intensity	4.37	CAI_SD ≥ 0
31	Barren Land	11.10	CAI_SD ≥ 0
41	Deciduous Forest	3.94	CAI_SD ≥ 0
42	Evergreen Forest	13.50	CAI_SD ≥ 0
52	Shrub/Scrub	10.80	CAI_SD ≥ 0
71	Herbaceous	9.24	CAI_SD ≥ 0
81	Hay/Pasture	19.00	CAI_SD ≥ 0
82	Cultivated Crops	34.00	CAI_SD ≥ 0
90	Woody Wetlands	9.96	CAI_SD ≥ 0
95	Emergent Herbaceous Wetlands	9.53	CAI_SD ≥ 0

Core Area Metrics: Standard Deviation of Core Area Index (CAI_SD) – 2013

NLCD Class	**NLCD Class**	**Value**	**Range**
11	Open Water	16.60	CAI_SD ≥ 0
21	Developed, Open Space	6.02	CAI_SD ≥ 0
22	Developed, Low Intensity	2.11	CAI_SD ≥ 0
23	Developed, Medium Intensity	2.25	CAI_SD ≥ 0
24	Developed, High Intensity	4.37	CAI_SD ≥ 0
31	Barren Land	11.30	CAI_SD ≥ 0
41	Deciduous Forest	4.17	CAI_SD ≥ 0
42	Evergreen Forest	13.50	CAI_SD ≥ 0
52	Shrub/Scrub	10.60	CAI_SD ≥ 0
71	Herbaceous	9.35	CAI_SD ≥ 0
81	Hay/Pasture	18.90	CAI_SD ≥ 0
82	Cultivated Crops	34.10	CAI_SD ≥ 0
90	Woody Wetlands	10.40	CAI_SD ≥ 0

95	Emergent Herbaceous Wetlands	9.28	CAI_SD ≥ 0

Core Area Metrics: Standard Deviation of Core Area Index (CAI_SD) – 2016

NLCD Class	**NLCD Class**	**Value**	**Range**
11	Open Water	16.50	CAI_SD ≥ 0
21	Developed, Open Space	6.16	CAI_SD ≥ 0
22	Developed, Low Intensity	2.05	CAI_SD ≥ 0
23	Developed, Medium Intensity	2.44	CAI_SD ≥ 0
24	Developed, High Intensity	4.93	CAI_SD ≥ 0
31	Barren Land	11.50	CAI_SD ≥ 0
41	Deciduous Forest	5.48	CAI_SD ≥ 0
42	Evergreen Forest	13.40	CAI_SD ≥ 0
52	Shrub/Scrub	10.40	CAI_SD ≥ 0
71	Herbaceous	9.36	CAI_SD ≥ 0
81	Hay/Pasture	19.60	CAI_SD ≥ 0
82	Cultivated Crops	33.60	CAI_SD ≥ 0
90	Woody Wetlands	9.77	CAI_SD ≥ 0
95	Emergent Herbaceous Wetlands	9.13	CAI_SD ≥ 0

Core Area Metrics: Coefficient of Variation of Core Area (CORE_CV) – 2001

NLCD Class	**NLCD Class**	**Value**	**Range**
11	Open Water	1,226	CORE_CV ≥ 0
21	Developed, Open Space	2,137	CORE_CV ≥ 0
22	Developed, Low Intensity	3,933	CORE_CV ≥ 0
23	Developed, Medium Intensity	1,926	CORE_CV ≥ 0
24	Developed, High Intensity	1,594	CORE_CV ≥ 0
31	Barren Land	2,357	CORE_CV ≥ 0
41	Deciduous Forest	351	CORE_CV ≥ 0
42	Evergreen Forest	3,979	CORE_CV ≥ 0
52	Shrub/Scrub	15,229	CORE_CV ≥ 0
71	Herbaceous	6,069	CORE_CV ≥ 0
81	Hay/Pasture	313	CORE_CV ≥ 0
82	Cultivated Crops	374	CORE_CV ≥ 0
90	Woody Wetlands	2,690	CORE_CV ≥ 0
95	Emergent Herbaceous Wetlands	1,840	CORE_CV ≥ 0

