Supporting Tribal-Led Conservation and Connectivity in the Northern Great Plains Ecoregion: Geospatial and Policy Tools to Prioritize Lands for Restoration and Funding

by

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Client: Buffalo Nations Grasslands Alliance

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Abstract

Grasslands occupy approximately 40% of Earth's terrestrial surface and have declined in area by 62%, despite their crucial importance to people, biodiversity, and economies. This research supports the Buffalo Nations Grasslands Alliance's (BNGA) initiatives to strengthen Tribal conservation and restoration strategies in the NGP ecoregion by integrating spatial ecology, remote sensing, and policy analysis to develop connectivity tools and advocate for federal grasslands policy. BNGA, a Native-led 501(c)(3), works to support conservation and sustainable livelihoods across 16 Native Nations in the NGP ecoregion. Collaborating with BNGA, we piloted two geospatial conservation tools at Rocky Boy's Reservation in Montana. First, we developed a spatial-ecological connectivity tool for pronghorn (*Antilocapra americana*), combining field data with landscape metrics to identify priority habitat areas. Results of the tool indicate the Reservation's large, contiguous grassland patches exceed published pronghorn habitat requirements. Second, we assessed the detectability of American bison (*Bison bison*) wallows using deep learning and Random Forest models applied to remotely sensed imagery. The Random Forest model performed best for the study area. Of the 28% of wallows that overlapped, the Random Forest model had the highest mean IoU (0.622) and median IoU (0.65), representing an initial attempt to quantify and predict areas of wallowing. These approaches provide cost-effective, reliable methods to characterize areas of connectivity and disturbance, and should be expanded in future studies to include additional areas and priority species. Finally, we evaluated the North American Grasslands Conservation Act (NAGCA), a bill which would appropriate approximately $9.2 million annually to Native Nations and Tribal organizations. Our analysis identifies grasslands' economic contributions and analyzes existing legislation, recommending strategies to finance NAGCA, as well as enhance NAGCA's chances of political support and adoption. Our research indicates that Indigenous-led stewardship – supported by sustained public investment – can shape the future of grasslands conservation and restoration across the NGP ecoregion, ensuring that these ecosystems remain for generations to come.

Keywords: Indigenous Peoples, grasslands conservation, ecological connectivity, remote sensing, conservation policy, Northern Great Plains

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Chapter 1: Introduction

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1.1 Background & Rationale

Grasslands occupy approximately 40% of the terrestrial surface of the earth and are critically important ecologically, economically, and culturally (Petermann & Buzhdygan, 2021). Ecosystem services from grasslands include wildlife habitat, carbon sequestration, flood and drought mitigation, pollination, soil health promotion, and recreation (Buffalo Nations Grasslands Alliance [BNGA], n.d.; United States Department of Agriculture [USDA], n.d.). In the United States, grasslands are a key economic driver. For example, temperate grasslands sequester three times as much carbon in their soil as they do after conversion to cropland (Neufeld & Smith, 2022) due to their high biomass of perennial grass root systems, rendering them a crucial ecosystem for increasing the United States' capacity to fight the harmful effects of atmospheric carbon. Temperate grasslands store roughly 243 tonnes of carbon per hectare (Neufeld & Smith, 2022). This is equivalent to roughly 98.3 tonnes of carbon stored in each acre of grassland, resulting in a per-acre grassland carbon sequestration value between $4,122.70 and $39,352.44, with a mid-range estimate of $13,492.66. For more information on the economic value of grasslands, see Khesin (2026).

These grasslands are a product of Indigenous Peoples'[1] active intervention – whereby they used fire and other practices to ensure the health and resilience of ecosystems and populations – including wildlife (Stewart, 2002). Grasslands are particularly vital for the Indigenous Peoples in the Northern Great Plains (NGP) ecoregion[2], supporting not only their livelihoods, cultures, and identities but also habitat for many plant and wildlife species (BNGA, n.d.). This knowledge and traditions are essential for understanding how to best restore and protect both ecosystems and culturally significant species.

Despite their importance, approximately 62% of intact grasslands in the U.S. have vanished to date, and only 10% remains formally protected, whether by state or federal agencies, non-profits, Tribal governments, or other organizations. This leaves the vast majority of grasslands unprotected and at-risk for land use conversion, among other human and natural threats (Hendrickson et al., 2019; United States Fish and Wildlife Service [USFWS], 2023; Winters-Michaud et al., 2024). Despite challenges to grassland ecosystems, there is reason for hope. While only 55% of the Great Plains as a whole is intact grassland, in the NGP ecoregion, 70% of grasslands remain intact – that is, those that have not been "planted or plowed" (Lark, 2020) for at least 25 years (Hancock & McCarthy, 2024; Lark, 2020). Furthermore, 80% of all Tribal lands held within the NGP ecoregion are intact grasslands (World Wildlife Fund, 2024), illustrating Native Nations' prominent role in grasslands conservation. Not only do Indigenous Peoples have local knowledge of these ecosystems, but they also possess the land and practical experience essential for restoration.

Many animal species native to the grasslands of the Northern Great Plains (NGP) ecoregion migrated seasonally over large territories (Liczner et al., 2024; Naidoo et al., 2025).

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[1] Groups recognized as having political and cultural self-determination, which, in the United States, predates the founding of the country (Native Governance Center, 2021; Whyte et al., 2023)

[2] In the context of this research, the Northern Great Plains (NGP) is delineated by the boundaries of the NGP ecoregion (Figure 1.1).

Given the extensive fragmentation of the NGP ecoregion due to diverse land ownership, roads, and fences, restoration of this area requires both restoring and reconnecting habitat for species. Restoring these stewardship practices, as well as the habitat and connectivity of related ecosystems, is made even more challenging by the fragmentation of Indigenous Peoples across the NGP ecoregion into 16 Native Nations, many separated by hundreds of miles (Figure 1.1).

The Buffalo Nations Grasslands Alliance (BNGA)[3] is a Native-led 501(c)(3) that works with partners to support conservation and sustainable livelihoods across 16 Native Nations[4] in the NGP ecoregion (Figure 1.1). The Native Nations that BNGA serves include:

- Blackfeet Tribe
- Cheyenne River Sioux Tribe
- Chippewa Cree Tribe
- Crow Creek Sioux Tribe
- Crow Tribe
- Fort Belknap Indian Community
- Fort Peck Assiniboine & Sioux Tribes
- Little Shell Band of Chippewa
- Lower Brule Sioux Tribe
- Northern Cheyenne Tribe
- Oglala Sioux Tribe
- Rosebud Sioux Tribe
- Standing Rock Sioux Tribe
- Three Affiliated Tribes
- Turtle Mountain Band of Chippewa Indians (trust lands in the NGP ecoregion)
- Yankton Sioux Tribe (BNGA, 2025).

BNGA began in 2015 as a small group of Indigenous biologists who were collaborating on fieldwork and research. Eventually, the group decided to formalize their collaboration and established a 501(c)(3) in 2021 to facilitate and scale up their work in building Tribal capacity and coalitions around grasslands conservation (BNGA, 2025). Today, BNGA's regional conservation priorities include:

[3] https://www.bnga.org/

[4] It is important to distinguish between Native Nations and Reservations. In this report, we use the term Native Nations to refer to Tribes that are formally recognized by the United States Government. Among many (but certainly not all) Indigenous Peoples in the U.S., the term Native Nation is preferred as it demonstrates respect for the legal sovereignty of those Peoples (Native Governance Center, 2021). The term reservation, by contrast, refers to a physical place rather than a group of people. The U.S. Bureau of Indian Affairs defines a reservation as "[An area] of land reserved for a tribe or tribes under treaty or other agreement with the United States, executive order, or federal statute or administrative action as permanent tribal homelands, and where the federal government holds title to the land in trust on behalf of the tribe" (BIA, 2017).

- Ensuring that 30% of Tribal land in the NGP ecoregion is under Indigenous-led conservation management;
- Establishing 10 paths of connectivity to provide a means for species to move across the landscape without barriers, thus helping to maintain biodiversity;
- Preserving Indigenous Peoples' livelihoods and relationship with nature, and
- Creating 300 new jobs and 60 new or expanded businesses in Indigenous communities (BNGA, 2024).

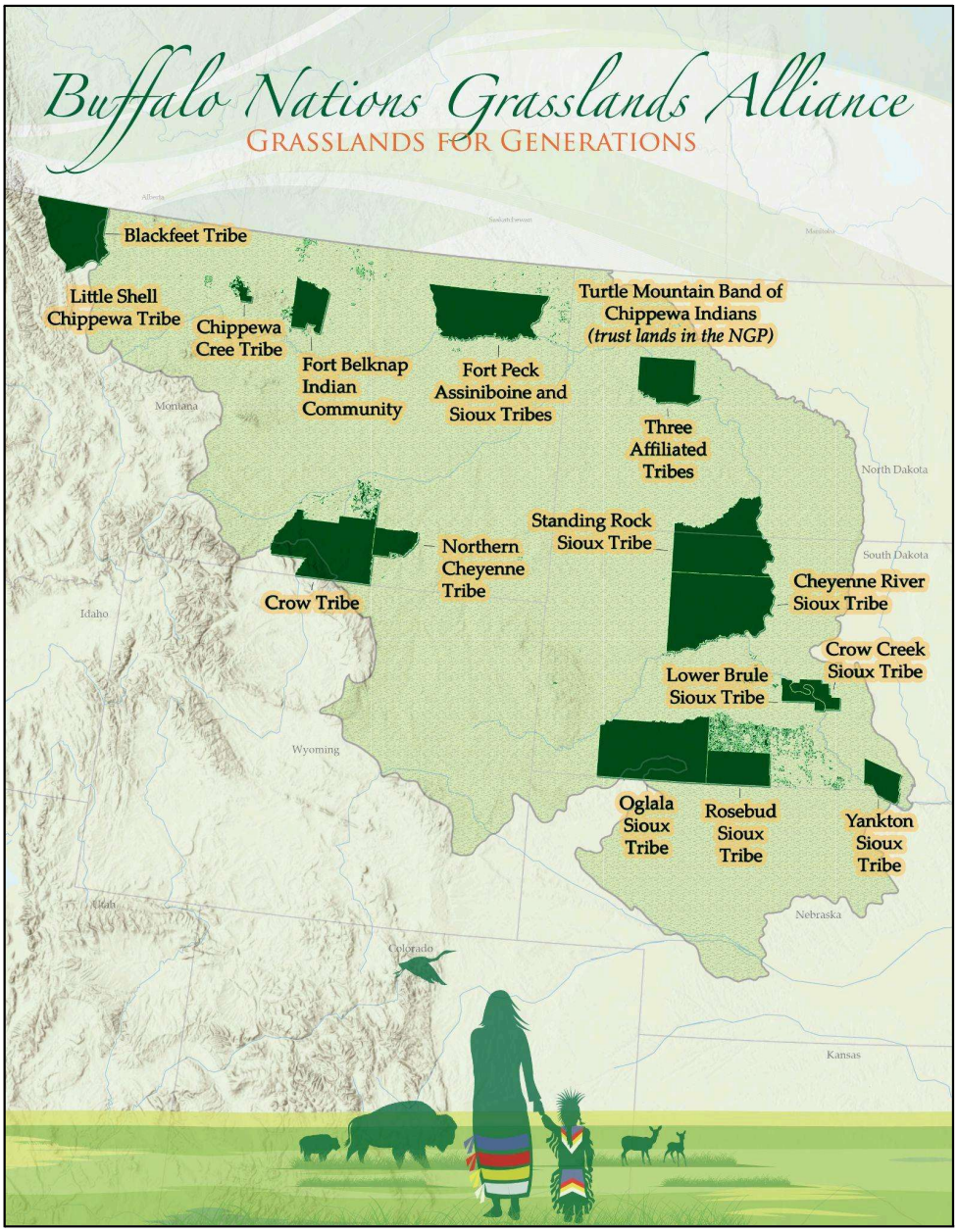


Figure 1.1. *The Buffalo Nations Grasslands Alliance is a Native-led 501(c)(3) that serves the 16 Native Nations who live within the U.S. Northern Great Plains ecoregion. Map provided by Antonio Morsette, BNGA.*

In the Fall of 2024, BNGA submitted a proposal for a Master's Project through the University of Michigan School for Environment and Sustainability (SEAS). SEAS Master's Projects are applied research projects for client organizations addressing a sustainability research need over a one-and-a-half-year timeframe, with teams of approximately five graduate students spanning multiple environmental disciplines (School for Environment and Sustainability [SEAS], 2025). SEAS students are encouraged to sustain commitment to client organizations past, present, and future. A team of SEAS master's students completed a project for BNGA previously, from January 2023 – April 2024 (Tafoya et al., 2024).

During the Fall 2024 semester, SEAS master's students reviewed proposals for all the projects, attended informational client webinars, and applied for the projects that interested them most. The BNGA project proposal, as part of a themed Master's Project course on Indigenous-Led Conservation and Climate Action, received many applications. Five students were selected for the BNGA project, based on a combination of:

- Interest in working with Indigenous Peoples and local communities;
- Prior experience with, or interest in, ecological or geospatial fieldwork and analysis, policy analysis, or environmental justice, and
- Potential to contribute in a meaningful way to project outcomes.

1.2 Project Purpose

The purpose of this Master's Project is to support BNGA's initiatives to strengthen Tribal conservation and restoration strategies in the Northern Great Plains (NGP) ecoregion by developing geospatial tools to assess ecological connectivity[5] and landscape change, as well as conducting policy analysis to prioritize federal funding for Indigenous-led grassland conservation initiatives (Figure 1.2).

[5] While there are many terms for connectivity, we use the term specifically to describe the overall capacity of landscapes to support ecological flows such as species movement, dispersal, and gene flow (Bouamrane & Cerasi, 2021).

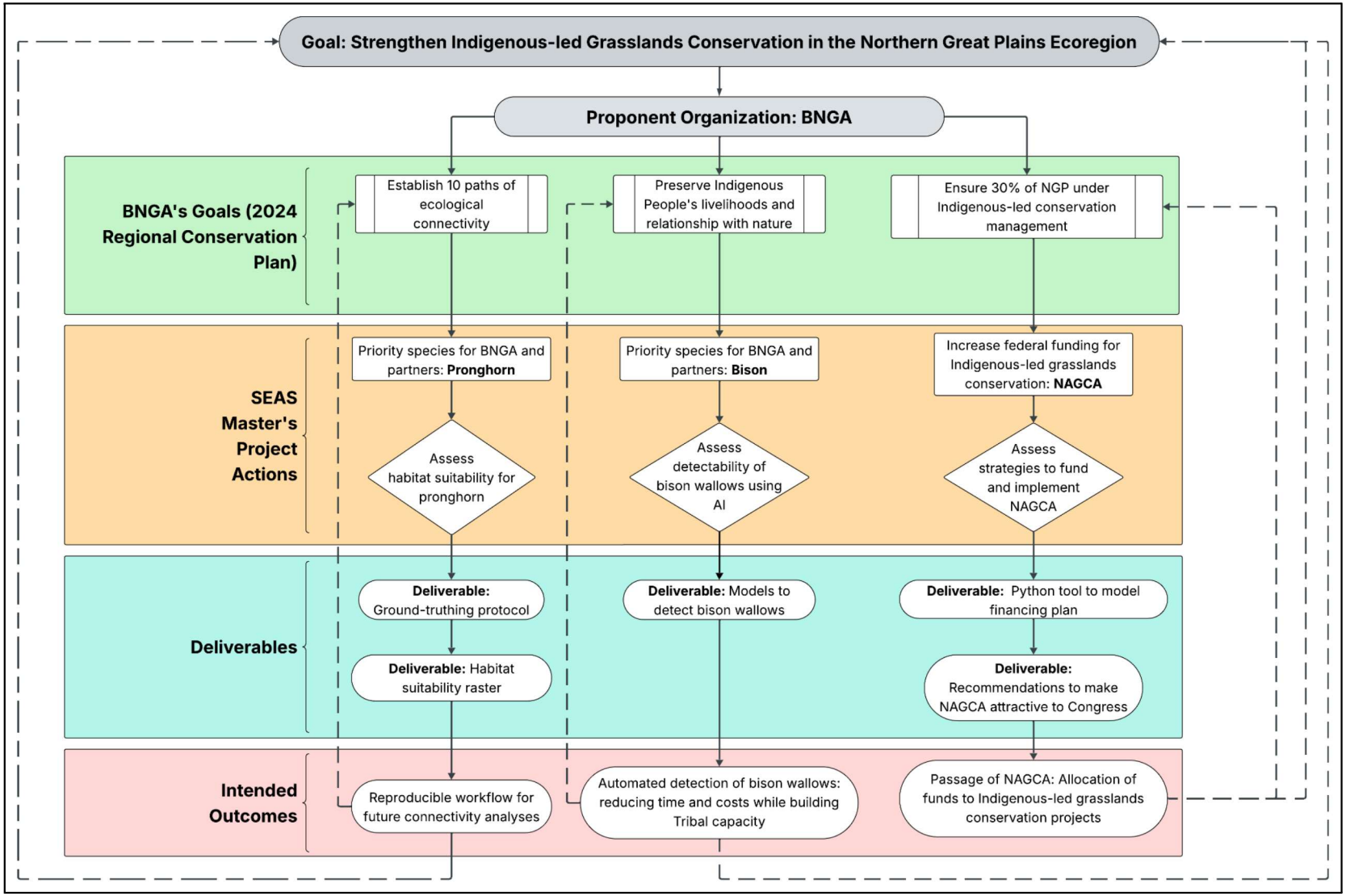


Figure 1.2. *The project actions, deliverables, and intended outcomes directly support the goals outlined in BNGA's 2024 Regional Conservation Plan, as well as a wider goal of strengthening Indigenous-led grasslands conservation in the NGP ecoregion. While the project components are unique in their disciplines, they are connected by their shared contribution to BNGA's goals.*

In this project, we focus on two priority species, chosen in collaboration with BNGA: pronghorn (*Antilocapra americana*) and American bison (*Bison bison*). Pronghorn are an endemic species[6] in the NGP ecoregion, though their distribution is shifting due to anthropogenic and climate forces such as agricultural expansion, energy and road development, and changing precipitation and vegetation patterns. These factors negatively impact landscape connectivity, which is critical for pronghorn life history and migratory patterns, leading to altered ecological interactions and subsequent effects on grassland ecosystems. Pronghorn also serve as an indicator species[7] in the NGP ecoregion because their presence is reflective of overall grassland ecosystem health (American Prairie, 2022).

Likewise, the American bison (*Bison bison*) is a symbol of resilience and resistance to land conversion (Knapp et al., 1999). We selected it as a species of interest due to its role as a keystone species[8] and ecosystem engineer[9], as well as its cultural significance to Native Nations as a major traditional food source (Brink, 2008). For more information on the ecological and cultural significance of bison, see Rytting & Kelly (2026).

1.2.1 Research Questions and Aims

The project addresses the following research questions:

1) Habitat Suitability for Pronghorn:
    a) What connectivity metrics can derive meaningful information about grassland habitat connectivity in the NGP ecoregion?
    b) What are the best software tools for preparing the required data and computing these metrics?
    c) What is the state of pronghorn (*Antilocapra americana*) habitability in Rocky Boy's Reservation, based on the connectivity tool run in this project? Which areas of the NGP ecoregion should be prioritized for grassland restoration?
2) Detectability of Bison Wallows Using Artificial Intelligence :
    a) Can artificial intelligence (AI) models accurately detect and characterize bison wallows, and what landcover types and soil textures are associated with detected wallowing?
    b) What are the limitations of AI-based object detection for identifying bison wallows in the NGP ecoregion? How do these limitations influence estimates of the magnitude and spatial distribution of disturbance?
    c) If bison wallows can be accurately identified, how can they contribute to restoration and connectivity of bison habitat?

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[6] An organism whose home range is confined to a specific geographic area (Sottosanti, 2026)

[7] An organism whose presence, absence, population density, or behavior reflects specific environmental conditions or the overall health of an ecosystem (Alexander et al., 2016; Costanzo et al., 2025; Rana et al., 2025)

[8] An organism that has a disproportionately large impact on its ecosystem; critical to ecosystem function and the survival of other species (National Geographic Society, 2025)

[9] An organism that physically alters its environment, affecting ecosystem structure and function (Nickell et al., 2018)

3) Federal Grasslands Policy Funding Strategy and Implementation:
    a) What are the politically and operationally feasible options for financing the North American Grasslands Conservation Act (NAGCA)?
    b) Based on existing federal incentive-based conservation funding programs and their associated challenges, how can NAGCA be designed to both earn the support of congressional delegations and be most effective in facilitating grassland conservation.

Guided by these questions, the project aims to:

1. Develop a pilot protocol for BNGA and their partners to use in assessing grassland ecological connectivity and evaluating prioritization areas, using pronghorn as a case study;
2. Assess landscape change in existing conservation programs, including disturbances by large herbivores such as bison and landscape change with associated disturbance and the temporal scale at which it occurs; and
3. Evaluate ways to fund and implement NAGCA to best support Indigenous-led grassland conservation and restoration efforts through an analysis of federal funding opportunities.

1.3 Project Scope

While each chapter of this project has its own audience, the entire report is applicable to BNGA and its partners in the 16 Native Nations who live within the NGP ecoregion.

1.4 Project Components

This report is organized into 6 chapters. Chapter 1 presents an introduction to the project and client. Chapter 2 describes the methodology for fieldwork and validation of ground-truthed geospatial data. The methods described in Chapter 2 inform the literature review of different connectivity metrics and tools presented in Chapter 3. Chapter 4 builds on both of these sections through the development of a habitat suitability model for pronghorn in the NGP ecoregion. Chapter 5 compares the use of Random Forest and Deep Learning models as tools for bison wallow detection. Finally, Chapter 6 provides recommendations for funding and implementing NAGCA. Together, the chapters make up a framework for supporting aspects of Indigenous-led grasslands conservation efforts in the NGP ecoregion.

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Chapter 2: Development of a Field Methodology for Validating Open-Source Geospatial Data from the Northern Great Plains Ecoregion

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2.1 Background & Rationale

This chapter discusses the GIS and field data collection methods for ground-truthing (Figure 2.1) that inform the subsequent chapters on connectivity metrics and pronghorn habitat connectivity. It serves as a pilot study of Rocky Boy's Reservation and could be used in the future by other Native Nations as they pursue similar field-based connectivity analyses.

In this chapter, we use the term *connectivity* specifically to describe the ability of species to move freely across a landscape without barriers (Bouamrane & Cerasi, 2021). The primary method discussed here is *ground-truthing*, defined as the validation of reference datasets using on-the-ground observations (Laszlo et al., 2022). The chapter stands alone as a description of field methods, while also acting as a framework for subsequent chapters on geospatial tools and pronghorn.

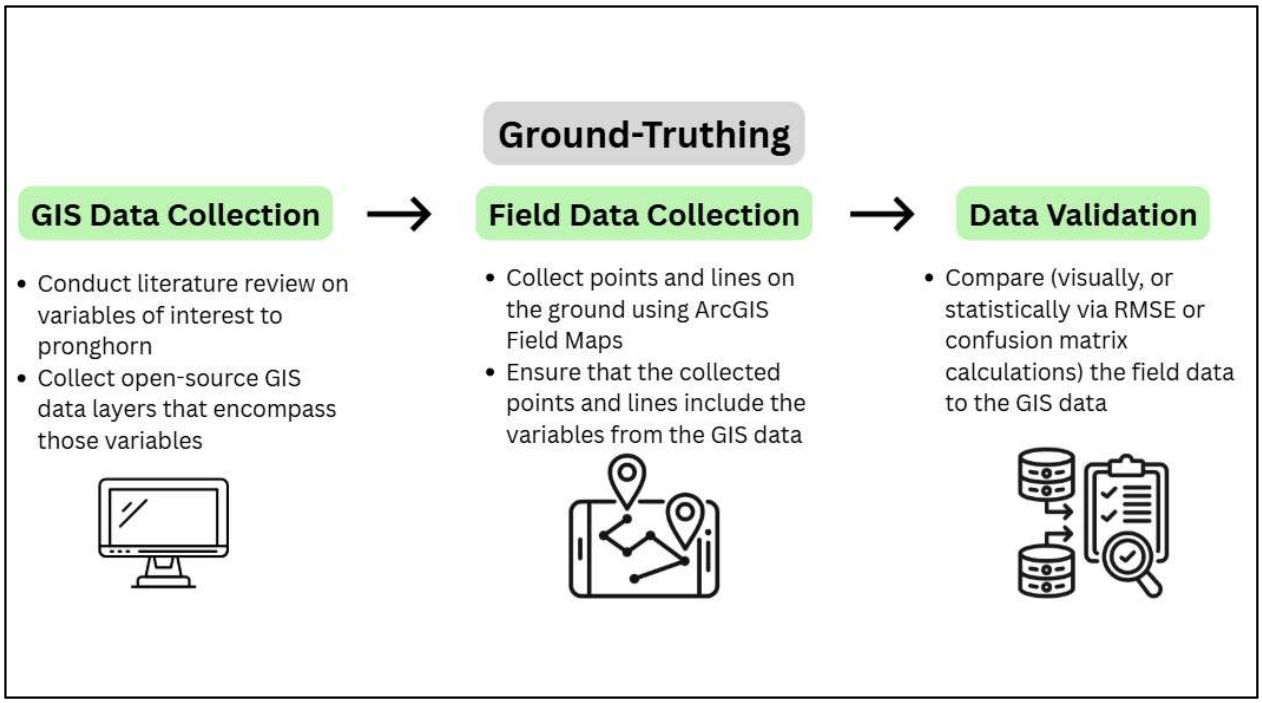


Figure 2.1. *Flowchart describing the project methods.*

The Buffalo Nations Grasslands Alliance (BNGA) is a Native-led 501(c)(3) that works with partners to support conservation and sustainable livelihoods across 16 Native Nations in the NGP ecoregion[10]. In the Fall of 2024, BNGA submitted a proposal for a Master's Project through the University of Michigan's School for Environment and Sustainability (SEAS). SEAS Master's Projects are applied research projects for client organizations addressing a sustainability research need over a one-and-a-half-year timeframe, with teams of approximately five graduate students spanning multiple environmental disciplines (SEAS, 2025). SEAS students are encouraged to sustain commitment to client organizations, past, present, and future. A team of SEAS master's

[10] In the context of this research, the Northern Great Plains (NGP) is delineated by the boundaries of the NGP ecoregion (see Figure 1.1 in Kelly, 2026).

students had completed a project for BNGA previously, from January 2023 – April 2024 (Tafoya et al., 2024).

Over the course of the Fall 2024 semester, SEAS master's students reviewed proposals for all the projects being offered, attended informational webinars hosted by the clients, and applied for the projects that interested them most. The BNGA project proposal, as part of a themed Master's Project course on Indigenous-Led Conservation and Climate Action, received many applications. Five students were selected for the BNGA project, based on a combination of:

- Interest in working with Indigenous peoples and communities;
- Prior experience with, or interest in, ecological or geospatial fieldwork and analysis, policy analysis, or environmental justice, and
- Potential to contribute in a meaningful way to project outcomes.

2.2 Study Area: Rocky Boy's Reservation

After consultation with colleagues from BNGA, we selected Rocky Boy's Reservation as the study area. Antonio Morsette (BNGA's Land Conservation Program Officer (LCPO)) was on-site to both facilitate access to data collection sites and connect the SEAS team with local knowledge-holders from the Rocky Boy Buffalo Project and the Chippewa Cree Tribe Natural Resources Department. The LCPO shared that the species of interest (pronghorn) was present on the Reservation. Furthermore, the Reservation's diversity of land-cover types (Figure 2.2) could provide many opportunities for ground-truthing.

Rocky Boy's Reservation is home to the Chippewa Cree Tribe. The Reservation is located in north-central Montana, and spans roughly 128,000 acres with 2,700 residents and 5,000 off-reservation members (Chippewa Cree Tribe, n.d.). An initial calculation of existing land cover data from LANDFIRE (2024a) shows that the Reservation consists of 50.50% Grassland, 25.24% Forest, 7.78% Shrubland, 5.40% Exotic, 5.03% Riparian, 4.28% Agriculture, 1.18% Developed, and 0.59% Water (Figure 2.3).

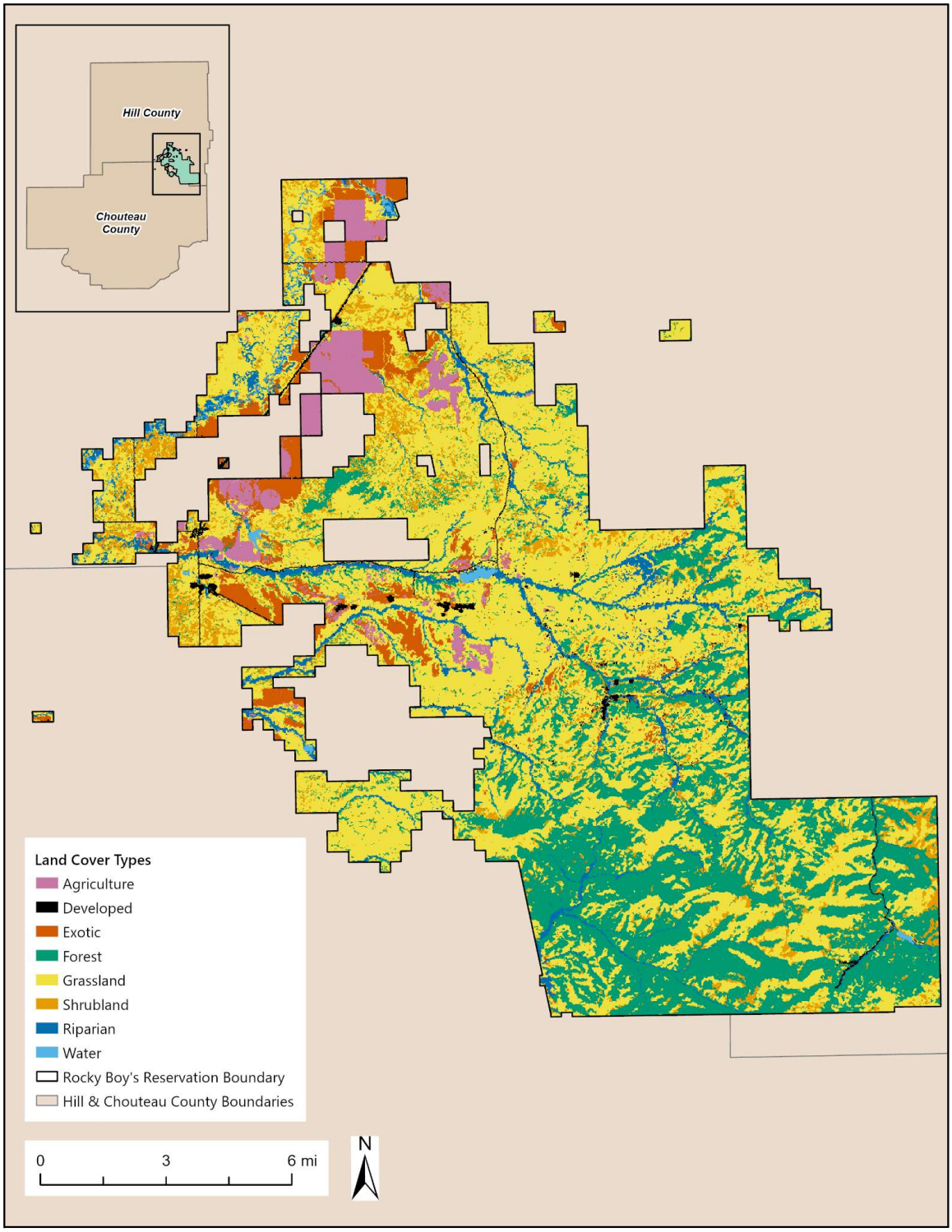


Figure 2.2. *Land Cover Types on Rocky Boy's Reservation. Sources: Land cover types from LANDFIRE Existing Vegetation Type (2024); County boundaries extracted from Esri "USA Counties - Generalized" layer (2020); Rocky Boy's Reservation Boundary extracted from BIA American Indian & Alaska Native Land Area Representations (2025).*

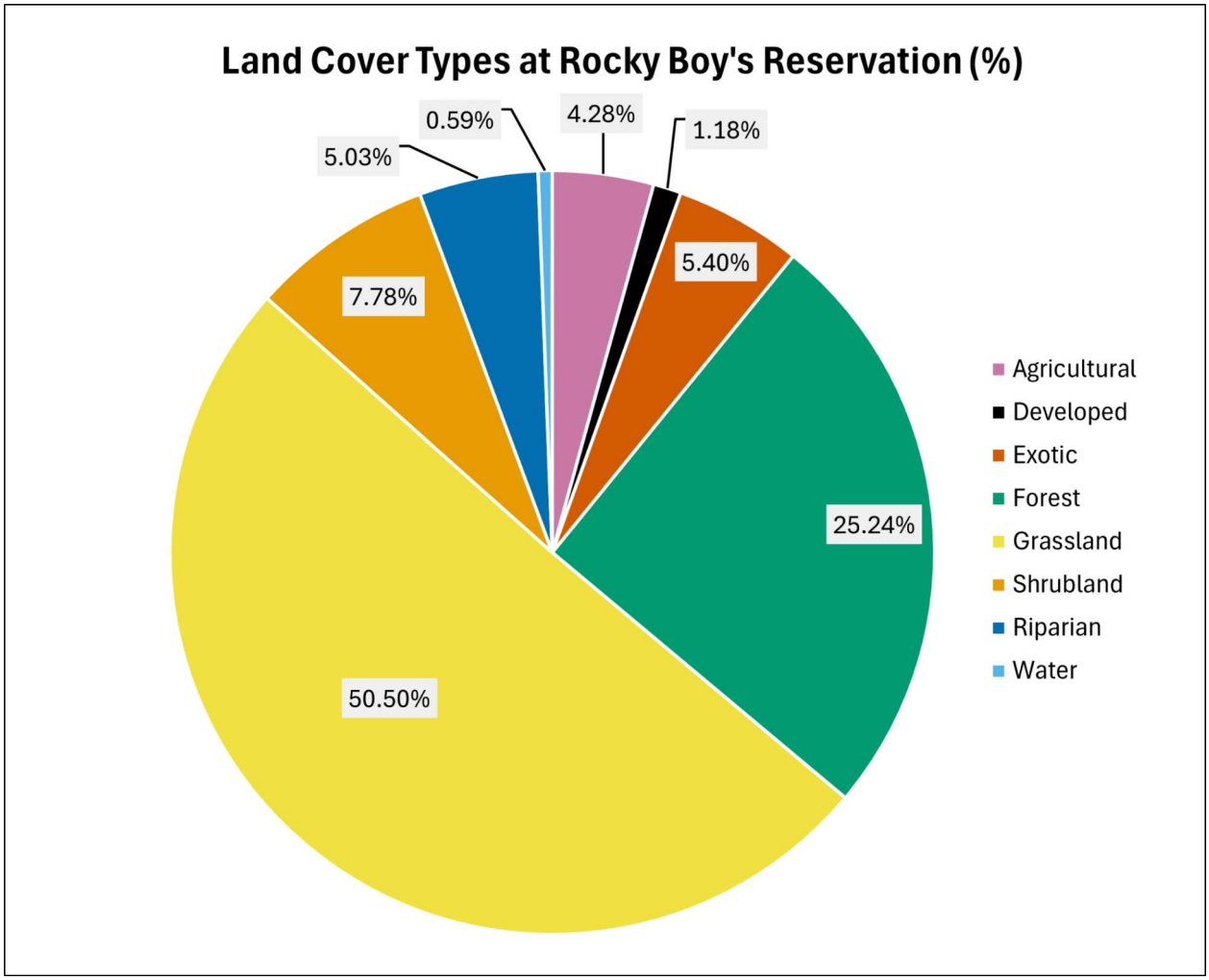


Figure 2.3. *Percentage of each land cover type on Rocky Boy's Reservation. Source: Land cover types from LANDFIRE Existing Vegetation Type (2024).*

2.3 Species Selection

In collaboration with BNGA, we chose pronghorn (*Antilocapra americana*) as the species of interest for the ecological connectivity component of the project. Pronghorn are an endemic species in the NGP ecoregion, though their distribution is shifting due to anthropogenic and climate forces such as agricultural expansion, energy and road development, and changing precipitation and vegetation. This distribution shift negatively impacts landscape connectivity, which is critical for pronghorn life history and migratory patterns, leading to altered ecological interactions and subsequent effects in the grassland ecosystem. Pronghorn serve as an indicator species in the NGP because their presence is reflective of the health of increasingly endangered grassland ecosystems (American Prairie, 2022; Manzer & Jones, 2020).

2.4 GIS Data Collection

This project involved two periods of data collection: (1) Existing open-source GIS data collection, and (2) Five (5) days of field data collection at Rocky Boy's Reservation in Montana.

A combination of literature review on habitat suitability modeling and guidance from BNGA informed the GIS data collection process. All layers were sourced from publicly available, open-access databases and resources to avoid extractive research practices and support the project's efforts towards knowledge co-production. Table 2.1 provides a complete list of the data sources ground-truthed for the pronghorn analysis.

Table 2.1. *Input data sources ground-truthed for the pronghorn analysis.*

Data Source	Description	Associated Variable(s) of Interest
U.S. Geological Survey, 3D Elevation Program. Elevation Source Data (3DEP) Seamless DEM Source (OPR). Reston, Virginia: USGS National Geospatial Program.	Digital elevation model	Topographic Position
Soil Survey Geographic Database (SSURGO)	Polygon boundaries of soil survey map units	Soil Properties
Existing Vegetation Type (EVT)	Categorical raster of vegetation communities	Vegetation Communities
Existing Vegetation Cover (EVC)	Categorical raster of vegetation cover	Percent Vegetation Cover
Existing Vegetation Height (EVH)	Categorical raster of vegetation height	Vegetation Height
U.S. Department of Agriculture, National Agricultural Statistics Service (NASS). Cropland Data Layer. 2024 Edition. Washington D.C., USDA-NASS Marketing and Information Services Office, February 27, 2025.	Categorical raster of land cover types	Land Cover Distance to Water
United States Census Bureau. TIGER/Line Shapefiles: Roads. Geographic Products Branch, Washington, DC.	Line shapefiles for all roads in the study area	Distance to Roads

Decisions of what data sources and layers to use, as well as which species to focus on, were made after literature review and consultation with experts from BNGA. Data sources were centered on habitat variables relevant to pronghorn, based on literature review. These variables included soil type and compaction, land cover, vegetation community type, vegetation height, fence location/type/condition, distance to roads, distance to water, and elevation (Bean et al., 2024; Gates et al., 2012; Irwin & Cook, 1985; Jakes et al., 2020; Poor, 2010; Poor et al., 2012; Rue & Ranglack, 2025; Zeller et al., 2021).

In July 2025, SEAS team members collected field data to verify the accuracy of the open-source reference data. While open-source GIS data and tools offer a cost-effective and collaborative approach to spatial analysis, drawbacks exist. One such challenge is that open-source data is not always reliable, and its accuracy should be verified prior to further analysis (Malakar & Roy, 2024). In habitat suitability modeling, a common way to validate a dataset's accuracy is through ground-truthing: the process of comparing a reference dataset (such as satellite imagery) to in-situ (e.g., field-based) observations (Laszlo et al., 2022). Through our field data collection, we attempted to mitigate this challenge.

2.5 Field Data Collection

Field data collection took place over five (5) days (July 27 to July 31, 2025) on Rocky Boy's Reservation in Montana. The purpose of collecting field data was to ground-truth the chosen open-source geospatial data. We collected three-hundred-ninety-two (392) data points and fifty-five (55) lines using ArcGIS Field Maps, utilizing an adaptive sampling method that allowed the team to adjust sampling protocols as the trip progressed.

Prior to the trip, SEAS team members worked with BNGA colleagues to write Standard Operating Procedures (SOPs) for data collection. The SOPs can be found in Appendix A, and provide a step-by-step framework for reproducing the field methodology, should BNGA or its partners choose to complete follow-up or separate ecological connectivity studies for additional areas or priority species in the NGP ecoregion. Out of respect for the Tribe's sovereignty, and in line with our goal to avoid extractive research practices, we also wrote a letter to the Chippewa Cree Tribe asking for permission to collect data on their land.

To facilitate the field data collection, we developed a field survey in ArcGIS Field Maps, a licensed software tool developed by Esri that allows the user to collect data in the field, usually from a mobile phone with a Bluetooth connection (Nowak et al., 2020).

Before creating the ArcGIS Field Maps workflow, the team decided which variables to collect. These decisions were made based on a combination of literature review on attributes important to pronghorn activity and conversations with BNGA about other recommended attributes. For more detail on these attributes, refer to Hennessy & Buller (2026). A complete list of variables used in the workflow can be found in Table 2.2.

Table 2.2. *Attributes used in the ArcGIS Field Maps workflow (points and lines - polygons were not collected).*

Attribute Field	Description
Surveyor Full Name	First and last name of the person recording the point/line
Date and Time of Sample	Date and time that the point/line/polygon is recorded
Property Owner	Name of the person/entity that owns the land on which the sampling is happening
Access Granted to Site	Whether or not access was granted to the sampling site
Authorization	Name of the person/entity that granted access to the sampling site
Site Name	Name of the sampling site
Sample ID	Sample ID
Sampling Method	Method used to collect the sample (transect, etc.)
Elevation	Elevation (meters) of the sample
Slope	Slope (percentage) of the sample
Aspect	Aspect (direction) of the sample
Temperature	Temperature (in °F) at the time of sampling
Weather	Weather at the time of sampling
Noise Type	Type of noise at the sampling site (natural, anthropogenic, no noise)
Noise Level	Noise level at the sampling site (low, moderate, high)
Road Access	Whether or not a road is accessible from the sampling site
Distance to Road	If a road is accessible, distance to the road from the sampling site (meters)
Road Surface Type	If a road is accessible, road surface type (dirt, paved)
Trail Access	Whether or not a trail is accessible from the sampling site

Attribute Field	Description
Distance to Trail	If a trail is accessible, distance to the trail from the sampling site (meters)
Soil Texture	Soil texture at the sampling site, following USDA NRCS "Soil Texture By Feel" guidelines/flowchart
Soil Penetration	Depth to soil penetration (centimeters), using a soil penetrometer
Land Cover	Land cover type, following LANDFIRE existing vegetation type reference data
Vegetation Community	Vegetation community type, following LANDFIRE existing vegetation type reference data
Vegetation Height	Vegetation height (centimeters)
Percent Vegetation Cover	Visual estimate of the percentage of the sampling site that is vegetated
Distance to Wallow[11]	If a bison wallow is present, distance to the wallow from the sampling site (centimeters).
Diagnostic Vegetation	If a bison wallow is present, type of dominant diagnostic vegetation also present, following LANDFIRE existing vegetation type reference data
Fence Condition	If a fence is present, condition of the fence (good, neutral, poor)
Fence Height	If a fence is present, height of the fence from ground to top wire/rail (cm)
Fence Gap Height	If a fence is present, height of the gap from ground to bottom wire/rail (cm)
Top Wire Type	If a fence is present, material type of the top wire/rail (barbed, smooth, other)
Bottom Wire Type	If a fence is present, material type of the bottom wire/rail (barbed, smooth, other)

[11] While attributes relevant to bison wallow detection (Distance to Wallow and Diagnostic Vegetation) were included in the ArcGIS Field Maps workflow, they were not used in the Rytting & Kelly (2026) analysis due to low sample size.

Attribute Field	Description
Wildlife Types	Wildlife observed at the sampling site
Distance to Water	If water is nearby, distance to the water body from the sampling site
Water Body Type	If water is nearby, type of water body (perennial stream, ephemeral stream, lake, wetland, river)
Water Body Audible	If water is nearby, whether or not the water body is audible from the sampling site
Photos	Photos of the sampling site (North, South, East West, Above - canopy/sky above site, Below - ground at the site, Site - aerial view of the site)
Additional Notes	Any additional notes/observations not captured in the workflow.

Point and line features were recorded at various sites around Rocky Boy's Reservation using an adaptive sampling strategy and following predetermined Standard Operating Procedures (see Appendix A). In total, three-hundred-ninety-two (392) data points and fifty-five (55) lines were collected (Figure 2.4).

As part of the adaptive sampling approach, many points were taken in areas of high variation and fewer in areas of low variation (Bolstad, 2022). This method also allowed the team to make real-time adjustments to data collection protocols. Fieldwork was time-limited, and having a flexible sampling strategy ensured that as many features as possible could be collected for ground-truthing.

The sampling protocol was informed by prior studies focused on field sampling strategies in grassland and rangeland environments. A point-intercept method was used for transects due to this being a small-scale analysis (as opposed to landscape-level) (Çakal et al., 2012; Sparrow et al., 2020). Quadrats were also used along the transects to record biodiversity measurements (De Stefano et al., 2021). The USDA's Guide to Soil Texture by Feel (USDA, 2022) provided a basis for soil texture determinations. In cases where putting down a transect or quadrats was not possible due to time or safety constraints, random points were collected instead.

Data were collected using 50-meter transects, with a point taken every 10 meters using a 1-meter by 1-meter quadrat to record the properties noted in Table 2.2[12]. We also carried GPS units: an RTK-enabled[13] Trimble, and a moderate-accuracy Garmin as backup in case technical

[12] While a point was taken for every sample site, not all attributes were collected at every site. In some cases, this was intentional (e.g., bison wallows were only documented in the bison pasture). In others, missing attributes were accidental or omitted due to time constraints.

[13] RTK (real-time kinematic) GPS provides high-accuracy, centimeter-level measurements (Trimble, 2024).

difficulties were encountered with the Trimble[14]. An explanation of the different GPS units, their estimated accuracy, and recommendations for when to use them can be found in Table 2.3. Other equipment included meter sticks for measuring vegetation height, a spray bottle with water to wet and manipulate the soil samples by hand, a small shovel to access the soil, a pocket penetrometer to measure soil compaction, and a laser rangefinder to measure distances to water and roads. For safety, team members wore high-vis vests when taking measurements along roads. Most points were collected via the ArcGIS Field Maps app on a mobile phone with Bluetooth connection to the RTK-enabled Trimble, while others were collected using the Garmin units. For the complete workflow, see the SOP document in Appendix A. Additionally, a cost analysis for the fieldwork equipment can be found in Appendix B.

Table 2.3. *Comparison of different GPS units used in the field methodology.*

Device	Level of Accuracy	When to Use
RTK-enabled Trimble Catalyst DA2[15] with range pole	High (sub-meter)	When precise data is needed (such as for ground-truthing).
Garmin eTrex® 10[16]	Moderate (3 - 4 meters)	Can also be used for ground-truthing, but will be less accurate than a sub-meter device. We had a few of these on hand in case of technical difficulties with the Trimble.

[14] During fieldwork, we used the Garmin units in the high-elevation mountainous areas due to technical difficulties connecting ArcGIS Field Maps with the Trimble and our cell phones. It is also important to note that this is the only time during fieldwork that we used the Garmin units, so it is not a good enough sample size to ascertain accuracy of the device.
[15] Trimble. (2024). Trimble DA2: GNSS Receiver for the Trimble Catalyst Service. 2024 Spec Sheet.
[16] Garmin. (2020). eTrex 10/20/20x/30/30x Owner's Manual.

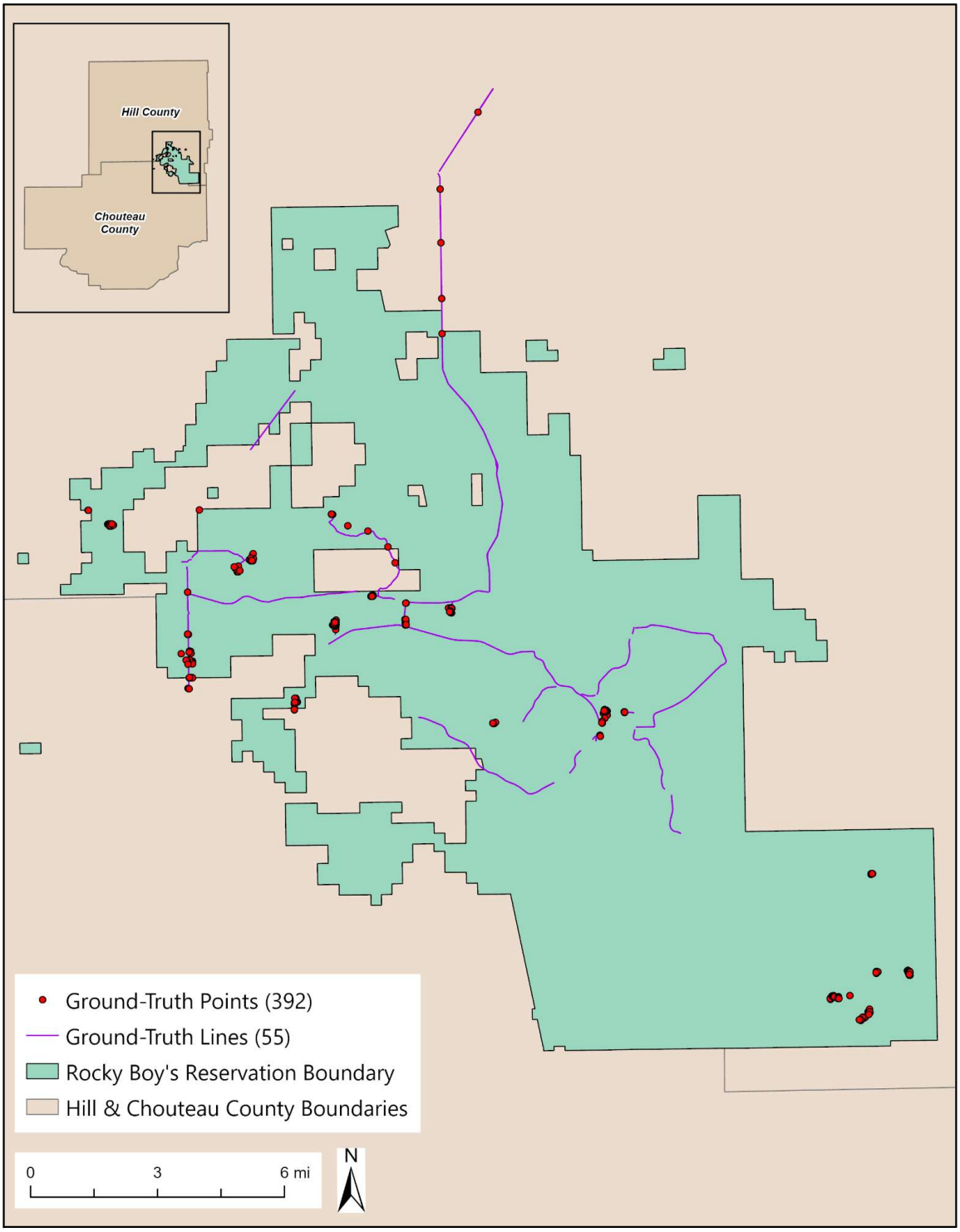


Figure 2.4. *Map of collected data points and lines in the study area. Most points utilized a point-intercept transect method. Sources: Ground-truth points and lines collected in the field by SEAS project team (2025); County boundaries extracted from Esri "USA Counties - Generalized" layer (2020); Rocky Boy's Reservation Boundary extracted from BIA American Indian & Alaska Native Land Area Representations (2025).*

2.6 Results: Validating Data Sources

Validating open-source reference data is important for predicting model reliability (Boldstad, 2022). After collecting our field data, we conducted a comparison between the field and reference datasets. For quantitative variables (e.g., elevation), error calculations involved computing a Root Mean Square Error (RMSE)[17]. A large RMSE indicates that errors are spread widely about the mean, while a smaller RMSE indicates that the errors are closer to the mean. Generally (but not always), a smaller RMSE is better and demonstrates higher accuracy (Boldstad, 2022). For qualitative variables, we displayed error between ground-truth and reference datasets with confusion matrices (Lillesand et al., 2015).

We calculated RMSEs for the 30m and 10m digital elevation models (DEM), LANDFIRE Existing Vegetation Height, and LANDFIRE Existing Vegetation Cover. We created confusion matrices for our qualitative variables: US Census Bureau roads, USDA soils, LANDFIRE Existing Vegetation Type, and the USDA Cropland Data Layer.

2.6.1 Elevation

Elevation in the study area ranged from 782 to 2107 meters above sea level (msl) (Figure 2.5).

[17] RMSE is a measure of positional error that looks at the spatial difference between actual and observed values (e.g., ground-truthed and reference data points) (Bolstad, 2022).

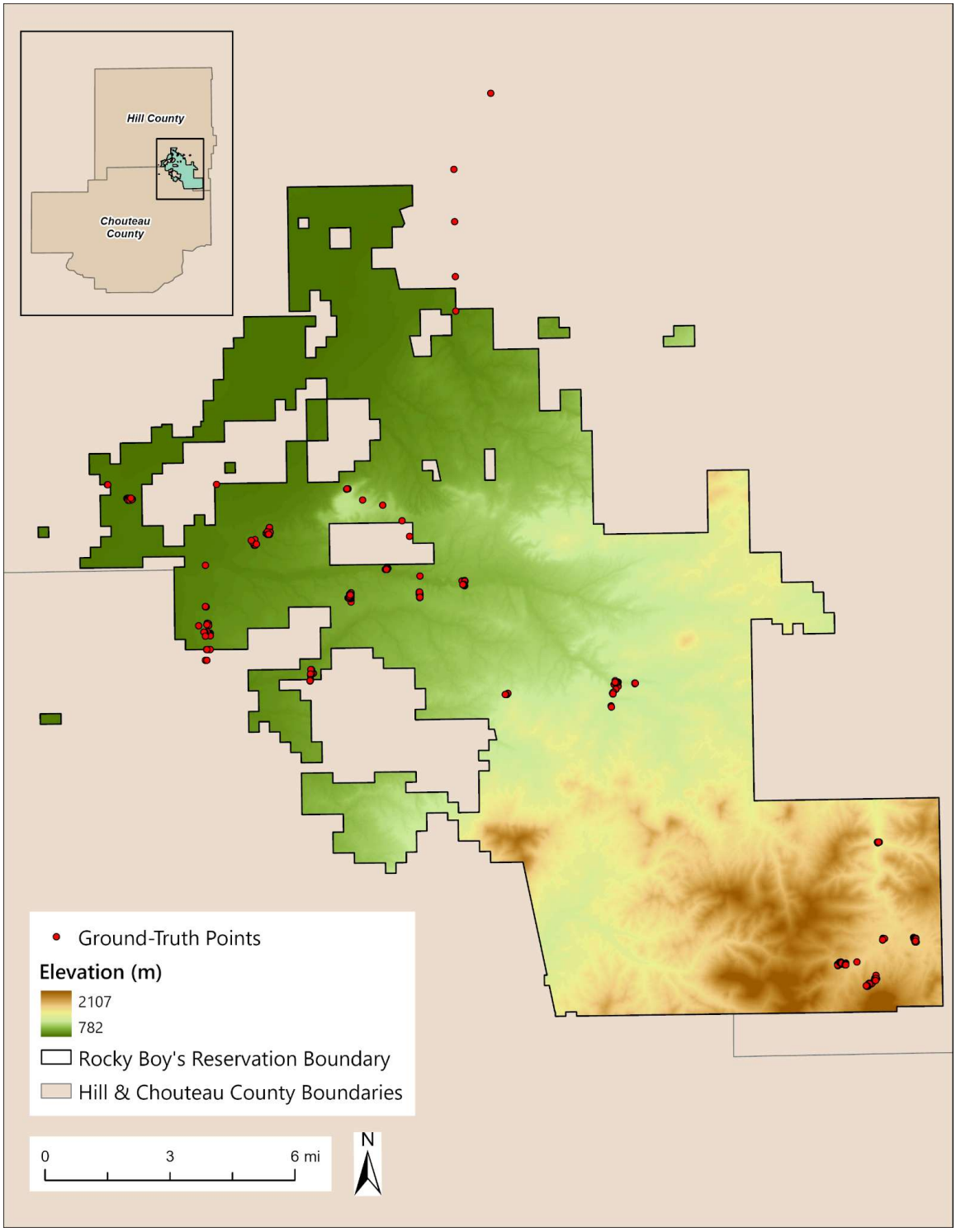


Figure 2.5. *Elevation on Rocky Boy's Reservation ranges from 782 - 2101 meters above sea level. Sources: Ground-truth points and collected in the field by SEAS project team (2025); Elevation from USGS 30m DEM (2024); County boundaries extracted from Esri "USA Counties - Generalized" layer (2020); Rocky Boy's Reservation Boundary extracted from BIA American Indian & Alaska Native Land Area Representations (2025).*

RMSE for the DEM (Table 2.4) varied between the 10m and 30m rasters. Further variation appeared when the Garmin eTrex points were removed from the calculation. Without the Garmin-collected points, the RMSE was between 9.85 and 9.87. Given that a typical RMSE value for the USGS DEM falls between 8-15 meters (Gesch et al., 2014), these values indicate that the DEM is highly accurate. However, including the Garmin points resulted in an RMSE between 20.35 and 20.24. The difference in RMSE could be due to the fact that we used the Garmin eTrex devices in higher elevation, mountainous areas. The sharp increase in elevation, combined with the 3 - 5 meter accuracy of the consumer-grade Garmin devices, could have caused the error to increase as well.

Table 2.4. *DEM RMSE - Overall*

Dataset	Sample Count[18]	Average Elevation (DEM)	Average Elevation (Sample)	RMSE
10m DEM	330	1063.68	1059.44	20.35
10m DEM, without Garmin eTrex® 10	251	922.67	917.76	9.87
30m DEM	330	1063.59	1059.44	20.24
30m DEM, without Garmin eTrex® 10	251	922.43	917.76	9.85

[18] Some of the data validation tables have varying sample counts. While a point was taken for every sample site, not all attributes were collected at every site. In some cases, this was intentional (e.g., bison wallows were only documented in the bison pasture). In others, missing attributes were accidental or omitted due to time constraints.

We also considered differences in RMSE between low- and high-elevation areas. Those calculations (Table 2.5) demonstrate that low- elevation areas – which we define as being less than 1,000 meters above sea level – tend to have a lower RMSE in both the 10m and 30m DEM. This result indicates that either DEM could work well, given that the majority of the study area falls within low-elevation areas. High-elevation areas performed worse, with an RMSE between 31.16 - 31.35 for both the 10m and 30m DEM. We recommend using either the 10m or 30m DEM for analyses of low-elevation areas, with the choice of resolution dependent on factors such as level of detail required and available computing space.

Table 2.5. *DEM RMSE - Low vs. High Elevation Areas*

Dataset	Sample Count	Average Elevation (DEM)	Average Elevation (Sample)	RMSE
10m DEM, low elevation areas (<1,000 msl)	211	888.26	883.62	9.68
10m DEM, high elevation areas (>1,000 msl)	119	1374.73	1371.18	31.35
30m DEM, low elevation areas (<1,000 msl)	211	888.11	883.62	9.64
30m DEM, high elevation areas (>1,000 msl)	119	1374.73	1371.18	31.16

2.6.2 Existing Vegetation Height

Overall RMSE for Existing Vegetation Height (EVH) (Figure 2.6, Table 2.6) followed a similar pattern to the DEM. The sample dataset that did not include the Garmin points had a lower RMSE than the one with the Garmin points. However, the RMSE for EVH was in the hundreds, indicating significant positional and temporal error. There is no published 'acceptable' RMSE range for LANDFIRE datasets, including EVH.

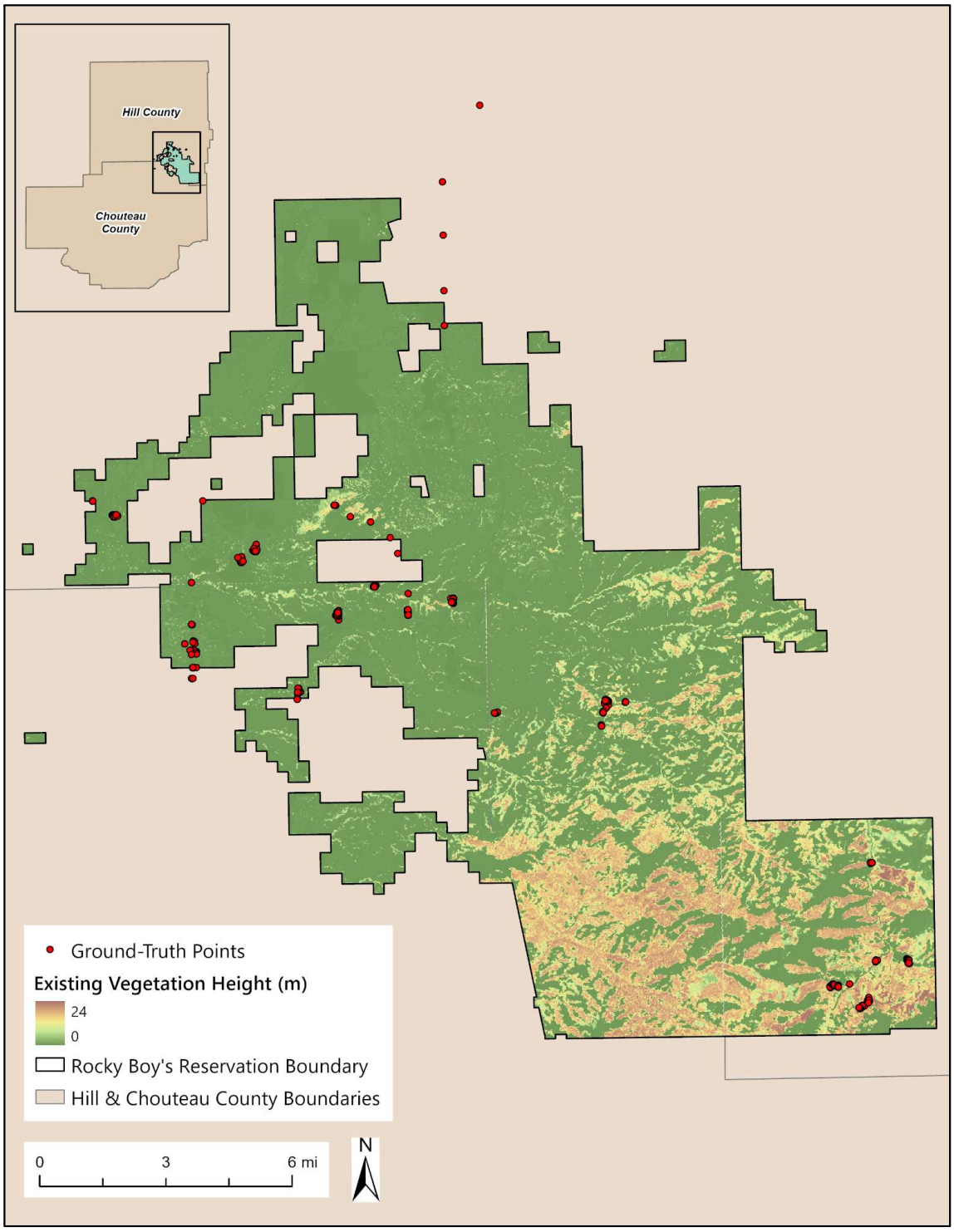


Figure 2.6. *Existing Vegetation Height for Rocky Boy's Reservation. Sources: Ground-truth points and collected in the field by SEAS project team (2025); Existing Vegetation Height from LANDFIRE (2024); County boundaries extracted from Esri "USA Counties - Generalized" layer (2020); Rocky Boy's Reservation Boundary extracted from BIA American Indian & Alaska Native Land Area Representations (2025).*

Table 2.6. *LANDFIRE Existing Vegetation Height Overall RMSE*

Dataset	Sample Count	Average Vegetation Height (Reference)	Average Vegetation Height (Sample)	RMSE
30m LANDFIRE Existing Vegetation Height (2024)	330	259.30	20.00	586.80
30m Existing Vegetation Height (2024), without Garmin eTrex® 10	251	89.31	26.41	224.60

As a comparison, we also did a breakdown of EVH by the vegetation type: herbaceous, shrubland, and agricultural. These vegetation types corresponded directly to the measurements we took in the field, whereas the overall values in Table 2.6 included classes such as water and development. Table 2.7 reflects these adjustments. Herbaceous plants (proxy for grassland) had the lowest RMSE, at 33.75. Due to a high RMSE, we caution against the use of the LANDFIRE EVH layer and recommend using a different data source for vegetation height.

Table 2.7. *LANDFIRE Existing Vegetation Height RMSE by Vegetation Type*

Dataset	Sample Count	Average Vegetation Height for Reference	Average Vegetation Height for Sample	RMSE
30m Existing Vegetation Height - Herb	156	30.71	26.78	33.75
30m Existing Vegetation Height - Shrub	49	80.00	10.82	77.99
30m Existing Vegetation Height - NASS (Agriculture)	6	0.00	60.83	63.22

2.6.3 Existing Vegetation Cover

The Existing Vegetation Cover (EVC) (Figure 2.7, Table 2.8) dataset had a slightly better RMSE when compared to EVH, at 34.34 and 36.54. This could indicate relatively consistent percent vegetation over time, resulting in less positional error between observed and predicted values. There is no published ‘acceptable’ RMSE range for LANDFIRE datasets, including EVC. Due to a high RMSE, we caution against the use of the LANDFIRE EVC layer and recommend using a different data source for percent vegetation cover.

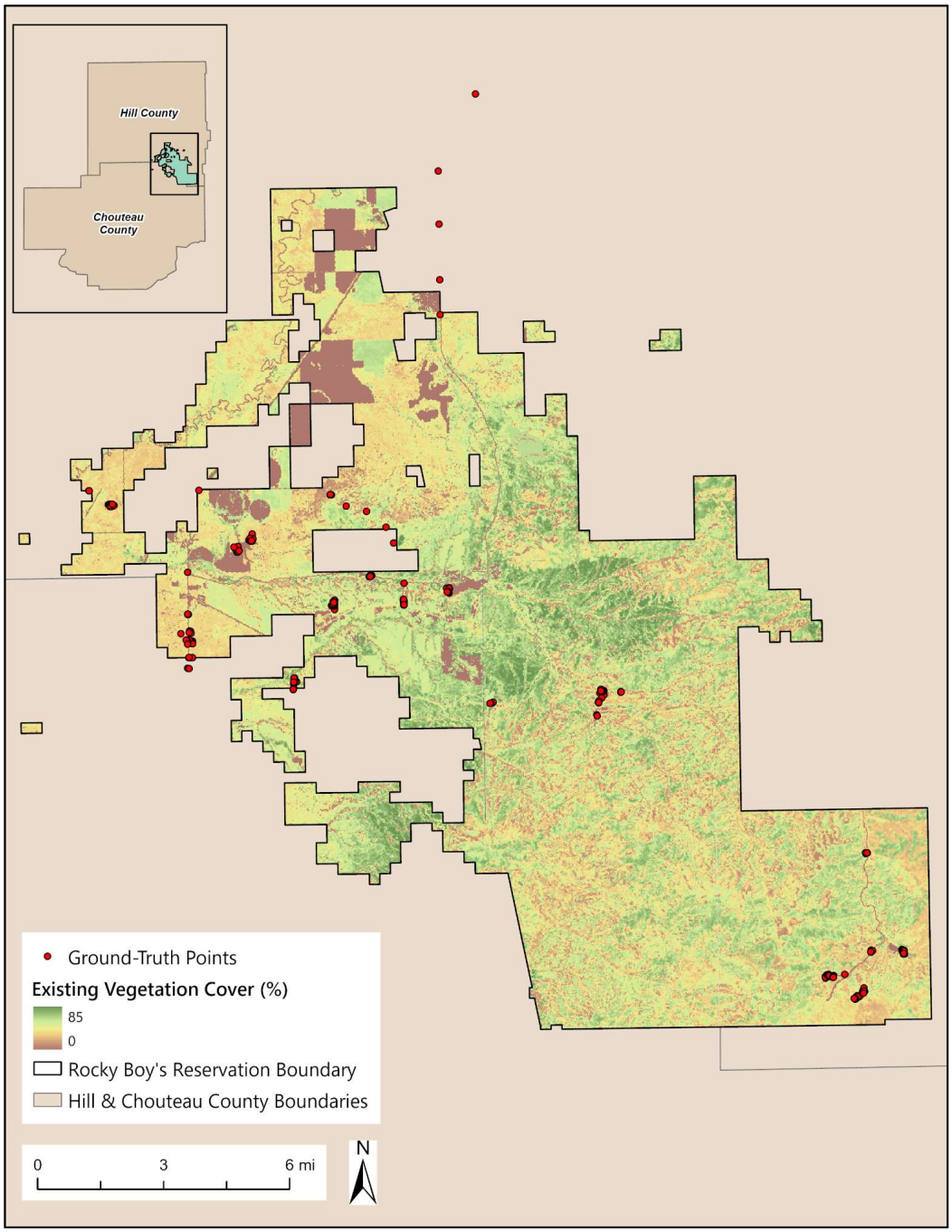


Figure 2.7. *Existing Vegetation Cover at Rocky Boy's Reservation. Sources: Ground-truth points and collected in the field by SEAS project team (2025); Existing Vegetation Cover from LANDFIRE (2024); County boundaries extracted from Esri "USA Counties - Generalized" layer (2020); Rocky Boy's Reservation Boundary extracted from BIA American Indian & Alaska Native Land Area Representations (2025).*

Table 2.8. *LANDFIRE Existing Vegetation Cover RMSE*

Dataset	Sample Count	Average % Vegetation Cover (Reference)	Average % Vegetation Cover (Sample)	RMSE
30m LANDFIRE Existing Vegetation Cover (2024)	330	28.63	15.82	34.34
30m Existing Vegetation Cover (2024), without Garmin eTrex® 10	251	30.61	20.84	36.54

2.6.4 Roads

With respect to roads, (Figure 2.8, Table 2.9), we verified both the road name and location. Only 10% of the road names matched the reference dataset, though 43 of those classified as “not a match” had a level of uncertainty because the name either did not match completely, or no name was provided in the reference data. This finding indicates that the roads dataset is inaccurate with regard to names.

The road location is slightly more valuable for our analysis, as it tells us whether the roads are where the data say they are. 61% of the road locations matched the reference data, which tells us that this is a moderately accurate dataset. We recommend the use of this roads dataset for studies that rely on road location rather than name. A drawback of this dataset, however, is that it does not get into details about road materials (e.g., paved vs dirt). Depending on the goals of future studies, a more comprehensive dataset that includes not just road location and name, but also variables like road composition, might be more appropriate.

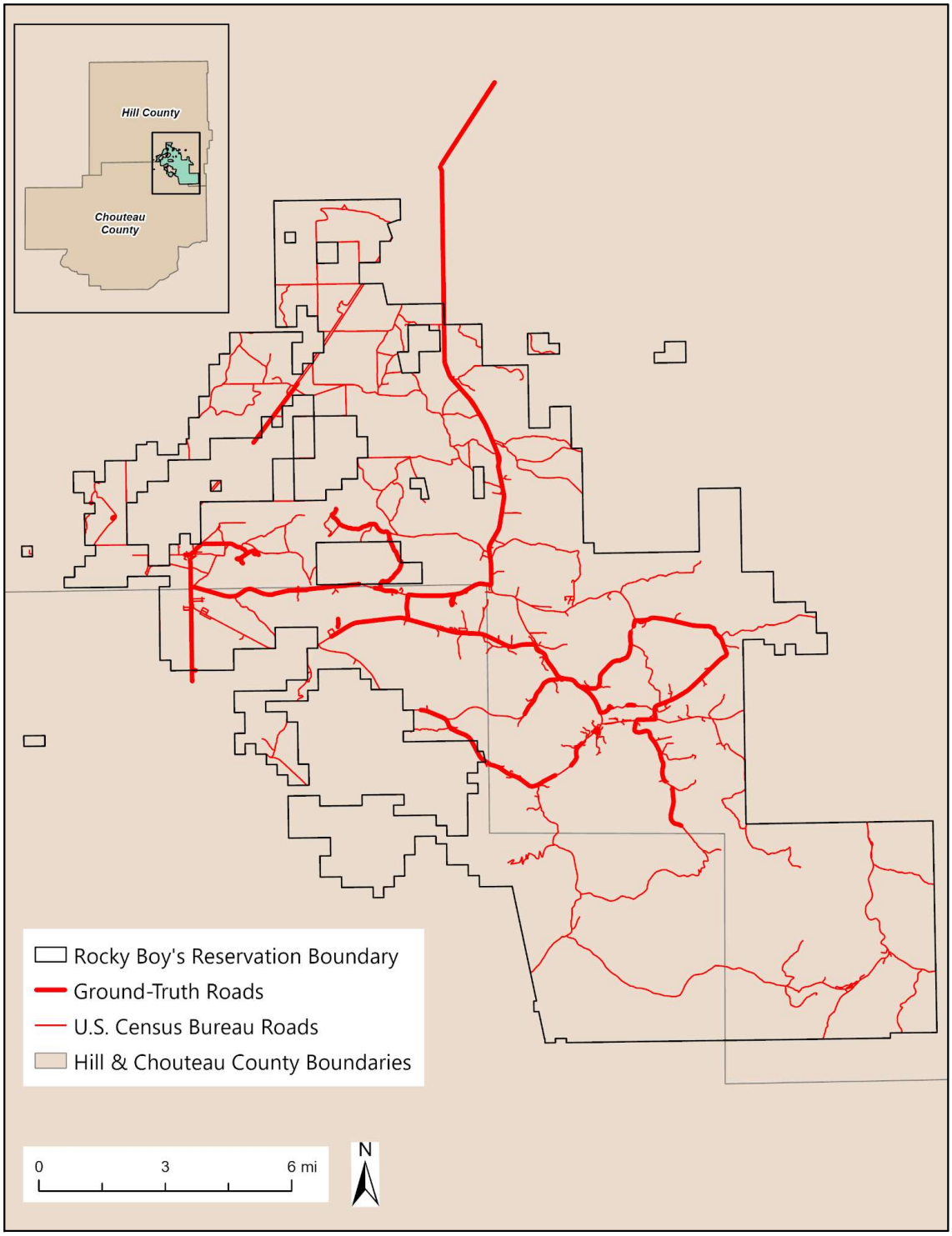


Figure 2.8. *U.S. Census Roads data compared to the ground-truthed roads. Sources: Ground-truth lines collected in the field by SEAS project team (2025); Roads from U.S. Census Bureau (2024); County boundaries extracted from Esri "USA Counties - Generalized" layer (2020); Rocky Boy's Reservation Boundary extracted from BIA American Indian & Alaska Native Land Area Representations (2025).*

Table 2.9. *U.S. Census Bureau Roads Confusion Matrix.*

Dataset	Sample Count	Match	Not a Match	Accuracy (%)
United States Census Bureau. TIGER/Line Shapefiles: Roads (*Road names*)	55	6	49	10.99
United States Census Bureau. TIGER/Line Shapefiles: Roads (*Road locations*)	55	34	21	61.81

2.6.5 Soils

The soils dataset was the most accurate of all of the input data, with 96% of the samples matching the reference data (Table 2.10). The SSURGO database is a reliable resource, and we recommend its use.

Table 2.10. *USDA Soils Confusion Matrix.*

Dataset	Sample Count	Match	Not a Match	Accuracy (%)
SSURGO Soils Geographic Database	28	27	1	96.43%

2.6.6 Existing Vegetation Type

The LANDFIRE 2024 Existing Vegetation Type (EVT) raster had an accuracy of 24.77%, with 27 out of 109 samples matching the reference dataset (Table 2.11). The top vegetation community in the study area is Northwestern Great Plains Mixedgrass Prairie (Figure 2.9). Due to the relatively low accuracy of the dataset, we caution against using LANDFIRE EVT for analyses.

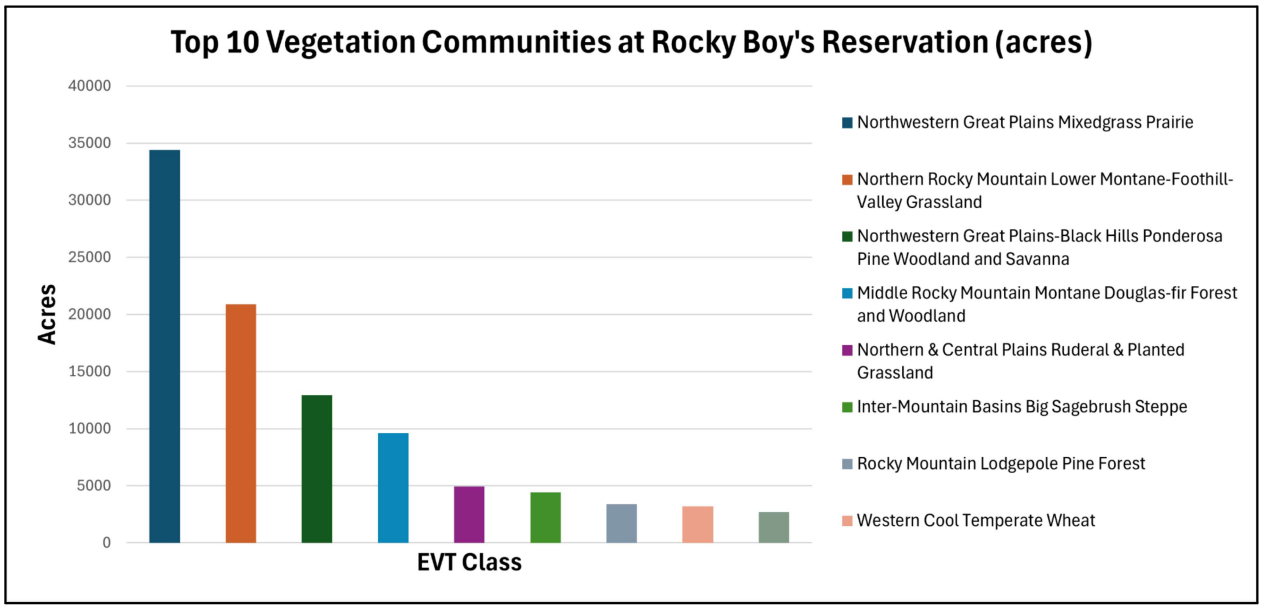


Figure 2.9. *Top 10 LANDFIRE Existing Vegetation Types at Rocky Boy's Reservation. Source: LANDFIRE Existing Vegetation Type (2024).*

Table 2.11. *LANDFIRE Existing Vegetation Type Confusion Matrix.*

Dataset	Number of Samples	Match	Not a Match	Accuracy (%)
30m LANDFIRE Existing Vegetation Type (2024)	109	27	82	24.77

2.6.7 USDA Cropland Data Layer vs. EVT

Finally, we compared the USDA Cropland Data Layer (Figure 2.10) to the LANDFIRE EVT raster (Table 2.12). Both datasets share a land cover classification, and it was important to determine which one might be a more accurate representation of land cover for the pronghorn analysis. The 30m and 10m Cropland Data Layers are almost 10% more accurate than the 30m LANDFIRE raster. Because they are so similar, either the 30m or 10m Cropland Data Layer could work for the analysis. The choice of layer might depend on factors such as the scope of analysis and computer capacity, as well as temporal scope (the 10m version was only introduced in 2024). 30m rasters are less detailed than 10m rasters, meaning that they take up less computer

space and work better for landscape-level analyses. 10m rasters are better for smaller study areas that perhaps require more fine-scale analysis.

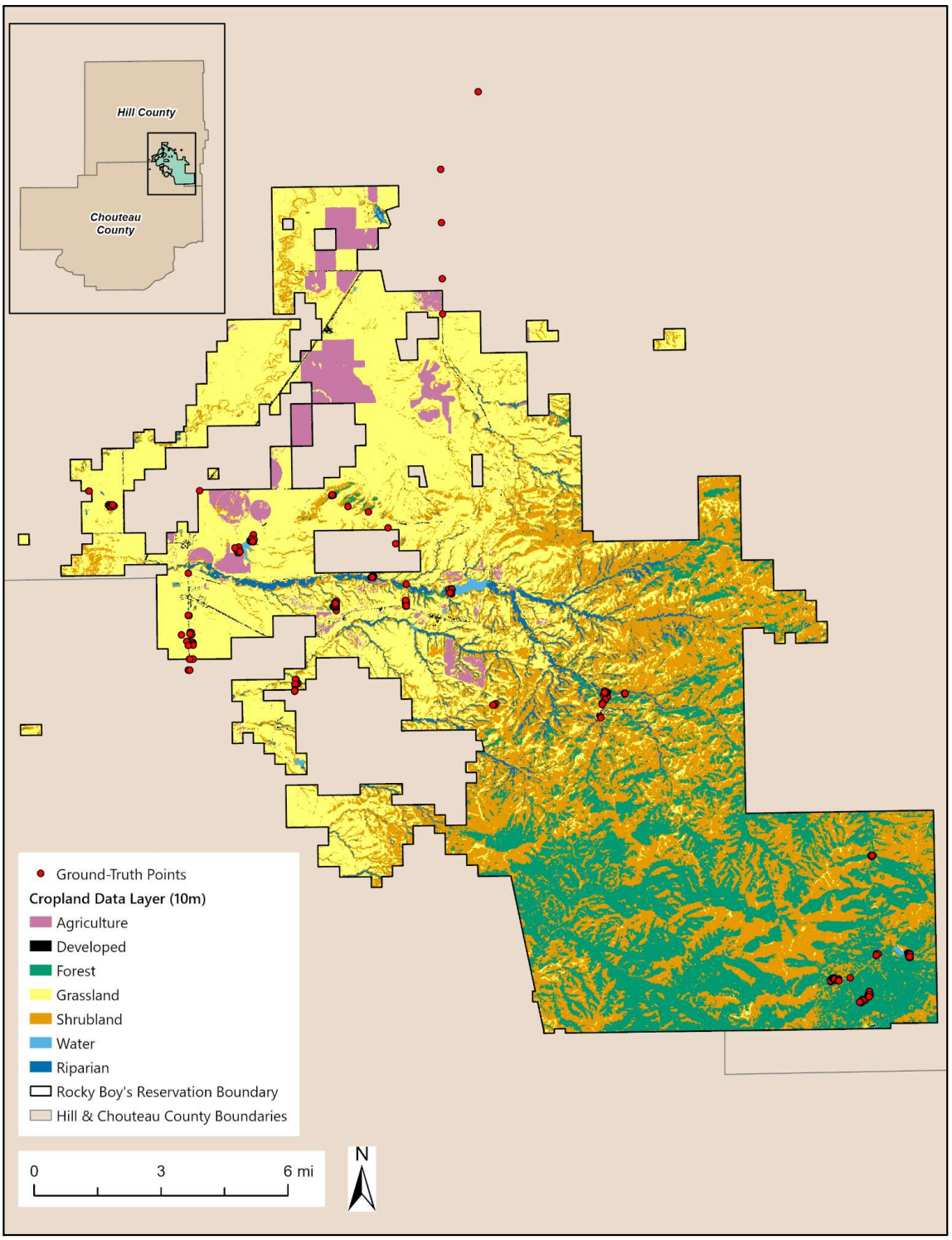


Figure 2.10. *USDA Cropland Data Layer, 10 meter raster.*

Table 2.12. *USDA Cropland Data Layer Confusion Matrix & Comparison to LANDFIRE EVT.*

Dataset	Number of Samples	Match	Not a Match	Accuracy (%)
30m LANDFIRE Existing Vegetation Type (2024)	192	73	119	38.02
30m Cropland Data Layer (2024)	192	90	101	46.88
10m Cropland Data Layer (2024)	192	91	101	47.40

2.7 Recommendations for Repeat Studies

More extensive ground-truthing could greatly improve this project and its accuracy. Data collection was limited due to time constraints, having extensive ground to cover, navigating mountainous terrain, and protocol development occurring concurrently with field data collection. Additionally, more data points would provide a larger sample size with which to compare accuracy of ground-points and open-source data points, which is important for RMSE score accuracy and consequent selection of data layers. The sampling strategy could also be strengthened by generating a set of random points in GIS beforehand, and visiting those random points in the field to verify the accuracy of the corresponding layers. Doing so might make more efficient use of time and reduce any bias in the distribution of sampling areas.

A few of the datasets that we used had high levels of error (Vegetation Height, Cover, and Type), indicating relatively low accuracy. We recommend finding alternate data sources for these variables. Our collected field data is a good starting point, but it should be improved upon in future studies by incorporating other variables. Additional care should be taken when selecting datasets to look at any available quality standards or information about how the reference data was validated before its public release. Also, depending on the amount of detail required for analysis, repeat ground-truthing and validation could take multiple weeks.

To reduce project time, we recommend streamlining the field workflow. The ArcGIS Field Maps survey should include fewer questions and focus on drop-downs and pick lists rather than write-in questions to standardize data inputs. When possible, all variables should be collected for all points to avoid gaps in the data. Lastly, it might be helpful to automate the data validation piece using a Python script, since the validation processes are repeated for multiple datasets.

2.8 Conclusion

In this chapter, we discussed the development of a field methodology for validating open-source geospatial data in the NGP ecoregion. While open-source data can be an effective tool in spatial analysis, its accuracy must be verified prior to the development of any models. Through GIS and field data collection on Rocky Boy's Reservation, we were able to validate our

reference data. However, the field mission was time-limited and future studies would benefit from additional time in the field to collect more data points. This chapter lays the groundwork for the following chapters focused on geospatial tools and pronghorn habitat connectivity.

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Chapter 3: A Review of Geospatial Methods and Tools for Analyzing Ecological Connectivity in the Northern Great Plains Ecoregion

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3.1 Introduction

Grasslands cover approximately 40% of the terrestrial surface of the earth (more area than any other terrestrial biome), and occur on every continent except Antarctica (Blair et al., 2014; Petermann & Buzhdygan, 2021). They provide critical habitat for many plants and animals, and play a major role in global geochemical cycles, storing an enormous amount of carbon and other nutrients in their soils. Grasslands are also among the most endangered ecosystems on the planet, with conversion to agriculture as one of the leading threats to grasslands worldwide (Blair et al., 2014). In the Northern Great Plains (NGP) ecoregion[19], approximately 630,000 acres per year of grassland was converted to cropland between 2012 and 2022 (World Wildlife Fund [WWF], 2024).

The Buffalo Nations Grasslands Alliance (BNGA) is a Native-led 501(c)(3) that works with partners to support conservation and sustainable livelihoods across 16 Native Nations in the NGP ecoregion. One of the goals of BNGA's Regional Conservation Plan is to establish 10 new pathways of ecological connectivity (BNGA, 2024), which could involve the use of geospatial methods for analyzing ecological connectivity. A variety of metrics have been proposed, and many different software tools developed for this purpose, but some of these techniques require detailed species-specific data that may be difficult to obtain.

The purpose of this chapter is to provide an overview of geospatial techniques for ecological connectivity analysis in the NGP ecoregion and recommendations for BNGA and their partners regarding the use of these techniques. This overview is intended to assist with both selecting the best tools for their intended applications, and identifying promising avenues for further research and data collection.

Section 3.2 of this chapter discusses several review articles that compare different approaches to quantifying ecological connectivity. In Section 3.3, we perform a systematic literature review of ecological connectivity analysis relating to grasslands to identify some potentially relevant geospatial tools. We also summarize key details about the associated software tools, and provide recommendations about which tools to use. In Section 3.4, we discuss examples of ecological connectivity studies and geospatial tools from the NGP ecoregion, highlighting data sources that facilitated those studies and summarizing the findings. Finally, Section 3.5 recommends potential applications of geospatial tools for ecological connectivity analysis that could be relevant to BNGA's work.

3.2 Background

Ecological connectivity[20] is an important factor in the health of ecosystems, and has received considerable attention as a tool to assist with applications such as the design and placement of green infrastructure and protected areas; prioritization of sites for conservation and restoration measures; understanding the effects of habitat fragmentation on populations; and forecasting impacts of climate change on species and ecosystems (Alexander et al., 2016;

[19] In the context of this research, the Northern Great Plains (NGP) is delineated by the boundaries of the NGP ecoregion (see Figure 1.1 in Kelly, 2026).

[20] The capacity of landscapes to support ecological flows such as species movement, dispersal, and gene flow (Bouamrane & Cerasi, 2021)

Costanzo et al., 2025; Kimberly et al., 2020; Rana et al., 2025). In the context of geospatial tools for ecological connectivity analysis, many authors also use the terms "landscape connectivity" and "habitat connectivity" for this concept (Correa Ayram et al., 2016; Foltête et al., 2021; Lindborg & Eriksson, 2004; Tischendorf & Fahrig, 2000).

In *Connectivity metrics for conservation planning and monitoring,* a 2021 review paper, Keeley et al. discuss, categorize, and compare a variety of ecological connectivity metrics, dividing them into structural connectivity metrics, which are based on a binary habitat map[21] and consider only the geometry and spatial arrangement of habitat patches, and functional connectivity metrics, which consider species-specific information. They also divide the functional metrics into three further categories. One group is based on a binary habitat map, similar to the structural metrics, but also accounts for species-specific parameters, such as dispersal distance or population size. The second category, resistance-based[22] metrics, include those that quantify how much the landscape impedes movement or increases mortality for a particular species. Finally, there are metrics based on observations or simulations of organisms. The metrics Keeley et al. (2021) discuss employ several mathematical approaches, including spatial pattern metrics, graph theory, circuit theory, and simulations of organism movements. Based on prior comparisons of simulation-based metrics (Tischendorf & Fahrig, 2000), spatial pattern indices (Tischendorf, 2001), and graph-based metrics (Saura & Pascual-Hortal, 2007), they exclude from their review all but the best performing and most recently developed metrics from those categories. Finally, they provide a flowchart indicating which metrics are recommended, according to the type of landscape and intended application (see Figure 3.1).

While some applications of connectivity analysis may be oriented towards a particular species, others aim to support conservation goals for a variety of species. Some attempt to achieve this by choosing a focal species that serves as an umbrella species[23] or an indicator species[24]. In a 2022 review of multi-species connectivity studies, Wood et al. find that this approach of choosing a single surrogate species[25] tends to fail to adequately represent the needs of other species. Alternatives to this approach include "species agnostic" approaches such as analyzing structural connectivity or geodiversity[26], or defining habitat as a lack of human modification. Others focus on a "generic species," where the traits of multiple species are combined into a single hypothetical species, as well as "multiple focal species" approaches, which conduct separate connectivity analyses for different focal species and then combine the results. Wood et al. (2022) report insufficient clarity about the goals of multi-species connectivity

[21] A map where all regions are classified as either habitat or non-habitat
[22] A measure of how difficult it is for a species to move across different parts of a landscape, with higher resistance representing greater barriers to movement
[23] A species whose conservation protects many other species because it requires large or high-quality habitats, encompassing the needs of other organisms
[24] An organism whose presence, absence, population density, or behavior reflects specific environmental conditions or the overall health of an ecosystem
[25] A species used in conservation planning as a proxy to represent the needs or responses of other species; examples include umbrella species, indicator species, and keystone species
[26] Heterogeneity of the physical landscape, such as soil, geological, and hydrological features

optimization, a lack of empirical validation in connectivity studies with multiple focal species, and a complete blind spot with regard to species interactions.