Core Area Metrics: Coefficient of Variation of Core Area (CORE_CV) – 2004

NLCD Class	**NLCD Class**	**Value**	**Range**

11	Open Water	1,149	CORE_CV ≥ 0
21	Developed, Open Space	2,137	CORE_CV ≥ 0
22	Developed, Low Intensity	3,933	CORE_CV ≥ 0
23	Developed, Medium Intensity	1,926	CORE_CV ≥ 0
24	Developed, High Intensity	1,594	CORE_CV ≥ 0
31	Barren Land	1,914	CORE_CV ≥ 0
41	Deciduous Forest	355	CORE_CV ≥ 0
42	Evergreen Forest	3,983	CORE_CV ≥ 0
52	Shrub/Scrub	15,167	CORE_CV ≥ 0
71	Herbaceous	6,211	CORE_CV ≥ 0
81	Hay/Pasture	308	CORE_CV ≥ 0
82	Cultivated Crops	371	CORE_CV ≥ 0
90	Woody Wetlands	2,681	CORE_CV ≥ 0
95	Emergent Herbaceous Wetlands	2,049	CORE_CV ≥ 0

Core Area Metrics: Coefficient of Variation of Core Area (CORE_CV) – 2006

NLCD Class	**NLCD Class**	**Value**	**Range**
11	Open Water	984	CORE_CV ≥ 0
21	Developed, Open Space	1,910	CORE_CV ≥ 0
22	Developed, Low Intensity	4,311	CORE_CV ≥ 0
23	Developed, Medium Intensity	1,949	CORE_CV ≥ 0
24	Developed, High Intensity	1,486	CORE_CV ≥ 0
31	Barren Land	1,697	CORE_CV ≥ 0
41	Deciduous Forest	355	CORE_CV ≥ 0
42	Evergreen Forest	3,974	CORE_CV ≥ 0
52	Shrub/Scrub	15,507	CORE_CV ≥ 0
71	Herbaceous	8,092	CORE_CV ≥ 0
81	Hay/Pasture	300	CORE_CV ≥ 0
82	Cultivated Crops	371	CORE_CV ≥ 0
90	Woody Wetlands	2,896	CORE_CV ≥ 0
95	Emergent Herbaceous Wetlands	2,102	CORE_CV ≥ 0

Core Area Metrics: Coefficient of Variation of Core Area (CORE_CV) – 2008

NLCD Class	**NLCD Class**	**Value**	**Range**
11	Open Water	1,196	CORE_CV ≥ 0
21	Developed, Open Space	1,910	CORE_CV ≥ 0
22	Developed, Low Intensity	4,311	CORE_CV ≥ 0
23	Developed, Medium Intensity	1,949	CORE_CV ≥ 0

24	Developed, High Intensity	1,486	CORE_CV ≥ 0
31	Barren Land	1,900	CORE_CV ≥ 0
41	Deciduous Forest	359	CORE_CV ≥ 0
42	Evergreen Forest	3,971	CORE_CV ≥ 0
52	Shrub/Scrub	15,588	CORE_CV ≥ 0
71	Herbaceous	6,060	CORE_CV ≥ 0
81	Hay/Pasture	335	CORE_CV ≥ 0
82	Cultivated Crops	365	CORE_CV ≥ 0
90	Woody Wetlands	2,850	CORE_CV ≥ 0
95	Emergent Herbaceous Wetlands	2,002	CORE_CV ≥ 0

Core Area Metrics: Coefficient of Variation of Core Area (CORE_CV) – 2011

NLCD Class	**NLCD Class**	**Value**	**Range**
11	Open Water	825	CORE_CV ≥ 0
21	Developed, Open Space	1,778	CORE_CV ≥ 0
22	Developed, Low Intensity	4,668	CORE_CV ≥ 0
23	Developed, Medium Intensity	1,821	CORE_CV ≥ 0
24	Developed, High Intensity	1,551	CORE_CV ≥ 0
31	Barren Land	1,383	CORE_CV ≥ 0
41	Deciduous Forest	375	CORE_CV ≥ 0
42	Evergreen Forest	4,378	CORE_CV ≥ 0
52	Shrub/Scrub	14,718	CORE_CV ≥ 0
71	Herbaceous	7,609	CORE_CV ≥ 0
81	Hay/Pasture	329	CORE_CV ≥ 0
82	Cultivated Crops	362	CORE_CV ≥ 0
90	Woody Wetlands	2,791	CORE_CV ≥ 0
95	Emergent Herbaceous Wetlands	2,008	CORE_CV ≥ 0

Core Area Metrics: Coefficient of Variation of Core Area (CORE_CV) – 2013

NLCD Class	**NLCD Class**	**Value**	**Range**
11	Open Water	1,102	CORE_CV ≥ 0
21	Developed, Open Space	1,778	CORE_CV ≥ 0
22	Developed, Low Intensity	4,668	CORE_CV ≥ 0
23	Developed, Medium Intensity	1,821	CORE_CV ≥ 0
24	Developed, High Intensity	1,551	CORE_CV ≥ 0
31	Barren Land	1,452	CORE_CV ≥ 0
41	Deciduous Forest	351	CORE_CV ≥ 0
42	Evergreen Forest	4,387	CORE_CV ≥ 0

52	Shrub/Scrub	16,239	CORE_CV ≥ 0
71	Herbaceous	7,195	CORE_CV ≥ 0
81	Hay/Pasture	351	CORE_CV ≥ 0
82	Cultivated Crops	378	CORE_CV ≥ 0
90	Woody Wetlands	2,703	CORE_CV ≥ 0
95	Emergent Herbaceous Wetlands	2,089	CORE_CV ≥ 0

Core Area Metrics: Coefficient of Variation of Core Area (CORE_CV) – 2016

NLCD Class	**NLCD Class**	**Value**	**Range**
11	Open Water	1,121	CORE_CV ≥ 0
21	Developed, Open Space	1,695	CORE_CV ≥ 0
22	Developed, Low Intensity	5,045	CORE_CV ≥ 0
23	Developed, Medium Intensity	1,821	CORE_CV ≥ 0
24	Developed, High Intensity	1,460	CORE_CV ≥ 0
31	Barren Land	1,383	CORE_CV ≥ 0
41	Deciduous Forest	400	CORE_CV ≥ 0
42	Evergreen Forest	4,386	CORE_CV ≥ 0
52	Shrub/Scrub	16,154	CORE_CV ≥ 0
71	Herbaceous	7,363	CORE_CV ≥ 0
81	Hay/Pasture	325	CORE_CV ≥ 0
82	Cultivated Crops	401	CORE_CV ≥ 0
90	Woody Wetlands	2,814	CORE_CV ≥ 0
95	Emergent Herbaceous Wetlands	2,097	CORE_CV ≥ 0

Contagion and Interspersion Metrics: Clumpy Index (CLUMPY) – 2001

NLCD Class	**NLCD Class**	**Value**	**Range**
11	Open Water	0.84	-1 ≤ CLUMPY ≤ 1
21	Developed, Open Space	0.48	-1 ≤ CLUMPY ≤ 1
22	Developed, Low Intensity	0.48	-1 ≤ CLUMPY ≤ 1
23	Developed, Medium Intensity	0.40	-1 ≤ CLUMPY ≤ 1
24	Developed, High Intensity	0.49	-1 ≤ CLUMPY ≤ 1
31	Barren Land	0.78	-1 ≤ CLUMPY ≤ 1
41	Deciduous Forest	0.41	-1 ≤ CLUMPY ≤ 1
42	Evergreen Forest	0.82	-1 ≤ CLUMPY ≤ 1
52	Shrub/Scrub	0.71	-1 ≤ CLUMPY ≤ 1
71	Herbaceous	0.70	-1 ≤ CLUMPY ≤ 1
81	Hay/Pasture	0.80	-1 ≤ CLUMPY ≤ 1
82	Cultivated Crops	0.93	-1 ≤ CLUMPY ≤ 1