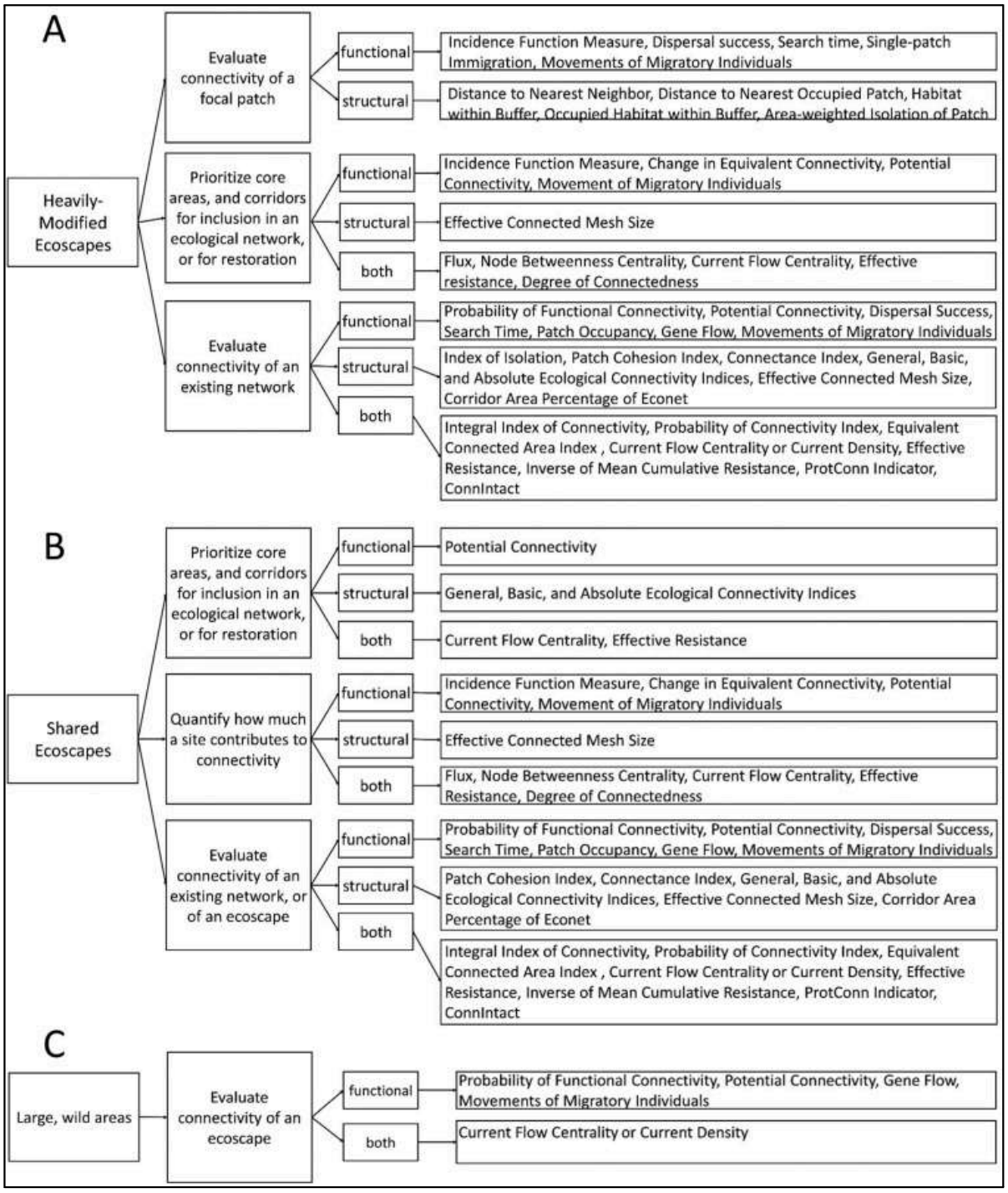


Figure 3.1. *Flowchart associating different applications and approaches with recommended connectivity metrics (Keeley et al., 2021).*

3.3 Software Tools for Connectivity Analysis

We conducted a review of ecological connectivity literature to identify what metrics and tools have been used to study the connectivity of grassland ecosystems. We performed systematic searches using Web of Science and Scopus and merged the results, yielding 693 unique articles (Table 3.1). Among these articles, only a subset of them considered grassland in particular as habitat, while others considered grassland as a part of the matrix surrounding wetland or forest habitat, or analyzed ecological connectivity of a broader collection of landscape components including grassland. These queries also captured some studies of connectivity for aquatic species within the wider Great Plains region.

The primary goal of this literature search was to identify geospatial tools for analyzing ecological connectivity with use cases that may be relevant to BNGA's work. This was not a comprehensive review of all such examples, since the only aspect of BNGA's work that we focused on was grasslands. A more comprehensive search for relevant ecological connectivity literature might include additional queries targeted towards different aspects of BNGA's work, such as Traditional Ecological Knowledge, fire ecology, or other concepts important to BNGA and their partners, rather than just grasslands.

Table 3.1. *Queries used to locate articles relating to both ecological connectivity and grasslands. To capture a variety of geospatial methods and applications, we included a few related terms, informed by variations in terminology we encountered in our preliminary literature review.*

Database	Query	Results as of Jan 3, 2026
Web of Science	(TS=("ecological connectivity" OR "habitat connectivity" OR "grassland connectivity" OR "prairie connectivity" OR "landscape connectivity" OR "habitat corridor*" OR "migration corridor*" OR "matrix permeability" OR "matrix quality")) AND (TS=("grassland*" OR "prairie*" OR "great plains"))	527
Scopus	TITLE-ABS-KEY(("ecological connectivity" OR "habitat connectivity" OR "grassland connectivity" OR "prairie connectivity" OR "landscape connectivity" OR "habitat corridor*" OR "migration corridor*" OR "matrix permeability" OR "matrix quality") AND ("grassland*" OR "prairie*" OR "great plains"))	581

The reviewed literature includes applications of many different tools, corresponding to the wide variety of connectivity analysis techniques. For some techniques, such as calculating the area of habitat within a buffer or finding least-cost paths, studies using them do not mention any particular dedicated ecological connectivity tools and simply indicate that these were analyses were performed using ArcGIS, Python, or R (Magle & Angeloni, 2011; Unnithan Kumar & Cushman, 2022). There are several specialized tools for computing graph-based connectivity metrics including Probability of Connectivity and Equivalent Connectivity, but for other graph metrics that are not specific to ecological applications (such as Betweenness

Centrality), more generic graph theory tools can be used, such as the igraph package in R (Johnston & McKintyre, 2019; Saura & de la Fuente, 2017).

In *Habitat connectivity in biodiversity conservation*, a review of ecological connectivity studies published during 2000-2013, Correa Ayram et al. (2016) found that least-cost analysis was the most commonly used method, and that Conefor Sensinode was the most widely used software. However, of the 162 publications included in that review, only 14 were focused on grassland biomes while 137 were focused on forested biomes (Correa Ayram et al., 2016). At the time of this writing, grasslands are still underrepresented in the ecological connectivity literature compared to forests[27].

Table 3.2 summarizes all the dedicated connectivity analysis tools mentioned in the reviewed abstracts and articles, along with general requirements for using the software. Most of the software tools encountered in this literature review are free and open source[28], with the exception of FRAGSTATS and LinkageMapper. FRAGSTATS is a tool for computing spatial pattern metrics which does not require any programming. For non-academic uses, the cost of a FRAGSTATS license is $149 per year (Ene & McGarigal, 2026). LinkageMapper is an ArcGIS toolbox (written in Python) which facilitates the use of Circuitscape within ArcGIS and further analysis of the Circuitscape results. The creators of LinkageMapper also offer paid consulting services, and the toolbox itself is free and open source.

Table 3.2. *Table of specialized software tools for ecological connectivity analysis. "Inputs" describes the minimum information required to run the tool, and the appropriate format. "Skills" indicates any coding or other specific computer skills involved in running the tool. "Issues" describes known computational limitations as well as concerns we identified regarding the current and future availability of the software. Gray boxes indicate information that we did not have time to investigate (Bosch, 2019; Foltête et al., 2021; Hesselbarth et al., 2018; Landguth et al., 2012; Leonard et al., 2017; McGarigal et al., 2023; McRae et al., 2016; McRae & Kavanaugh, 2011; Peterman, 2018; Saura & Torné, 2009; Vogt & Riitters, 2017).*

Name	Software type	Purpose	Inputs	Skills	Issues
Omniscape	Julia package	Omnidirectional connectivity analysis using circuit theory	Resistance raster	Use of command line interface	
GFlow	Standalone tool	Connectivity analysis using circuit theory	Resistance raster, source locations (points or polygons)		Less frequently used/maintained, not available for Windows
Circuitscape	Julia package				May fail with more

[27] As a point of comparison to the Web of Science query in Table 3.1, (TS=("ecological connectivity" OR "habitat connectivity" OR "forest connectivity" OR "landscape connectivity" OR "habitat corridor*" OR "migration corridor*" OR "matrix permeability" OR "matrix quality")) AND (TS=("forest*")) yielded 2,347 results.

[28] Software where the source code is publicly available, allowing anyone to copy and modify it

Name	Software type	Purpose	Inputs	Skills	Issues
LinkageMapper	ArcGIS toolbox (based on Circuitscape)	Connectivity analysis using circuit theory & least-cost paths			than a few hundred source areas
UNICOR	Python package	Connectivity analysis using resistant kernels & least-cost paths	Resistance raster, source points	Python	Less frequently used/maintained
ResistanceGA	R package	Optimization of resistance raster based on genetic data	Rasters of predictor variables, genetic distances between point locations	R	Less frequently used/maintained
Conefor Sensinode	Standalone tool	Connectivity analysis using graph theory			Has not been updated since 2012
Graphab	Standalone tool (requires Java)				
FRAGSTATS	Standalone tool	Calculation of spatial pattern metrics	Categorical raster of habitat types		
landscapemetrics	R package			R	
PyLandStats	Python package			Python	Contiguity Index and Proximity Index not yet implemented
GUIDOS	Standalone tool	Morphological spatial pattern analysis	Binary habitat raster		GUI version can't process rasters >10,000^2 pixels
Zonation	Standalone tool	Prioritization of sites based on multiple criteria			
Marxan	Standalone tool				
Marxan Connect	Python package with GUI				Less frequently used/maintained

In a review of landscape metrics, Kupfer (2012) describes the release of the FRAGSTATS software in 1995 as revolutionizing the analysis of landscape structure and establishing spatial pattern metrics that would later be incorporated into many other tools. Currently, most of the metrics provided by FRAGSTATS have been implemented in R as the landscapemetrics package and in Python as the PyLandStats package (Bosch, 2019).

Morphological spatial pattern analysis (MSPA) is another recent approach to analyzing landscape structure. Unlike FRAGSTATS and related tools, which distinguish only 'edge' and

'core' areas based on whether a raster cell is surrounded by only the same habitat type as itself, MSPA further breaks down the 'edge' category. It identifies 'islets' (isolated patches too small to contain core area), narrow 'branches' connected to one core, 'bridges' connecting different core areas together, 'loops' connecting parts of the same core, and 'perforations' (edges surrounding a hole in a patch, as opposed to the outer edge of a patch) (Vogt & Riitters, 2017). These distinctions can be helpful for visual analysis of landscape structure.

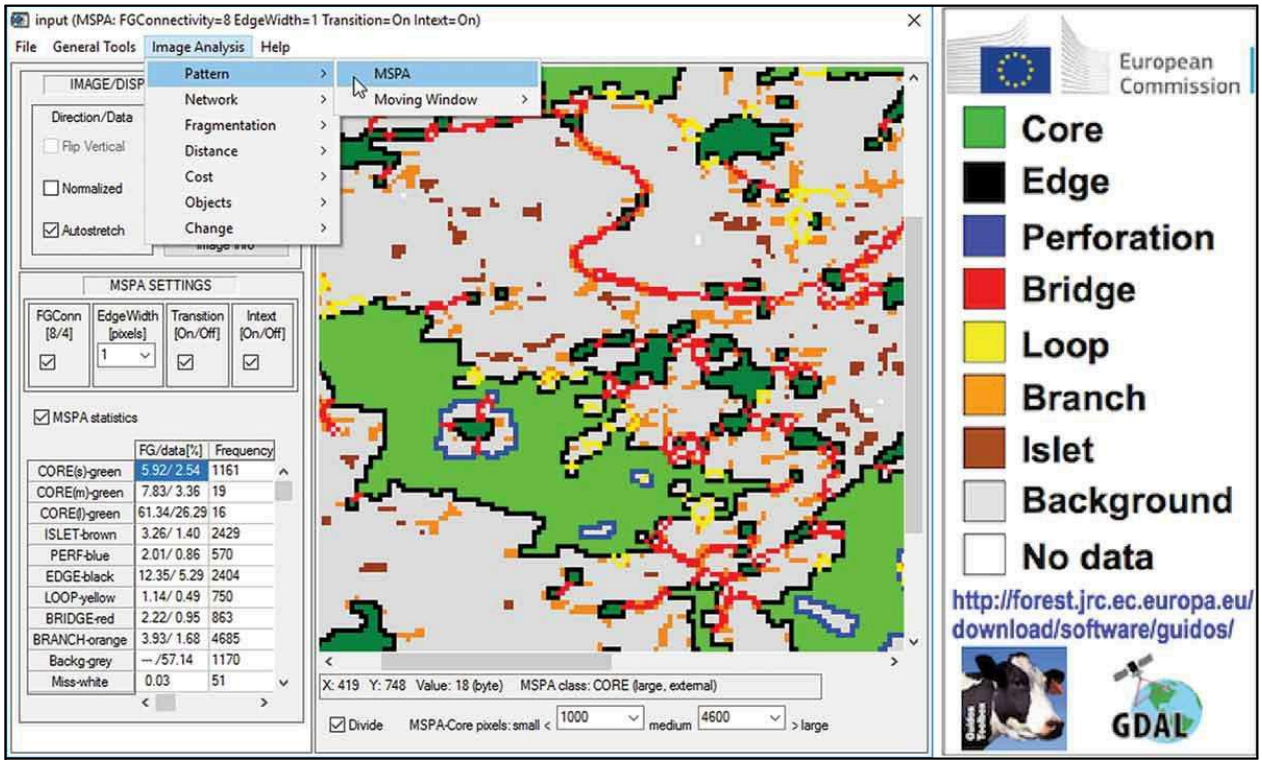


Figure 3.2 *Example of Morphological Spatial Pattern Analysis* (*Vogt & Riitters, 2017).*

Another notable approach to ecological connectivity analysis is the use of circuit theory. These tools are based on an analogy between organism movement and the flow of electricity through circuits, whereby organism movement across a landscape is modeled as the flow of electrical current through a network of resistors. One of the main motivations for using these methods rather than least-cost paths is that circuit theory evaluates the contributions of multiple dispersal pathways (McRae et al., 2008). Circuitscape is the most widely used of the circuit-based software tools, but recent studies have also begun to use Omniscape. Some Circuitscape users have chosen to use points or areas surrounding their study region – sometimes in a moving-window fashion – as the sources and sinks for current, instead of identifying specific habitat patches between which to calculate the current. Omniscape was created to facilitate that approach, using a circular moving window to calculate the current density from all directions through each raster cell (McRae et al., 2016). Another implementation of circuit-based

connectivity modeling, GFlow, was developed for parallelization[29] in high-performance computing systems to facilitate scaling up to high-resolution, large-extent rasters (Leonard et al., 2017).

All of the tools discussed so far are designed only for connectivity analysis. There are other tools designed for prioritization applications, such as Marxan and Zonation, that perform both connectivity analysis and prioritization. This added functionality supports identification of priority areas for conservation, based on spatial information about biodiversity and ecosystem services as well as costs and threats (Kukkula & Moilanen, 2016). Zonation 5 incorporates connectivity in terms of dispersal kernels representing the distribution of dispersal distances for a species (Moilanen et al., 2022). Marxan Connect can consider structural connectivity, resistance distances, or measures of actual demographic connectivity derived from genetic data or GPS tracking of animals (Daigle et al., 2020).

3.4 Examples Relating to the Northern Great Plains Ecoregion

Among the abstracts examined, we identified several articles relating to grasslands within the NGP ecoregion and reviewed these in greater detail to understand how the authors selected focal species, what data sources facilitated modeling of habitat suitability and/or resistance, and which techniques and software were used to analyze connectivity. Nearly all of these examples included some form of resistance-based analysis. Circuit theory was the most popular technique, and Circuitscape the most widely used software.

3.4.1 Pronghorn

Pronghorn (*Antilocapra americana*) are an indicator species for grassland ecosystems, and are particularly sensitive to fragmentation[30] (Manzer & Jones, 2020). Poor et al. (2012) applied both least-cost paths and Circuitscape, and compared their results for modeling migration corridors of pronghorn. They found the least-cost paths to be slightly more accurate than the Circuitscape corridors. They also compared two methods of habitat suitability modeling: one using GPS data from collared pronghorn to compute variable weights using a maximum entropy model, and the other using Analytic Hierarchy Process[31] (AHP) to derive variable weights from surveys of expert opinion. Finally, they constructed resistance rasters based on each of the two habitat suitability models and found that the version based on pronghorn location data performed better than the one based on expert opinion (Poor et al., 2012).

3.4.2 Black-tailed Prairie Dogs

Black-tailed prairie dogs (*Cynomys ludovicianus*) are a keystone species[32] in the Northern Great Plains ecoregion, and have been the focus of several connectivity studies. The visible impacts of prairie dogs on the landscape make it possible for researchers to conduct comprehensive surveys in the field that facilitate connectivity analysis.

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[29] Speeding up computations by running independent calculations simultaneously on different processing elements
[30] The disruption of continuous habitat, resulting in smaller, unconnected habitat patches
[31] A procedure for multi-criteria decision making in which experts are asked to make pairwise comparisons of the importance of different variables and of categories within each variable
[32] An organism that has a disproportionately large impact on its ecosystem; critical to ecosystem function and the survival of other species

Davidson et al. (2022) used several spatial pattern metrics (mean nearest-neighbor distance, clumpiness[33], contagion, and core area percentage of landscape) to describe the spatiotemporal dynamics of prairie dog colonies in Thunder Basin National Grassland as part of an investigation of the roles of connectivity and climate in driving plague outbreaks among prairie dogs. For that study, boundaries of active prairie dog colonies were mapped in the field using handheld GPS units and converted to raster format for analysis. This data made it possible to document drastic fluctuations in the area occupied by prairie dogs as they went through several cycles of population growth and collapse due to plague. Although their results indicated higher connectivity preceding plague years, they were not able to establish a consistent threshold beyond which plague would consistently occur (Davidson et al., 2022).

Other studies have made use of high resolution aerial imagery to manually delineate habitat patches, followed by field surveys to verify the presence of black-tailed prairie dog colonies. Magle et al. (2009) compared 12 metrics of connectivity for predicting the presence of prairie dogs around Denver, Colorado, and determined the best metric to be an incidence function model that considers both colony areas and cost-weighted distances to nearby colonies. Their results demonstrated that including cost weights, rather than simple Euclidean distances, was necessary to create a model with any explanatory power. They used AHP to create cost weights for a set of eight landscape features, and performed a sensitivity analysis, which showed that the results were not very sensitive to changes in the cost weights (Magle et al., 2009). This supports the idea that the expert opinions summarized by AHP need not be very numerically precise to provide a significant improvement over ignoring spatial variations in movement cost entirely.

Magle and Angeloni (2011) re-used the cost weights from an earlier Magle et al. (2009) paper to study the effects of ecological connectivity on black-tailed prairie dog behavior. They found that amicable social behavior was positively correlated with the area and age of the colony, the fraction of a 2 km buffer occupied by other colonies, and cost distance to the nearest neighboring colony. They also found that greater Euclidean distance to the nearest neighboring colony was associated with prairie dogs spending more time in vigilance behaviors and less time foraging, but vigilance decreased with the age of the habitat fragment, suggesting that the animals gradually adapt to new surroundings (Magle & Angeloni, 2011). Although these latter two studies took place in a different region than BNGA's work in the NGP ecoregion, they serve as further demonstrations of the utility of mapping prairie dog colonies for ecological connectivity analysis. They also indicate that the extra work of estimating cost distances may be important for this species.

3.4.3 Invasive Species

Another application of ecological connectivity analysis is mapping the potential spread of invasive species[34]. In a study funded by the National Feral Swine Damage Management Program, Kramer et al. (2024) used circuit-based connectivity analysis to evaluate the potential

[33] A metric of habitat aggregation comparing the proportion of raster cell adjacencies that are between cells of the same type to what would be expected from a spatially random distribution.
[34] A non-native species that causes harm to the environment.

for wild pigs (*Sus scrofa*) to spread from Canada into the northern United States. This species was introduced into Canada in the 1980s through releases of livestock and established a thriving population in western Canadian prairies, where it presently causes a great deal of damage to crops and native vegetation and can carry diseases that threaten wildlife and livestock. Kramer et al. (2024) used GPS data collected by collaring pigs in Saskatchewan to determine coefficients representing the degree to which the pigs selected or avoided each of ten land cover classes. To construct the input raster for Circuitscape, they applied those coefficients to a land cover raster encompassing three ecoregions and extending across the US-Canada border. The model was validated with independent GPS locations of wild pig sightings beyond the spatial extent of the collar study, and showed good performance. The authors identified four hotspots of connectivity, including two along the US-Canada border, which they recommend monitoring due to a high risk of invasion (Kramer et al., 2024). Two of the hotspots, including one high risk zone, are within the NGP ecoregion.

3.5 Recommendations

3.5.1 Software

For applications that involve identifying corridors between habitat areas or other specified locations, we recommend LinkageMapper toolbox for ArcGIS. It includes two widely-used resistance-based functional connectivity tools: least-cost paths and Circuitscape. LinkageMapper appears to be well-maintained and relatively easy to use.

For prioritization applications where there are multiple factors to consider, we recommend looking into specialized multi-criteria prioritization tools for conservation planning, particularly Zonation. For example, such a tool could be used to prioritize areas for restoration based on both the potential ecological connectivity improvements and the costs of restoration measures.

For structural connectivity analysis, we recommend the landscapemetrics package in R as a starting point; however there are other tools with very similar capabilities that may be more convenient in certain use cases. See Hennessy & Buller (2026) for an example application of landscapemetrics.

3.5.2 Applications

3.5.2.1 Pronghorn

We recommend the workflow demonstrated by Poor et al. (2012) for analyzing ecological connectivity of pronghorn, and in particular, modeling pronghorn habitat suitability using GPS collar data. LinkageMapper could be used to perform the connectivity analysis steps of that workflow. The LinkageMapper toolbox includes additional tools that could be used to extend this workflow for specific applications, such as the Pinchpoint Mapper for identifying areas where any loss of habitat would disproportionately reduce connectivity (Castilho et al., 2015). A particular application that may be of interest to BNGA and their partners is investigating the impact of fences on pronghorn movement to evaluate the potential conservation value of removing or modifying fences.

3.5.2.2 Black-tailed Prairie Dogs

We recommend black-tailed prairie dogs as another focal species to consider for ecological connectivity analysis, on the basis of prior successful applications as well as the ecological importance of the species. Species such as the endangered black-footed ferret rely upon keystone species like black-tailed prairie dogs for habitat and other ecosystem services (Augustine et al., 2021; Guernsey et al., 2023).

Structural connectivity analysis of prairie dog colonies (such as the methodology used by Davidson et al. (2022)) could complement other prairie dog mapping work that BNGA or their partners may be doing. Functional connectivity analysis using cost distances could be even more valuable, but this would involve the extra step of creating a resistance raster for the desired study area. Using a published weighting system is one option, but there can be difficulties with applying models originally developed in different study areas or for different geospatial datasets (Hennessy & Buller, 2026). Another option could be to survey local experts on prairie dogs and develop a weighting system through AHP.

3.5.3 Gaps in Ecological Connectivity Research in the NGP

3.5.3.1 Impact of Fences on Pronghorn

Studies of pronghorn connectivity in the NGP have attempted to incorporate information about fences into their analysis, but these have notable limitations. Poor et al. (2012) included fence presence in their habitat suitability model using a series of assumptions about where fences occur along roads and property boundaries. They collected ground truth data on actual fence locations to validate their model of fence presence and found it to be 82% accurate within their study area. They did not find fence presence to have much influence on pronghorn habitat suitability, however they point out that their technique of habitat suitability modeling may not be capable of capturing the effects of fence presence, and recommend that a measure of fence density be used instead. Similarly, DeVoe et al. (2025) considered fence density and did not find it to be a significant factor in any of their models; however, their analysis only considered fence density at the spatial scale of pronghorn herd annual ranges, and acknowledged that there could still be effects of fence density at finer spatial scales. Both of these studies also recommended that future research should consider permeability attributes of fencing (DeVoe et al., 2025; Poor et al., 2012).

In addition to pronghorn location data, addressing this gap in the research would require accurate data on fence locations, which could be used to compute fence density at a finer spatial scale and assess its impact on habitat suitability. BNGA's partners may have local knowledge and data about the locations and characteristics of fences on their lands that could facilitate such research.

3.5.3.2 Grassland Plants in the NGP

The abstracts examined during the literature review described in Section 3.3 did not include any cases from the NGP ecoregion that focused on ecological connectivity for grassland plants. However, our search did retrieve some studies from elsewhere in the world where data on

grassland plant communities was used to investigate the effects of ecological connectivity in grassland ecosystems.

3.6 Conclusion

In this chapter, we conducted an extensive literature review of geospatial tools utilized in ecological connectivity analysis. While grasslands are an endangered ecosystem and provide critical habitat as well as cultural and economic value, they are heavily underrepresented in connectivity research when compared to other biomes (such as forests). Geospatial tools ranging from structural metrics to those based on resistance and circuit theory provide opportunities to improve connectivity models. Specifically, packages like LinkageMapper, Zonation, and R landscapemetrics are flexible and efficient methods. These programs could be applied to other priority species that BNGA has identified, including pronghorn (see Hennessy & Buller, 2026) and black-tailed prairie dogs, as well as areas of future research, such as grassland plants and fences. Together, these approaches support BNGA's goal of establishing paths of connectivity.

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Chapter 4: Assessment of Habitat Connectivity: A Case Study of Pronghorn Habitability in Rocky Boy's Reservation, Montana

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4.1 Introduction

4.1.1 Purpose and Audience

Grasslands occupy approximately 40% of the earth's terrestrial surface and provide critical ecosystem services, including water regulation, biodiversity support, habitat for migratory wildlife, and carbon storage (Buffalo Nations Grasslands Alliance [BNGA], n.d.; Petermann & Buzhdygan, 2021; United States Department of Agriculture [USDA], n.d.). Globally, grasslands store approximately 34% of terrestrial carbon stocks, with nearly 90% stored below ground as root biomass and soil organic carbon (BNGA, n.d.). Despite their ecological importance, grasslands are among the most threatened ecosystems globally due to agricultural expansion, infrastructure development, and other forms of land conversion. The Northern Great Plains (NGP) ecoregion[35] faces many of these pressures, including agricultural intensification, energy development, road expansion, and climate-driven shifts in precipitation and vegetation (Perkins et al., 2019). These changes contribute to habitat loss and fragmentation[36] which reduce ecological connectivity[37] and alter species distributions across the region (Beckmann et al., 2010; Perkins et al., 2019; Thompson et al., 2015).

In addition to their ecological value, grasslands are an integral part of Indigenous lifeways in the NGP ecoregion. These landscapes support culturally significant species and plants used in traditional practices, and contribute to the physical, cultural, and spiritual well-being of Native Nations (BNGA, n.d.). Grasslands of the NGP are also deeply connected to the stewardship of Indigenous Peoples who have shaped, managed, and relied on these landscapes since time immemorial. The Buffalo Nations Grasslands Alliance (BNGA), a Native-led 501(c)(3) working with partners across 16 Native Nations in the NGP ecoregion, supports efforts to conserve and restore these ecosystems while strengthening ecological connectivity for wildlife.

This chapter focuses on a case study of pronghorn (*Antilocapra americana*) to determine the species' potential habitat in Rocky Boy's Reservation and areas for migration corridor[38] restoration, with the broader goal of examining grassland connectivity in the area. Pronghorn, an ungulate endemic to western North America, depend on large, connected habitats to support seasonal movements and migrations. Because their distribution and movement patterns reflect broader ecosystem conditions, pronghorn serve as an indicator species[39] for grassland health and connectivity in the NGP ecoregion (American Prairie, 2022). The case study provides a rationale and reproducible methodology for assessments of other priority species and Tribal areas for continued efforts towards grassland conservation and restoration. This report is intended for use by BNGA, its affiliated Native Nations, and partner organizations. The findings detailed in the

[35] In the context of this research, the Northern Great Plains (NGP) is delineated by the boundaries of the NGP ecoregion (see Figure 1.1 in Kelly, 2026).
[36] The disruption of continuous habitat, resulting in smaller, unconnected habitat patches
[37] The overall capacity of landscapes to support ecological flows such as species movement, dispersal, and gene flow; can be thought of as the overall, broader outcome of structural and functional connectivity
[38] Paths that animals use to travel between summer and winter habitats
[39] An organism whose presence, absence, population density, or behavior reflects specific environmental conditions or the overall health of an ecosystem

following sections could provide a broad framework of connectivity analysis for those interested in NGP ecoregion grassland ecosystems and species, as well as inform conservation planning and development actions.

4.1.2 Background

4.1.2.1 Pronghorn

Pronghorn are an endemic ungulate species located in western North America (Figure 4.1), and are the last remaining species of the taxonomic family *Antilocapra* (Jones et al., 2023). Pronghorn are highly mobile and admired as the fastest land mammal in the Americas (and second fastest species globally) (Krejci & Dewey, 2009). The most populous species in the NGP ecoregion and in North America is *A.a.americana*, though there are four other subspecies, two of which are endangered (Howard, 1995; Krejci & Dewey, 2009; National Wildlife Federation, n.d.). Pronghorn in the NGP ecoregion are primarily distributed across grassland habitats and occupy rangelands concurrently with domestic livestock, leading to competition when the ecosystem conditions are unhealthy and lack resources (Jones et al., 2023). However, pronghorn also have the ability to migrate to more favorable habitats – a trait that is becoming increasingly essential – as human disturbances and land use changes continue to alter their environment.

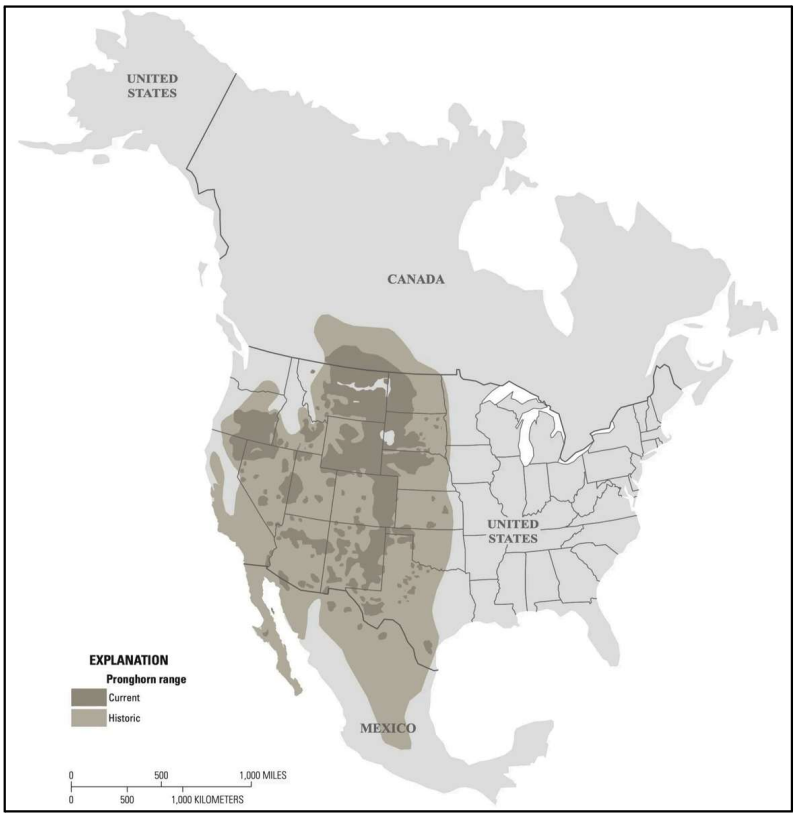


Figure 4.1. *Historic and current pronghorn range in North America (North American Pronghorn Foundation, n.d.).*

Climate change, invasive species, altered disturbance regimes, land use change, and anthropogenic forces are significant challenges facing grassland ecosystems and the species that depend on them (Donovan et al., 2024; Perkins et al., 2019). The grasslands of the NGP ecoregion are increasingly threatened due to widespread conversion to cropland, leading conservation organizations such as the World Wildlife Fund, the National Fish and Wildlife Foundation, and The Nature Conservancy to prioritize the region for conservation. These landscape-level changes exacerbate habitat degradation and fragmentation, causing biodiversity loss, diminishing ecosystem services, and negatively affecting pronghorn populations by limiting the connectivity and quality of migratory corridors (Haddad et al., 2015). Fragmentation (Figure 4.2) often alters native plant and animal communities by introducing microclimatic shifts between fragments and surrounding areas. Additionally, it alters spatial genetic structure, which can cause inbreeding depression[40] in isolated populations, and impacts dispersal characteristics and migration rates for certain species (Collinge, 1996; Collingham & Huntley, 2000; Keyghobadi, 2007; Wilson et al., 2016). Fragmentation also often occurs concurrently with habitat loss, which is especially relevant to BNGA's grassland conservation goals (Collinge, 2009).

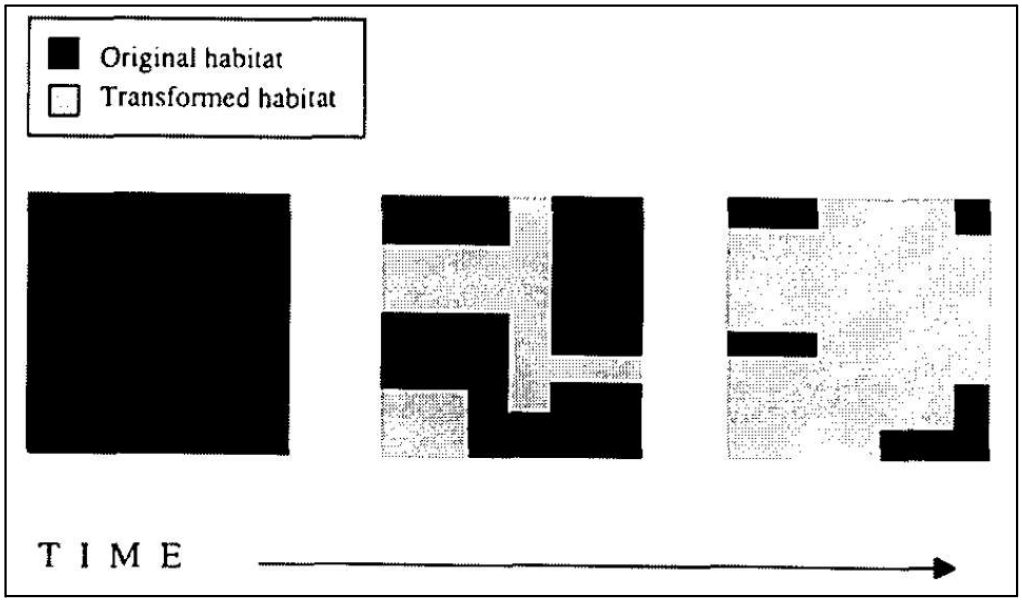


Figure 4.2. *Representation of the generalized process of habitat fragmentation. Over time, the original habitat type is reduced in area, and remnants of the original habitat type are isolated from one another (Collinge, 1996).*

After discussion with BNGA, pronghorn was chosen as a priority species for the study area. Pronghorn serve as an indicator species for grassland ecosystems, meaning that their population health and dynamics can signal changes in ecosystem function and overall grassland

[40] The reduction in survival, fertility, and fitness of offspring resulting from mating between closely related individuals

condition (American Prairie, 2022; Manzer & Jones, 2020). Their large home ranges and requirement for open, connected grassland habitat make them particularly sensitive to fragmentation and long-term disturbances (Manzer & Jones, 2020). Long-term studies indicate that pronghorn populations have declined by approximately 40% in some regions since the 1980s, with many herds experiencing reduced fawn production and productivity (BNGA, n.d.; Donovan et al., 2024; LaCava et al., 2020; World Wildlife Fund [WWF], n.d.). These trends suggest that broader threats may be affecting grassland-dependent wildlife.

Due to their size, pronghorn are more visible than other grassland species, allowing their distribution, population structure, and migration patterns to be more easily monitored. Changes in pronghorn population health and dynamics can therefore provide early warning signals of stress within grassland ecosystems and potential impacts on other keystone species, including greater sage-grouse, black-tailed prairie dog, black-footed ferret, and American bison. Additionally, healthy, intact grasslands that support sustenance species such as pronghorn, mule deer, and elk hold cultural significance and support recreation and economic opportunities for Native Nations. Due to this, sustainable management of grasslands to maintain habitat connectivity for pronghorn is crucial for supporting broader ecosystem health, informing effective grassland conservation strategies, and supporting Indigenous lifeways (Perkins et al., 2019).

4.1.2.2 Connectivity

Ecological connectivity encompasses the relationship between spatial patterns in the environment and species movement, referring to the degree to which the landscape facilitates or impedes the movement of organisms and the flow of ecological processes. Connected landscapes allow animals to access daily forage and required resources during migration, prevent and reverse biodiversity loss, enable species to avoid anthropogenic forces, and ultimately improve population persistence (Liczner et al., 2024; Naidoo et al., 2025). Connectivity is commonly divided into structural and functional connectivity, both of which provide different metrics (Keeley et al., 2019; Spanowicz & Jaeger 2019; Taylor et al., 2006):

- *Structural connectivity* describes the physical characteristics and arrangement of habitat patches in the landscape, commonly focusing on land cover designations and utilizing metrics such as patch size, edge length, and distance between patches to describe landscape connectivity in the study area (Keeley et al., 2019; Spanowicz & Jaeger 2019; Taylor et al., 2006).
- *Functional connectivity* refers to the ability of organisms to move through the landscape according to their specific behavioral, physiological, and ecological traits, focusing on species-specific movement patterns using techniques such as radio telemetry, mark-recapture studies, and matrix resistance models (Keeley et al., 2019; Spanowicz & Jaeger 2019; Taylor et al., 2006).

Both of these types of connectivity are essential for understanding fragmentation in the landscape, which can be shown through a reduction in structural connectivity (increasing distance between patches and isolation of patches) and functional connectivity (increasing resistance to movement), ultimately disrupting population dynamics and ecosystem functioning (Martínez-Richart et al., 2024). Measuring and mapping ecological connectivity can inform conservation planning and habitat restoration, which are essential for preserving biodiversity in threatened ecosystems such as grasslands. Refer to Buller & Kelly (2026) for a literature review of recent connectivity research in the NGP ecoregion and assessment of connectivity tools.

4.2. Research Goal and Data Collection Methods

4.2.1 Goal of Research

This chapter aims to offer BNGA a framework for assessing structural and functional connectivity that can be built upon and applied to different areas and species. Pronghorn were chosen as the focal species due to their correlation with overall grassland health and through conversations with BNGA about priority species, though other culturally important species such as sage grouse, black-footed ferret, and prairie dogs are also important for Native Nations and other advocates of grassland health, for which this chapter's work could be adjusted and applied to in future work. Additionally, this research includes a comparative analysis of structural connectivity between Rocky Boy's Reservation and its surrounding counties to understand whether connectivity metrics differ between these areas, in order to inform possible improvements. Refer to Figure 4.3 for an overall workflow of this chapter's research.

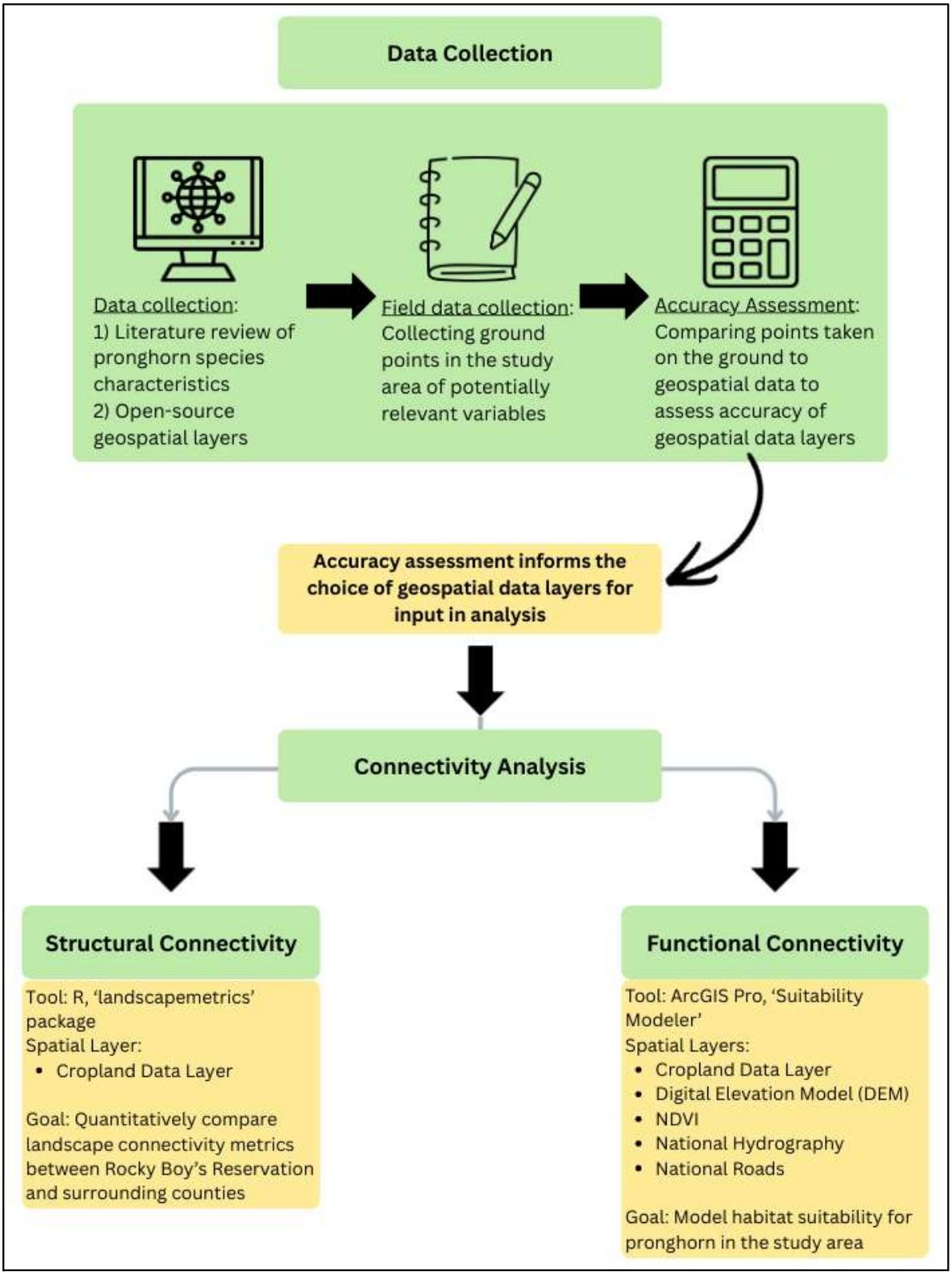


Figure 4.3. *Workflow of data collection and analysis.*

Data on actual pronghorn locations and movement were unavailable and unable to be collected, limiting the scope of connectivity analysis. Thus, structural connectivity of the landscape and functional connectivity up to and including a habitat suitability raster were assessed. Despite the limitations, this research aims to provide a roadmap of initial efforts to assess connectivity and habitability, with recommendations for future work.

4.2.2 Study Area

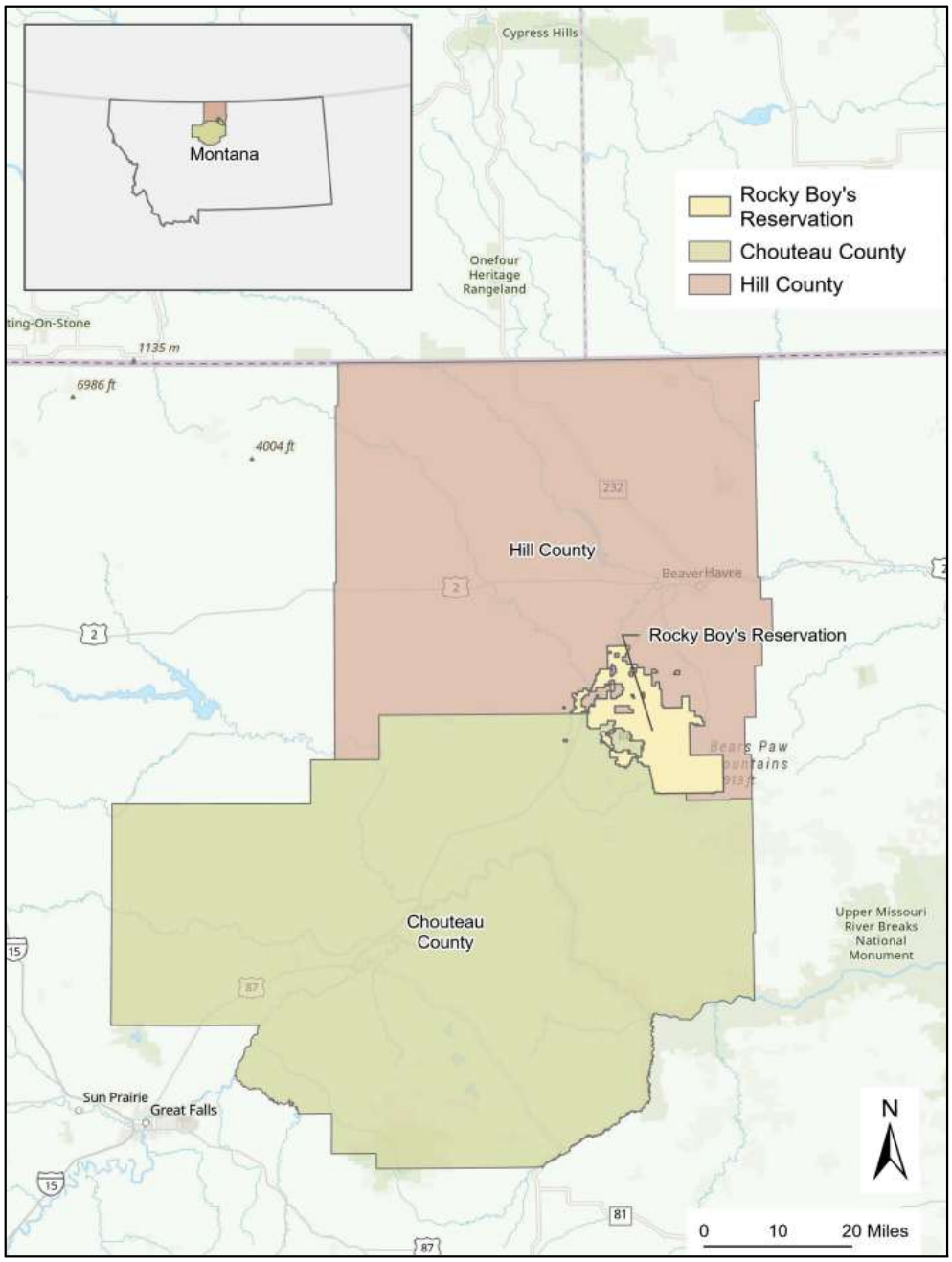


Figure 4.4. *The study area of Rocky Boy's Reservation - Chouteau County and Hill County in Montana.*

Rocky Boy's Reservation was chosen as the study area due to the client's physical location and knowledge of the area. The Reservation comprises approximately 171.4 square miles (443.9 square kilometers), encompassing portions of Chouteau and Hill counties in Montana (Figure 4.4). Calculations of land cover area using the 2024 USDA Cropland Data Layer (CDL) (Figure 4.5) show that the landscape over these counties is predominately composed of approximately 45% grassland/pasture, 39% agricultural land, and 11% shrubland (Figure 4.6).

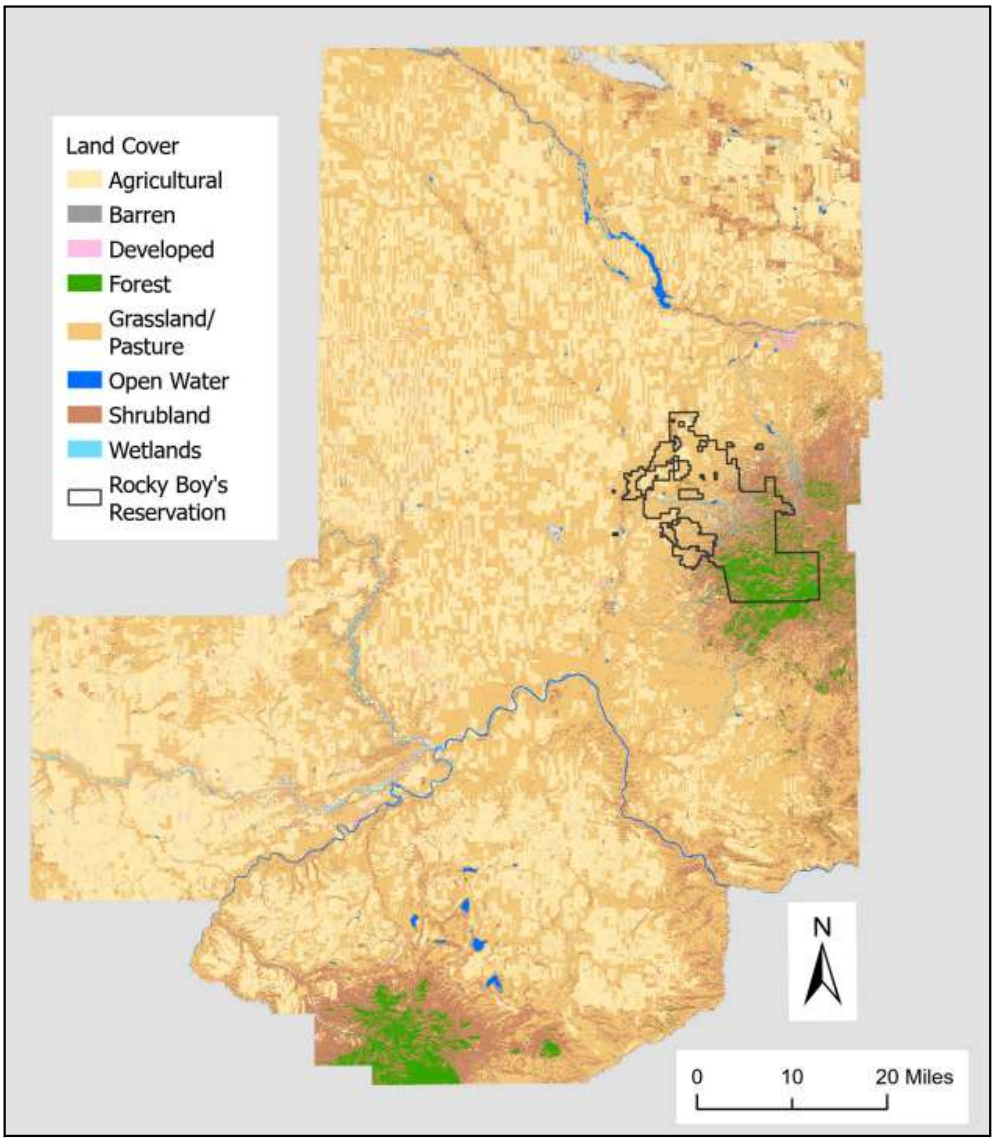


Figure 4.5. *Land cover types in the study area.*

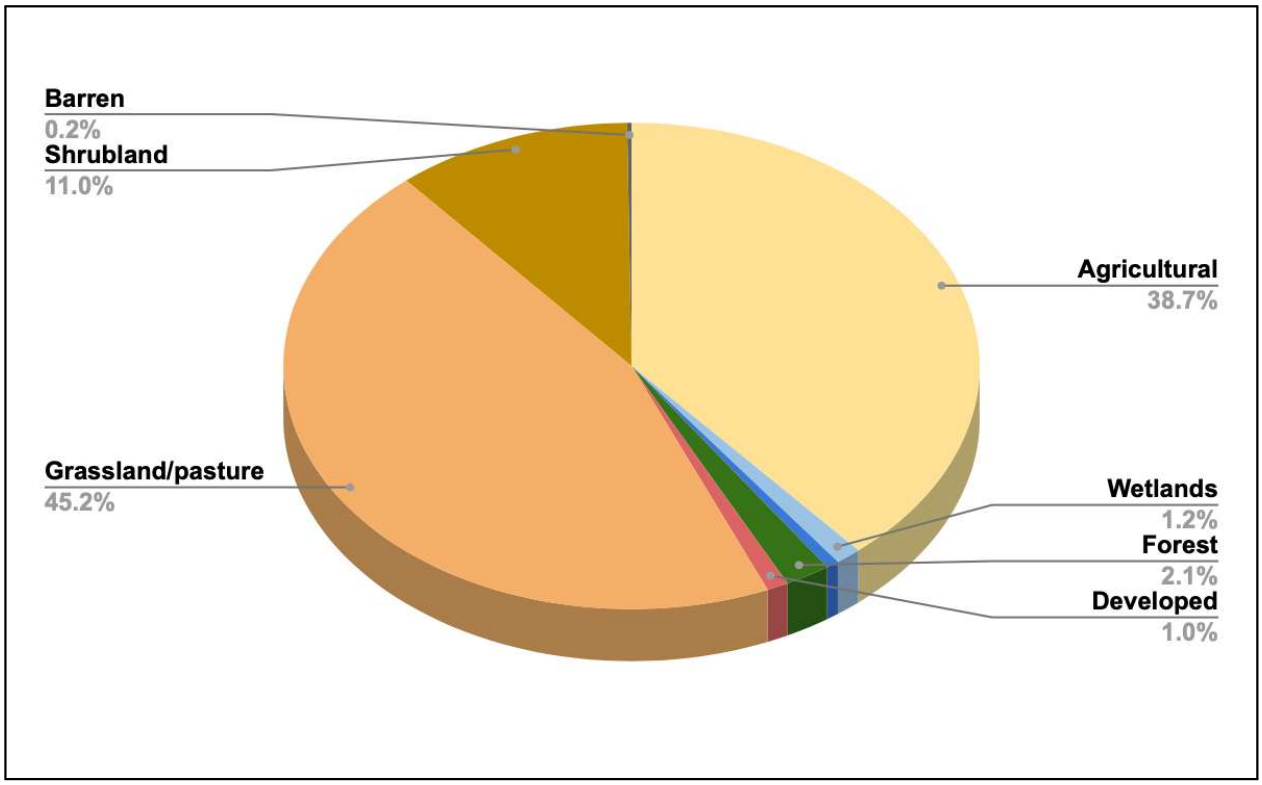


Figure 4.6. *Percentage of land cover category across the entire study area.*

The extent of land required for connectivity analysis can differ based on the goal(s) of the study, which in this project pertains to a relatively small-scale analysis of the Reservation. However, pronghorn daily movement can vary between 0.88 - 12.86 miles (1.42 - 20.4 kilometers) depending on season and resource availability, which could quickly extend beyond the Reservation bounds (Reynolds, 1984; Reynolds & Laundre, 1990).

These factors informed the choice to extend the study area to the Reservation and its surrounding counties for the connectivity analysis, which is additionally useful for comparing grassland management and conservation *within* the Reservation to non-Reservation lands and for informing conservation measures to increase connectivity.

4.2.3 Variables and Data Layers: Rationale and Process

Understanding pronghorn species characteristics is essential for assessing connectivity methods and modeling habitat suitability. Historically, pronghorn ranged widely across the central and western United States and in northern Mexico, though due to the aforementioned challenges, their core population now persists mainly in the open grassland and sagebrush habitats of Wyoming, Montana, Colorado, and New Mexico (Jones et al., 2023). Pronghorn prefer wide-open areas that offer maximum visibility to avoid predation, leading them to avoid steep, forested, or heavily wooded terrain (Kindschy et al., 1982). Pronghorn are selective browsers that favor forbs and shrubs over grasses, though they are predominantly found in grassland areas as these plant communities often intermix with shrubland and support high diversity and abundance (Bender et al. 2023; Ganey, 1998; Hlavachick, 1968; Mitchell &

Smoliak, 1971; O'Gara & Greer, 1970; Russell, 1964; Schwartz & Nagy, 1976). Their foraging habits are shown to shape landscape vegetation composition by suppressing dominant shrubs and encouraging diversity, which is increasingly important as non-native vegetation species colonize the landscape (Boccadori et al., 2008). Life history traits such as high reproductive rates, speed, and seasonal migrations – sometimes exceeding 150 miles – and showing fidelity to previously successful rearing areas, are driven by changes in forage and water availability (Gates et al., 2012). These characteristics lend themselves towards a dependence on large, unfenced, and heterogenous grassland landscapes, highlighting the necessity of understanding their habitat needs and the connectivity of the NGP ecoregion grassland ecosystems (Proffitt et al., 2025). Refer to Table 4.1 for this study's considered variables and pronghorn species characteristics that inform their habitat requirements.

Table 4.1. *Species and habitat characteristics of pronghorn that were considered in this study as important variables to determine habitability of an area.*

Category	Pronghorn Preference	Relevant Variable(s)	Variable Collected in Ground-Truthing	Variable Used in Analysis
Distance to Anthropogenic Disturbance	Avoid anthropogenic disturbance; prefer an increased distance to human activity (Donovan et al., 2024)	Distance to Anthropogenic Disturbance	No	No[41]
Distance to Roads	Avoid road disturbance; prefer an increased distance to roads (Donovan et al., 2024; Gavin & Komers, 2006)	Distance to Roads	Yes	Yes
Distance to Water	Vegetation is main source of water, allowing pronghorn to inhabit areas farther from traditional water sources during certain seasons; variable preference to distance to water, though pronghorn	Distance to Water	Yes	Yes

[41] Variable not used in analysis due to difficulty in obtaining open-source data and difficulty ground-truthing. However, the weighting system used in the functional connectivity analysis disfavors a close proximity to roads and the "Developed" landcover type, two contributors of anthropogenic disturbance, which provides some integration of this pronghorn preference. See Section 4.4 of this chapter for additional details.

Category	Pronghorn Preference	Relevant Variable(s)	Variable Collected in Ground-Truthing	Variable Used in Analysis
	are often found within 3mi of water (LandPKS, n.d.; North Dakota State Library, n.d.)			
Elevation	Prefer relatively flat, rolling hill landscapes and ridge tops (Kindschy et al., 1982)	Elevation - Slope/TPI	Yes	Yes
Fences and Impedement to Movement	Prefer open landscapes, though able to navigate around wildlife friendly fencing (maximum height of 42in, at least 18in between ground and first wire) (South Dakota Game, Fish, and Parks, n.d.)	Fence Location, Type, Height	Yes	No
Forage Preference	Favor forbs and shrubs, though also seen foraging specific crops (wheat, alfalfa) with the increase in cropland conversion (Christie et al., 2015; Cole, 1956)	Vegetation Community	Yes	No
Land Cover	Primarily prefer grassland, secondarily prefer shrubland (Bender et al., 2023; Ganey, 1998; Hlavachik, 1968; Mitchell & Smoliak, 1971; O'Gara & Greer, 1970; Russell, 1964; Schwartz & Nagy, 1976)	Land Cover	Yes	Yes
Precipitation	Variable preference in precipitation, though	Precipitation	No	No

Category	Pronghorn Preference	Relevant Variable(s)	Variable Collected in Ground-Truthing	Variable Used in Analysis
	winter precipitation is likely more important than summer precipitation (North Dakota State Library, n.d.)			
Soil Type	Prefer soil environments associated with big sagebrush (*Artemisia tridentata*) and silver sagebrush (*Artemisia cana*) (Mackie et al., n.d.)	Soil	Yes	No
Vegetation Height	Prefer vegetation height between 10-18in (25-46cm) (LandPKS, n.d.)	Vegetation Height	Yes	No

The following case study of pronghorn habitat connectivity in Rocky Boy's Reservation utilizes knowledge of these species attributes to conduct the suitability analysis. Effective habitat suitability and connectivity modeling for this study requires an understanding of species-specific ecological and behavioral characteristics to identify relevant environmental variables. This case study will provide a reproducible and transferrable framework for evaluating landscape structure and grassland connectivity. Development of this framework for other species will require knowledge of core species characteristics like habitat selection, movement ecology, and barrier sensitivity to guide variable selection.

4.2.3.1 Ground-truthing

An extensive literature review of pronghorn habitat and life history characteristics revealed multiple variables of interest for further exploration and data collection (Table 4.1) (Bean et al., 2024; Gates et al., 2012; Irwin & Cook, 1985; Jakes et al., 2020; Rue & Ranglack 2025; Zeller et al., 2021). During field surveys and subsequent ground-truthing in the study area, data were collected on these variables, including soil type and compaction, land cover, vegetation community type, vegetation height, fence location/type/condition, road location/type, and elevation. Three hundred ninety-two (392) data points were collected using ArcGIS Field Maps, utilizing an adaptive sampling method that allowed the team to adjust sampling protocols throughout the course of the fieldwork. Refer to Kelly (2026) for further information on ground-truthing protocols, collected variables, and results.

4.2.3.2 Data Layers for Analysis

Further literature review of pronghorn habitat modeling studies indicated that a subset of the originally collected variables were most relevant for pronghorn habitat connectivity analysis and able to be utilized in habitat modeling: land cover, slope/elevation (topographic position), Normalized Difference Vegetation Index (NDVI)[42], distance to water, distance to roads, distance to wells[43], and fence location[44] (Poor, 2010; Poor et al., 2012). Refer to Section 4.4.1 of this chapter for additional information on these variables and their relevance in the study. Analysis of ground-truthing accuracy of the various open-source land-cover data layers found that the 2024 USDA CDL had better accuracy, leading to its use in the following analysis. This layer is available in both 30m and 10m resolution with very little difference in accuracy (see Table 2.12 in Kelly (2026)), thus the 30m resolution layer was used to limit computational load. Tables 4.2 and 4.3 provide information on the software and data sources used in the connectivity analyses.

Table 4.2. *List of software used in this chapter's analysis*

Software	Packages or Functions	Analysis Used In
R R Foundation for Statistical Computing (Version 4.5.2)	landscapemetrics terra dplyr tidyr sf	Structural Connectivity
ArcGIS Pro Environmental Systems Research Institute (Esri)(Version 3.6.0)	Suitability Modeler	Functional Connectivity

Table 4.3. *List of data used in this chapter's analysis*

Analysis	Data Source	Associated Variable(s) of Interest
Structural Connectivity	U.S. Department of Agriculture, National Agricultural Statistics Service (NASS). Cropland Data Layer. 2024 Edition. Washington D.C., USDA-NASS Marketing and Information Services Office, February 27, 2025.	Land Cover
Functional	U.S. Department of Agriculture, National	Land Cover

[42] Not able to be collected in the field or ground-truthed, as this is an index calculated from remote sensing data

[43] 'Distance to wells' in the Poor (2010) study refers to distance to mining/extractive activities. Due to lack of data and inability to visit locations such as those during the ground-truthing visit, this variable was not included in the habitat assessment.

[44] Not openly accessible information, so not included in the habitat assessment

Analysis	Data Source	Associated Variable(s) of Interest
Connectivity	Agricultural Statistics Service (NASS). Cropland Data Layer. 2024 Edition. Washington D.C., USDA-NASS Marketing and Information Services Office, February 27, 2025.	
	U.S. Geological Survey, 3D Elevation Program. Elevation Source Data (3DEP) Seamless DEM Source (OPR). Reston, Virginia: USGS National Geospatial Program.	Topographic Position
	NASA Earthdata. MODIS/Terra Vegetation Indices 16-Day L3 Global 250m SIN Grid V061. 2024. NASA EOSDIS Land Processes Distributed Active Archive Center (LP DAAC), USGS/Earth Resources Observation and Science (EROS) Center, Sioux Falls, South Dakota, USA.	NDVI
	U.S. Census Bureau. TIGER/Line Shapefiles: Roads. Geographic Products Branch, Washington, DC.	Distance to Roads
	U.S. Geological Survey, USGS National Hydrography Dataset Best Resolution (NHD) - Montana (2023). Reston, Virginia: USGS National Geospatial Program.	Distance to Water
Study Area	U.S. Census Bureau. Cartographic Boundary Files (1:500,000). Geographic Products Branch, Washington DC.	N/A
	U.S. Environmental Protection Agency, U.S. Department of Interior, Bureau of Indian Affairs. American Indian & Alaska Native Land Area Representation (2015). Washington D.C.: EPA Office of Information Management.	N/A

4.3 Structural Connectivity

4.3.1 Methods

Structural connectivity is considered a “species agnostic” approach that focuses only on the spatial configuration of landcover, and is important to analyze as it is not limited to only

representing the connectivity and needs of a single species (Wood et al., 2022). In the study of structural connectivity, patch and class metrics are used to quantitatively assess habitat arrangement. Patch metrics include descriptors such as patch size, shape, perimeter-area ratio, and isolation (e.g., Euclidean nearest-neighbor distance), all of which offer insight into the spatial attributes of individual habitat remnants (Hesselbarth et al., 2019). Class metrics aggregate properties across all patches of a specific land cover class, describing landscape-level patterns with measures such as total class area, patch density, and edge density, which reflect habitat availability and fragmentation of specific land cover classifications and can better inform generalized conservation management plans (Hesselbarth et al., 2019).

In order to compare the structural connectivity of the Reservation to its encompassing counties, the study area was split into three areas of interest (AOI): Rocky Boy's Reservation, Hill County, and Chouteau County. In these locations, the Cropland Data Layer was used as a raster of land cover categories. The package "landscapemetrics" was used in R in its default settings to compute patch and class metrics of the Reservation and class metrics of the two additional areas of interest, Hill County and Chouteau County, of which the grassland/pasture class was prioritized for analysis as the preferred habitat for pronghorn. The resulting metrics provide a descriptive comparison of landscape structure among the three AOIs. Because the analysis evaluates complete spatial datasets rather than samples drawn from a larger population, statistical significance testing was not required (University of Michigan Consulting for Statistics, Computing, and Analytics Research Group, personal communication, February 2026). R scripts used for data preparation and analysis will be provided to BNGA for their use.

The behavioral and habitat requirements of pronghorn – such as being highly mobile and preferring large, contiguous patches of open grassland with minimal barriers – informed the relative importance of the available metrics. The metrics listed in Table 4.4 were chosen to focus on from all available metrics after an extensive literature review focused on patch size, configuration, edge context, and connectedness in the context of pronghorn. See Appendix C for all available metrics from the 'landscapemetrics' package.

Table 4.4. *Reported metrics for assessing structural connectivity. Metrics with literature support include a reference in the 'Name' column.*

Name	**Description** (Hesselbarth et al., 2018) **& Species Relevance**	Units	Patch- or Class-based
Contiguity Index	Shape metric; assesses the spatial connectedness of cells in patches Relevance: A higher contiguity index would reflect higher internal connectivity of a patch, therefore higher patch integrity and lower risk of fragmentation. This would be an important metric to monitor for large grassland patches as it could signal imminent fragmentation.	N/A	Patch

Name	Description (Hesselbarth et al., 2018) & Species Relevance	Units	Patch- or Class-based
Euclidean Nearest Neighbor Distance (Keeley et al., 2021)	Aggregation metric; the distance (measured edge-to-edge) to the nearest neighboring patch of the same class. This metric is a simple way to describe patch isolation. Relevance: This metric provides an idea of patch isolation, which may only affect pronghorn if the distances are very large since pronghorn are migratory and travel long distances daily.	Meters	Patch
Patch Area	Area and edge metric; the area of each patch in hectares Relevance: This metric is important to understand whether patches are sizable enough to support pronghorn.	Hectares	Patch
Aggregation Index	Aggregation metric; equals the number of like adjacencies divided by the theoretical maximum possible number of like adjacencies for that class Relevance: This metric quantifies the degree to which patches of the same class are spatially aggregated or clustered. Higher values indicate that patches are located close to each other, which would benefit pronghorn who would have to travel shorter distances to migrate across grassland patches for forage.	Percent	Class
Core Area Percentage of Landscape	Core area metric; equals the percentage of core area of a certain class in relation to the total landscape area Relevance: This metric quantifies how much habitat within the total landscape is removed from edges and experiences less negative edge effects[45]. In this specific landscape, where human disturbance is expanding, a higher value would indicate safer habitat for pronghorn,	Percent	Class

[45] The phenomenon where habitat fragmentation alters the physical and biological conditions at the boundary of a habitat patch, which creates a distinct transition zone where conditions differ significantly from the patch interior

Name	Description (Hesselbarth et al., 2018) & Species Relevance	Units	Patch- or Class-based
	away from roads, developed areas, and predation.		
Edge Density	Area and edge metric; the sum of all edges of a class in relation to the landscape area. This metric describes the configuration of the landscape (e.g.: aggregation of the same class will result in low edge density) and is comparable across landscapes. Relevance: This metric represents the total length of habitat edges per unit area across the landcover class, with higher values indicating more boundaries between land cover types. In addition to being an indication of fragmentation, this metric signals that pronghorn may need to transition between landcover types more often.	Meters per hectare	Class
Effective Mesh Size (Keeley et al., 2021; Spanowicz & Jaeger, 2019)	Aggregation metric; relatively measures patch structure Relevance: This metric quantifies landscape fragmentation by estimating the probability that two randomly chosen points fall within the same patch. Higher values indicate larger, more connected patches, which would benefit pronghorn who prefer large, unrestricted areas.	Hectares	Class
Euclidean Nearest Neighbor Distance (Keeley et al., 2021)	Aggregation metric; measures the distance to the nearest neighboring patch of the same class (edge to edge). This metric is easily comparable among different landscapes. Relevance: This metric provides an idea of patch isolation of the whole landcover class, which gives an idea if all patches in the entire landcover class are relatively close together, which would benefit pronghorn if they did not need to travel far distances to other patches.	Meters	Class
Interspersion and Juxtaposition Index	Aggregation metric; describes the intermixing of classes Relevance: This metric quantifies how evenly	Percent	Class

Name	Description (Hesselbarth et al., 2018) & Species Relevance	Units	Patch- or Class-based
	patches of different classes are interspersed across the landscape, with higher values indicating that the class is interspersed across the entire area and lower values indicating that patches of that landcover class are clumped together. Pronghorn would benefit from lower values, as this would mean grassland patches require less travel to access.		
Largest Patch Index	Area and edge metric; equal to the percentage of the landscape covered by the corresponding largest patch of each class. This metric is a simple measure of class dominance. Relevance: This metric indicates whether a landcover class dominates the landscape, which would indicate large, intact habitat for pronghorn.	Percent	Class
Number of Patches	Aggregation metric; describes the fragmentation of a class Relevance: This metric provides a simple count of patches belonging to a given class, which gives insight into overall fragmentation as higher values would indicate more patches.	N/A	Class
Patch Area	Area and edge metric; summarizes each class as the mean of all patch areas belonging to a class. This metric describes the composition of the landscape and gives an idea of patch structure. Relevance: This metric is important to understand whether patches in the entire landcover class are, on average, sizable enough to support pronghorn.	Hectares	Class
Patch Cohesion Index (Keeley et al., 2021)	Aggregation metric; characterizes the connectedness of patches belonging to a class. This metric can be used to assess if patches of the same class are aggregated by location, or isolated. Relevance: This metric quantifies the physical	Percent	Class

Name	**Description** (Hesselbarth et al., 2018) **& Species Relevance**	Units	Patch- or Class-based
	connectedness of habitat patches across the landscape, with higher values indicating greater connectivity. In addition to the aggregation index and effective mesh size, this metric provides insight into whether pronghorn habitat is well-connected.		
Patch Density	Aggregation metric; describes the fragmentation of a class. In comparison to the Number of Patches metric, Patch Density is standardized to the area, and can be compared among landscapes with different total areas. Relevance: This metric is a simple measure of fragmentation, as a higher value indicates that there are many small patches rather than fewer large patches. This could be an important metric for future monitoring to study where grassland fragmentation is occurring.	Number per 100 hectares	Class
Perimeter-Area Fractal Dimension	Shape metric; describes the patch complexity of a class while being scale independent (i.e., increasing the patch size while keeping the patch shape constant will not change the metric's value). Relevance: This metric quantifies patch shape complexity across a landcover class, providing insight into whether grassland patches are more irregularly shaped and therefore fragmented.	N/A	Class
Perimeter-Area Ratio (Helzer & Jelinski, 1999)	Shape metric; summarizes each class as the mean of each patch belonging to a certain class. This metric describes the patch complexity. Relevance: This metric also reflects shape complexity across a landcover class through measuring the amount of perimeter edge relative to the area. Higher values would indicate irregular or elongated patches, which experience more edge influences that are likely detrimental to pronghorn.	N/A	Class
Total Class Area	Area and edge metric; sums the area of all	Hectares	Class

Name	Description (Hesselbarth et al., 2018) & Species Relevance	Units	Patch- or Class-based
	patches belonging to a class. This metric shows if the landscape is dominated by one class or if all classes are equally present. Relevance: This is a simple measure of the total area occupied by a specific class in order to quantify how much the preferred landcover type (grassland) is within the study area.		

4.3.2 Results and Discussion

4.3.2.1 Patch-Based Metrics: Analysis of Individual Patches and Land Cover within Rocky Boy's Reservation

The analysis of patch metrics across Rocky Boy's Reservation revealed quantitative differences in fragmentation among land cover categories. Forest and shrubland exhibited the highest numbers of patches (4,750 and 3,527, respectively), suggesting that these land cover classes are more broken up and interspersed throughout the Reservation's landscape, resulting in smaller, isolated fragments. Grassland habitat, with the third highest number of patches at 2,447 patches, is less fragmented relative to forest and shrubland, but still comprises a substantial number of discrete habitat units. Wetlands, developed area, open water, and barren land cover types all had markedly fewer patches. Refer to Table 4.5 for patch number results.

Examining patch area data provides further insight into these patch dynamics. Grassland patches cover the largest total area (17,555.40 hectares), yet this land cover type has the third-highest number of patches. This result suggests that grassland patches tend to be larger and potentially more contiguous than those found in other land cover categories. Shrubland occupies the second highest total area (15,921.63 hectares), which, considering the high number of patches, indicates these patches are smaller on average. Forest habitats have a markedly lower overall habitat area (8,965.08 hectares), reinforcing that its high number of patches could correlate to landscape patchiness and interspersion. Refer to Table 4.5 for results of total area of land cover categories.

Table 4.5. *Total number and area of habitat patches in Rocky Boy's Reservation, by land cover classification.*

Land Cover Category	Number of Patches	Total Area of Habitat Patches (hectares)
Grassland/Pasture	2,447	17,555.40
Shrubland	3,527	15,921.63

Land Cover Category	Number of Patches	Total Area of Habitat Patches (hectares)
Forest (mixed forest, evergreen forest, deciduous forest)	4,750	8,965.08
Agricultural (fallow/idle cropland, all crops)	732	1,919.88
Wetlands (woody wetlands, herbaceous wetlands)	1,988	1,307.16
Developed (high intensity, medium intensity, low intensity, open space)	571	154.98
Open water	51	114.30
Barren	6	1.89

Pronghorn home range requirements in the summer (minimum of 260 hectares) and winter (minimum of 650 hectares) provide a valuable lens for identifying available grassland habitat patches (Krejci & Dewey, 2009). Within Rocky Boy's Reservation, four large grassland patches exceed the minimum requirements for summer home ranges, marking them as potential priority areas for grassland conservation. Three of these patches are large enough to qualify as a home range in the winter (743.49, 1,263.78, and 12,287.07 hectares), making them important for pronghorn habitability year-round. Notably, the largest of these grassland patches contains approximately 70% of the total grassland habitat in Rocky Boy's Reservation. These large grassland patches should be prioritized for conservation and management, as their size and connectivity may be crucial for supporting pronghorn. Monitoring the size of these large patches over time could be essential for grassland management, as new divisions in these patches or significant changes in patch size could indicate critical pronghorn, and therefore grassland, loss that requires more intensive intervention. Refer to Table 4.6 for the patch metrics and Figure 4.7 for location of these four sizable patches within Rocky Boy's Reservation.

Table 4.6. *Grassland/pasture patches in Rocky Boy's Reservation that are sufficient size (above 260 hectares / 2.6 sq km) to be considered home range for pronghorn in the summer. Asterisk (*) represents patches sufficient for home range in the winter (650 hectares / 6.5 sq km).*

Patch Area (hectares)	Contiguity Index	Euclidean Nearest Neighbor (meters)
513.90	0.90	60

Patch Area (hectares)	Contiguity Index	Euclidean Nearest Neighbor (meters)
743.49*	0.90	60
1,263.78*	0.94	60
12,287.07*	0.91	60

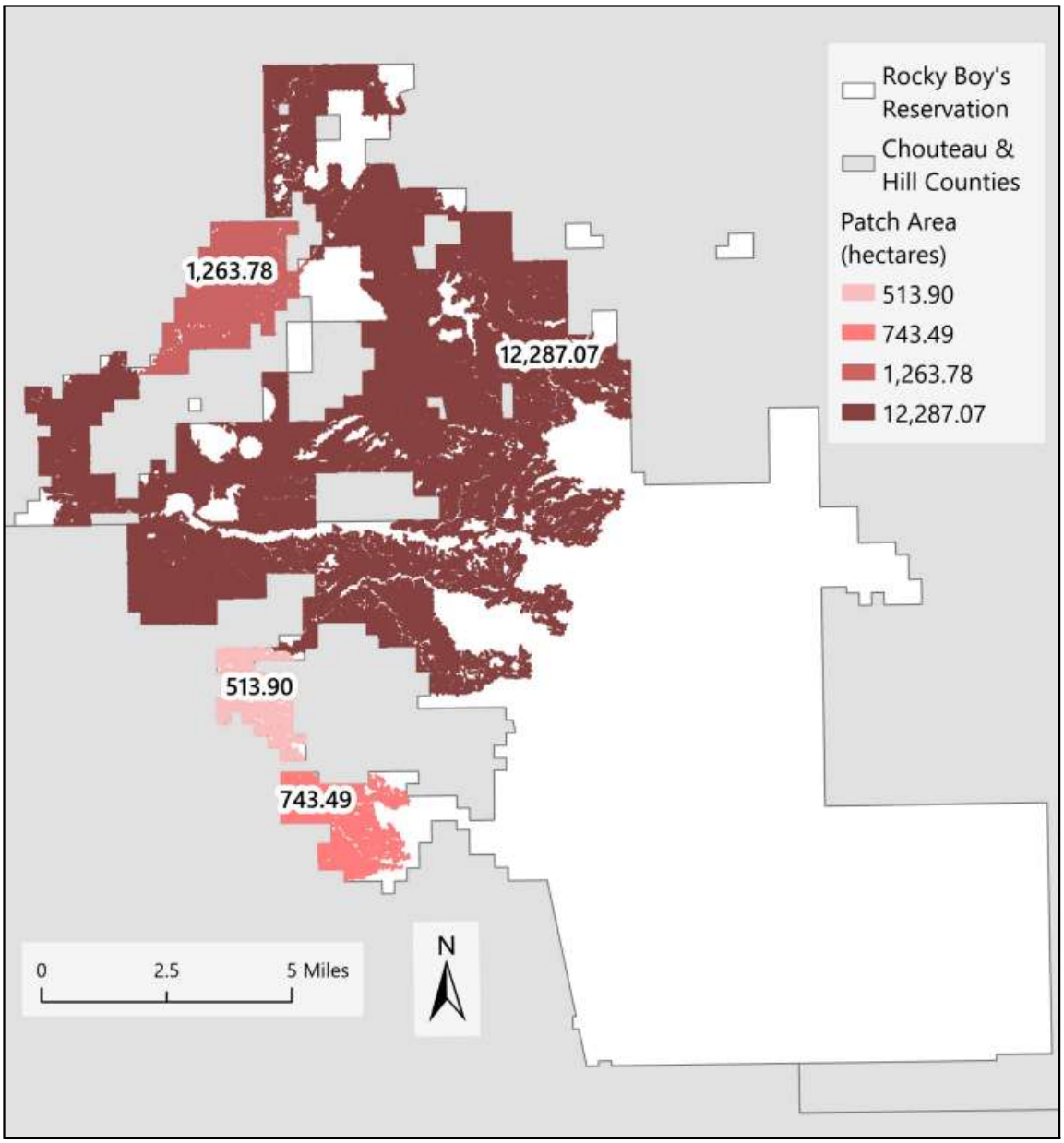


Figure 4.7. *Patches within Rocky Boy's Reservation that exceed pronghorn habitat area requirements.*

The contiguity index, which ranges from 0 to 1, reflects the degree of internal connectivity within a habitat patch. Each of the four identified grassland patches exhibits a contiguity index greater than 0.90, indicating that they are highly contiguous and largely free from internal disturbances or 'perforations.' This high level of within-patch connectivity suggests that these areas maintain robust, uninterrupted habitat conditions. Despite these favorable metrics, there may still be a risk of future fragmentation, particularly in as dynamic a landscape as grasslands.

Additionally, each patch is located near another grassland patch, with Euclidean nearest neighbor distances of 60 meters for each patch. This proximity may facilitate interpatch movement, contributing positively to landscape connectivity for pronghorn. Though this close proximity is beneficial, further information is needed on the size and quality of the nearby patches, as restoring grassland patches adjacent to these large patches may not be worthwhile for pronghorn conservation purposes if the nearby patch is too small to support pronghorn or other future priority species.

Examining the location and shape of these patches calls into question how Rocky Boy's Reservation's complex shape could influence these findings. Specifically, the Reservation is interspersed with land that geographically belongs to either Hill or Chouteau County, and as this project's analysis uses these territory borders to separate the study areas, grassland patches that are contiguous have been artificially cut to abide by these borders. Consequently, metrics associated with these grassland patches are not fully representative of the connectivity of grassland in the landscape. Figure 4.8 depicts three examples of where grassland in the outlying landscape connects grassland patches within Rocky Boy's Reservation to each other.

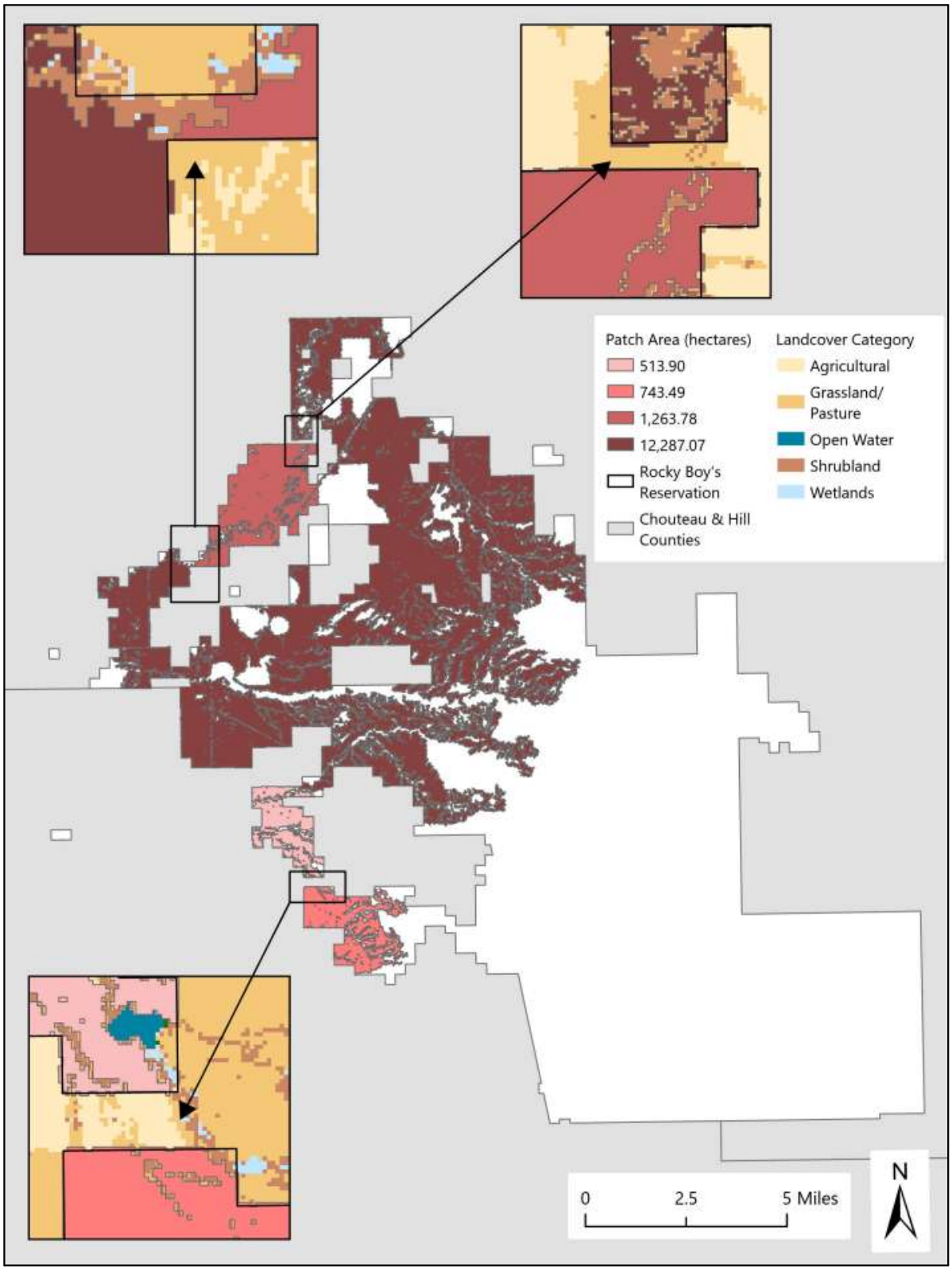


Figure 4.8. *Areas on the border of Rocky Boy's Reservation (in either Chouteau or Hill County) that would be contiguous grassland/pasture areas connected to existing patches if geographical boundaries were not imposed.*

When geographical boundaries are not imposed on the landscape and a 12.86 mile buffer[46] is added, we see that the four sizable patches are not only connected to each other, but also connected to a large swatch of grassland that extends significantly outside of the Reservation (Reynolds, 1984; Reynolds & Laundre, 1990) (Figure 4.9). This finding indicates that the connectivity of grassland in the area is not sufficiently represented when territorial boundaries are in place, which raises questions into how the boundaries impact pronghorn movement and the interpretation of grassland fragmentation across the AOIs, which future research could further examine.

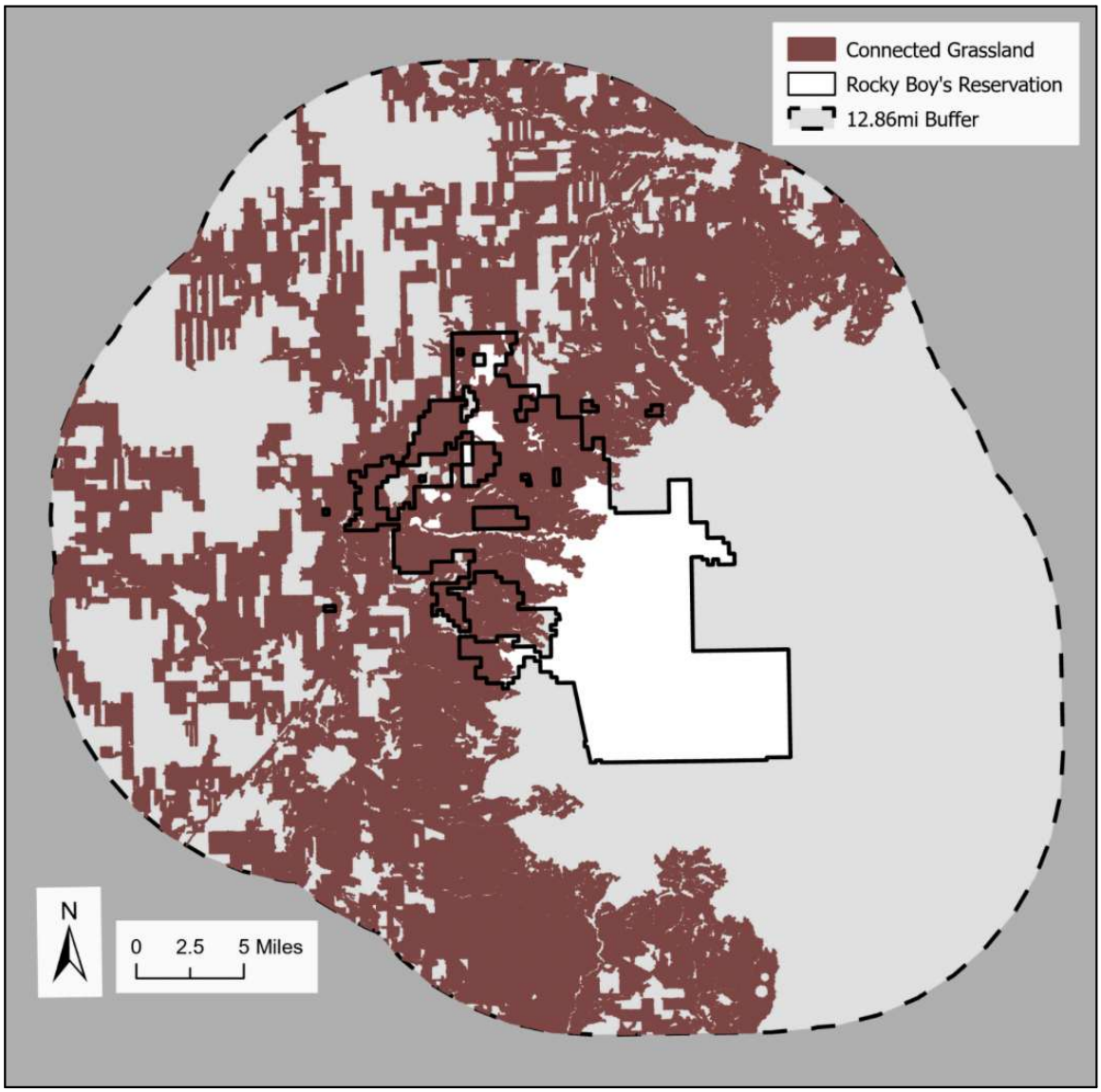


Figure 4.9. *Large grassland patch that connects with grassland in a 12.86 mile buffer zone (the maximum daily movement of pronghorn (Reynolds, 1984; Reynolds & Laundre, 1990) of Rocky Boy's Reservation.*

[46] 12.86 miles is the average daily movement for pronghorn (Reynolds, 1984; Reynolds & Laundre, 1990).