90	Woody Wetlands	0.85	-1 ≤ CLUMPY ≤ 1
95	Emergent Herbaceous Wetlands	0.77	-1 ≤ CLUMPY ≤ 1

Contagion and Interspersion Metrics: Clumpy Index (CLUMPY) – 2004

NLCD Class	**NLCD Class**	**Value**	**Range**
11	Open Water	0.86	-1 ≤ CLUMPY ≤ 1
21	Developed, Open Space	0.48	-1 ≤ CLUMPY ≤ 1
22	Developed, Low Intensity	0.48	-1 ≤ CLUMPY ≤ 1
23	Developed, Medium Intensity	0.40	-1 ≤ CLUMPY ≤ 1
24	Developed, High Intensity	0.49	-1 ≤ CLUMPY ≤ 1
31	Barren Land	0.76	-1 ≤ CLUMPY ≤ 1
41	Deciduous Forest	0.41	-1 ≤ CLUMPY ≤ 1
42	Evergreen Forest	0.82	-1 ≤ CLUMPY ≤ 1
52	Shrub/Scrub	0.71	-1 ≤ CLUMPY ≤ 1
71	Herbaceous	0.70	-1 ≤ CLUMPY ≤ 1
81	Hay/Pasture	0.80	-1 ≤ CLUMPY ≤ 1
82	Cultivated Crops	0.93	-1 ≤ CLUMPY ≤ 1
90	Woody Wetlands	0.85	-1 ≤ CLUMPY ≤ 1
95	Emergent Herbaceous Wetlands	0.76	-1 ≤ CLUMPY ≤ 1

Contagion and Interspersion Metrics: Clumpy Index (CLUMPY) – 2006

NLCD Class	**NLCD Class**	**Value**	**Range**
11	Open Water	0.87	-1 ≤ CLUMPY ≤ 1
21	Developed, Open Space	0.49	-1 ≤ CLUMPY ≤ 1
22	Developed, Low Intensity	0.46	-1 ≤ CLUMPY ≤ 1
23	Developed, Medium Intensity	0.40	-1 ≤ CLUMPY ≤ 1
24	Developed, High Intensity	0.49	-1 ≤ CLUMPY ≤ 1
31	Barren Land	0.76	-1 ≤ CLUMPY ≤ 1
41	Deciduous Forest	0.41	-1 ≤ CLUMPY ≤ 1
42	Evergreen Forest	0.83	-1 ≤ CLUMPY ≤ 1
52	Shrub/Scrub	0.72	-1 ≤ CLUMPY ≤ 1
71	Herbaceous	0.71	-1 ≤ CLUMPY ≤ 1
81	Hay/Pasture	0.81	-1 ≤ CLUMPY ≤ 1
82	Cultivated Crops	0.93	-1 ≤ CLUMPY ≤ 1
90	Woody Wetlands	0.84	-1 ≤ CLUMPY ≤ 1
95	Emergent Herbaceous Wetlands	0.76	-1 ≤ CLUMPY ≤ 1

Contagion and Interspersion Metrics: Clumpy Index (CLUMPY) – 2008

NLCD Class	**NLCD Class**	**Value**	**Range**
11	Open Water	0.86	-1 ≤ CLUMPY ≤ 1
21	Developed, Open Space	0.49	-1 ≤ CLUMPY ≤ 1
22	Developed, Low Intensity	0.46	-1 ≤ CLUMPY ≤ 1
23	Developed, Medium Intensity	0.40	-1 ≤ CLUMPY ≤ 1
24	Developed, High Intensity	0.49	-1 ≤ CLUMPY ≤ 1
31	Barren Land	0.76	-1 ≤ CLUMPY ≤ 1
41	Deciduous Forest	0.41	-1 ≤ CLUMPY ≤ 1
42	Evergreen Forest	0.83	-1 ≤ CLUMPY ≤ 1
52	Shrub/Scrub	0.73	-1 ≤ CLUMPY ≤ 1
71	Herbaceous	0.72	-1 ≤ CLUMPY ≤ 1
81	Hay/Pasture	0.80	-1 ≤ CLUMPY ≤ 1
82	Cultivated Crops	0.93	-1 ≤ CLUMPY ≤ 1
90	Woody Wetlands	0.84	-1 ≤ CLUMPY ≤ 1
95	Emergent Herbaceous Wetlands	0.77	-1 ≤ CLUMPY ≤ 1

Contagion and Interspersion Metrics: Clumpy Index (CLUMPY) – 2011

NLCD Class	**NLCD Class**	**Value**	**Range**
11	Open Water	0.81	-1 ≤ CLUMPY ≤ 1
21	Developed, Open Space	0.49	-1 ≤ CLUMPY ≤ 1
22	Developed, Low Intensity	0.44	-1 ≤ CLUMPY ≤ 1
23	Developed, Medium Intensity	0.40	-1 ≤ CLUMPY ≤ 1
24	Developed, High Intensity	0.47	-1 ≤ CLUMPY ≤ 1
31	Barren Land	0.77	-1 ≤ CLUMPY ≤ 1
41	Deciduous Forest	0.40	-1 ≤ CLUMPY ≤ 1
42	Evergreen Forest	0.82	-1 ≤ CLUMPY ≤ 1
52	Shrub/Scrub	0.76	-1 ≤ CLUMPY ≤ 1
71	Herbaceous	0.77	-1 ≤ CLUMPY ≤ 1
81	Hay/Pasture	0.80	-1 ≤ CLUMPY ≤ 1
82	Cultivated Crops	0.93	-1 ≤ CLUMPY ≤ 1
90	Woody Wetlands	0.84	-1 ≤ CLUMPY ≤ 1
95	Emergent Herbaceous Wetlands	0.76	-1 ≤ CLUMPY ≤ 1

Contagion and Interspersion Metrics: Clumpy Index (CLUMPY) – 2013

NLCD Class	**NLCD Class**	**Value**	**Range**
11	Open Water	0.85	-1 ≤ CLUMPY ≤ 1
21	Developed, Open Space	0.49	-1 ≤ CLUMPY ≤ 1

22	Developed, Low Intensity	0.44	-1 ≤ CLUMPY ≤ 1
23	Developed, Medium Intensity	0.40	-1 ≤ CLUMPY ≤ 1
24	Developed, High Intensity	0.47	-1 ≤ CLUMPY ≤ 1
31	Barren Land	0.78	-1 ≤ CLUMPY ≤ 1
41	Deciduous Forest	0.41	-1 ≤ CLUMPY ≤ 1
42	Evergreen Forest	0.82	-1 ≤ CLUMPY ≤ 1
52	Shrub/Scrub	0.75	-1 ≤ CLUMPY ≤ 1
71	Herbaceous	0.76	-1 ≤ CLUMPY ≤ 1
81	Hay/Pasture	0.80	-1 ≤ CLUMPY ≤ 1
82	Cultivated Crops	0.93	-1 ≤ CLUMPY ≤ 1
90	Woody Wetlands	0.85	-1 ≤ CLUMPY ≤ 1
95	Emergent Herbaceous Wetlands	0.75	-1 ≤ CLUMPY ≤ 1