4.3.2.2 Class-Based Metrics: Comparative Analysis of Class-Based Metrics Across Three Areas of Interest (Rocky Boy's Reservation, Chouteau County, Hill County)

The analysis of class-based metrics provides useful information about the landscape across all three AOIs and enables a comparison of Rocky Boy's Reservation to the surrounding counties of Hill and Chouteau. The calculated metrics can be grouped into three categories describing: (1) landscape composition (number of patches, patch density, patch area, total class area, largest patch index, and core area percentage of landscape); (2) patch configuration and shape (perimeter-area ratio, perimeter-area fractal dimension, and edge density); and (3) connectivity, proximity, and patch relationships (Euclidean nearest neighbor distance, interspersion and juxtaposition index, aggregation index, patch cohesion index, and effective mesh size). Refer to Appendix D for a table of all results, which are analyzed separately in the following section.

4.3.2.2.1 Landscape Composition

Rocky Boy's Reservation contains the lowest absolute number of grassland patches (2,447) when compared to Hill (22,380) and Chouteau (38,124) counties. Despite its smaller extent, Rocky Boy's Reservation exhibits the highest patch density (5.33 patches per 100 hectares), indicating that the landscape is divided into a larger number of small habitat fragments per unit area. This higher patch density suggests greater fragmentation, meaning pronghorn would encounter more boundaries between suitable and unsuitable habitat. By contrast, Hill (3.09 patches per 100 hectares) and Chouteau (3.73 patches per 100 hectares) have lower patch densities, reflecting landscapes where grassland habitat is more continuous, less fragmented, and potentially more favorable for pronghorn movement.

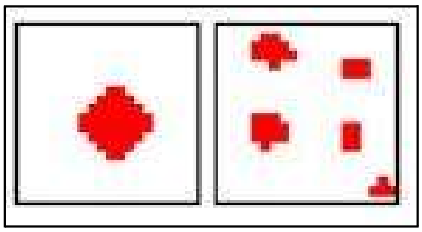


Figure 4.10. *Comparison of a landscape with low patch density (left) and high patch density (right) (Wan et al., 2023)*

Chouteau and Hill counties encompass much larger total areas of grassland/pasture (452,647.53 and 338,166.63 hectares, respectively) compared to Rocky Boy's Reservation (17,555.40 hectares), a difference primarily resulting from the overall geographic size of the three AOIs (refer to Figures 4.11 and 4.12). It follows, then, that the average patch size is smallest in Rocky Boy's Reservation (2.3 hectares), with larger patch sizes in Chouteau (11.87 hectares) and Hill (15.11 hectares) counties. This means that pronghorn in Rocky Boy's Reservation must navigate a landscape composed of smaller and more numerous patches,

increasing the need for movement between habitat fragments and potentially increasing exposure to non-preferred habitat.

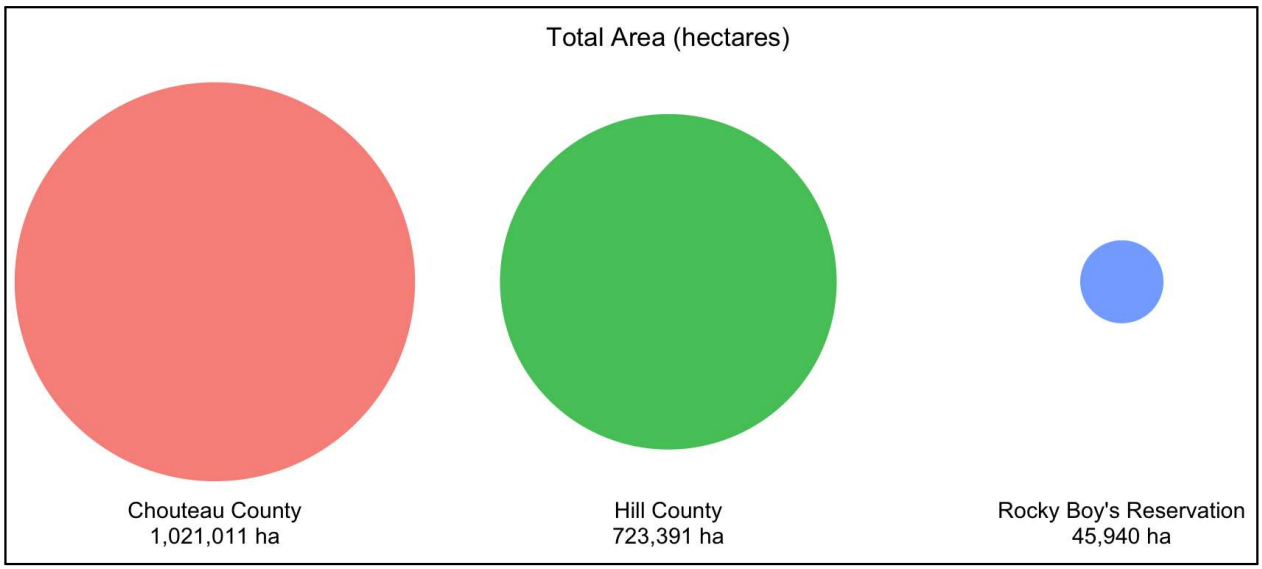


Figure 4.11. *Comparison of total area of each AOI.*

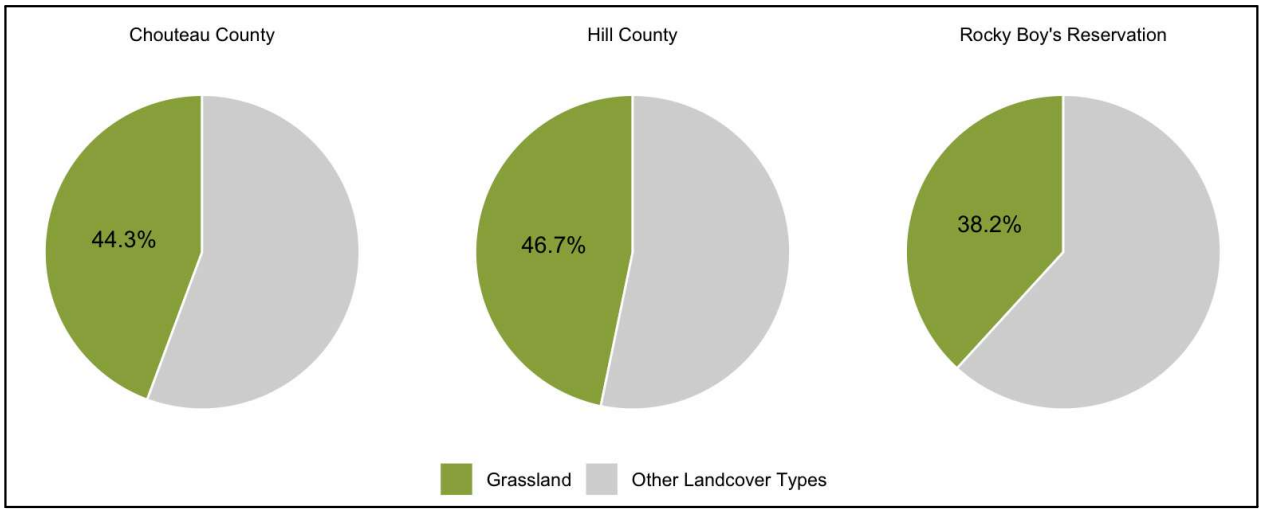


Figure 4.12. *Percentage of grassland/pasture compared to total area for each AOI.*

Assessing the largest patch index provides insight into the dominance of the largest contiguous block of a certain landcover class in relation to the total landscape of that area. Hill County possesses the largest contiguous grassland block, with its largest patch comprising 29.57% of Hill's total landscape. Rocky Boy's Reservation follows with its largest grassland patch forming 26.75% of its landscape, while Chouteau's largest patch accounts for 16.89%. Higher values relate to lower fragmentation, indicating that Hill County and Rocky Boy's Reservation have potentially significantly more continuous area for pronghorn habitat that could be a stronghold amidst landcover change.

The core area percentage of landscape metric calculates the proportion of habitat far removed from edges, and thus less exposed to disturbance. Chouteau (31.72%) and Hill (36.10%) have higher percentages of core grassland/pasture area compared to Rocky Boy's Reservation (27.04%). For pronghorn, interior habitat shielded from edge effects is critical, as it reduces predation risks and exposure to anthropogenic disturbance. While Rocky Boy's Reservation supports less core area relative to its total area, all three AOIs maintain roughly a third of their grassland habitat in core, interior zones.

Overall, these landscape composition metrics demonstrate that Rocky Boy's Reservation, with its smaller area and higher fragmentation, may pose ecological challenges for pronghorn due to decreased connectivity and smaller, isolated patches of habitat. In contrast, the more expansive and less fragmented landscapes of Hill and Chouteau, characterized by larger patches and a greater proportion of core area, offer more suitable conditions for pronghorn occupancy and population persistence. Because pronghorn are capable of traversing the wider landscape, they may increasingly utilize the substantial grassland patches found in Hill and Chouteau counties outside of Rocky Boy's Reservation, which could inform conservation planning and the need to connect habitat patches in the surrounding counties to those within Rocky Boy's Reservation to promote pronghorn movement long-term. Additionally, altering fences in these zones of grassland connection between the counties and Rocky Boy's Reservation could be a key conservation measure to implement. Refer to Table 4.7 for a summary of these class metrics for each of the three AOIs.

Table 4.7. *Class metrics related to landscape composition for grassland/pasture land cover of the three AOIs.*

Metric	AOI		
	Rocky Boy's Reservation	**Hill**	**Chouteau**
Core Area Percentage of Landscape (%)	27.04	36.10	31.72
Largest Patch Index (%)	26.75	29.57	16.89
Number of Patches	2,447	22,380	38,124
Patch Area (mean) (hectare)	7.17	15.11	11.87
Patch Density (patch/100 ha)	5.33	3.09	3.73
Total Class Area (hectare)	17,555.40	338,166.63	452,647.53

4.3.2.2.2 Patch Configuration and Shape

The configuration and shape of habitat patches determines the degree of exposure to edges, microclimates, and accessibility for predators. Metrics such as the perimeter-area ratio and

perimeter-area fractal dimension describe the regularity and complexity of these patch shapes. Rocky Boy's Reservation exhibits a slightly lower perimeter-area ratio (0.10) compared to Hill and Chouteau (both 0.11), indicating that patches within Rocky Boy tend to be slightly more regular and compact. Similarly, the fractal dimensions across all three areas (Rocky Boy's Reservation and Hill both at 1.45, and Chouteau at 1.48) suggest that overall shape complexity is fairly consistent, with Chouteau's patches being marginally more irregular. These lower values are representative of simpler and less convoluted patch shapes, which is advantageous for pronghorn as they reduce unnecessary exposure to edge habitats. Future and repeat studies should monitor changes in perimeter-area ratio or perimeter-area fractal dimension, which would indicate patch degradation and increased edge effects, ultimately exposing pronghorn to greater predation risk and disturbance.

Edge density reflects how much boundary exists between habitat and non-habitat. Higher edge density can mean more frequent transitions between grassland and surrounding land cover, which could influence resource accessibility, plant diversity, and predation. Hill had the lowest Edge Density (55.28 m/ha), followed by Rocky Boy's Reservation (57.25 m/ha) and Chouteau (67.1 m/ha). High edge density in Chouteau could reflect more fragmented landscapes or complex patch boundaries, potentially affecting pronghorn movement and exposing the grassland habitat to more edge-related disturbances. Refer to Figure 4.13 for a visualization of increasing edge density due to fragmentation.

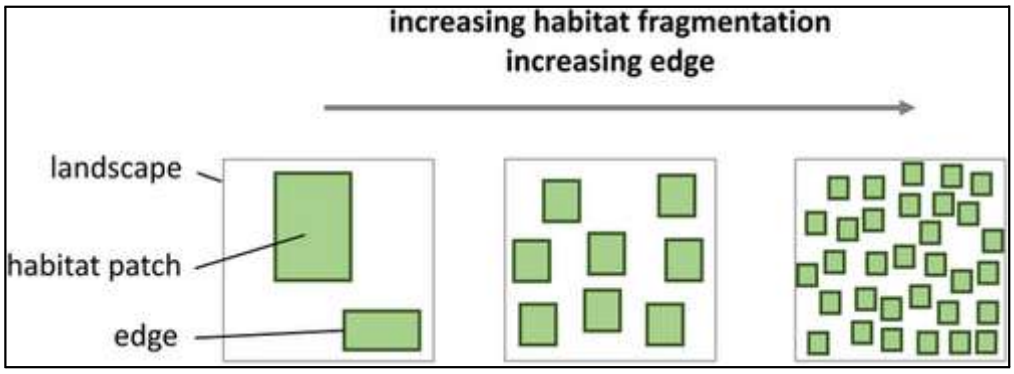


Figure 4.13. *For a given total amount of habitat in a landscape (green areas within the large squares), the total amount of habitat edge (darker green boundaries of habitat) increases with increasing habitat fragmentation (Fahrig, 2024).*

Overall, the configuration and shape analysis reveals that Rocky Boy's Reservation, Hill, and Chouteau all maintain relatively simple patch shapes, which is favorable for pronghorn habitability. Monitoring these metrics over time is essential, as increases in patch complexity and edge density could signal worsening habitat conditions for pronghorn and inform adaptive management strategies. Refer to Table 4.8 for a summary of these class metrics for each of the three AOIs.

Table 4.8. *Class metrics related to patch configuration and shape for grassland/pasture land cover of the three AOIs.*

Metric	AOI		
	Rocky Boy's Reservation	Hill	Chouteau
Edge Density (m/ha)	57.25	55.28	67.10
Perimeter-Area Fractal Dimension	1.45	1.45	1.48
Perimeter-Area Ratio (mean)	0.10	0.11	0.11

4.3.2.2.3 Connectivity, Proximity, and Patch Relationships

The Euclidean nearest neighbor distance metric, which assesses how isolated patches are from each other, shows that Rocky Boy's Reservation has the most isolated patches with a mean nearest neighbor distance of 102.18 meters. In comparison, Hill (88.01 meters) and Chouteau (85.8 meters) possess patches that are closer together. Greater distances between patches in Rocky Boy's Reservation indicate that pronghorn may face more difficulties navigating between suitable habitat fragments, which can hinder dispersal, reduce access to vital resources, and potentially threaten population viability through increased isolation.

The aggregation index reveals how tightly patches are grouped. Rocky Boy's Reservation exhibits the highest aggregation (93.8), suggesting that grassland patches here are clustered in groups, which can facilitate pronghorn movement within these clusters and support dispersal and migration. Hill (81.2) and Chouteau (75.7), with lower aggregation values, present a more scattered patch arrangement, potentially making movement across the landscape more challenging for pronghorn.

Patch cohesion, which ranges from 0 to 100, measures the physical connectedness of habitat patches. All three AOIs score exceptionally high (>99.5), indicating that grassland habitats remain largely intact and connected in these areas. This is beneficial for pronghorn, due to their reliance on wide-ranging movement through continuous landscapes, and suggests that the landscape still supports movement and migration across the three AOIs, despite their varying levels of fragmentation and patch arrangement. Refer to Figure 4.14 for a diagram describing patch cohesion.

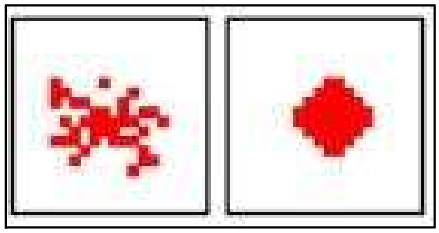


Figure 4.14. *Comparison of a patch with low patch cohesion (left) and high patch cohesion (right) (Wan et al., 2023).*

Effective mesh size estimates the average accessible habitat block size, standardized across each AOI's overall area, and measures habitat connectivity by calculating the probability that two random points are connected. A higher effective mesh size indicates less fragmentation. Chouteau (64,637.88 ha) and Hill (49,154.41 ha) offer considerably larger contiguous habitat blocks than Rocky Boy's Reservation (3,340.29 ha). Rocky Boy's Reservation's significantly smaller mesh size aligns with other metrics, insinuating a fragmented, densely patched landscape, potentially limiting long-range movements and suitable foraging grounds for pronghorn.

The interspersion and juxtaposition index (IJI) measures how intermixed habitat patches are with other types. A higher IJI means more mixing of landscapes, which is good for some species that need diverse patches. A lower IJI suggests larger, homogenous blocks, which could be better for species that favor a certain land cover type, like pronghorn. Hill (61.11) and Chouteau (49.55) exhibit higher intermixing than Rocky Boy's Reservation (25.43); this result is beneficial for pronghorn, who favor large, contiguous habitats. Less intermixing also relates to lower exposure to patch edges, which may be preferential for pronghorn, who avoid most other land cover types. Further work analyzing whether these grassland areas are interspersed with shrubland–another preferential land cover type for pronghorn–would be beneficial to further understand the effects and outcomes of intermixing in this landscape.

Overall, these metrics indicate that while Rocky Boy's Reservation presents clustered and physically cohesive patches, it also has greater isolation and lower mesh size, which may pose barriers to pronghorn movement over larger distances. In contrast, Hill and Chouteau offer larger, more accessible grassland blocks and cohesive patch networks, which are favorable for pronghorn and provide important targets for grassland conservation and connectivity planning. Refer to Table 4.9 for a summary of these class metrics for each of the three AOIs.

Table 4.9. *Class metrics related to connectivity, proximity, and patch relationships for grassland/pasture land cover of the three AOIs.*

Metric	AOI		
	Rocky Boy's Reservation	Hill	Chouteau
Aggregation Index	88.25	91.11	88.65
Effective Mesh Size (ha)	3,340.29	64,637.88	49,154.41
Euclidean Nearest Neighbor Distance (mean) (meter)	102.18	88.01	85.80
Interspersion and Juxtaposition Index	25.43	61.11	49.55
Patch Cohesion Index	99.59	99.91	99.89

Overall, these structural connectivity metrics suggest significant differences in grassland configuration across the AOIs. For Rocky Boy's Reservation, broader landcover context helps explain some observed patterns: the densely forested south-eastern area likely concentrates grasslands into the northern portion of the Reservation, producing a higher patch density. This landcover divide is especially influential in Rocky Boy's Reservation due to its much smaller size compared to Hill and Chouteau counties, where a comparable sized forest-grassland split would be less likely to dominate county-scale metrics. Additionally, it is essential to consider the sensitivity of these metrics to the geographical boundaries that define each AOI. Administrative borders can divide patches, alter patch shape, and bias class-based comparisons, with these effects likely amplified due to the substantial difference in total area of these AOIs. While it was out of the scope of this project, future management and conservation decisions should consider this concept, as well as additional artificial boundaries like fences and roads, which could further subdivide grassland patches and impact pronghorn's ability to access large grassland patches.

4.4 Functional Connectivity

4.4.1 Methods

Functional connectivity quantifies the actual movement and flow of focal species through the landscape using metrics such as dispersal success rate, frequency of movement between patches (often tracked through telemetry or mark-recapture studies), and landscape resistance, measured through approaches such as least-cost path analysis and circuit theory modeling (Vogt et al., 2009), which is further discussed in Buller & Kelly (2026). Gene flow estimates represent another form of functional connectivity, measuring the dispersal of genes across separate populations. These genetic approaches can reveal population connectivity over multiple generations. Gene flow estimates may also be particularly relevant for species that are not

considered “migratory,” but still experience effects of fragmentation. Together, these approaches integrate spatial landscape structure with realistic ecological functioning to better understand species movement and landscape permeability.

Due to a lack of accessible pronghorn location data, functional connectivity analysis within this study was only assessed up to and including the development of a habitat suitability raster. Analysis beyond this stage would require pronghorn occurrence or movement data to define thresholds and polygons for patch-occupancy designation and corridor assessment. However, creation of this habitat suitability raster aims to provide an initial framework for identifying potential habitat distribution and areas of relative suitability for pronghorn within the study area.

Variables included in the habitat suitability model were selected based on ecological relevance to pronghorn habitat requirements, data availability within the study area, and from modeling a similar approach conducted by Poor (2010). Land cover, Normalized Difference Vegetation Index (NDVI), digital elevation model (DEM), major road data, and water, stream, and waterbody locations were acquired through open-source spatial databases. Preparation of these layers included clipping to the study area boundary, reprojection into a common coordinate system (NAD 1983 UTM Zone 12N), and more outlined in the following section. Spatial data on fence location and condition were unavailable, therefore fencing could not be incorporated into the habitat suitability model. This gap in data represents a limitation of the analysis, as fencing is a significant barrier to pronghorn movement and migration across grassland ecosystems. Additionally, this model lacks the variable ‘distance to wells,’ which Poor (2010) utilized, as pronghorn tend to avoid extractive activities. Satellite data on this variable was similarly difficult to obtain, leading to the exclusion of this variable.

4.4.1.2 Preparation of Data Layers

Land cover was included in the model to represent vegetation communities and land use across the study area, both of which strongly influence pronghorn habitat selection. Spatial land cover data was obtained from the USDA Cropland Data Layer (2024) and clipped to the study area. Land cover classes were reclassified (Table 4.10) to better align the suitability categories represented in the Poor (2010) paper.

Table 4.10. *Reclassification of the USDA (2024) Cropland Data Layer (CDL) into broadened categories to align better with the Poor (2010) landcover classifications.*

New Classification	CDL Landcover Categories within the New Classification
Agricultural	Alfalfa, barley, buckwheat, camelina, canola, cantaloupes, chickpeas, clover/wildflowers, corn, durum wheat, fallow/idle cropland, flaxseed, herbs, lentils, millet, misc vegs & fruits, mustard, oats, other crops, other hay/non-alfalfa, other small grains, peas,

New Classification	CDL Landcover Categories within the New Classification
	potatoes, rye, safflower, sod/grass seed, sorghum, speltz, spring wheat, sweet corn, triticale, vetch, winter wheat
Barren	Barren
Developed	Developed/open space, developed/low intensity, developed/med intensity, developed/high intensity
Forest	Deciduous forest, evergreen forest, mixed forest
Grassland/Pasture[47]	Grassland/Pasture
Open Water	Open Water
Shrubland	Shrublands
Wetlands	Herbaceous wetlands, woody wetlands

A Normalized Difference Vegetation Index (NDVI) was included as an indication of vegetation productivity and potential forage availability. NDVI uses satellite imagery and the visible and near infrared spectral bands to measure the relative greenness and biomass of vegetation on a scale from -1 to 1. This relative greenness provides an indicator of "healthy" forage resources for herbivores such as pronghorn, so serves as a proxy for forage quality. NDVI data was obtained from NASA Earthdata for the year 2024 in 16-day segments. The Poor (2010) paper outlines their spring season from February 18th to April 30th and averages the NDVI over those days. Following this methodology, the 'cell statistics' tool was used to average the NDVI data over days 49-113 of the year (the closest 16-day periods to the February 18th to April 30th timeline) into one raster layer (Figure 4.15).

[47] The Poor (2010) paper separately categorized grasslands and pastures, which differs from the USDA 2024 CDL data that inseparably combines those categories.

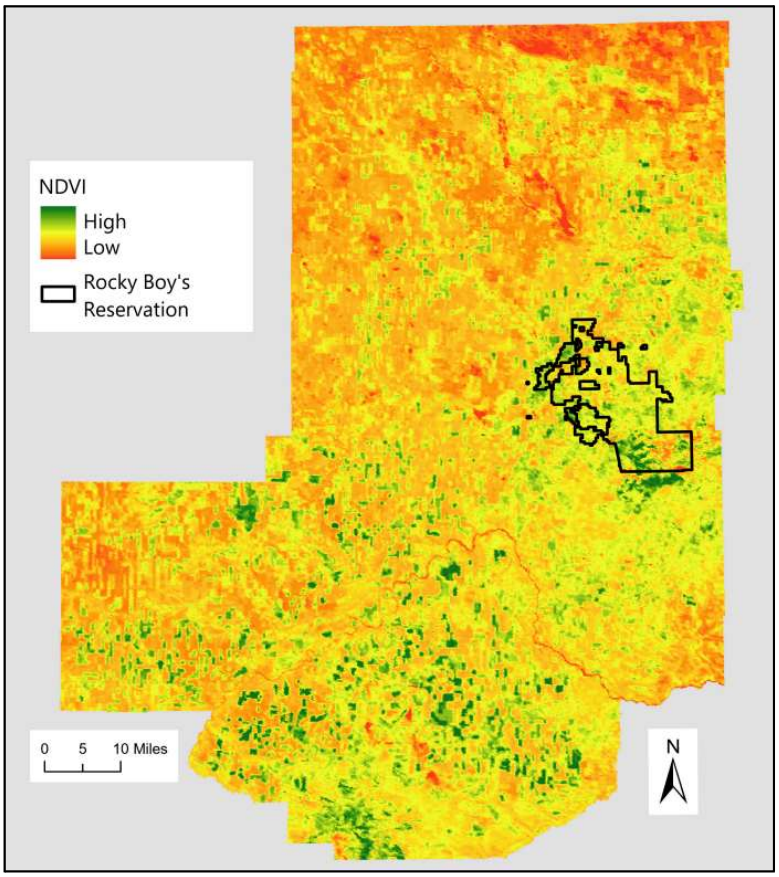


Figure 4.15. *NDVI layer used in the suitability raster.*

Elevation was incorporated into the model using a digital elevation model (DEM). Pronghorn typically prefer relatively flat or gently rolling terrain that allows for increased visibility and early predator detection. The DEM was obtained from the U.S. Geological Survey 3D Elevation Program and processed within ArcGIS Pro. Following the methodology described by Poor (2010), the DEM was clipped to the study area and filled. Then the 'focal statistics' tool was utilized using a 200 cell neighborhood circle to create a mean value of the DEM within the neighborhoods. Slope of the DEM was calculated using the 'surface parameters' tool, and then subtracted from the mean DEM to create the variable 'Topographic Position Index (TPI)[48].'

In order to apply the weighting system described in section 4.4.1.3, values within 'TPI' were categorized using the 'raster calculator' tool based on categorization described in the Poor (2010) and Zeller (2018) studies. See Table 4.11 for this categorization and Figure 4.16 for visualization of this layer.

[48] TPI is the difference between the elevation of the current cell and the mean elevation of its neighborhood (Esri, 2025).

Table 4.11. *Categorization of TPI values for the weighting system.*

TPI Category	TPI Value Derivation
Canyon Bottom	≤ -8
Flat-Gentle Slopes	-8 to 8, slope ≤ 6°
Ridge Tops	≥ 8
Steep Slopes	-8 to 8, slope ≥ 6°

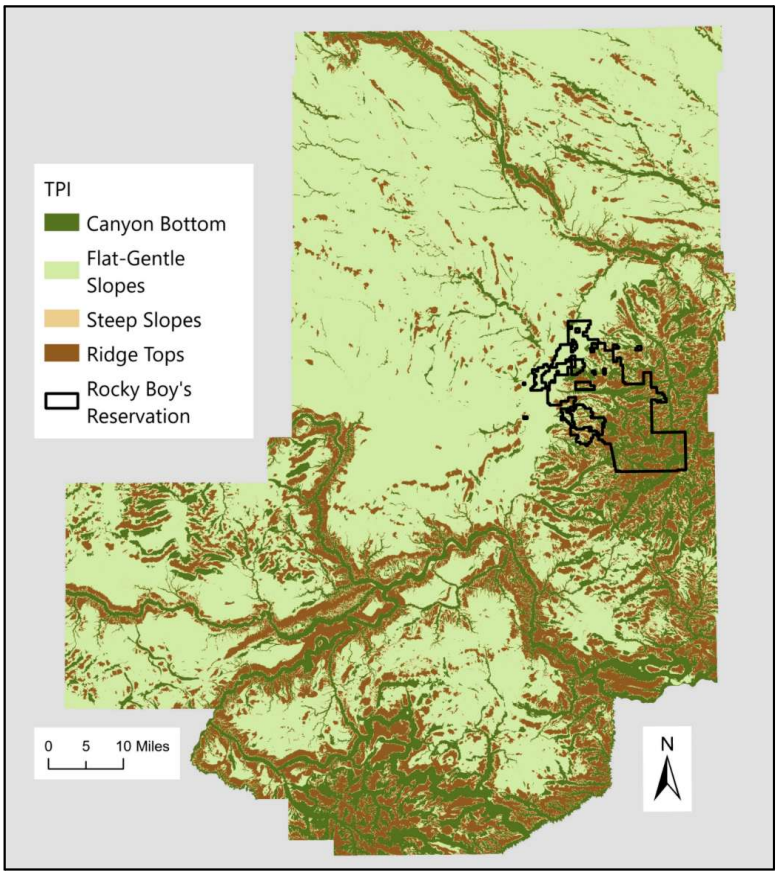


Figure 4.16. *TPI layer used in the suitability raster.*

Major roads were included as a representation of anthropogenic disturbance and potential barriers to movement. Road infrastructure can fragment habitat and influence pronghorn behavior through avoidance of human activity. Major road data were obtained from the U.S. Census Bureau for each county (Chouteau and Hill). These two line features were combined using the 'merge' tool and then transformed into a raster using the 'feature to raster' tool. Finally, the 'distance accumulation' tool was used in ArcGIS Pro to create the variable 'distance to roads,' a raster layer that quantifies each cell's distance to the nearest road, which was then clipped to the study area (Figure 4.17).

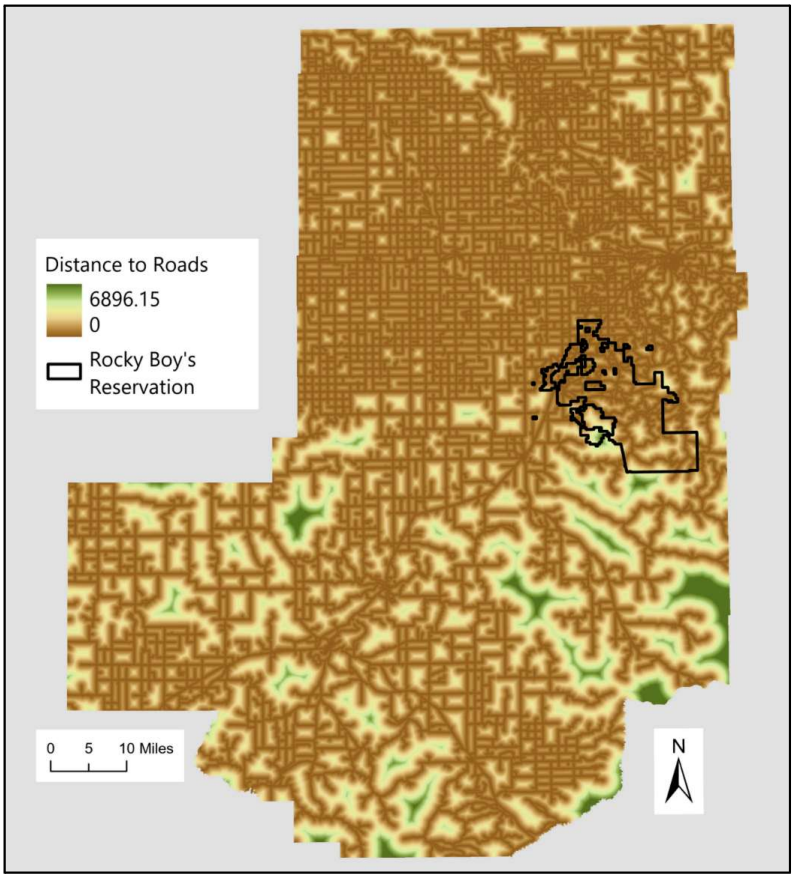


Figure 4.17. *Distance to Roads layer used in the suitability raster.*

While pronghorn are mostly dependent on forage for water, water availability can still influence their distribution and habitat use (Pronghorn are commonly found within 3 miles of a water source). Spatial datasets of two different features, waterbodies and streams (named 'Flowlines' in the dataset), were obtained from the U.S. Geological Survey National Hydrography Dataset. Using the 'polygon to line' tool, the waterbodies feature was transformed into a line feature, then combined with the stream data using the 'merge' tool. The distance accumulation tool was then utilized in ArcGIS Pro to create the raster layer 'distance to water,' which was then clipped to the study area (Figure 4.18).

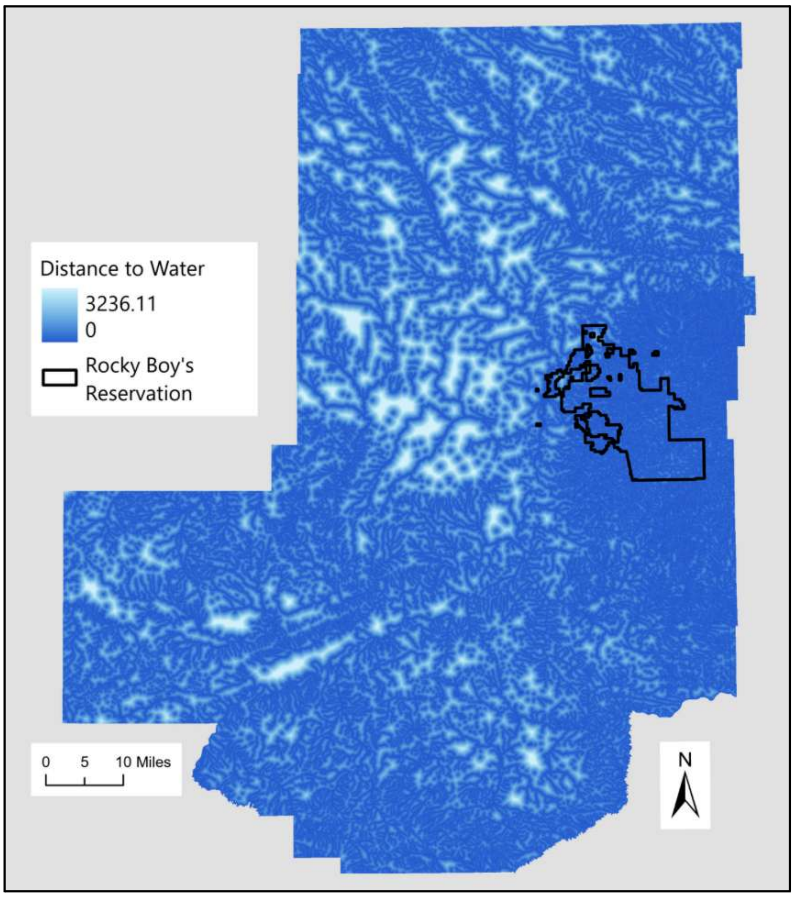


Figure 4.18. *Distance to Water layer used in the suitability raster.*

4.4.1.3 Weighting of Variables

Following the preparation of each spatial variable, a weighted approach was used based on an expert-driven weighting system designed in the Poor (2010) study. In this weighting framework, relative importance values were assigned to each category of variable based on their ecological influence on pronghorn habitat use, and then additional weights were assigned to within-category classifications. The Poor (2010) developed a weighting system for both spring and fall seasons, and in this project, only the spring weighting system was utilized for the habitat suitability raster. Refer to Table 4.12 for a description of how these spring-season weights were assigned to each variable, and to the within-variable categories.

Table 4.12. *Assigned weights for the habitat suitability raster.*

Variable	Weight	Within-Variable Classification	Weight
Land Cover	3.82	Agricultural Areas	4.13
		Developed Land	1.00

Variable	Weight	Within-Variable Classification	Weight
		Shrublands-Grasslands-Pastures[49]	11.09
		Wetlands-Riparian Areas	3.16
		Water	1.91
NDVI	3.54	>0.6	2.10
		0.3-0.6	1.99
		0.2-0.3	4.70
		<0.2	1.00
Topographic Position (TPI)	2.74	Canyon Bottom	1.94
		Flat-Gentle Slopes	8.91
		Ridge Tops	3.26
		Steep Slopes	1.00
Distance to Roads	1.34	0-300m	1.00
		300-1,000m	2.44
		>1,000m	4.97
Distance to Water	1.00	0-1,000m	3.03
		1,000-10,000m	1.36
		>10,000m	1.00

The resulting raster represents the relative suitability of the landscape for pronghorn habitat use within the study area. Suitability values range from 12.8 (least suitable habitat) to 93.105 (most suitable habitat), and emphasize areas that may support pronghorn occupancy and movement. The complete ArcGIS Pro project will be available to the client for details of the full map creation process.

[49] In the USDA Cropland Data Layer, the 'Pastures' category is inherently combined with 'Grasslands.' This differs from the Poor (2010) study, which combined 'Shrublands' and 'Grasslands'. Due to this discrepancy, this study weighted the landcover categories of 'Grassland/Pasture' and 'Shrubland' with the weight of 11.09, which deviates from Poor's original weighting system where 'Pasture'=5.21 and 'Shrublands-Grasslands'=11.09.

4.4.2 Results and Discussion

The resulting habitat suitability raster was developed following the methodology described by Poor (2010) to inform the functional connectivity analysis for pronghorn. The model incorporated environmental variables relevant to pronghorn habitat preferences, including land cover, Normalized Difference Vegetation Index (NDVI), Topographic Position Index (TPI), distance to roads, and distance to water. The resulting map indicates relatively suitable habitat across much of Rocky Boy's Reservation, suggesting that the landscape contains several environmental characteristics generally associated with favorable pronghorn habitat (Figure 4.19).

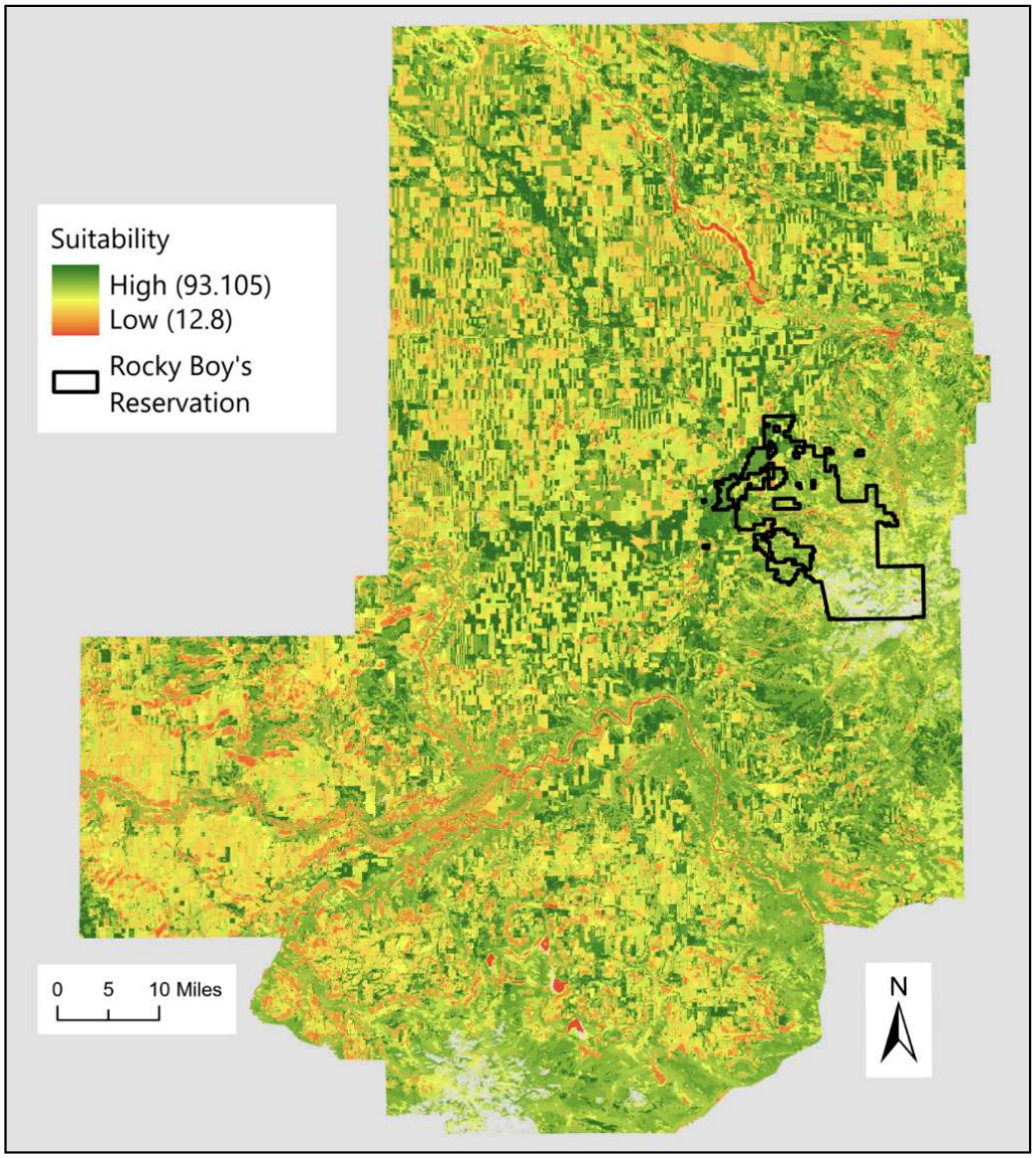


Figure 4.19. *Habitat suitability map of the entire study area.*

Many of the most suitable areas for pronghorn habitat in Rocky Boy's Reservation (Figure 4.20) are nearest to its borders, and nearest to areas that intermix with Hill and Chouteau counties. In future studies, it would be imperative to assess these areas for barriers to movement, namely non-wildlife friendly fencing, that may limit pronghorn access to these suitable areas. As Rocky Boy's Reservation has the smallest amount of area of the three AOIs, and therefore limited opportunity to make land more habitable for pronghorn, restrictions to movement may be the most significant, alterable factor with which to restore pronghorn to the landscape.

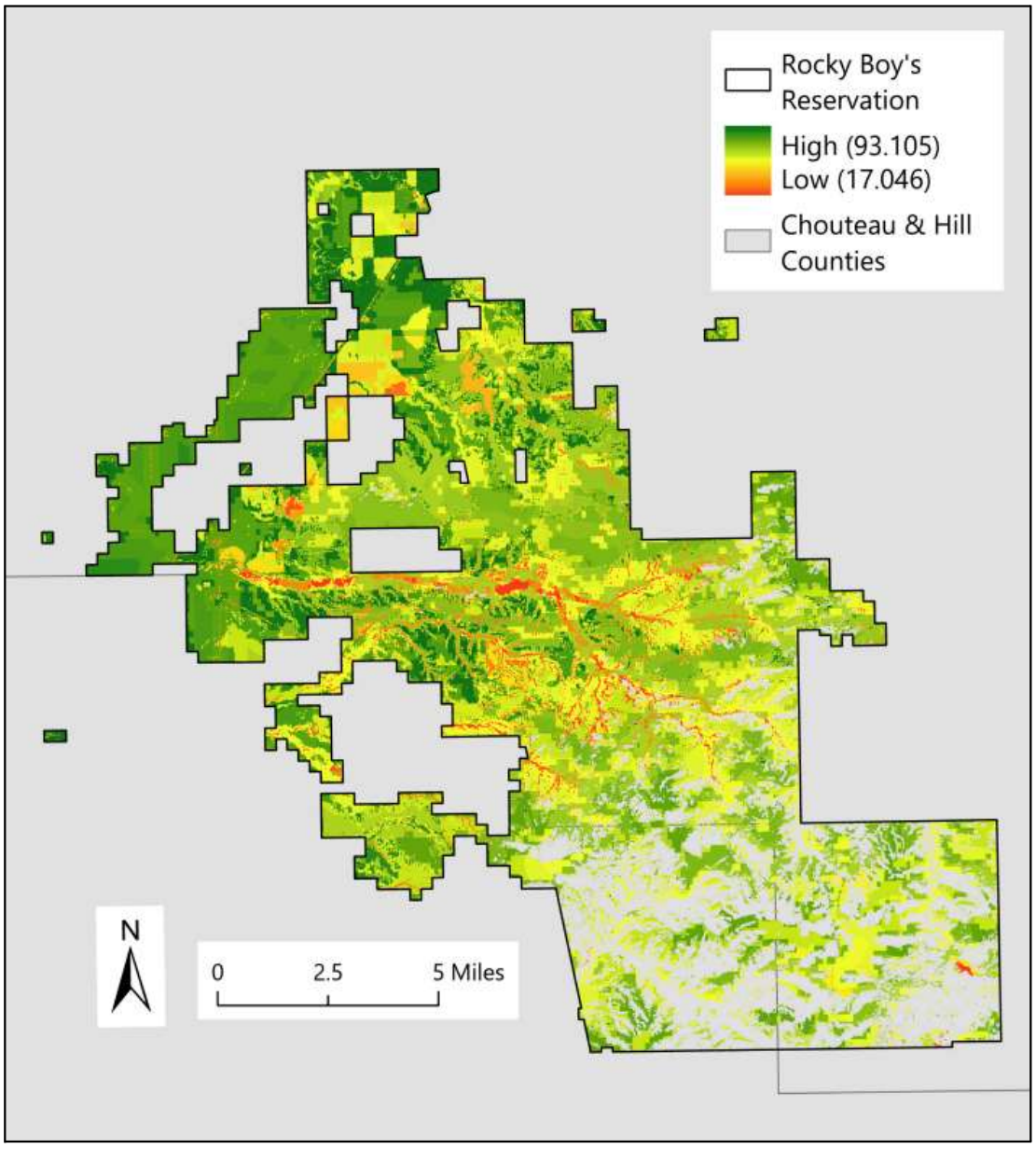


Figure 4.20. *Habitat suitability map of Rocky Boy's Reservation.*

There are some limitations to this functional connectivity analysis. This model lacks certain potentially influential variables that Poor (2010) included, such as fence location and distance to wells, which are known to affect pronghorn movement and habitat use. The absence of these factors may help explain observations from BNGA that pronghorn populations appear more numerous in the surrounding counties than within Rocky Boy's Reservation, where these differences and other landscape features may influence accessibility or movement. Additionally, the weighting system from the Poor (2010) study imparted here did not account for forest landcover, which is present in Rocky Boy's Reservation. Due to this, the known forested areas in the Reservation show a lack of data. Future improvements to the model could include the incorporation of pronghorn location GPS data to validate habitat suitability predictions, data on fence location and height, and the development of resistance-based rasters to better represent movement constraints across the landscape. Nonetheless, the current habitat suitability map provides a useful initial assessment of whether Rocky Boy's Reservation might contain suitable pronghorn habitat, which could help guide future research aimed at understanding where the species be found or where access needs to be improved.