Contagion and Interspersion Metrics: Clumpy Index (CLUMPY) – 2016

NLCD Class	**NLCD Class**	**Value**	**Range**
11	Open Water	0.87	-1 ≤ CLUMPY ≤ 1
21	Developed, Open Space	0.50	-1 ≤ CLUMPY ≤ 1
22	Developed, Low Intensity	0.42	-1 ≤ CLUMPY ≤ 1
23	Developed, Medium Intensity	0.39	-1 ≤ CLUMPY ≤ 1
24	Developed, High Intensity	0.47	-1 ≤ CLUMPY ≤ 1
31	Barren Land	0.78	-1 ≤ CLUMPY ≤ 1
41	Deciduous Forest	0.44	-1 ≤ CLUMPY ≤ 1
42	Evergreen Forest	0.82	-1 ≤ CLUMPY ≤ 1
52	Shrub/Scrub	0.74	-1 ≤ CLUMPY ≤ 1
71	Herbaceous	0.73	-1 ≤ CLUMPY ≤ 1
81	Hay/Pasture	0.81	-1 ≤ CLUMPY ≤ 1
82	Cultivated Crops	0.93	-1 ≤ CLUMPY ≤ 1
90	Woody Wetlands	0.85	-1 ≤ CLUMPY ≤ 1
95	Emergent Herbaceous Wetlands	0.76	-1 ≤ CLUMPY ≤ 1

Diversity Metrics

Shannon's Diversity Index (SHDI)					Range: SHDI ≥ 1	
2001	**2004**	**2006**	**2008**	**2011**	**2013**	**2016**
0.733	0.730	0.756	0.765	0.828	0.821	0.807
Simpson's Diversity Index (SIDI)					Range: 0 ≤ SIDI < 1	

2001	**2004**	**2006**	**2008**	**2011**	**2013**	**2016**
0.357	0.355	0.369	0.376	0.427	0.418	0.400
Patch Richness (PR)					Range: PR ≥ 1	
2001	**2004**	**2006**	**2008**	**2011**	**2013**	**2016**
14	14	14	14	14	14	14
Patch Richness Density (PRD)					Range: PRD ≥ 0	
2001	**2004**	**2006**	**2008**	**2011**	**2013**	**2016**
0.00055	0.00055	0.00055	0.00055	0.00055	0.00055	0.00055
Shannon's evenness index (SHEI)					Range: 0 ≤ SHEI < 1	
2001	**2004**	**2006**	**2008**	**2011**	**2013**	**2016**
0.278	0.277	0.286	0.290	0.314	0.311	0.306
Simpson's evenness index (SIEI)					Range: 0 < SIEI ≤ 1	
2001	**2004**	**2006**	**2008**	**2011**	**2013**	**2016**
0.384	0.382	0.398	0.405	0.460	0.450	0.431

Appendix C *LII* values and LCM Values for Model Validation

Table of *LII* value and LCM values (*LII*_LCM variable in R Markdown)

OID	***LII*_Value**	**LCM_Value**
1	0.507061	88
2	0.540633	100
3	0.512471	100
4	0.536162	70
5	0.438775	70
6	0.465446	100
7	0.465215	67
8	0.481052	100
9	0.508359	100
10	0.196712	28
11	0.523356	98
12	0.544645	70
13	0.494623	98
14	0.469222	92
15	0.511743	100
16	0.487586	98
17	0.322849	20
18	0.537398	100
19	0.485023	100

20	0.507781	100
21	0.517532	70
22	0.486459	88
23	0.488039	70
24	0.517731	100
25	0.512488	100
26	0.486303	63
27	0.474127	98
28	0.491344	95
29	0.515071	93
30	0.481362	65
31	0.490334	100
32	0.473876	26
33	0.544825	100
34	0.499425	98
35	0.532944	100
36	0.519079	70
37	0.538403	83
38	0.464194	60
39	0.487845	67
40	0.491651	45
41	0.466127	100
42	0.497011	83

43	0.447463	70
44	0.511479	100
45	0.461048	62
46	0.515468	56
47	0.513639	88
48	0.379457	100
49	0.521584	88
50	0.46471	37
51	0.510081	100
52	0.531166	70
53	0.586949	100
54	0.473013	70
55	0.47359	66
56	0.505251	70
57	0.482825	53
58	0.531216	34
59	0.48936	70
60	0.471661	100
61	0.479537	100
62	0.472096	70
63	0.517264	100
64	0.438283	100
65	0.485968	70

66	0.476776	24
67	0.498625	98
68	0.509831	88
69	0.418751	99
70	0.493656	100
71	0.519828	88
72	0.525642	30
73	0.536188	88
74	0.461057	91
75	0.182372	37
76	0.48967	100
77	0.508072	100
78	0.504031	100
79	0.459072	97
80	0.505294	100
81	0.486359	88
82	0.501651	98
83	0.493336	70
84	0.488122	70
85	0.504493	70
86	0.503706	94
87	0.447484	44
88	0.507609	100

89	0.504074	86
90	0.510223	100
91	0.509943	99
92	0.201698	0
93	0.48267	70
94	0.182823	36
95	0.382976	22
96	0.50254	70
97	0.503198	26
98	0.485859	70
99	0.521986	100
100	0.478407	70

Table of *LII* values in Protected Areas or Multiple-Use Areas (*LII*_PADUS_100 in R Markdown)

OID	**RASTERVALU**	**group**
1	0.479084	Protected
2	0.480042	Protected
3	0.501907	Protected
4	0.501019	Protected
5	0.474674	Protected
6	0.547407	Protected
7	0.490589	Protected
8	0.497564	Protected
9	0.53569	Protected
10	0.478197	Protected
11	0.511125	Protected
12	0.500255	Protected
13	0.51147	Protected
14	0.520881	Protected
15	0.517646	Protected
16	0.488333	Protected
17	0.542949	Protected
18	0.559083	Protected
19	0.490912	Protected
20	0.453005	Protected

21	0.490856	Protected
22	0.490633	Protected
23	0.468514	Protected
24	0.476357	Protected
25	0.471646	Protected
26	0.478189	Protected
27	0.529337	Protected
28	0.463209	Protected
29	0.52526	Protected
30	0.523877	Protected
31	0.457668	Protected
32	0.50062	Protected
33	0.543463	Protected
34	0.498557	Protected
35	0.463255	Protected
36	0.541929	Protected
37	0.496821	Protected
38	0.557516	Protected
39	0.472581	Protected
40	0.478606	Protected
41	0.489	Protected
42	0.496746	Protected
43	0.521122	Protected

44	0.503573	Protected
45	0.4883	Protected
46	0.457678	Protected
47	0.529721	Protected
48	0.436923	Protected
49	0.475973	Protected
50	0.528192	Protected
51	0.478312	Protected
52	0.517202	Protected
53	0.495025	Protected
54	0.434089	Protected
55	0.549679	Protected
56	0.490334	Protected
57	0.550763	Protected
58	0.477253	Protected
59	0.455615	Protected
60	0.523612	Protected
61	0.519409	Protected
62	0.489472	Protected
63	0.483062	Protected
64	0.477214	Protected
65	0.500976	Protected
66	0.532278	Protected

67	0.50061	Protected
68	0.501019	Protected
69	0.480833	Protected
70	0.485737	Protected
71	0.483849	Protected
72	0.491054	Protected
73	0.479333	Protected
74	0.534523	Protected
75	0.540275	Protected
76	0.478808	Protected
77	0.522823	Protected
78	0.555473	Protected
79	0.547746	Protected
80	0.457162	Protected
81	0.483737	Protected
82	0.476213	Protected
83	0.517449	Protected
84	0.53136	Protected
85	0.443585	Protected
86	0.436516	Protected
87	0.494409	Protected
88	0.549679	Protected
89	0.526437	Protected