4.5 Key Findings and Recommendations

4.5.1 Key Findings

Landscape pattern analysis indicated that grassland habitat within Rocky Boy's Reservation scored lower in several metrics than the grassland habitat in the encompassing counties, signaling that the Reservation may exhibit overall lower structural connectivity. Several metrics suggested that grassland patches within the Reservation are more fragmented and irregularly shaped, which may reduce their suitability for species such as pronghorn that rely on large, continuous grassland landscapes. Despite these indications of fragmentation, the analysis also identified several relatively large and contiguous grassland patches within Rocky Boy's Reservation, which may function as core habitat areas for pronghorn and other grassland species. Monitoring these larger patches over time will be important for detecting fragmentation patterns and maintaining habitat connectivity within the Reservation.

The habitat suitability raster produced in this study provides an initial spatial representation of areas that could support pronghorn habitat within and surrounding Rocky Boy's Reservation. The Reservation appears to contain several areas of relatively high habitat suitability, located close to the Reservation boundaries, thus, understanding the connection of those suitable areas to the surrounding non-Reservation landscape will be imperative. This emphasizes the importance of considering connectivity at the landscape level. Although this is a preliminary assessment, it demonstrates the potential for using spatial analysis tools to identify areas of suitable habitat and to highlight locations where connectivity can be maintained or improved. The habitat suitability raster generated in this study hopefully provides a foundational dataset that could support future connectivity analyses.

Though out of scope for this project, future studies could also examine how funding should be prioritized to make the most impact on improving connectivity through restoration, both within the Reservation and externally from the Reservation to the surrounding landscape.

Rocky Boy's Reservation has suitable habitat that is mostly constrained to the northwestern section of the Reservation, an area that intermixes with the surrounding landscape. These areas could be important pinch-points that require funding and restoration to maintain connection to the larger grassland landscape.

4.5.2 Recommendations

Both the structural connectivity metrics and the habitat suitability model developed in this study provide a starting point for identifying grassland areas that may support pronghorn habitat within Rocky Boy's Reservation and in the surrounding counties. These results could be used by the Chippewa Cree Tribe Natural Resources Department in Rocky Boy's Reservation and BNGA to prioritize areas for conservation monitoring, habitat restoration, or future connectivity analysis. In particular, the four relatively large and contiguous grassland patches identified within the Reservation represent important habitat areas that should be monitored to ensure they remain intact and connected to the larger grassland landscape over time. Additionally, these patches and the highly suitable areas identified by the habitat suitability raster should be examined for barriers to movement, which could limit pronghorn access to them and create a lack of connectivity that is not recognizable through the satellite imagery used in the structural and functional connectivity methodologies in this chapter.

While the workflow developed in this study provides a useful framework for assessing habitat suitability and structural connectivity, several methodological improvements could strengthen future analyses. More extensive ground-truthing could improve this project and its accuracy greatly. Data collection was limited due to time constraints and due to fine-tuning of protocols occurring concurrently with field data collection. More data points would provide a larger sample size with which to compare accuracy of ground-points and open-source data points, which is important for RMSE score accuracy and consequent selection of data layers. The CDL, though the most accurate of the land cover data source options, still had generally low accuracy at 47.40 (10m) and 46.88 (30m). This may indicate that this source was not the best choice for analysis, and acquisition of a different data source or additional samples could improve the accuracy of the connectivity analysis.

Additionally, computing graph-based metrics and analysis would improve the structural connectivity results. Graph-based metrics provide insight into the connectedness of patches, and metrics such as patch connectedness, network centrality, and shortest path analyses can highlight which grassland patches serve as crucial stepping stones or bottlenecks for pronghorn movement. This information would help guide grassland restoration efforts, as it would identify locations where management would enhance the connectivity of the landscape network through such actions as improvements to forage quality, conversion of cropland back to grassland, and utilization of wildlife-friendly fencing. In addition to informing conservation measures, this information could highlight areas outside of Rocky Boy's Reservation where grassland conservation or land acquisition could enhance landscape connectivity for pronghorn and other grassland-dependent species.

Finally, acquiring data on GPS location of pronghorn in the area would be the most effective way to achieve a full perspective on functional connectivity in the area. Actual movement patterns of pronghorn would provide direct information about pronghorn habitat use and movement patterns across the landscape. This information would not only help identify core habitat areas and potential movement corridors, but would also allow researchers to evaluate how structural connectivity metrics relate to actual species movement. Incorporating pronghorn movement data, through methods such as GPS collaring, would therefore provide a valuable opportunity to assess the ecological relevance of the structural connectivity metrics used in this study and to improve the accuracy of future connectivity models.

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Chapter 5: AI-Based Detection of North American Bison Wallows: Disturbance Patterns Across Tribal Bison Programs

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5.1 Introduction

5.1.1 Purpose & Audience

Grasslands are also culturally significant ecosystems for Indigenous Peoples[50] – particularly in the NGP ecoregion – where they have supported traditional ecological practices, food systems, and lifeways since time immemorial (BNGA, n.d; Shamon et al., 2022). Indigenous management practices include prescribed burns, foraging, and animal husbandry (Roos et al., 2020; Schuster et al., 2019). These stewardship practices are integral to the maintenance and sustainability of grassland ecosystems and their culturally significant species, while emphasizing the reciprocal relationships between people and the environment.

Grasslands occupy approximately 40% of the terrestrial surface of the earth, and are critically important ecosystems ecologically, economically, and culturally (Petermann & Buzhdygan, 2021). Grasslands provide a wide range of ecosystem services, including habitat for diverse plants and animals, carbon sequestration, flood and drought mitigation, soil formation and stabilization, and recreation (Buffalo Nations Grassland Alliance [BNGA], n.d; Hoekstra et al., 2004; United States Department of Agriculture [USDA], n.d).

Grasslands are also assets in climate regulation, due to their extensive below-ground biomass (Conant, 2010; Jobbágy & Jackson, 2000). Deep-rooted graminoids, forbs, and shrubs (and the organisms that rely on them) allow for the below-ground storage of roughly 243 tonnes of atmospheric carbon per hectare in some systems (Neufeld & Smith, 2022). Additionally, grasslands function as some of the most species rich environments on earth for insects and vertebrate herbivores with both top-down and bottom-up effects on trophic energy flow[51] (Petermann & Buzhdygan, 2021).

Despite their importance, grasslands are some of the most threatened ecosystems worldwide (Hoekstra et al., 2004; Sala et al., 2000). In the United States, approximately 62% of intact grasslands in the United States have vanished to date, and only 10% remain under formal protection, leaving the majority of grasslands unprotected and at-risk to agricultural conversion, fragmentation, and mismanagement (Hendrickson et al., 2019; United States Fish and Wildlife Service [USFWS], 2023). Grassland birds have undergone significant declines across North America, with an estimated loss of 700 million birds from 31 species (Burns et al., 2021; The Nature Conservancy, n.d). These losses, and those of other species, reduce the biodiversity of these critical environments and impair the processes that sustain ecosystem resilience, including nutrient cycling, water regulation, and disturbance-based heterogeneity. Many animal species native to the grasslands of the Northern Great Plains (NGP) ecoregion migrated seasonally over large territories (Liczner et al., 2024; Naidoo et al., 2025). Given the extensive fragmentation of the NGP ecoregion due to diverse land ownership, roads, and fences, restoration of this area requires both restoring and reconnecting habitat for species.

[50] Groups recognized as having political and cultural self-determination, which, in the United States, predates the founding of the country (Native Governance Center, 2021; Whyte et al., 2023)

[51] The flow of energy through living things within an ecosystem (Lindeman, 1942)

Restoring Indigenous stewardship practices, as well as the habitat and connectivity of related ecosystems, is made even more challenging by the fragmentation of the Native Nations[52] across the NGP ecoregion, many separated by hundreds of miles. The Buffalo Nations Grassland Alliance (BNGA) is a Native-led 501(c)(3) working with 16 Native Nations in the NGP ecoregion[53]. BNGA was created in 2015 by a group of Indigenous biologists working to support grassland restoration initiatives for tribes in the NGP ecoregion.

One of BNGA's goals is to preserve Indigenous Peoples' livelihoods and relationship with nature (BNGA, 2024). Building capacity to monitor and manage grassland disturbance by native species is therefore a critical component of supporting Indigenous sovereignty and stewardship for future generations (Tengo et al., 2014; Tran et al., 2020). Traditional methods for monitoring disturbance at the regional scale are expensive, time-consuming, and labor-intensive. Therefore, implementation of artificial intelligence (AI)-based[54] automated disturbance detection may serve as a potential solution in monitoring grassland ecosystems at larger scales.

This chapter focuses on the automated detection of American bison (*Bison bison*) wallows[55] using AI. Bison impact the landscape through grazing, movement, and wallowing as ecosystem engineers[56]. They are also widely recognized as an ecological keystone species[57] central to Indigenous cultures and land stewardship practices, as well as a sacred relative and major traditional food source (Kolipski et al., 2014). The reintroduction of bison as a component of Indigenous-led conservation programs has strengthened sovereignty, place-based relationships, and Traditional Ecological Knowledge[58] systems to many Native Nations across the United States and NGP ecoregion (Moerman, 1998; Schubert, 2021; Shamon et al., 2022).

Remotely-sensed imagery of bison wallows can provide a measurable indicator of behavioral disturbance. The identification of wallowing across large, fragmented landscapes is challenging to monitor through existing methods of field survey and visual imagery interpretation. Therefore, AI-based tools might be a scalable[59], transferable[60], efficient, and cost-effective method to identify wallowing signatures for conservation planning.

---

[52] Tribes that are formally recognized by the United States Government; among many (but certainly not all) Indigenous Peoples in the U.S., the term Native Nation is preferred as it demonstrates respect for the legal sovereignty of those Peoples (Native Governance Center, 2021).

[53] In the context of this research, the Northern Great Plains (NGP) is delineated by the boundaries of the NGP ecoregion (see Figure 1.1 in Kelly, 2026).

[54] Computer systems that can perform complex tasks normally done by human-reasoning, decision making, creating, etc. (National Aeronautics and Space Administration, n.d.)

[55] Wallowing is behavior in which bison create depressions (wallows) through rolling and trampling (Knapp et al., 1999).

[56] A species that physically changes its environment, which creates or modifies habitats for other organisms by changing biotic or abiotic resource availability (Jones et al., 1994)

[57] A species with a disproportionately large effect on its ecosystem despite its small population (Paine, 1969)

[58] Collective knowledge system possessed by Native Nations founded in the relationships of living beings with one another and their environment (Berkes, 2018)

[59] Applicable to model inputs of varying sizes (Qin & Liu, 2022)

[60] Applicable to different geographical regions (Qin & Liu, 2022)

5.1.2 Background & Rationale

The North American bison, long a symbol of resilience and resistance to land conversion, embodies the goals of this project, linking ecological restoration with Indigenous stewardship and grassland conservation. Historic bison herds ranged across the North American continent in the tens of millions (Shaw, 1995), and were harvested by Native Nations of the Great Plains, Eastern and Western Woodlands, Canyons, and Mesas as a sustainable food source (Figure 5.1). During European colonization of North America, settlers intentionally hunted bison to near-extinction in order to deprive Native Nations of this traditional food source and sacred relative as part of their genocidaleffort genocide against them.. In recent decades, many Native Nations have sought to reintroduce and restore bison as a way to heal these fractured kinship ties (Schubert, 2021).

In collaboration with BNGA, we selected bison as a species of interest for its role as a keystone species and ecosystem engineer in grassland ecosystems. The ecological role of bison is dependent upon its innate behaviors (such as grazing, movement, and wallowing), which helped maintain prairie ecosystems for tens of thousands of years (Froese et al., 2017). Restoration of bison – both as wildlife and within conservation herds – is integral to grassland restoration and the mitigation of incumbent threats to landscape change, such as invasive species and woody encroachment (Ling et al., 2023; Musto et al., 2025; Noble et al., 2025).

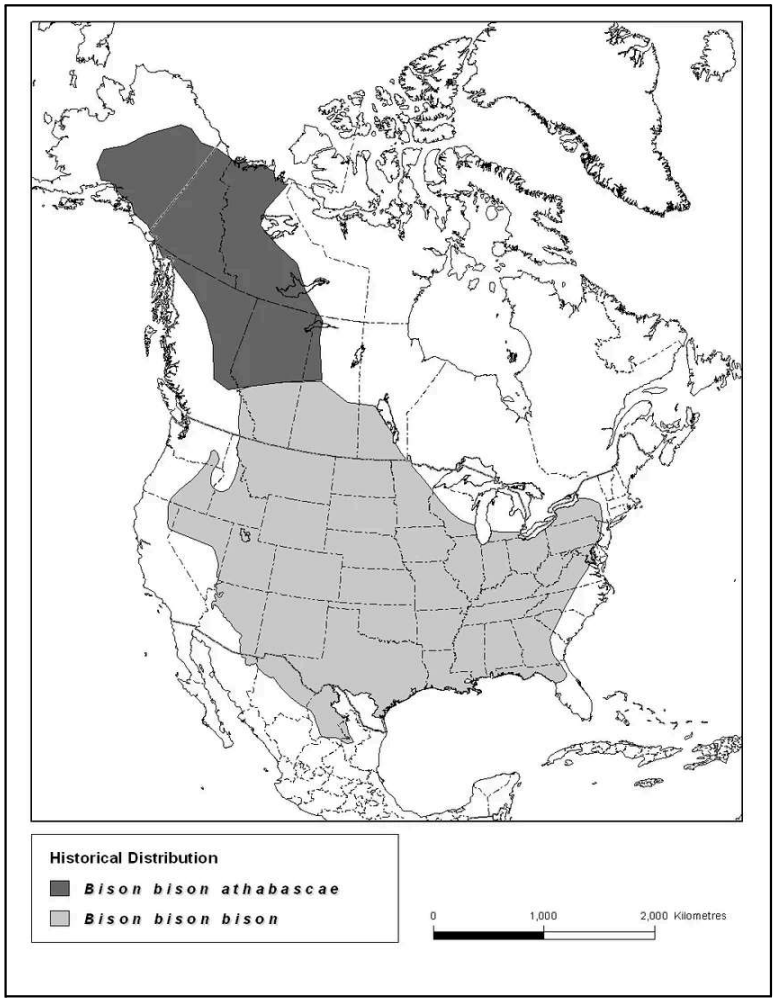


Figure 5.1. *Historic distribution of wood bison and plains bison. Modified from Gates et al. (2010). Polygons courtesy of Keith Aune, Wildlife Conservation Society.*

Indigenous management goals with respect to bison conservation herds include the restoration of ecological processes such as wallowing. Wallows are a characteristic of healthy and functional landscapes due to its contribution to habitat creation and species diversity (World Wildlife Fund [WWF], n.d.). A wallow (Figure 5.2) is formed from the stamping, rolling, horning, and rumbling of bison on the ground, which creates ground depressions of bare earth. The legacy of wallows persists in the long-term effects of landscape change (Coppedge & Shaw, 2000; Knapp, 1999), which include:

- Compressed soils resistant to water infiltration, which often result in mud acting as pseudo vernal pools (temporary wetlands filled with water) (Knapp, 1999);
- Provision of habitat for insects reliant on moist environments and landscape heterogeneity (Nickell et al., 2018);
- Nesting resources for pollinator habitat in shortgrass prairie/sagebrush steppe ecosystems (Campbell et al., 2025), and

- Resistance to woody plant encroachment and invasive species (Donovan et al., 2025; Noble et al., 2025; Yu et al., 2023).



Figure 5.2. *Bison wallows visible via Natural Color remotely-sensed in the Flint Hills of the Konza Prairie Biological Station, Kansas (National Aerial Imagery Program, 2021).*

Despite its ecological importance to grassland ecosystems, wallowing remains difficult to quantify across landscapes due to time and labor constraints of field surveys and remote sensing interpretation (Horne et al., 2024; Reinhardt, 1985). Conventional methods, including field surveys or manual image interpretation, are time-intensive and difficult to complete at large scales (Horne et al., 2024; Reinhardt, 1985). Advances in remote sensing and machine learning offer new tools to detect fine-scale ecological disturbances using high-resolution imagery (Wang et al., 2024). This chapter aims to contribute streamlined and scalable artificial intelligence (AI) tools using deep learning[61] and machine learning[62] models that detect bison wallows. By mapping wallows across landcover types and soil textures, such models and future studies could help determine where bison are wallowing, which landcover types experience the most wallowing, and how disturbance varies across landscapes (Krejcar & Namazi, 2026; Tuia et al., 2022). These evaluations can guide Tribal decision-making by highlighting areas suitable for grazing, grassland restoration, and land acquisition, thereby supporting Indigenous management through ecological outcomes such as increased habitat heterogeneity. Such data may also help to prioritize conservation actions and inform restoration planning, enabling bison to fulfill cultural and ecological roles across the NGP ecoregion.

[61] A type of machine learning that uses multilayered neural networks to learn from data patterns (LeCun et al., 2015)
[62] A field within Artificial Intelligence that enables computers to learn from data patterns and make predictions or decisions (Mitchell, 1997)

5.2 Research Goals & Data Collection

5.2.1 Research Aims and Questions

This research aims to support BNGA's goal to preserve Indigenous Peoples' livelihoods and relationships with nature by providing tools for AI-based automated identification of localized disturbances (wallows) which alter the soil, vegetation structure, and habitat availability, serving as a proxy for grassland health and ecosystem function.

Specifically, we ask:

1. Can artificial intelligence (AI) models accurately detect and characterize bison wallows from high-resolution imagery?
2. What are the limitations of AI-based object detection for identifying bison wallows in the NGP ecoregion? How do these limitations influence estimates of the magnitude and spatial distribution of disturbance?
3. How can wallow detection inform grassland restoration and habitat connectivity in Indigenous-managed bison programs?

5.2.3 Data Collection

This research was conducted with assistance from the Rocky Boy Buffalo Project and the Chippewa Cree Tribe Natural Resources Department on Rocky Boy's Reservation in Montana over five days (Kelly, 2026). This short data collection period left us without significant time to gather a comprehensive ground-truthed validation set. For this reason, a dataset of ground truthed wallows was gathered from previous research conducted on the physical characteristics of bison wallows from the Konza Prairie Biological Station (KPBS) in Manhattan, Kansas (Horne et al., 2024). This choice of dataset, as well as decisions about satellite imagery, were informed by availability, as well as resolution needed for wallow identification. The KPBS wallow data was used as a training set to conduct manual change detection of wallows on Rocky Boy's Reservation. Change detection consisted of classification of wallows before and after bison reintroduction on Rocky Boy's Reservation in 2021. We also used National Aerial Imagery Program (NAIP) imagery. NAIP coverage is freely available across Kansas and Montana, resampled during the same year, and provides fine spatial resolution (0.6 meters) and multispectral[63] coverage across counties.

5.3 Methods

5.3.2 Modeling Framework

AI learning models are computer programs trained to recognize patterns across large datasets and have been developed to conduct ecological monitoring across topics such as land use/land cover change, disturbance, and phenology (Willis, 2015). We developed a methodology for bison wallow identification across two forms of artificial intelligence modeling: (1) Deep Learning and (2) Machine Learning. Deep Learning and Machine Learning models were created

[63] Imagery involving multiple different and isolated regions of the electromagnetic spectrum

to identify wallows and assess model performance. A flowchart describing these methods can be found in Figure 5.3.

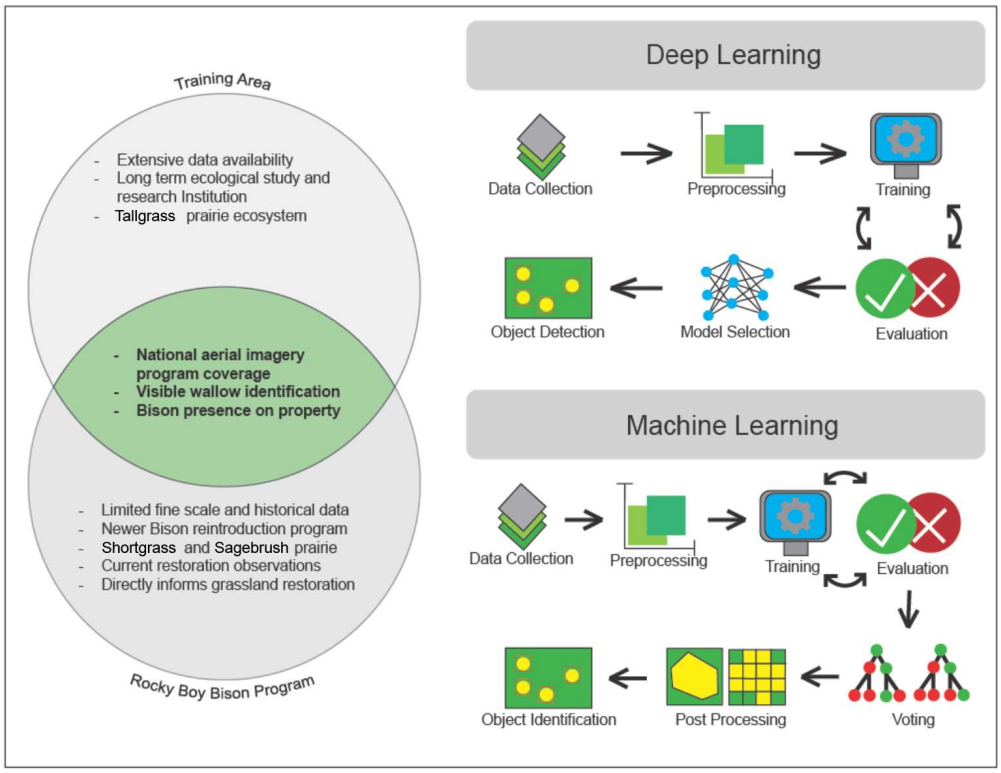


Figure 5.3. *Methodology for variable selection in congruence with training area and research (Horne et al., 2024), as well as subsequent model development.*

5.3.3 Deep Learning

Deep learning is a sub-specialty of machine learning which falls under the greater umbrella of AI. Deep learning utilizes a combination of mathematical computer vision (raster values and statistics) as well as spatial analysis (shape, segmentation) to identify objects (Gui et al., 2024). It also classifies objects through the use of neural networks, mimicking the neural networks of the human brain (Fukushima, 2013). Neural network architectures are designed for the detection of specific object characteristics, but can be applied to objects within other imagery so long as they meet similar spatial and spectral signatures (Li et al., 2017). The use of deep learning architectures is computationally heavy, and requires extensive training to predict objects accurately (Zhao et al., 2019).

We utilized the ArcGIS Deep Learning toolkit due to its availability. Using this toolkit, we analyzed the KPBS training features in our NAIP imagery to create and recommend model architectures based on the most accurate model evaluation. Throughout the deep learning process we iteratively evaluated models adjusting the raster inputs based on ArcGIS Deep Learning model evaluation. The most accurate model evaluation was used in object detection of wallows and translated to model usage in Rocky Boy Buffalo Project.

5.3.3.1 Deep Learning Data Collection

Our ground-truthing efforts at Rocky Boy's Reservation did not garner a large enough sample size of bison wallows for modeling. Likewise, very little published data exists on bison wallow locations for the NGP ecoregion (including Montana). Therefore, we used available data from the wider Great Plains region, specifically Kansas. The bison wallow training dataset used in our analysis was gathered from *Spatial and physical characteristics of bison wallows in the Flint Hills of Kansas* (Horne et. al., 2024). This study provides a collection of x-y coordinates for field-mapped bison wallows within the Konza Prairie Biological Station (KPBS), which supported subsequent model development and training for that area. To ensure scalability of models to Rocky Boy's Reservation it is imperative that we use the same predictors that in Kansas as available in Rocky Boy (Esri, 2026).

NAIP Orthoimagery[64] was also used across training datasets in Kansas and the Rocky Boy Buffalo Project to support model development. NAIP provides orthoimagery for the contiguous United States during the growing season (USDA, n.d). The spatial resolution of these images was standardized to 0.6 meters in 2018 through 2025. The 2025 imagery was the only imagery in which resampling was limited to 0.6 meters to maintain continuity of imagery used in change comparison (D. Gounaridis, personal communication, March 2026). We used NAIP imagery in two tile formats: natural color[65] and color infrared[66] (USDA NAIP, 2019). Both the natural color and the color infrared band NAIP collections were composited and used in a principal components analysis (PCA) as a method for deriving variance in the values Red, Green, Blue, and Near-Infrared Reflectance (NIR) bands (Jolliffe, 2002).

5.3.3.2 Deep Learning Chip Creation

Chip creation is the validation of objects to serve as model training. Using the 10-band limited composite raster, polygons were digitized over top of field-mapped wallows recorded in KPBS (Horne et al*.,* 2023) . Manually, vertex polygons were used to approximate the typical round and oblong shape of wallows, as seen in Figure 5.4. Only wallows greater in size than the 0.60-meter spatial resolution were included to ensure detectability and remove noise greater than the spatial resolution. After all objects were identified, the results were saved as labeled objects ready to be used in model processing.

[64] Aerial photography taken from plane or satellite that has been geometrically corrected to account for distortions in flight

[65] Band combination of the wavelengths in the visible spectrum: Red, Green, and Blue

[66] Band combination of visible wavelengths larger than blue, and inclusive of non-visible Near Infrared

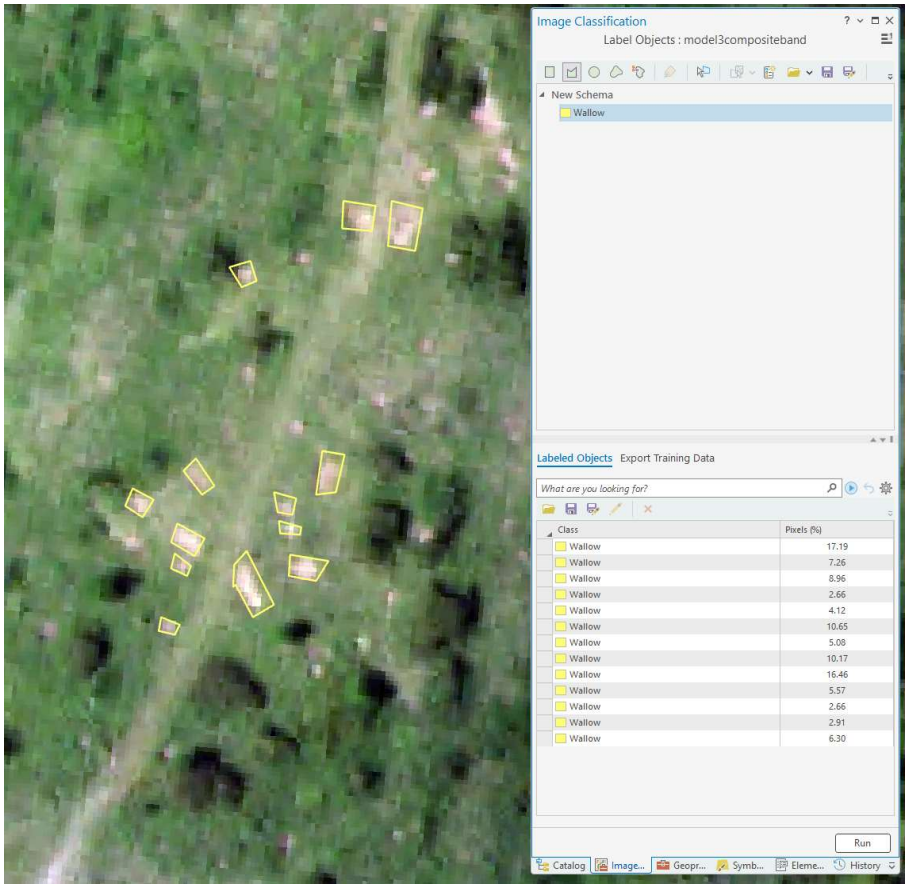


Figure 5.4. *The chipping process in the ArcGIS Pro Deep Learning creation wizard.*

5.3.3.3 Deep Learning Band Composite

A composite band of rasters was produced for each model evaluation using the ArcGIS Deep Learning Toolkit. In this stage of model evaluation we substituted rasters as model predictors, and based their performance on the overall model accuracy and precision produced by the best fit deep learning architecture. We maximized the amount of predictor inputs in the deep learning model at 10 predictors. Each of the models evaluated included the 4 multispectral bands (Red, Green, Blue, and Near Infrared), leaving 6 additional bands as inputs. To facilitate transfer and scalability across regions we limited additional predictors to freely available data or created data. The best model evaluation (see Table 5.2, Model 3) used a combination of multispectral, principal components of multispectral bands, Normalized Difference Vegetation Index (NDVI), and distance accumulation from roads and barriers.

NDVI is a spectral index created by the mathematical normalization of the values of two close wavelengths, Near Infrared and Red (Rouse et al., 1974). The formula for this normalization is available in Table 5.3. NDVI is a measure of the health of vegetation based on chlorophyll absorption, favoring red light over near-infrared light. The highest values represent dense healthy vegetation, typically at peak growth season for mid-latitude areas, while the lower values represent bare soil, characteristic of wallows (Tucker, 1979).

PCA is an analysis of the variance of multiple variables (Jolliffe, 2002). In our study, we used a principal component analysis of the four color infrared bands: Red, Blue, Green, and Near Infrared. The bands function as filters from a camera, which only record reflected wavelengths corresponding to distinct ranges of visible light and infrared. Principal components are used to reduce multicollinearity[67] and highly correlated inputs for the brightness values recorded by each pixel in an image (Jolliffe, 2002). The output of a principal component analysis enhances visual variance representation of the dataset and was added to our 10-band model training (S. Brines, personal conversation, October 2025).

Distance accumulation rasters were created based on the outline of trails and boundaries within each of the study boundaries. Distance accumulation is a geospatial data tool that increases pixel values the further the distance from input features increases (Esri, n.d.). Trails and roads were easily identifiable using Near-Infrared imagery, due to the high contrast between the bare earth tracks from vehicles and the vegetation. Researchers noted wallowing at the Konza Prairie Biological Station had some correlation to paths in the Flint Hills (Horne et al., 2024). Existing trails and bison wallows led us to believe that bison wallow modeling could be related to the Rocky Boy Buffalo Project.

5.3.3.4 Deep Learning Model Evaluation

Deep Learning Data Preprocessing was used for model evaluation before use of the ArcGIS Object Detection tool (Esri, n.d). ArcGIS Deep Learning toolkit evaluates models and their fit to multiple deep learning architectures provided in the Deep Learning library (GitHub, 2025). Besides multispectral and principal components analysis, the deep learning toolkit was utilized as a black box in which multiple variables were assessed. Ten preliminary models were used to determine the best 10-band combination that could be used to identify wallows in our preprocessing stage (Qamar & Bawany, 2023; S. Brines, personal conversation, October 2025; Yang et al., 2020). The best performing combination of layers suitable for remote sensing of wallows included multicolor (R, G, B, NIR), principal components of color infrared layers, distance accumulation raster from trails within the site, and the Normalized Difference Vegetation Index (NDVI).

The best fit model type was Faster Regional Convolutional Neural Network (FasterRCNN), a two-stage deep learning model that uses a regional proposal network for training for faster identification; its architecture can be seen in Figure 5.4. After fine-tuning the preliminary models, results based on object detection accuracy and minimized training and validation loss were produced and can be seen in Table 5.2 (GitHub, 2025). Outputs include training diagnostics and visual assessments of detection performance. Benefits of using a pre-trained model input include decreases in run time and more batch processing[68] of chips to identify wallows.

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[67] A linear correlation between independent predictors in a regression model. Results in reduced model interpretability by removing the individual effects of predictors on a dependent variable.

[68] Running of high volume automated computer processes iteratively to minimize loss

Table 5.2. *Three Training Models created using composite band data layering. Averages over the machine confidence of predictions versus chipping items.*

Model	1	2	3
Layers	R, G, B, NIR, PCA(R,G,B,NIR), DEM, Slope	R, G, B, NIR, PCA(R,G,B,NIR), DEM, Dist to Barrier	R, G, B, NIR, PCA(R,G,B,NIR), NDVI, Dist to Barrier
Average Confidence	0.357	0.314	0.27
Highest Accuracy Achieved	30%	84%	85%
Validation Loss[69]	1.09	1.23	0.33
Training Loss[70]	0.77	0.93	0.59

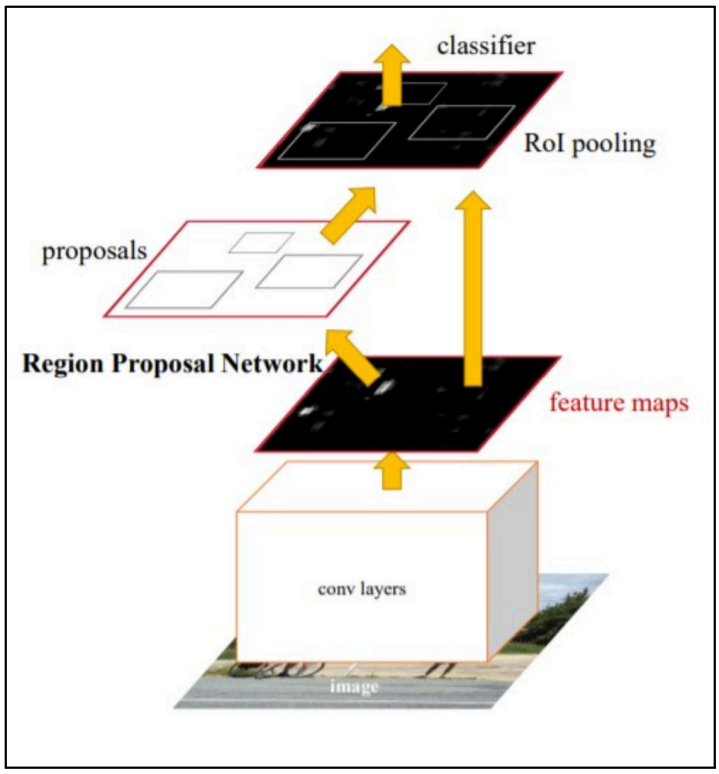


Figure 5.4. *Model architecture of Faster RCNN, used in deep learning identification of bison wallows (Ren et al., 2015).*

[69] Statistic computed for how well the model performs on non-training data (Mitchell, 1997)
[70] Statistics for how well the model performs when compared to training images (chips), returning and recalling differences to calculate the error (Goodfellow et al., 2016)

Object detection was performed using the Detect Objects Using Deep Learning geoprocessing tool, which divides imagery into manageable processing tiles and indicates features similar to the training dataset. Tool parameters include tile size, padding, batch size, and confidence threshold (Pathak et al., 2018). Decreasing tile sizes increases the computational demand by segmenting the imagery into smaller parts, increasing padding, and mitigating the edge effects from tile segmentation. The confidence threshold indicates the minimum probability of matching between the Deep Learning model and object detection. To decrease computational demand and the overproduction of false negatives, parameters were only adjusted for the confidence threshold of 50%.

Following the use of the Object Detection tool in the ArcGIS Deep Learning toolset, Intersection over Union was used as a foundational evaluation metric and accuracy indicator for Random Forest wallowing. The test utilized the amount of area intersected by the predicted wallow over the combined area to judge whether object detection was successful. To indicate performance success, threshold values from respective object detection literature used 0.3, 0.5, and 0.7 as identifiers of low, medium, and high identification rates, respectively (Padilla et al, 2021; Paniego Blanco et al, 2022).

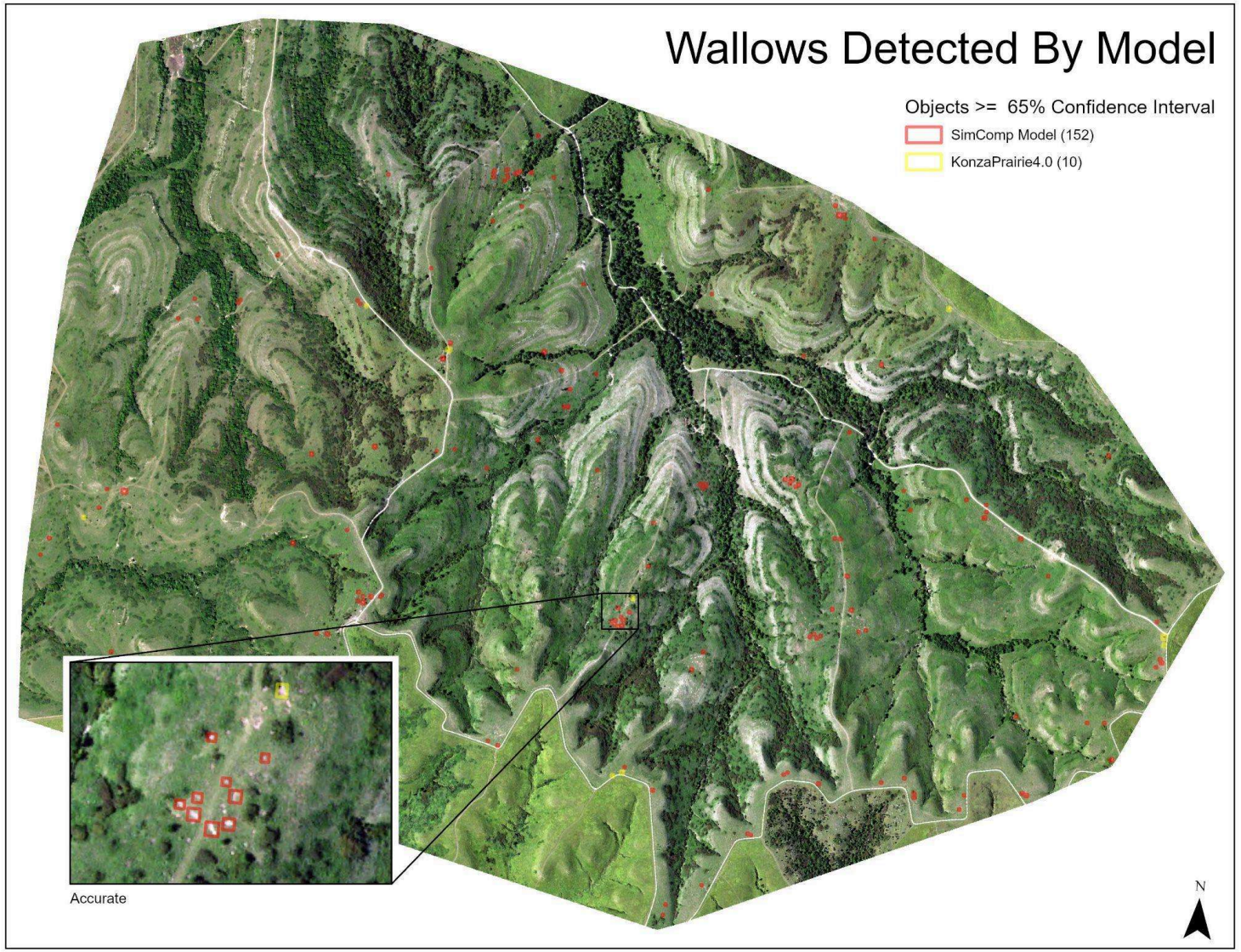


Figure 5.5. *Confidence Thresholding of the Konza Prairie Biological Station training model up to 65% confidence interval, bounding boxes created as a result of the Object Detection tool* (Esri, n.d.).

5.3.4 Random Forest

Random Forest (RF) are ensemble machine learning methods developed to identify spectral signatures indicative of wallowing behavior. This form of classification constructs multiple decision trees of predictor variables based on training data; the model selects pixels that match the majority decision of the given trees (Breiman, 2001; Belgiu & Dragut, 2016). The tradeoff between deep learning models and RF models is that RF are more customizable, while deep learning models are more data hungry and designed for specific object identification (Maxwell et al., 2018; Ma et al., 2019). These machine learning models can be used with smaller datasets and are sensitive to numeric indices and statistical predictors, rather than requiring a dense neural network, so long as the classification of groups are well defined (Pelletier et al., 2016). For our model, we used binary classification to indicate wallowing (1) and not wallowing (0); while wallows consisted of the same training as deep learning models, non-wallows were selected from different landcovers to ensure non-wallows would not be misclassified (D. Gounaridis, personal conversation, March 2026).

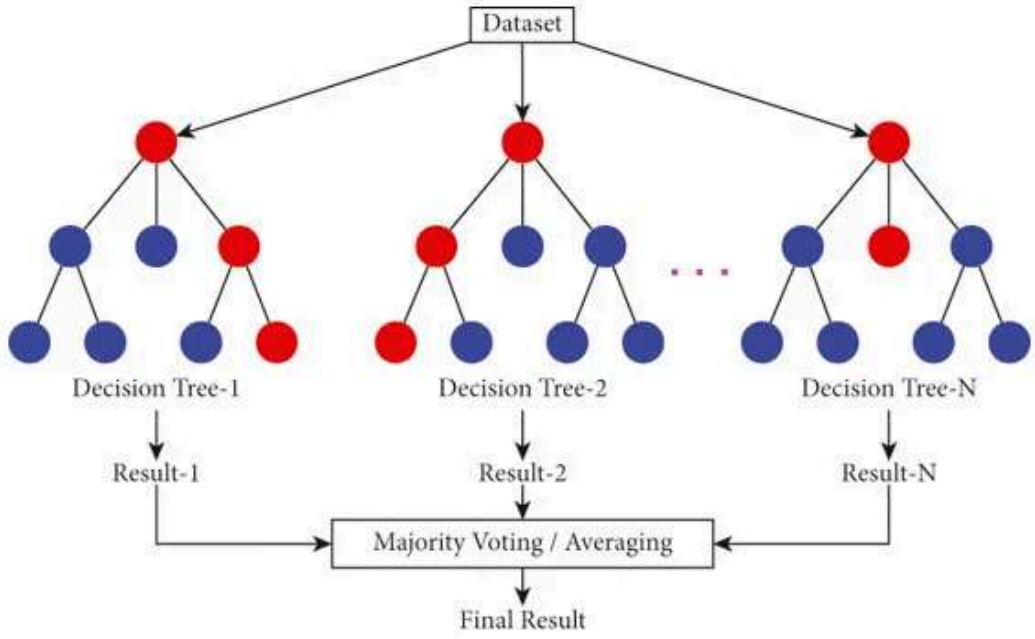


Figure 5.6. *Illustration of Random Forest decision trees (Khan et al., 2021).*

5.3.4.1 Random Forest Data Collection

All data used in the RF model were acquired or transformed from NAIP color infrared and natural color orthoimagery after the year 2021, when NIR was consistently offered as a spectral band, and the resolution of 0.6 meters was adopted (United States Department of Agriculture [USDA], 2021-2025). The range of years 2021-2025 was selected to include all of the available NAIP sampling that has occurred since the reintroduction of bison to the Rocky Boy Buffalo Project, encompassing all of the disturbances before bison reintroduction. The year

2025 was spatially resampled from 0.3 meters to 0.6 and georeferenced to the 2023 raster. Orthoimagery was obtained for Hill County, which includes the Rocky Boy Buffalo Project within Montana, and for Blaine County, which includes Fort Belknap Indian Community Buffalo Program Restoration and Grazing System. The best-fit model was trained and validated based on the NAIP imagery from 2025 and applied to the NAIP 2023 and 2021 for the construction of prediction surfaces and wallow identification across years.

5.3.4.2 Random Forest Preprocessing

A total of 18 bands were used as predictors in the preliminary RF. These bands included the visible bands (Red, Blue, Green), Near Infrared, the spectral indices visible in Table 5.3, and three textural indices using standard deviation and range of the NDVI and NIR values based on a surrounding 5-pixel neighborhood (D. Gounaridis, personal conversation, January 2026).

These spectral indices were used to maximize spectral contrast between vegetation and bare soil, which makes it possible to identify wallows after statistical analysis of their reflectance values (Heute, 1988). All bands were stacked to a common spatial resolution, 0.6 meters, and clipped to the 2023 study boundary. In the final model we eliminated spectral and textural indices, which did not account for greater than 5% of model variation (D. Gounaridis, personal conversation, March 2026) Final prediction models included multicolor (R, G, B, NIR) bands, and the three spectral indices which explained the most model variability (Blue Near Infrared Reflectance of Vegetation, Green Normalized Difference Vegetation Index, and Blue Wide Dynamic Range Vegetation Index) in order to reduce unnecessary noise [71] (D. Gounardis, personal conversation, March 2026).

Table 5.4. *Spectral indices used in deep learning and machine learning training.*

Name	Formula	Source
Normalized Difference Vegetation Index	(NIR-Red)/(NIR+Red)	Rouse, J. W. et al., 1974
Transformed Vegetation Index	sqrt((NIR - Red) / (NIR + Red) + 0.5)	Rouse, J. W. et al., 1974
Optimized Soil Adjusted Vegetation Index	(NIR-Red)/(NIR+Red+0.16)	Rondeaux, G. et. al, 1996
Difference Vegetation Index	NIR/Red	Jordan, 1969
Green Optimized Soil Adjusted Vegetation Index	(NIR - Green) / (NIR + Green + 0.16)	Gilbert et al., 2002
Fluorescence Corrected Vegetation Index	NIR-((Red+Green+Blue)/3)	Yang et al., 2020

[71] Non contributional data; can create inaccuracies and false positives and does not represent true patterns

Name	Formula	Source
Modified Red Blue Vegetation Index	$(Red^2-Blue^2)/(Red^2+Blue^2)$	Guo et al., 2020
Red Green Blue Vegetation Index	$(Green^2 - Blue * Red)/(Green^2 + Blue * Red)$	Ranjbar et al., 2024
Blue Near Infrared Reflectance of Vegetation	((NIR - Blue)/(NIR + Blue)) * NIR	Bendig et al., 2015
Green Normalized Difference Vegetation Index	(NIR - Green) / (NIR + Green)	Yang et al., 2004
Blue Wide Dynamic Range Vegetation Index	(0.1* NIR - Blue) / (0.1 * NIR + Blue)	Hancock & Dougherty, 2007

5.3.4.3 Random Forest Model Training

Manually interpreted wallows within the Rocky Boy Buffalo Project were identified based on their visual identification of spatial and spectral characteristics (Horne et al., 2024; Sigaud et al., 2020). Within the wallows, over 1,400 pixels were identified as unique spectral signatures of bare earth in bison wallows, and 2,667 pixels were identified as non-wallows (D. Gounardis, personal conversation, March 2026). Both classes were identified by their spectral values, and the statistical differences were calculated between the binary categorization (wallow, non-wallow) within the RF model.

Pixels were categorized by how well they fit into either of the selected groups (wallows or non-wallows). A high threshold of 0.85 was selected based on trial and error optimization in the selection of predictive wallowing. Across the study area, 244,623 pixels were predicted as matching the spectral signature of wallows, and 15,178,639 pixels were identified as not matching for the year 2025.

5.3.4.4 Random Forest Post-Processing

The large predicted areas for wallows were narrowed down using selections for size and circularity based on shape area and length of wallows found in literature (Horne et al., 2024; Lott, 1974; Sigaud et al., 2020). Rasters were first transformed to objects using the Raster to Polygon tool (ArcGIS, n.d.), and then selected based on the size of the 25th and 75th percentile shape area as minimum and maximum bounds of 3m to 25m for 2025. Bison form approximately oval-shaped wallows across the landscape; thus, polygons were selected based on an objective circularity[72] above 0.45 (Gounaridis, personal conversation, March 2026). The final output was a total of 423 identifications of wallows for the year 2025 and 222 identifications for 2023.

Accuracy and scalability assessment of the RF model was conducted on 15 randomly selected 40,000 m^2 samples across the Fort Belknap Indian Community Buffalo Program

[72] Measurement of how close a polygon is to being a perfect circle (4 * pi * !Shape_Area!) / (!Shape_Length! ** 2)

Restoration to both create a complete validation set and remove any biases that may have been associated with manual wallow inspection and model training across the Rocky Boy Buffalo Program. 'Intersection over Union (IoU)' was used as a foundational evaluation metric and accuracy indicator for RF wallowing. The test utilizes the amount of area intersected by the predicted wall over the combined area to judge whether object detection was successful with 100% of overlap being a score of 1 and 0% of overlap as a score of 0. To indicate performance success, threshold values from respective object detection literature used 0.3, 0.5, and 0.7 as identifiers of low, medium, and high identification rates, respectively (Padilla et al, 2021; Paniego Blanco et al, 2022).

5.4. Results

5.4.1 Deep Learning Results

We ran Deep Learning Object Detection tool on the 2023 raster of Rocky Boy Buffalo Program and detected 379 non-overlapping objects greater than the confidence interval of 50%, with the highest confidence level detected by the model being 97.00% (see Figure 5.6). We used IoU for quantitative analysis of results and identified overlaps in 43.7% of validated wallows at the 0.3 threshold, 28% at the 0.5 threshold, and 2 % overlap in the higher threshold of 0.7. Overall, this suggested the presence of 4.725 wallows per hectare, on average, and indicated a large amount of false positives.

Additionally the wallows identified through object detection were intersected with the Landfire Existing Vegetation Type 2023 dataset. The results indicated that over 50% of wallowing occurred in the Northwestern Great Plains Mixed Grass Prairie vegetation, followed by the Inter-mountain Basin Greasewood at 27%, and the Inter-mountain Basin Big Sagebrush at 16%. Wallowing occurred below 5% across all other landfire vegetation types. Wallowing was intersected with the United States Department of Agriculture Web soil survey for the Rocky Boy study area. Over 60% of wallows occurred on Marvan Complex, a soil unit characterized by clay texture in A, B, and B-subhorizons. Wallows occurred on loam and other clay-dominant soils throughout the study area.

The translation of the deep learning object detection to the Rocky Boy Buffalo Program produced much higher average confidence than the same object detection at Konza Prairie Biological Station (66% to 34%). The shortgrass prairie ecosystem consists of many more pockets of bare earth than the tallgrass prairie found in Kansas. The shortgrass prairie is largely composed of prairie grasses and sagebrush or greasewood, and it has greatly reduced riparian zones compared to the tallgrass ecosystem of the Konza Prairie Biological Station. The bison program in Rocky Boy started recently, as of five years ago, and has produced variable change compared to the much older, wallow-filled system of the Konza Prairie Biological Station. Although the size of the KPBS is double the size of the Rocky Boy Buffalo Program, only 226 bison wallows were identified in the training set above a 50% confidence interval, compared to

379 in Rocky Boy. In Rocky Boy, high confidence levels at 84.36% are likely attributed to model underfitting[73] and the identification of false positives.

Detection confidence within Rocky Boy was likely to have been influenced by a smaller amount of batch processing relative to the Konza Prairie Biological Station. Furthermore, deep learning neural networks are designed for large training datasets, and although they can be run with a few samples, the results are significantly degraded with fewer samples (Han et al., 2022). This could also be a source of underfitting, or an indication that the training data is too generalized, resulting in false positives, and the identification of non-wallows as wallows. False positives are more likely to occur with the patchy vegetation structure common in sagebrush and greasewood habitats. Limited availability of sufficient ground truth may disproportionately affect deep learning models rather than machine learning. The selected model architecture for deep learning was a 2-stage convolutional neural network (Faster RCNN). While 2-stage models can be useful for clustered data, the 112 bounding boxes used for model detection would be considered the minimum dataset for robust object detection.

Our deep learning model predictions significantly differed from the validation set, mainly due to the overprediction of wallowing. Wallows successfully identified had some correlation to occurrence in mixed prairie habitats and loam soils, although this finding may not be significant due to poor overall prediction accuracy.

5.4.2 Random Forest Results

The RF model and its comparison of 2023 deep learning predicted wallows are visible in Figure 5.7, and based on the interpreted wallow surface seen in Figure 5.8. After post-processing, the accuracy of the predicted wallows from 2025 was measured against a validation set of 226 manually identified wallows. Predicted wallowing from the Rocky Boy Buffalo Program (2025) resulted in a mean IoU of 0.622 and a median IoU value of 0.65, with the highest levels of precision and recall over any artificial intelligence model. This IoU rating indicated that there was 62% overlap in predicted wallow polygons and validation polygons. This neared but did not pass our threshold for high identification rates. When applied to other years and bison areas, the machine learning model produced large amounts of false positives and reduced the average IoU. Only 31% of the validation wallows overlapped with predicted wallows in 2023, and the true positives had a mean IoU score of 0.53 and a median score of 0.52. Bison typically use wallows across large temporal scales, and this was prevalent from the 58 wallows that overlapped between the two classifications of 2023 and 2025. Modeling accuracy and model transferability was assessed across samples sections of Fort Belknap Indian Community Buffalo Program Restoration and Grazing System for 2025, and similar amounts of overprediction occurred compared to Rocky Boy Buffalo Program indicating that both places within the NGP ecoregion showed similar model performance (Figure 5.8).

Machine learning wallows were intersected with the Landfire Existing Vegetation Type 2023 dataset to better understand which landcovers were receiving the most amount of

[73] Generalized training which results in the overproduction of object predictions based on congruent landcover similarities

disturbance. In 2023, 48.5% of wallows occurred in the Northwestern Great Plains Mixedgrass Prairie, followed by 18% of wallows in the Inter-mountain Basins Greasewood flat, and 16% of wallows occurring in the Inter-mountain Basins Big Sagebrush Steppe. In the Open Water vegetation type, 5.4% of wallowing occurred, indicating limitations to raster intersection across spatial resolutions, and all other wallowing occurred at lower than 5% in the remaining Landfire Vegetation Types.

In intersections with soil data, 77% of wallowing occurred on the Marvan soil complex, 12% of wallowing occurred on Benz clay loam soils, and less than 5% of modeled wallowing occurred in all other soil types. The intersection of both vegetation types and soil types highlights the hypothesized relationship between wallowing and habitat characteristics. Updates to the model accuracy and precision may identify a differing correlation in wallowing vegetation and soil preference.

Table 5.5. *Results of Final Model Outputs from Deep Learning and Machine Learning*

	Deep Learning: Faster - RCNN	**Machine Learning: Random Forest**		
	Rocky Boy 2023	**Rocky Boy 2023**	**Rocky Boy 2025**	**Fort Belknap 2025**
True Positives	80	43	99	62
False Positives	299	177	43	49
False Negatives	103	101	40	343
Mean IoU	0.516	0.531	0.639	0.556
Median IoU	0.532	0.523	0.667	0.581
Precision - 0.3	0.211	0.203	0.992	0.689
Precision - 0.5	0.134	0.126	0.831	0.544
Precision - 0.7	0.011	0.018	0.254	0.011
Recall - 0.3	0.437	0.308	0.624	0.153
Recall - 0.5	0.279	0.192	0.522	0.121
Recall - 0.7	0.022	0.027	0.159	0.002
F1 Score - 0.3	0.285	0.245	0.766	0.250
F1 Score - 0.5	0.181	0.152	0.641	0.198
F1 Score - 0.7	0.014	0.022	0.196	0.004

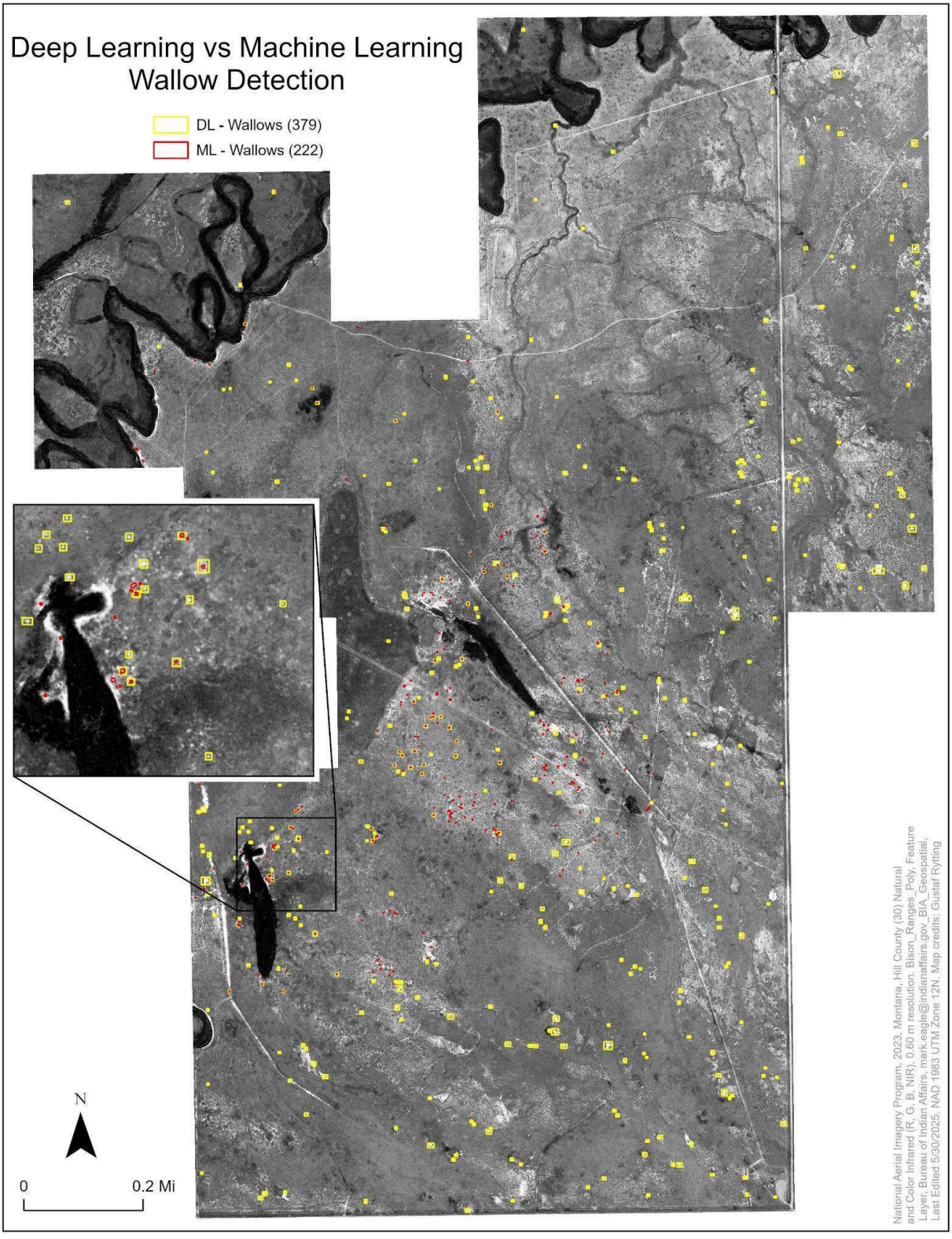


Figure 5.6. *Rocky Boy Buffalo Program (2023) with implementation of Deep Learning and Machine Learning Object Identification*

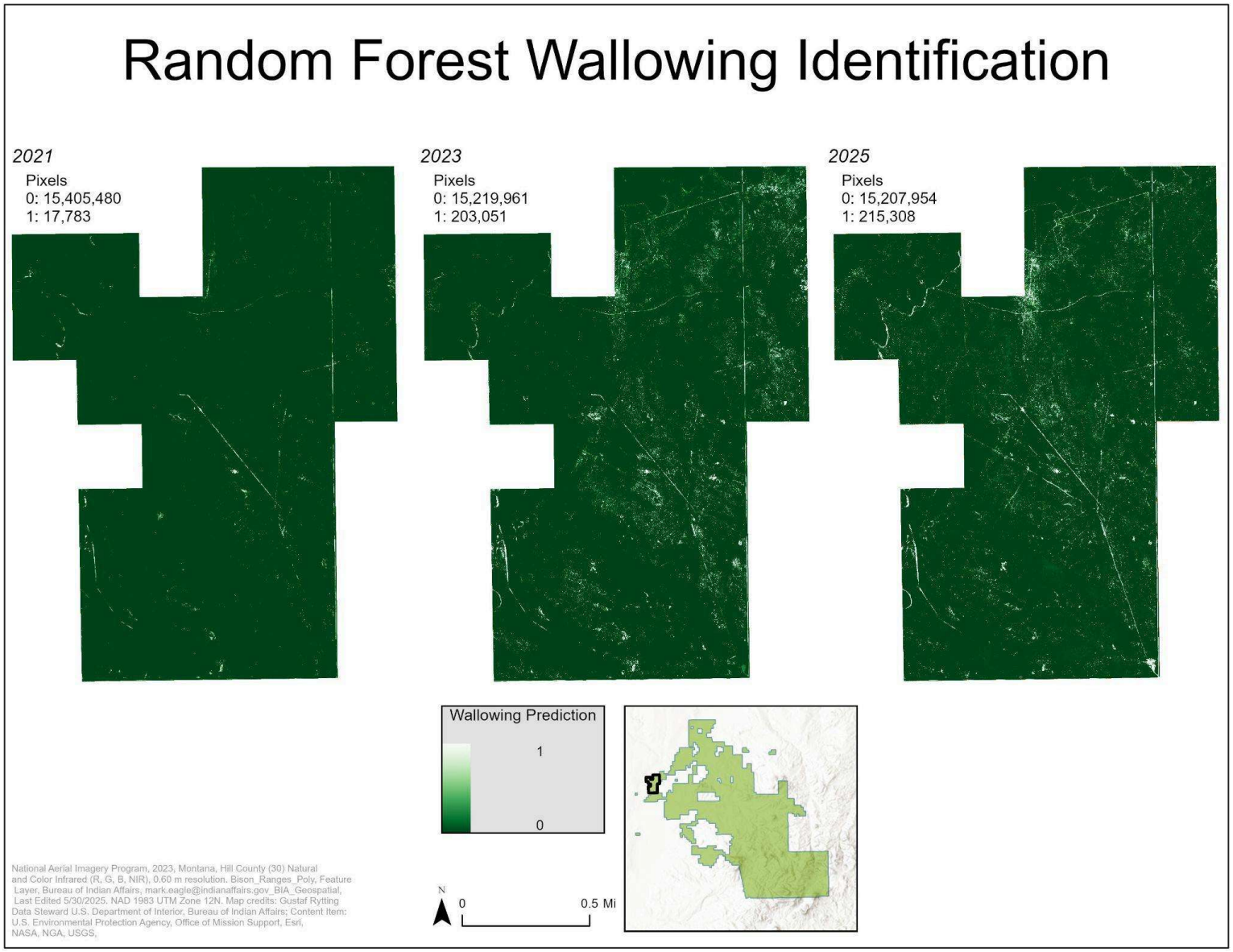


Figure 5.7. *Random Forest predicted modeling of wallows before post-processing for the size and circularity of wallowing behavior.*

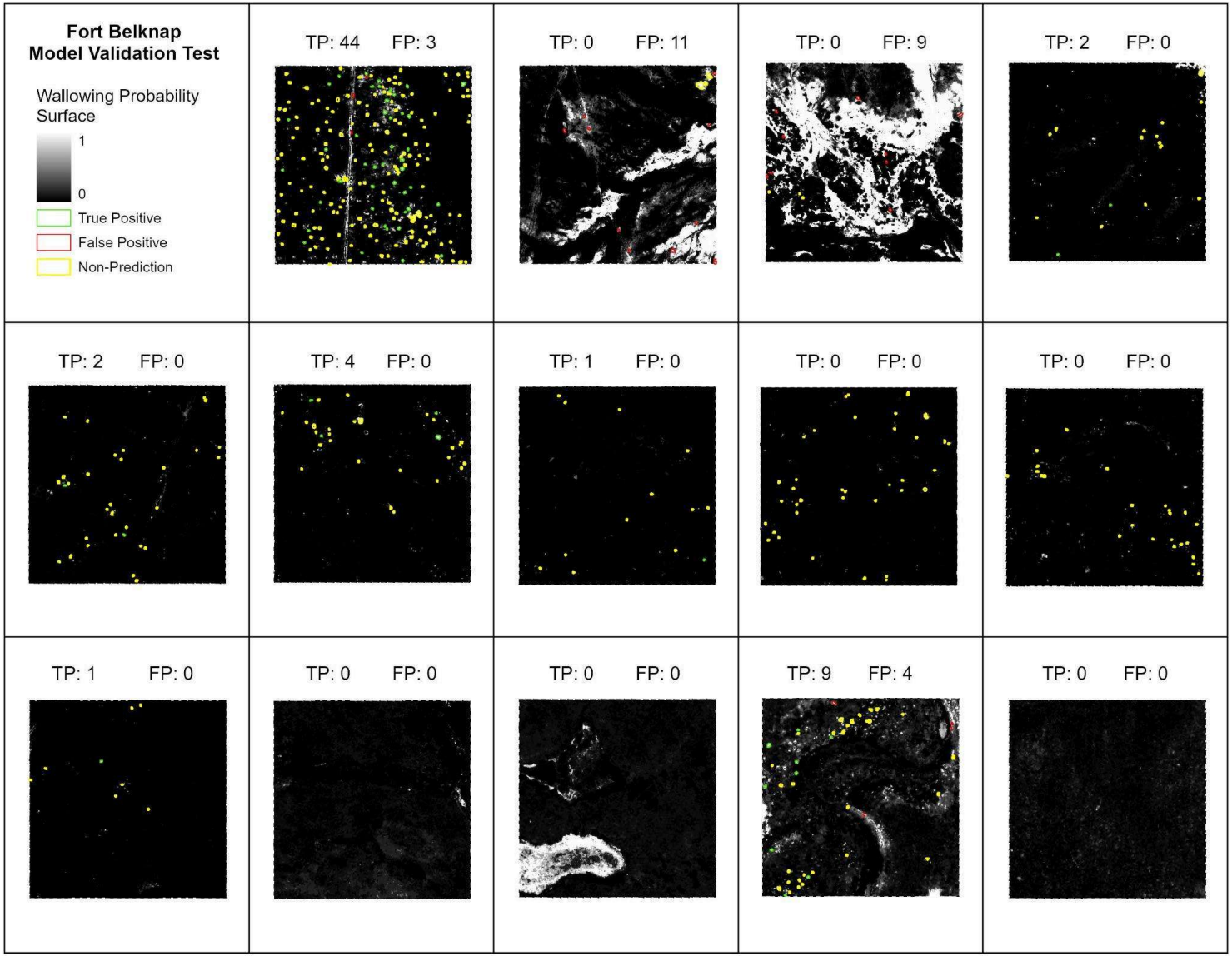


Figure 5.8. *Random Forest accuracy assessment from random sample selection of Fort Belknap Indian Community Buffalo Program Restoration and Grazing System (2025).*

5.5. Discussion

Under Buffalo Nations Grassland Alliance goals in supporting culturally- and ecologically-important wildlife species while enhancing capacity for scalable conservation impact at Rocky Boy's Reservation in Montana, this project aimed to identify and protect key habitats for bison and grassland habitat. This study also aimed to develop insight into the rapidly changing grasslands of the NGP ecoregion and the role of bison and Indigenous-led management in grassland restoration. Observations of wallowing serve as one proxy for ecosystem function due to their engineered improvement of habitat heterogeneity, plant community composition, and microhabitat creation by bison. Using an AI-based object detection tool may be able to provide insight into areas of restoration for

5.5.1 Key Findings

With respect to whether wallows could be identified using artificial intelligence object detection, our results showed that identification of bison wallows with existing AI tools and datasets is challenging: the spectral signature of bison wallows matched many other landscape features, including water banks, roads, and components of sagebrush and greasewood habitats. In both deep learning and machine learning, overlapping signatures caused overprediction of the amount of wallows that are created by bison across the landscape compared to what is actually there. The deep learning model overpredicted more wallows than the machine learning model, but also predicted more wallows correctly. The machine learning model predicted fewer wallows correctly and had fewer false positives.

Limitations of AI-based modeling are largely due to the lack of available data at the scale needed to identify wallows. Deep learning models were developed using principal component analysis and distance accumulation rasters, two tools that add additional time to any given prediction, whereas machine learning was developed all from NAIP imagery and spectral indices. The processing power for both models was dependent not only on the tools (distance accumulation, raster calculator, composite band) used to create predictor rasters but also on the models themselves, with deep learning models being more complex and time-consuming. The machine learning model object detection took only a fraction of the time that deep learning models evaluation took, on top of a shorter preprocessing time. Based on processing requirements alone, machine learning is a better option based on size and discontinuity of Native Nations across the NGP ecoregion.

Both the deep learning and machine learning models successfully detected wallows in the grassland vegetation type. Nearly 50% of wallows occurred on the Northwestern Great Plains Mixedgrass Prairie, and over 60% occurred on the Marvan soil complex. While more research (and conclusive evidence) is needed to determine whether this relationship is indicative of causation rather than correlation, this association could inform future grassland recovery efforts in bison conservation programs that wish to encourage behavioral engineering by bison. Bison managers should prioritize acquiring and restoring more land in the Northwestern Great Plains Mixedgrass Prairie vegetation community and/or Marvan soil complex categories to create more suitable landscape for bison habitat. Furthermore, updates to model precision and accuracy may

provide more context for the association between the wallowing, land cover, and soil factors. Finally, the land cover types are limited to those available in the Rocky Boy Buffalo Project, which might not cover the full variety that every bison program supported by BNGA works with.

5.5.2 Challenges

The largest limitation within this study came from a lack of usable raster data, particularly fine-resolution rasters. There were very few predictor layers that were compatible with the 0.6-meter resolution provided by NAIP and necessary for wallow detection. At a size of 0.6-meters, wallows are perceptible to the human eye, but are at the lower range limit of wallow identification using a computer vision approach. A few datasets, such as DEMs and other fine spatial data, which were available in model training, introduced inordinate uncertainty in the study area and were excluded.

Model effectiveness was constrained by the overprediction of wallows in each of the models across multiple predictors. The signature of wallows matched the signature of other features across the landscape, including roads and embankments along rivers and standing water. Additionally, the biennial temporal resolution of imagery data restricted the indication of wallowing differences in short-term seasonal variability to climatic shifts.

5.5.3 Recommendations

Advancing wallow detection and understanding the potential role of remote sensing models in assisting and understanding the prioritization for lands for the restoration of bison habitat and connectivity requires data availability at high spatial resolution, improved ecological context, and model refinement to strengthen detection accuracy and reduce variability.

Improving data resolution and availability will enable more effective detection of fine-scale disturbances. Increasing spatial resolution improves the detectability of wallow difference in wallowing spectral signatures, and increases in temporal resolution allow for a better understanding of wallow persistence and rate of increase. While the 2025 NAIP rasters used in this study were resampled to match the 2021 and 2023 resolution, future studies would benefit from the updated 0.3m resolution going forward. Yearly sampling of NAIP only occurs across North Dakota, but updates to temporal sampling, whether freely available, play a large role in identifying the rate of wallowing and wallowing in relation to yearly conditions.

To make models truly scalable, efforts should be made to ensure more environmental variability is used in model training beyond and within the Northern Great Plains. The transferability of wallowing detection models between KPBS and Rocky Boy Buffalo Project showed higher confidence in wallows detected in Rocky Boy, rather than Manhattan, Kansas, although it is unclear what factors caused the difference. Accounting for consistency across regions is necessary for wider conservation applications across discontinuous landscapes.

More research is needed to inform whether wallowing is preferential towards vegetation types and soils. Correlations between the two can inform which grassland patches are preferred for greater grassland ecosystem function. While research is needed to determine causation between the two, traditional ecological management techniques in the form of fire and seeding of native plants can assist in the promotion of bison activity and grassland restoration. In future

iterations of the tool, identification of habitat suitability based on wallowing preference may indicate prioritization for restoration and purchases of areas with high ecological function based on wallowing.

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Chapter 6: Assessing Options for the Design and Financing of NAGCA to Build Capacity for Implementation

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Executive Summary: Recommendations for the North American Grasslands Conservation Act (NAGCA)

Grasslands are vital ecosystems for Tribal, local, state, and federal economies, for furthering various goals of the United States government, and for ensuring the cultural continuity of numerous Indigenous Peoples. The North American Grasslands Conservation Act (NAGCA) is a bipartisan piece of legislation introduced to the United States Congress in 2022 that, if passed, would facilitate cost-share grants to state, local, Tribal, and private entities seeking to undertake grassland conservation or restoration projects. The Buffalo Nations Grasslands Alliance (BNGA) has endorsed NAGCA, citing its highly promising strategy of "creat[ing] a flexible and innovative grant program for voluntary, incentive-based conservation and restoration of North American grasslands and sagebrush shrub-steppe while supporting farmers, ranchers, Native communities, sportsmen and women, and rural communities." The bill is currently in the Subcommittee on Conservation, Research, and Biotechnology of the Congressional Committee on Agriculture, and a key barrier to its further movement through the legislative process remains the question of how to finance it.

In this chapter, we outline a strategy for financing NAGCA, as well as a set of suggestions for furthering its effectiveness by making it more accessible to a broader range of potential partners. These recommendations were developed through a gap analysis of existing federal grassland conservation legislation, a case study of the benefits and challenges associated with the North American Wetlands Conservation Act (NAWCA) – an existing bill with a highly similar structure to NAGCA – and a quantitative model for determining a financing strategy for NAGCA. Our recommendations can be summarized as follows:

1. Increase the federal land leasing rate for grazing by 25% annually from the current rate of $1.35 per AUM to $7.97 per AUM, and use the additional funds generated by this increase to finance NAGCA;
2. Create a set of standardized, federally-applicable metrics for grassland performance to establish a toolkit for reporting on the effectiveness of projects facilitated by NAGCA; and
3. Simplify the NAGCA grant application process to reduce associated administrative burdens that can create barriers to participation. Additionally, we recommend that the regional councils established through NAGCA provide free or low-cost consulting services to applicants in order to assist with the application process.

6.1 Introduction

This chapter aims to contribute to capacity-building for Indigenous-led conservation by evaluating ways to increase federal funding toward it in the U.S. Our client organization, the Buffalo Nations Grassland Alliance (BNGA) is a Native-led 501(c)(3), works with 16 Native Nations in the Northern Great Plains (NGP) ecoregion (see Figure 1.1 in Kelly, 2026). BNGA was created in 2015 by a group of Indigenous biologists working to support grassland restoration initiatives for Tribes in the NGP ecoregion.

One of BNGA's overarching goals is to ensure that 30% of the NGP ecoregion is under Indigenous-led conservation management (BNGA, 2024). Securing funding for Indigenous-led grassland conservation is a key strategy in doing so. In alignment with this strategy, the main purpose of this chapter is to provide recommendations for funding, implementing, and earning political support for NAGCA, a bipartisan bill that would fund a wide variety of grassland conservation and restoration interventions and ethically draw from Indigenous Traditional Ecological Knowledge. Its passage is an important area of advocacy supporting Indigenous-led grassland conservation, as NAGCA would promote partnership between Native Nations (among other groups) and the federal government in conserving and managing grasslands. This would be a significant step toward recognizing Native Nations' role in co-creating and maintaining grassland ecosystems – largely through controlled burning – since time immemorial together with non-human elements of their natural environments (Stewart, 2009). The key audience will be the U.S. Congress and stakeholders in NAGCA, including the Buffalo Nations Grasslands Alliance, other Tribal-led grassland conservation-focused organizations, local and state governments, and farming and ranching interests. The landscape analysis of existing funding opportunities is also intended for use by grant applicants for grassland conservation projects, as we hope that this database can be a resource for those seeking funding for such projects. Since NAGCA is a proposed federal bill, the geographic scope of this chapter will be grasslands in the entire United States (see Figure 6.1).

In this chapter, we begin by providing background on grasslands in the United States, including the plant and animal species that rely on these ecosystems for habitat, as well as grasslands' immense economic value and their vital role in carbon sequestration as atmospheric greenhouse gas levels continue to increase. Then, we carry out a gap analysis of existing funding opportunities for grassland conservation. Next, we examine the North American Wetlands Conservation Act, which is highly comparable to NAGCA, and identify lessons from its financing and implementation that can help increase capacity for a broader range of projects. Finally, we provide a set of recommendations for NAGCA, including how to finance the bill.

6.2 Background: Importance of Grasslands in the United States and the North American Grassland Conservation Act (NAGCA)

Grasslands are among the most endangered ecosystems globally (Lark, 2020). Over half of grasslands in the United States have vanished due to conversion to agricultural land, industrial development, and the spread of invasive species since European settlement. According to the U.S. Fish and Wildlife Service's estimates, at least 62% of grasslands in the United States have

vanished to date (Knuth, 2024). Less than 10% of the remaining grasslands in the country are under governmental protection, meaning that the vast majority of what is left of the biome is at risk of agricultural conversion (USFWS, 2018). In the mid-Southeastern United States, under 10% of grasslands remain intact, and these remaining grasslands are projected to vanish within the next 25 years under business-as-usual conditions (Estes et al, 2016). Unless urgent action is taken to protect what is left of and restore degraded sections of the grassland biome, the vanishing of grasslands will continue to have devastating consequences for the species that rely on them for survival, the United States economy, the country's capacity to mitigate climate change, and the physical and cultural continuity of a number of Native Nations. Grasslands are found in almost every state (Allred et al., 2021), rendering their conservation a national concern. This section will characterize grasslands in the United States, outline several attributes of these ecosystems that can be useful in advocacy for federal action to conserve grasslands, and describe NAGCA, a federal bill for grassland conservation.

6.2.1 Overview of Grasslands in the United States

Grasslands are defined by their dominant land cover of grasses and sometimes small shrubs. The two main grassland biomes globally are savannahs and temperate grasslands. This chapter focuses on temperate grasslands, as that is the major category encountered in the United States. Characteristics of temperate grasslands include nutrient-rich topsoil due to the deep, interwoven root systems of grassland plants, as well as frequent disturbances, such as fires, grazing by large mammals, and seasonal droughts, which prevent woody plants from becoming established. There is great variation among grassland vegetation communities, depending largely on rainfall, proximity to coasts, and elevation, but grasslands are present in nearly every region of the United States, rendering their conservation of great federal, state, local, and Tribal concern. See Figure 6.1 for a map of all grasslands in the United States, Figure 6.2 for a breakdown of grasslands by Congressional district, and Appendix E for a comprehensive list of United States grassland ecoregions and the native grasses that prevail in each region.

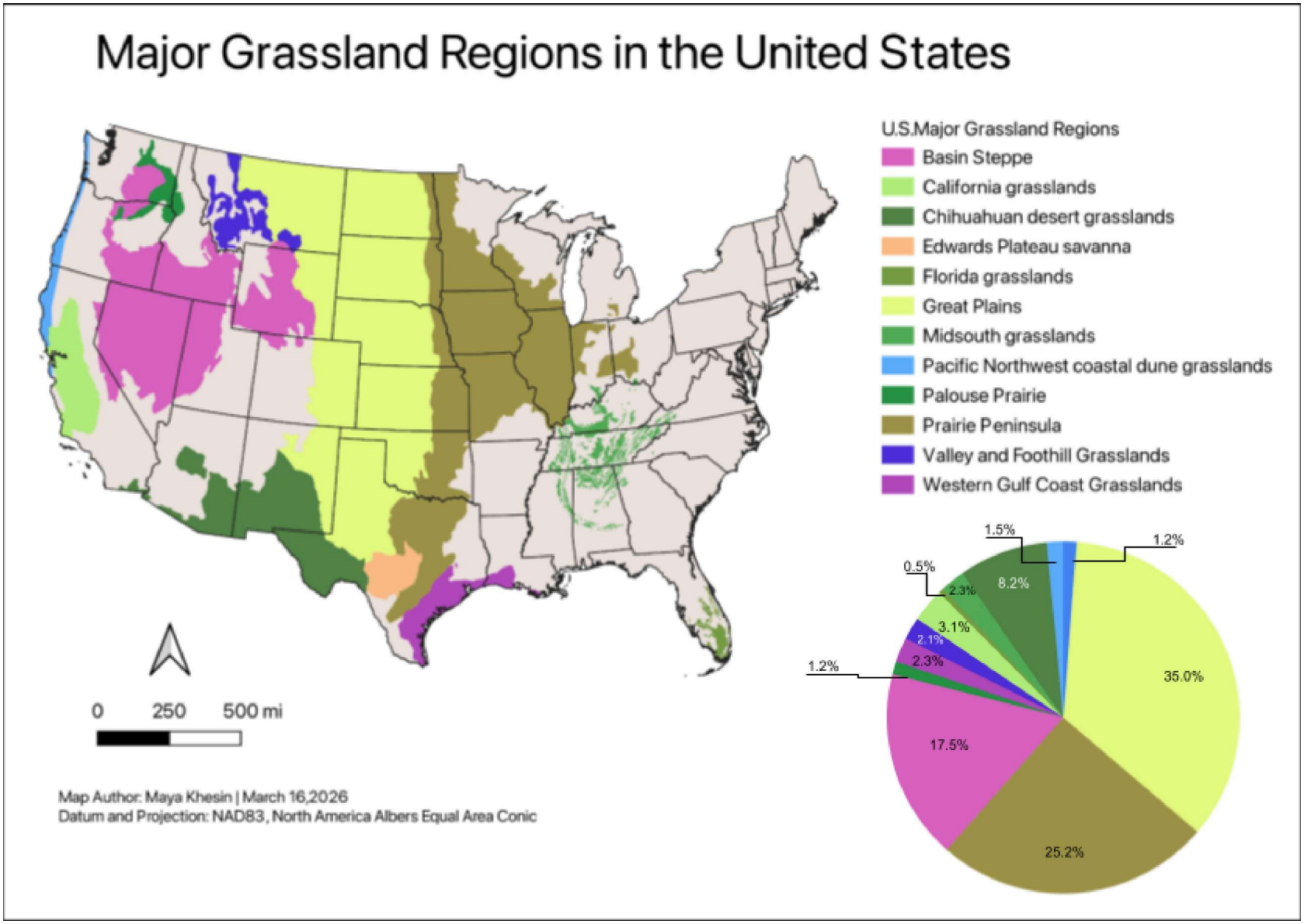


Figure 6.1. *Major grassland regions of the United States. The pie chart illustrates a percent breakdown of these regions by area.*

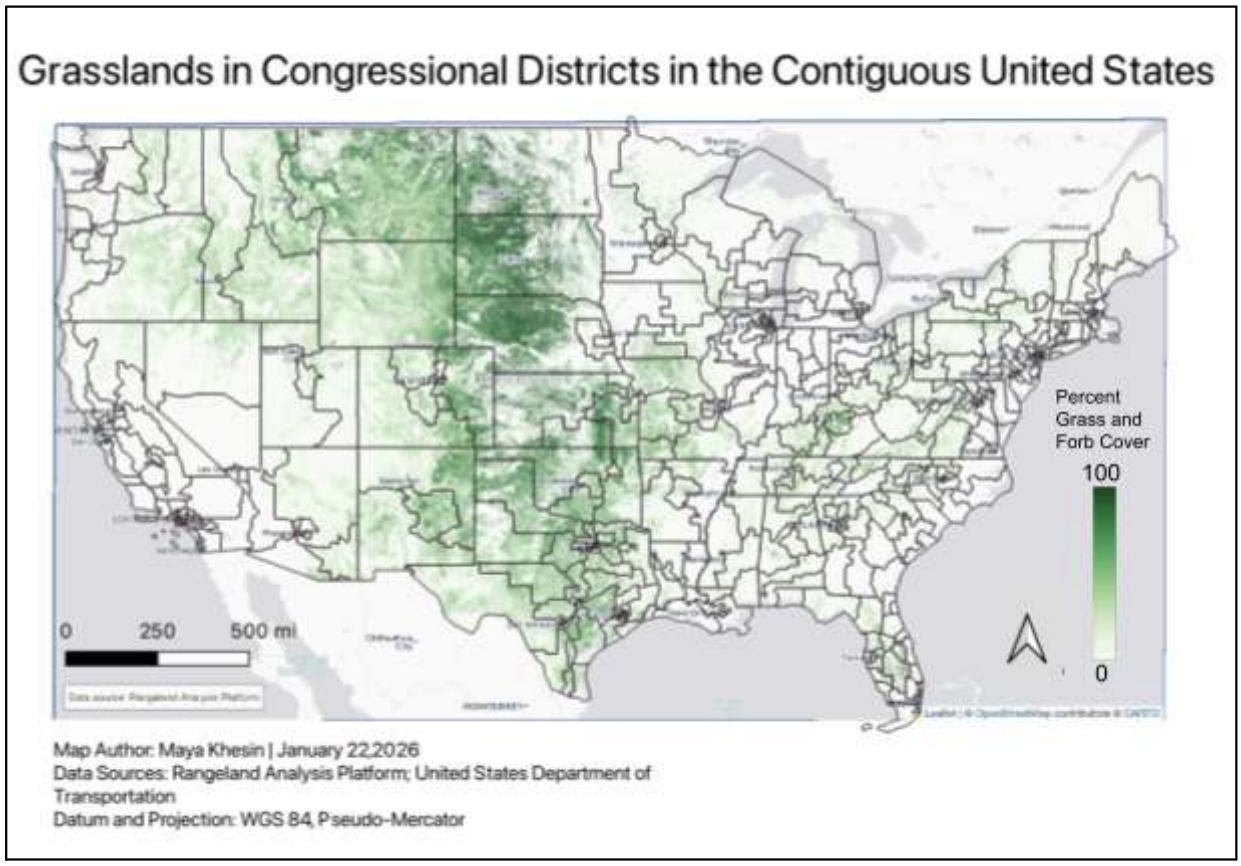


Figure 6.2. *Prevalence of grasslands in 2025 Congressional districts in the contiguous United States.*

6.2.2 Grasslands as Critical Habitats

Grasslands provide vital food and habitat for many species, including a number of keystone species[74] and endangered species. In addition to federally-identified species for conservation, many Native Nations have identified priority species that include culturally- or ecologically-significant species, some of which overlap with the U.S. Endangered Species Act list. Thus, increasing capacity for Tribal-led grassland conservation has great potential to further federal conservation goals by blending federal government initiatives with local and traditional knowledge to achieve long-term, sustainable conservation.

6.2.3 Economic Contributions of Grasslands

Grasslands contribute significantly to the U.S. economy through a range of ecosystem services and uses. See Table 6.1 for an overview of several of these contributions.

[74] Keystone species are species that have a disproportionate impact on their ecosystem, relative to their population size. The removal of a keystone species from an ecosystem would drastically change the structure and/or wellbeing of the ecosystem.

Table 6.1. *Estimates of contributions of grasslands to the U.S. economy.*

Contribution Stream		Per-Acre Contribution	Total Contribution
Forage production		$5.80 (per year)	$3.8 billion (per year)
Wildlife recreation		$26.70 (per year)	$17.5 billion (per year)
Other ecosystem services		$4.88 (per year)	$3.2 billion (per year)
Beekeeping		$304.45 (per year)	$262 billion (per year)
Carbon sequestration	Low estimate	$4,122.70 (total); 75.49 (per year)	$2.7 trillion (total); $49.5 billion (per year)
	Mid-range estimate	$13,492.66 (total)	$8.8 trillion (total)
	High estimate	$39,352.44 (total); $1,641.35 (per year)	$25.8 trillion (total); $1.1 trillion (per year)

Maher et al. (2021) quantify revenue from several aspects of grasslands, specifically forage production, wildlife recreation, and other ecosystem services. The authors estimate an annual revenue of $3.8 billion from forage production revenue, $17.5 billion from wildlife recreation, and an additional $3.2 billion for other ecosystem services that relate to biodiversity. Approximately 29% of the 2.26 billion acres of U.S. land area is grasslands, making for a total grassland area of roughly 655.4 million acres. The values provided by Maher et al. thus translate into annual per-acre values of $5.70, $26.70, and $4.88 for forage production, wildlife recreation, and other ecosystem services, respectively.

Another study, Otto et al. (2022), measures the revenue derived from beekeeping in the Prairie Pothole Region of North and South Dakota, finding that that every 10 km^2 increase in grassland area surrounding the routes of birds in the North American Breeding Bird Survey (NABBS) is associated with an increase in expected annual revenue from honey bee colonies of $7,525. This translates into an increase of $304.53 per acre of grasslands around NABBS routes. In general, grasslands provide critical habitat for pollinators, which contribute between $4 billion and $6 billion annually to the United States economy (United States Department of Agriculture [USDA] Forest Service, n.d.).