90	0.440661	Protected
91	0.518173	Protected
92	0.482767	Protected
93	0.524042	Protected
94	0.470283	Protected
95	0.463179	Protected
96	0.556959	Protected
97	0.494164	Protected
98	0.469658	Protected
99	0.481625	Protected
100	0.49594	Protected
1	0.468572	Multiple-Use
2	0.520155	Multiple-Use
3	0.47186	Multiple-Use
4	0.498978	Multiple-Use
5	0.511508	Multiple-Use
6	0.483726	Multiple-Use
7	0.487944	Multiple-Use
8	0.493899	Multiple-Use
9	0.476737	Multiple-Use
10	0.466534	Multiple-Use
11	0.460113	Multiple-Use
12	0.508826	Multiple-Use

13	0.493513	Multiple-Use
14	0.519825	Multiple-Use
15	0.511102	Multiple-Use
16	0.560985	Multiple-Use
17	0.531744	Multiple-Use
18	0.478779	Multiple-Use
19	0.493602	Multiple-Use
20	0.464205	Multiple-Use
21	0.451005	Multiple-Use
22	0.48675	Multiple-Use
23	0.478822	Multiple-Use
24	0.480982	Multiple-Use
25	0.489191	Multiple-Use
26	0.462792	Multiple-Use
27	0.461041	Multiple-Use
28	0.475372	Multiple-Use
29	0.489597	Multiple-Use
30	0.517958	Multiple-Use
31	0.49924	Multiple-Use
32	0.494106	Multiple-Use
33	0.504031	Multiple-Use
34	0.47124	Multiple-Use
35	0.540468	Multiple-Use

36	0.459279	Multiple-Use
37	0.452474	Multiple-Use
38	0.478274	Multiple-Use
39	0.483011	Multiple-Use
40	0.510597	Multiple-Use
41	0.471559	Multiple-Use
42	0.473022	Multiple-Use
43	0.417273	Multiple-Use
44	0.477178	Multiple-Use
45	0.436605	Multiple-Use
46	0.555461	Multiple-Use
47	0.464811	Multiple-Use
48	0.525161	Multiple-Use
49	0.472316	Multiple-Use
50	0.451213	Multiple-Use
51	0.477264	Multiple-Use
52	0.520422	Multiple-Use
53	0.50793	Multiple-Use
54	0.452859	Multiple-Use
55	0.461041	Multiple-Use
56	0.483855	Multiple-Use
57	0.498682	Multiple-Use
58	0.467832	Multiple-Use

59	0.488314	Multiple-Use
60	0.479803	Multiple-Use
61	0.492889	Multiple-Use
62	0.461902	Multiple-Use
63	0.478678	Multiple-Use
64	0.489302	Multiple-Use
65	0.507905	Multiple-Use
66	0.512495	Multiple-Use
67	0.551705	Multiple-Use
68	0.466424	Multiple-Use
69	0.488655	Multiple-Use
70	0.462115	Multiple-Use
71	0.493628	Multiple-Use
72	0.501725	Multiple-Use
73	0.455363	Multiple-Use
74	0.478705	Multiple-Use
75	0.6911	Multiple-Use
76	0.477769	Multiple-Use
77	0.51162	Multiple-Use
78	0.512147	Multiple-Use
79	0.452351	Multiple-Use
80	0.477264	Multiple-Use
81	0.508263	Multiple-Use

82	0.51204	Multiple-Use
83	0.498594	Multiple-Use
84	0.46593	Multiple-Use
85	0.508393	Multiple-Use
86	0.49344	Multiple-Use
87	0.477572	Multiple-Use
88	0.464205	Multiple-Use
89	0.480495	Multiple-Use
90	0.464833	Multiple-Use
91	0.509816	Multiple-Use
92	0.517193	Multiple-Use
93	0.504031	Multiple-Use
94	0.484374	Multiple-Use
95	0.461041	Multiple-Use
96	0.460261	Multiple-Use
97	0.454689	Multiple-Use
98	0.495072	Multiple-Use
99	0.491028	Multiple-Use
100	0.484863	Multiple-Use