Grasslands are also important for sequestering carbon. Temperate grasslands store three times as much carbon in their soil as they do after conversion to cropland (Neufeld & Smith, 2022) due to their high biomass of perennial grass root systems, rendering them a crucial ecosystem for increasing the United States' capacity to fight the harmful effects of atmospheric carbon. Hungate et al. (2017) calculate several estimates of soil carbon storage values based on

federal estimates of the social cost of carbon[75]. This study reports a low-end estimate of $41.94 per tonne of carbon (C), a mid-range estimate of $137.26 per tonne of C, and a high-end estimate of $400.33 per tonne of C. Temperate grasslands store roughly 243 tonnes of carbon per hectare (Neufeld & Smith, 2022). This is equivalent to roughly 98.3 tonnes of carbon stored in each acre of grassland, resulting in a per-acre grassland carbon sequestration value between $4,122.70 and $39,352.44, with a mid-range estimate of $13,492.66. Due to the difficulty and expenses associated with repeatedly testing soil for carbon content, it is difficult to translate soil carbon sequestration into annual values. However, according to several studies, native grassland soils in the U.S. are estimated to have a carbon sequestration potential between 2 and 4.5 tons (1.8 tonnes to 4.1 tonnes) per acre per year (Gaskill, 2021). Applying the carbon pricing levels discussed in Hungate et al. (2017), this results in a per-acre annual carbon sequestration value ranging between $75.49 and $1,641.35. Multiplying these values by the total current grassland acreage in the U.S. results in estimated annual contributions ranging from $49.5 billion to $1.1 trillion.

Estimating the total economic value of U.S. grasslands is not as simple as summing up the above values, as they likely overlap to an extent and do not constitute the comprehensive range of indirect economic contributions of grasslands. However, summing up these values provides a loose, highly imperfect estimate of grasslands' annual contributions to the U.S. economy, which, even if not fully accurate, allows us to carry out a crude cost-benefit analysis of NAGCA. Additionally, we use this method to provide a range of values, which is more likely to capture the actual economic value of grasslands than a singular value would be. Using this method, we estimate that the total annual revenue from U.S. grasslands economy ranges from $332.8 billion to $1.2 trillion, depending on the extent to which beekeeping intersects with the "other ecosystem services" discussed in Maher et al. (2021), which carbon pricing value is used, and where the actual annual carbon sequestration rate of grasslands falls in the range presented above. Regardless of the specific number, this range shows that the economic benefits of conserving grasslands outweigh the cost of NAGCA by many orders of magnitude (see Figure 6.3). The vast area of grasslands in the United States contributes immensely to the U.S. economy, and preserving these grasslands – and restoring previously converted ones – is key to ensuring that they continue to do so.

[75] The social cost of carbon is an economic estimate of the total future damages (including health effects, agricultural damages, and many others) resulting from the emission of one additional ton of carbon dioxide (CO2) into the atmosphere. While this is a subjective number that varies greatly depending on how much future wellbeing is valued, what effects are included, and a number of other factors, it is a key figure in political decision-making because it attaches a measurable quantity, in financial terms, of damages associated with carbon emissions.

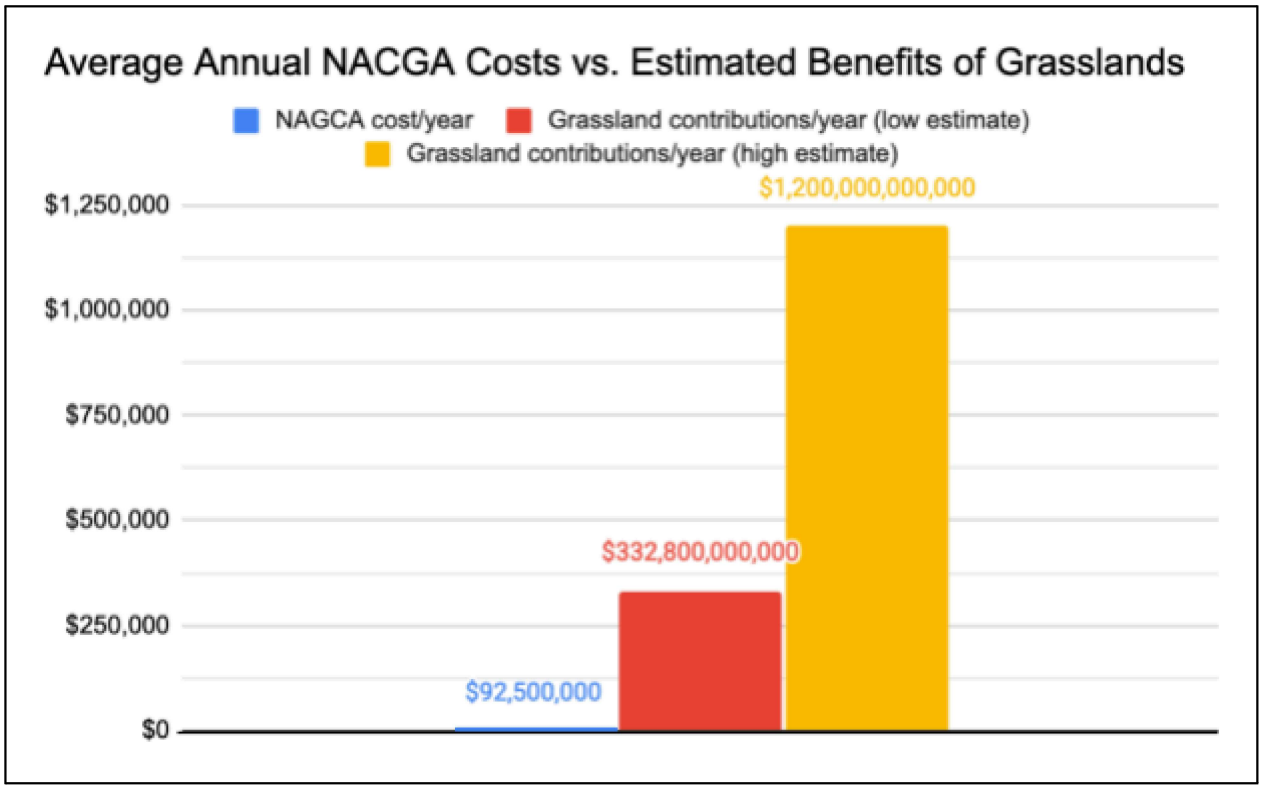


Figure 6.3. *Comparison between the annual cost of NAGCA and the range of estimates of annual economic contributions of U.S. grasslands.*

6.2.4 Cultural Significance of Grasslands

In addition to their importance to federal, state, and local interests and economies, grasslands bear great significance to the Indigenous Peoples that have co-created these ecosystems and established modes of mutual thriving with their non-human relatives. These Peoples depend on grasslands for physical sustenance in addition to cultural continuity, as they view land and the species it sustains as relatives and have sustained themselves through countless generations by coexisting with and stewarding their natural environments. In addition to providing food in the form of plants and animals that feed on grassland flora, Indigenous Peoples have sacred relationships with certain plants, animals, and landforms that are native to grasslands (BNGA, n.d.). Therefore, not only is grassland conservation crucial for the cultural and physical survival of numerous Indigenous Peoples, but it also stands to benefit greatly from the equitable inclusion of their leadership, perspectives, and traditional stewardship practices.

6.2.5 Legislative Landscape of Grassland Conservation in the United States

While a number of federal grassland conservation acts already exist, they do not adequately cover the full extent of United States grasslands, and they come with certain barriers to participation for some applicants. Grasslands are present in 35 out of the 48 States comprising the contiguous U.S. (see Figure 6.1), or in roughly 73% of these States, rendering their conservation a national concern, and a constituent concern for the majority of U.S. legislators

(see Figure 6.4). Thus, a more comprehensive grassland conservation bill is necessary to ensure that grasslands are able to continue to provide the benefits discussed in this section.

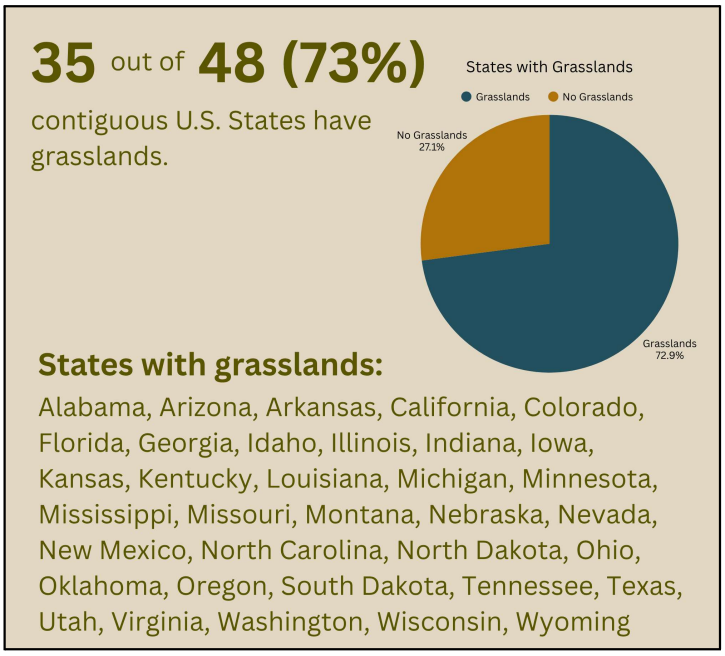


Figure 6.4. *Statistics about grassland presence in the U.S.*

NAGCA was introduced in the U.S. Senate in 2022, and to the U.S. House of Representatives in 2024 (see Table 5.2 for a full list of sponsors of the bill). In November 2024, the bill was referred to the Subcommittee on Conservation, Research, and Biotechnology of the Congressional Committee on Agriculture, where it remains (NAGCA, 2024). In this chapter, we present three recommendations for financing and implementing NAGCA, developed through 1) A gap analysis of existing federal-, state-, and local-level public funding opportunities for grassland conservation, 2) An evaluation of strengths and opportunities for growth in the similar North American Wetland Conservation Act (NAWCA), and 3) A quantitative tool created to determine a funding strategy for the Act. Methodologies for these analyses included literature reviews, informal conversations with members of BNGA and the Rocky Boy Buffalo Project, and quantitative analyses using the programming language Python.

Table 6.2. *Legislative history of NAGCA.*

Legislative Body	Sponsors	Year
U.S. Senate	Ron Wyden (D-OR); Amy Klobuchar (D-NM); Michael Bennet (D-CO)	2022
U.S. House of Representatives	Nancy Mace (R-SC);	2024

Legislative Body	Sponsors	Year
	Sharice Davids (D-KS); Brian Fitzpatrick (R-PA); Mike Thompson (D-PA)	

6.3 Literature Review: Federal Funding Programs for Grassland Conservation

While NAGCA is a relatively young bill, public awareness of the fragile status of grasslands and their conservation importance is well-established. This section discusses incentive-based policy as a popular method of grassland conservation, and evaluates the efficacy of enacted grassland conservation legislation. These components later inform our recommendations for NAGCA, specifically in terms of its reach, data collection, and accessibility to potential applicants. We utilized the database Google Scholar for this literature review, with keyword-based searches using the terms "grassland conservation federal policy USA," "incentive-based grassland conservation policy USA," and "North American Grasslands Conservation Act."

6.3.1 Considerations for Grassland Conservation Policies

Lark (2020) discusses a set of policy opportunities for conserving United States grasslands. Lark cites several existing highly promising and successful federal policies, such as conservation incentives and easements. He concludes that more funding should be allocated to these initiatives to scale their influence. Other opportunities that Lark identifies include:

- Reducing incentives to convert grasslands to cropland;
- Establishing a goal of net-zero loss of grasslands across all federal agencies; and
- Increasing federal, state, and local governmental partnership with Tribal nations in the creation of grassland conservation policies.

Another study (Bardgett et al., 2021) identifies actionable steps for grassland conservation on a global scale, but these steps are also applicable at the U.S. federal level. Firstly, the authors cite a need for policies to recognize the crucial role that grasslands play in mitigating climate change, combating food insecurity, conserving biodiversity, and alleviating poverty. Secondly, the study calls for more standardized assessments of grassland conditions – including the severity of their degradation, and the implications of this degradation for biodiversity and ecosystem services – as well as standard procedures for evaluating the success of restoration initiatives. Due to the current lack of standardization, datasets are often incompatible and inaccessible, and a lack of widespread communication around successful grassland conservation methods prevails.

Shaffer et al. (2001) argue that incentive-based habitat conservation is the best way to further the goals of the Endangered Species Act, as habitat loss is a major driver of biodiversity reduction. The authors point to historical evidence of regulatory approaches to habitat conservation being highly unpopular and ineffective in the United States, concluding that

incentive-based approaches are much more promising. Specifically, they recommend that the federal government grant funding to each State to establish an office that helps administer existing federal, state, and local biodiversity habitat conservation incentive programs and provides feedback to policymakers on these programs. They emphasize that in order to be successful, incentive programs should be flexible, as habitat conservation is highly context-dependent and thus has no singular ideal approach.

The three studies discussed above are representative examples of a broader range of literature on ecosystem and habitat conservation (see, for example, Baker et al., 2020, Briske et al., 2016, and Enck & Cojocariu, 2010) that promotes incentive-based policies as a promising option for the conservation and restoration of grasslands in the United States. In addition to arguing in favor of incentive-based conservation, these studies emphasize the need for greater knowledge-sharing, evidence-based direction of efforts, and public-private partnerships to implement conservation goals. There are already a number of federal incentive-based conservation programs referred to in this literature that are applicable to grasslands, yet the problem of severe grassland endangerment persists. The gap analysis of federal grassland conservation incentive offerings conducted in the following section aims to understand why these existing programs have fallen short in preventing grassland decline. Lessons drawn from this analysis will allow us to tailor recommendations for NAGCA to existing needs.

6.3.2 Gap Analysis of Existing Federal Funding Programs for Grassland Conservation

A comprehensive list of federal funding programs related to grassland conservation is provided in Table 6.4 (see end of this section), summarized in chronological order in Figure 6.6. In this subsection, we carry out a gap analysis of these programs. The shortcomings of federal incentive-based grassland conservation programs identified through this gap analysis are summarized in Table 6.3.

Table 6.3. *Summary of gaps in federal incentive-based grassland conservation programs.*

Gap	Significance
Complexity and monetary needs of application processes	Barriers for participation in federal grassland conservation funding programs for entities with limited time and money to spare
Insufficient monitoring of incentive-based conservation impacts	Lack of data to support arguments for re-authorization of incentive-based conservation bills, benefits of these programs are not quantified
Most federal grassland conservation grants are limited to working lands	Working lands often involve converted grasslands, but intact grasslands offer more in terms of biodiversity conservation and carbon sequestration. Native Nations also conserve large portions of intact grasslands, so these programs systematically underfund Native-led conservation.

As Table 6.4 shows, most federal grassland conservation funding programs apply to working lands, largely farms. These farm-based programs work with agricultural producers to promote conservation by subsidizing specific on-farm practices or reserving land from production. While highly effective for approved projects, many of these programs come with high administrative burdens pertaining to the application process. For example, Pennsylvania dairy farmers interviewed in one study (Baylis et al., 2008) identified the time and labor requirements of applying to these programs as a barrier to participation. As one farmer said, "We've got 800 cows to milk. We don't need to be sitting down and doing an hour's worth of paperwork for [a government grant]." Other farmers interviewed in this study voiced similar frustrations. Given the fact that farmers already often work full-time, additional time and energy to spend on these applications is hard to come by. As a result, many of the farmers interviewed in this study turned to independent agricultural consulting companies, which charge fees for their services, to assist with the administrative burdens of applying to these grants. Given the declining profitability of the farming industry, these fees can be burdensome for farmers, especially for small-scale operators. Farmers also find the administrative costs that come with applying to these programs "prohibitive." Finally, farmers have taken issue with the fact that they are sometimes portrayed by these programs as inherently having negative impacts on the environment, harming their public image and forcing them to shoulder disproportionate blame for environmental degradation.

These farmers put forth several solutions that would help reduce these burdens. First, they stated that partnering with private sector agribusiness consulting firms to assist with the process of applying to federal grants has been helpful in the past. They also suggested that better communication about incentive programs and how they can benefit the public can both inform farmers of these programs who otherwise would not have known of their existence and help uplift farmers' public image by increasing visibility of the conservation work that they carry out. Several of the farmers interviewed explicitly stated that these measures would increase their likelihood of participating in federal incentive-based conservation programs (Houser et al., 2024).

Another gap identified in the literature is insufficient monitoring involved in incentive-based conservation programs. For example, Bardgett et al. (2021) state:

> New approaches are needed to enable standardized assessment of grassland conditions globally under different situations. These approaches should assess the severity of grassland degradation and its consequences for biodiversity and ecosystem services, and evaluate the success of restoration schemes. Currently, restoration efforts are disjointed across regions and carried out by a wide range of organizations, which often leads to incompatible and inaccessible datasets, and a lack of communication about successful methods.

As a result, the authors claim, “Evidence of success or failure of grassland restoration programmes is scant.” Other studies (see, for example, Havstad et al., 2007, and Vandever et al., 2021) echo the call for more robust monitoring, arguing that more data (as well as consistent nationwide procedures and norms around gathering and analyzing these data) on grassland degradation and restoration is imperative to both reporting on the successes and shortcomings of existing conservation programs and providing information on the current state of the grassland ecosystem, including priority areas for preservation and restoration. These authors recommend a standardized, nationwide adoption of methods such as biomass carbon and primary productivity mapping, nationwide and global remote sensing initiatives, and ecological site descriptions. Since NAGCA would require periodic re-authorization, it is crucial that data is gathered to support advocacy for its re-authorization.

Finally, most of the funding appropriated through federal grassland conservation programs applies only to working lands (see Figure 6.5). While working lands have great potential for grassland restoration, these programs fail to address the need for preserving grasslands that have not been converted to cropland. Addressing the latter group of lands is important for two reasons: firstly, conversion to cropland is among the greatest sources of endangerment to the grassland ecosystem in the United States (Lark et al., 2020), and secondly, studies have shown that grasslands that had never been converted showed higher rates of biodiversity and carbon sequestration than grasslands restored after conversion (Kobe University, 2025). Thus, while federal conservation programs focusing on working lands are highly promising due to the vast acreage of United States farms (880.1 million acres, or 39% of all U.S. land in 2022 (Census of Agriculture, 2022)), this practice fails to fully address the threat of biodiversity loss on grasslands, as well as to meet the funding needs of Native-led grassland conservation.

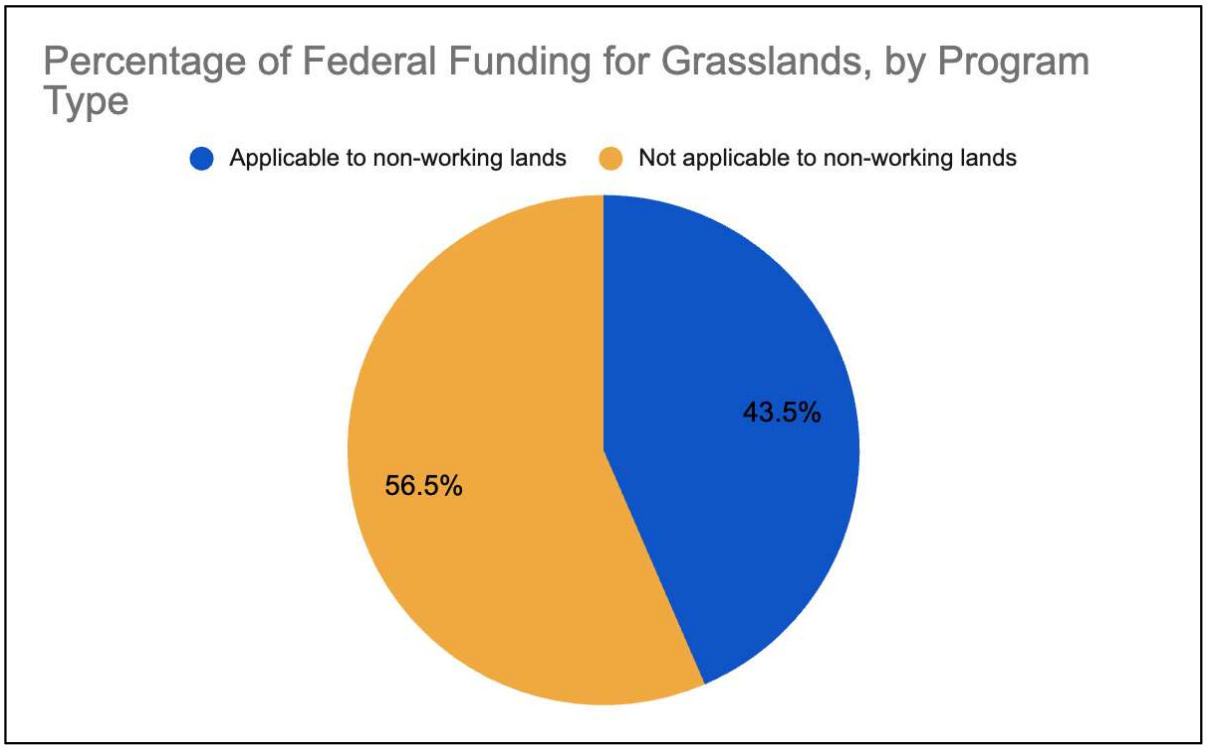


Figure 6.5. *Percentage of total federal funding for incentive-based grassland conservation programs applicable to working lands and non-working lands. Note that the funding that is applicable to non-working lands is still applicable to both working and non-working lands, meaning that the percentage of federal funds allocated to grassland conservation that actually goes toward non-working lands is likely much lower than the number displayed in this graph.*

Even among federal conservation programs that do not exclusively apply to working lands, several apply only to specific regions:

- The **Western Big Game Fund** is limited to lands in Arizona, California, Colorado, Idaho, Montana, Nevada, New Mexico, Oregon, Utah, Washington, and Wyoming;
- The **USDA-Wyoming Partnership** focuses on migration corridors in Wyoming, Montana, and Idaho.

While these states contain a significant portion of U.S. grasslands, they are far from encapsulating the entire extent of the biome in the U.S. Additionally, many of these programs have specific requirements, such as committing to contracts for periods of over 10 years, which may not always be feasible. Finally, as seen in the "funding amount" column of Table 5.3, this category of programs generally comes with smaller budgets: they typically operate on budgets on the order of millions of dollars, while programs applicable exclusively to working lands and/or converted grasslands tend to have budgets of at least a billion dollars. Due to the high conservation value but limited federal protection of non-converted grasslands, increasing funds to projects that target non-converted grasslands is crucial. By mandating that at least 10% of its

funds are used to fund grants to Native Nations and their affiliated organizations, NAGCA would help close this gap, as a significant portion of lands stewarded by many Native Nations are intact grasslands (Rangelands Atlas, n.d.). This further corroborates the vital role that NAGCA would play in conserving grasslands and their biodiversity in the U.S.

The gaps in incentive-based federal conservation offerings discussed in this section can be summarized as follows. First, these programs include a burdensome application process, creating a barrier to participation. Second, there are insufficient standardized nationwide grassland monitoring norms, leading to a lack of data on the efficacy of existing incentive-based conservation programs. Finally, there is currently not enough federal funding allocated to conservation projects on non-converted grasslands, which are essential for maintaining grassland biodiversity, along with the vast array of ecosystem services that they provide, detailed in the previous section.



Figure 6.6. *Timeline of U.S. federal-level grassland and grassland-relevant conservation policy.*

Table 6.4. *Federal incentive-based conservation programs applicable to grasslands, in chronological order.*

Program Name	Administering Agency	Program Description	Date Enacted	Funding Amount	Eligible Entities	Applicable to Non-Working Lands?
Bankhead-Jones Tenant Act	U.S. Forest Service	Gives Secretary of Agriculture mandate to acquire “submarginal” lands by purchase or donation “to correct maladjustments in land use, and thus assist in controlling soil erosion, reforestation, preserving natural resources, mitigating floods, preventing impairment of dams and reservoirs, conserving surface and subsurface moisture, protecting the watersheds of navigable streams, and protecting the public lands, health, safety, and welfare."	1935	$514.7 million in 2020	U.S. citizens who obtain most of their income from farming operations (USDA, 1937)	No

Program Name	Administering Agency	Program Description	Date Enacted	Funding Amount	Eligible Entities	Applicable to Non-Working Lands?
Conservation Technical Assistance Program	USDA NRCS	Provides farmers, ranchers, and forestland owners with free assistance in the form of knowledge and tools for natural resource maintenance, conservation, and restoration.	1936	$1 billion in FY 2023	Farmers and ranchers interested in regenerative agriculture. Eligible participants must meet a base level of stewardship. Contract lengths have a minimum of 5 years (USDA, n.d.).	Yes
Pittman-Robertson Wildlife Restoration Act	USFWS	Funding for states and territories to support wildlife restoration, conservation, and hunter education and safety programs. Funding comes from federal excise taxes on firearms, ammunition, and archery equipment. Native Nations do not receive funding through this Act.	1937	$1.3 billion in 2025	All State fish and wildlife agencies. Eligible activities include wildlife restoration and hunter education and safety. To be eligible, States must have laws ensuring all hunting license fees collected are directed solely toward the administration of the state wildlife agency (16 U.S.C. §§ 669–669i [1937]).	Yes
Land and Water Conservation Fund (LWCF)	National Park Service	Initially: using revenues from the depletion of offshore oil and gas to support the conservation of land and water. Expanded to include grants to protect working forests, city parks, wildlife habitat, critical drinking water supplies and disappearing battlefields, as well as increased use of easements. Supports public access to and protection for public lands and waters and provides matching grants to state governments for the acquisition and development of public parks and other outdoor recreation sites.	Established 1964; 2020: permanently fund at $900 million per year in oil and gas royalties	$900 million annually since 2020	States must update regularly their Statewide Comprehensive Outdoor Recreation Plan (SCORP) to be eligible for LWCF matching grant funding from NPS (U.S. Department of Interior, n.d.).	Yes

Program Name	Administering Agency	Program Description	Date Enacted	Funding Amount	Eligible Entities	Applicable to Non-Working Lands?
Conservation Reserve Program (CRP)	USDA Farm Service Agency (USDA FSA)	Voluntary program that pays agricultural producers and landowners rent for removing environmentally sensitive land from agricultural production and planting species that will improve environmental quality (e.g. native grasses, trees, riparian buffers). Also includes cost-share assistance.	Part of Food Security Act of 1985	$1.8 billion in FY 2023	Agricultural producers and landowners with environmentally sensitive land. The producer must have operated the land for at least 12 months (USDA FSA, 2025).	No
CRP Grasslands	USDA FSA	10-15 year contracts with landowners and operators. USDA assists in protecting grassland with the aim of preventing agricultural conversion. FSA pays participants rent in return for implementing conservation measures into grassland-related activities (haying, grazing, etc.) and provides cost-share assistance for approved fence/livestock watering facility installation to facilitate grazing distribution.	Authorized by Food Security Act of 1985; reauthorized by 2018 Farm Bill	Part of CRP budget	Eligible land must have established cover containing forbs or shrubs, located in historically grassland-dominated (≤5% tree canopy) area, and provide habitat for plants or animals of significant ecological value. Lands with expiring previous contracts through this program or general CRP are eligible (USDA FSA, n.d.).	No
Partners for Fish and Wildlife	U.S. Fish and Wildlife Service (USFWS)	Provides free technical and financial assistance to landowners, managers, tribes, corporations, schools, and nonprofits interested in improving wildlife habitat on their land through voluntary ≥10-year projects. No forfeit of property rights or public access.	1987; entered Fish and Wildlife jurisdiction in 2006	$15 million in 2024	All private landowners interested in restoring wildlife habitat on their land (USFWS, n.d.)	Yes

Program Name	Administering Agency	Program Description	Date Enacted	Funding Amount	Eligible Entities	Applicable to Non-Working Lands?
Environmental Quality Incentives Program (EQIP)	USDA NRCS	Technical and cost-share assistance for agricultural producers and forest landowners to address natural resource concerns (including habitat improvement and creation)	1996 Farm Bill	$2.025 billion in FY 2023	Agricultural or nonindustrial private forestland. Applicants must be agricultural producers (USDA NRCS, 2023).	No
Conservation Stewardship Program	USDA NRCS	Works with agricultural producers who are already taking steps to improve the condition of their land. Also offers free technical assistance. Contracts last 5 years with the opportunity to compete for renewal.	2008 Farm Bill	$1 billion in FY 2023	Owning or renting and managing land for agricultural or forest production. Must have an adjusted gross income less than $900,000 (with exceptions for Native Nations). Eligible entities must maintain control of the land for at least five years. Eligible land is highly erodible (USDA, 2022).	No
Working Lands for Wildlife Initiative	USDA NRCS	Partnering with ranchers and researchers to put Farm Bill resources to work for wildlife by implementing science-backed conservation that improves agricultural and forest productivity and enhances wildlife habitat.	2010	$500 million over 5 years starting 2023	Agricultural producers with a registered farm number (Rural Advancement Foundation International–USA, 2025).	No
Agricultural Conservation Easement Program	USDA Natural Resources Conservation Service (USDA NRCS)	Helps private and tribal landowners, land trusts, and other entities (such as state and local governments) protect croplands and grasslands on working farms and ranches by limiting non-agricultural uses	2014 Farm Bill	$450 million in FY 2023	Eligible entities include Tribes, state and local governments, and non-governmental organizations that have farmland, rangeland or grassland protection programs. All landowners must not exceed an adjusted gross annual income of $900,000 and must	Yes

Program Name	Administering Agency	Program Description	Date Enacted	Funding Amount	Eligible Entities	Applicable to Non-Working Lands?
		of the land through conservation easements.			be compliant with the HEL/WC provisions of the Food Security Act of 1985. (USDA, n.d.)	
Joint Chiefs' Landscape Restoration Partnership	USDA NRCS	Works to improve the health and resilience of forest and grassland landscapes across National Forest System land and state, Tribal, and private lands. Three-year-long projects consisting of NRCS and Forest Service partnerships with state forestry agencies, NGOs, and private landowners to apply targeted management practices across public and private lands.	Established as discretionary initiative 2014; codified into law by 2021 Bipartisan Infrastructure Law	$40 million in 2025 ($32 million for 24 ongoing projects, $8 million for 5 new projects)	Eligible applications must be signed by the Forest Service Forest Supervisor, the Natural Resources Conservation Service State Conservationist, the State Forester, and the Forest Service Regional Forester; include a combination of proposed activities on private and public land; propose land treatments and education and outreach to local communities about the project (USDA NRCS, n.d.).	Yes
Regional Conservation Partnership Program	USDA NRCS	Provides funding to partners to support conservation activities.	2014 Farm Bill	$300 million in FY 2023	Organizations that can hold conservation easements (e.g., producer associations, state and local governments, Tribes, acequias,[76] farmer cooperatives, water districts or associations, municipal water entities, higher education institutions, entities working with agricultural producers, conservation districts, land trusts) (USDA NRCS, n.d.).	

[76]Acequias are community-operated irrigation canals used for agriculture. They originated in Spain and in former Spanish colonies in South America, Mexico, and the southwestern United States.

Program Name	Administering Agency	Program Description	Date Enacted	Funding Amount	Eligible Entities	Applicable to Non-Working Lands?
Western Big Game Seasonal Habitat and Migration Corridors Fund *conservation achievements by state in 2024	USFWS	Grants for grasslands connectivity projects. Eligible lands: areas prioritized under SO 3362 or Native Nations in Arizona, California, Colorado, Idaho, Montana, Nevada, New Mexico, Oregon, Utah, Washington, and Wyoming. 6-10 grants/year.	2021	$3 million	Non-profits, federal agencies, state agencies, local and municipal governments, Native Nations, and Indigenous-led organizations. Applications must be accompanied by letter of support from the director's office of the respective state or Tribal wildlife agency (NFWF, n.d.).	Yes
USDA-Wyoming Big Game Partnership Program	USDA NRCS and State of Wyoming	Grant program: partnerships between USDA, Wyoming, and private ranchers on voluntary conservation of private working lands and migratory big game populations from Wyoming to Idaho and Montana.	2022	$21.4 million in FY 2024	Agricultural producers in Wyoming, Idaho and Montana (USDA, n.d.)	No
America the Beautiful Challenge	National Wildlife Federation	Public-private grant program for locally led ecosystem restoration projects that invest in watershed restoration, resilience, equitable access, workforce development, corridors and connectivity, and collaborative conservation.	2022	$122.5 million in 2025	State agencies, U.S. territories, Native Nations are eligible to apply for all grant categories. Non-profits, local governments, municipal governments, and educational institutions are eligible to apply for select grants. (National Fish and Wildlife Foundation, n.d.)	Yes

6.4. Case Study: Lessons from the North American Wetland Conservation Act (NAWCA)

NAGCA is almost identical to the North American Wetland Conservation Act (NAWCA), with several notable exceptions, which we cover in this section. Since NAWCA has been operational since 1989, there exists almost three decades worth of data on NAWCA's use, as well as testimonies of both its utility and challenges. Therefore, we use lessons from various stakeholders' experience employing NAWCA toward conservation goals to inform our recommendations for NAGCA.

6.4.1 Overview of NAWCA

NAWCA was introduced to the U.S. Senate in April 1989 by a bipartisan group of Senators led by George Mitchell (D-ME) and Silvio Conte (R-MA), in order to counter critical habitat loss, particularly for migratory birds, but also for other endangered species that depend on wetlands for survival. It officially became law in December of the same year. Since then, the Act has contributed to sponsoring over 3,300 projects in partnership with more than 7,000 landowners, state and local governments, conservation and sport organizations, Native Nations, land trusts, and corporations. These projects have helped conserve over 32.6 million acres of wetlands (U.S. Fish and Wildlife Service [USFWS], n.d.).

Like NAGCA, NAWCA is a voluntary, grant-based conservation bill. Eligible applicants include state and local governments, Native Nations, and private organizations ranging from conservation nonprofits to sportsmens' organizations. Each applicant may apply to one of two types of grants: the Standard Grant, which runs twice each fiscal year and consists of funding packages up to $3 million, and the Small Grant, which supplies up to $250,000 per project and has application cycles once per fiscal year (USFWS, 2023). Applications for the Standard Grant are reviewed first by the nine-member North American Wetlands Conservation Council (NAWCC), which selects project proposals to recommend to the Migratory Bird Conservation Commission (MBCC) for final approval. In the Small Grant model, the North American Wetlands Conservation Council (NAWCC) selects projects to fund from a pool of funding pre-approved by the Migratory Bird Conservation Commission (MBCC). All grants are ultimately administered by the U.S. Fish and Wildlife Service's Division of Bird Habitat Conservation (DBHC). Both NAWCA and NAGCA require at least a one-to-one match from applicants for the amount of funding that they request.

6.4.2 Comparison between NAGCA and NAWCA

Similarities and differences between NAWCA and NAGCA will inform recommendations for NAGCA's financing and implementation. See Table 6.5 for a broad overview of these similarities and differences, which is discussed in further detail in this section.

Table 6.5. *Comparison between NAGCA and NAWCA.*

Component	NAGCA	NAWCA
Purpose	Incentivizing voluntary grassland conservation and restoration, with emphasis on supporting private and/or agricultural landowners, recreation, and Tribal partners.	Wetland ecosystem protection, enhancement, restoration, and management, with a strong focus on migratory bird population preservation.
Governance Structure	North American Grasslands Conservation Council (federal) + Regional Grasslands Conservation Councils.	North American Wetlands Conservation Council.
Conservation Strategies	Private-public partnerships (largely grants); incorporation of Indigenous Traditional Ecological Knowledge; creation of a new North American Grasslands Conservation Strategy that draws from existing local, State, regional, Tribal, and international conservation plans and frameworks.	Private-public partnerships (largely grants); regulations and strategies established by Endangered Species Act, Migratory Bird Treaty Act, North American Waterfowl Management Plan, United States Shorebird Conservation Plan, North American Waterbird Conservation Plan, Partners In Flight Conservation Plans.
Cost-Share	Selected partners must contribute at least a 1-1 match to the grant, with the exception of Indigenous-led projects.	Selected partners must contribute at least a 1-1 match to the grant.
Provisions for Native Nations	At least 10% of annual grant funding through NAGCA must go toward Native Nations and affiliated organizations.	None

The main differences between NAWCA and NAGCA lie in their purposes, their governance structures, and their conservation strategies.

As stated in the text of the NAWCA legislation, the purpose of the Act is threefold: “to protect, enhance, restore, and manage an appropriate distribution and diversity of wetland ecosystems and other habitats for migratory birds and other fish and wildlife in North America; to maintain current or improved distributions of migratory bird populations; and to sustain an abundance of waterfowl and other migratory birds consistent with the goals of the North American Waterfowl Management Plan and the international obligations contained in the migratory bird treaties and conventions and other agreements with Canada, Mexico, and other

countries" (NAWCA, 1989). Meanwhile, NAGCA's goal relates to voluntary grassland conservation and restoration in response to the historical and ongoing loss of native grassland ecosystems. NAGCA's goals also center around several grassland-specific ecosystem functions and services, including maintaining and building biodiversity, improving habitat for wildlife that depend on grasslands (especially birds and pollinators), increasing carbon storage, and supporting various recreational opportunities. NAGCA also emphasizes a commitment to create stronger partnerships between the federal government and farmers, ranchers, Tribes, state and local governments, and other stakeholders. A major point of departure from NAWCA is NAGCA's particular dedication to supporting Tribal conservation, restoration, and management projects. Specifically, NAGCA is committed to "(A) the ethical incorporation of Indigenous Traditional Ecological Knowledge into grassland management and restoration activities; and (B) identifying, encouraging, and providing funding for partnerships between Indian Tribes and Federal agencies to co-manage grassland ecosystems, including ecologically important flora and fauna" (NAGCA, 2024). A significant measure to support Indigenous-led projects included in NAGCA is a cost waiver for the one-to-one match requirement, which would help remove financial barriers to Native-led conservation projects.

If passed, NAGCA will have a slightly different governance structure than NAWCA. While both include a federal Conservation Council that informs which projects are selected for funding and provides an annual update on funded projects, NAGCA's federal Council provides recommendations to shape a North American Grasslands Conservation Strategy, while NAWCA's conservation strategy is based on several acts that were established prior to NAWCA, (16 U.S.C. 4401) namely the 1973 Endangered Species Act (16 U.S.C. 1531 et seq.) and the 1918 Migratory Bird Treaty Act (16 U.S.C. 707), as well as management plans including the North American Waterfowl Management Plan (NAWMP, 2018), the United States Shorebird Conservation Plan (Brown et al., 2001), the North American Waterbird Conservation Plan (Kushlan et al., 2002), and the Partners In Flight Conservation Plans (Partners in Flight, n.d.). Furthermore, NAGCA establishes Regional Grasslands Conservation Councils with representation from nongovernmental and Tribal organizations, Tribal Governments, ranching and farming interest groups, State fish and wildlife agencies, and other entities deemed necessary by the federal governance structure for NAGCA. These councils are tasked with providing input on which projects should be funded through NAGCA, in addition to recommending grasslands conservation strategies based on existing regional grasslands conservation plans. In general, the conservation strategy associated with NAGCA is intended to draw from "existing local, State, regional, and international conservation plans and frameworks, conservation plans of Indian Tribes, and State wildlife action plans, with an emphasis on supporting existing science- and ITEK[77]-based frameworks" (NAGCA, 2024). Overall, NAGCA's approach to governance and strategic planning is more collaborative with local, State, and regional goals and entities, more innovative, and more flexible than the approach that NAWCA takes.

[77] Indigenous Traditional Ecological Knowledge

6.4.3 Lessons from NAWCA: Guiding Principles for NAGCA

NAWCA is funded by a combination of general appropriations and fines, penalties, and property forfeitures gathered through violations of Section 6 of the Migratory Bird Treaty Act, which prohibits the taking (defined as killing, capturing, selling, trading, or transport) of protected migratory bird species without prior authorization from the U.S. Fish and Wildlife Service (16 U.S.C. §§ 703–712). This funding strategy exemplifies the principle of using existing governmental programs and laws to fund new conservation bills. We apply a similar lens to determine funding strategies for NAGCA.

While NAWCA has been highly effective since its foundation, there are several challenges associated with its implementation and utilization. First, NAWCA must be reauthorized every five years in order for it to continue to exist, and Congress sets specific funding levels for NAWCA annually. Thus far, support for NAWCA has been bipartisan and largely uncontroversial, but its reauthorization also depends on its elevation to Congressional attention by stakeholders, as there are a plethora of issues competing for attention and funding at any given moment (Yaich, 2014). In order to perpetuate NAWCA's existence, stakeholders must continue advocating for its funding in order to generate the attention it needs. Similar conditions are anticipated with NAGCA, as it also depends on continued authorization and funding.

Secondly, NAWCA's cost-share requirement, which mandates that grantees must provide at least an equal sum of money as they received through NAWCA grants, poses financial challenges for many applicants. Along with the competitive application process, this factor has reduced many potential applicants' motivation to apply for grants through NAWCA. Not only does this create equity issues where entities with more financial assets essentially become more eligible for NAWCA grants than their less well-off counterparts, but it has also left many wetlands unprotected (Mahler & Richardson, 2024). NAGCA's cost-share waiver for Tribal organizations is a significant step in reducing these barriers, but challenges due to the cost-share requirement are still anticipated for other potential applicants.

The last challenge is similar to that discussed in the literature on grassland conservation. Funding through NAWCA is largely directed to implementing the North American Waterfowl Management Plan (NAWMP), which has long been urged to promote more strategically-targeted conservation projects (Brasher et al., 2019). While periodic updates to the NAWMP have partially addressed this issue, another helpful step would be the establishment of standardized, comprehensive metrics for measuring ecosystem decline and conservation, an action item that will be discussed further in the Section 6.6 of this chapter.

While NAWCA has been a highly successful initiative that has helped conserve a significant acreage of wetlands in the United States, there are several lessons to be learned from its almost thirty years of operation that would help guide a similar bill such as NAGCA to even higher levels of success. These lessons (barriers to applying for grants due to the cost-share requirement, concerns about NAWCA's continued financing, and the need for more standardized metrics to determine the success of funded projects), along with NAWCA's financing strategy,

will be used to inform the recommendations for funding and implementing NAGCA put forth in the next two sections of this chapter.

6.5 Financing the North American Grassland Conservation Act

This section will focus on grazing fees from federally leased grasslands as a funding source for NAGCA, as grazing is a key output of grasslands from which the federal government derives direct revenue. We propose increasing federal grazing rates and using the additional revenue generated from this increase to account for the expenses associated with NAGCA. While NAGCA is a relatively recent bill, various groups have expressed concerns over current grazing fees being too low and therefore encouraging overgrazing, (see, for example, On Land 2025; Vincent, 2019) which comes with a suite of environmental and economic harms, as discussed later in this section. At the same time, many stakeholders are likely to push back against grazing fee increases; however, we carry out two analyses that can mitigate this discontentment. First, we compare federal grazing fees to the cost of renting land for grazing from private entities, which vary by locality but are universally far greater than current federal grazing rates. Secondly, we demonstrate that increasing this fee for the purpose of funding NAGCA would increase the longevity of the ranching industry, which will be appealing to stakeholders associated with ranching. We further suggest the possibility of introducing a graduated public grazing fee system, in which lower-income landowners would still be able to access lower grazing fees and therefore ensure the viability of their operations.

The Bureau of Land Management (BLM) administers vast amounts of federal land leasing for grazing, as shown in Figure 6.7. In this system, private graziers may contract with the BLM to effectively rent public land on which they may graze their livestock. Currently, the federal grazing rate is $1.35 per Animal Unit Month (AUM).[78] This fee is calculated using a formula that starts with the base rate of $1.23 per AUM and takes into account current private grazing land lease rates, beef cattle prices, and the cost of livestock production (Bureau of Land Management, 2023). As Figure 6.8 demonstrates, the federal grazing rate shows a downward trend since the inception of federal land leasing for grazing in 1981. If inflation were taken into account, this decrease over time would be even more significant. This shows that the federal government has increasingly subsidized grazing, which has led to overgrazing. As discussed later in this section, overgrazing is unsustainable both in terms of environmental health and the future of the ranching industry.

[78] Animal Unit Month (AUM) is a quantification of the amount of air-dry forage needed to feed a 1000-pound cow and her unweaned calf in one month.

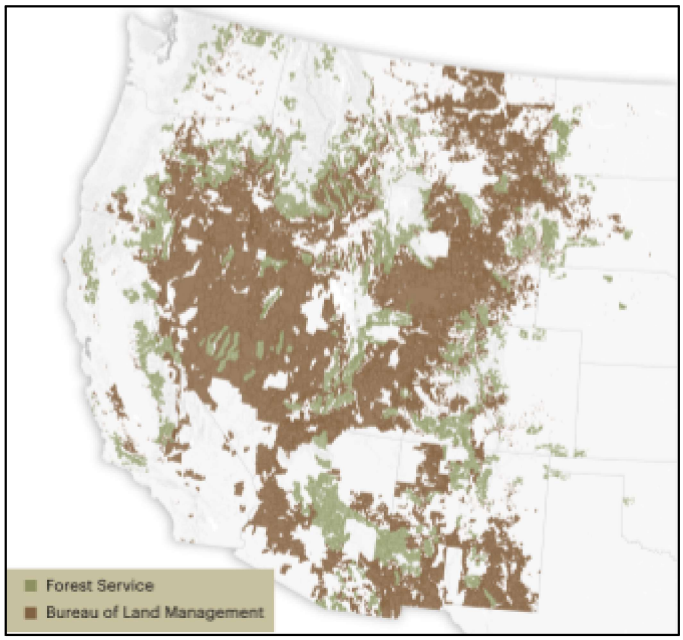


Figure 6.7. *Forest Service and Bureau of Land Management Grazing Allotments (Olalde & Tobias, 2025).*

One way to finance NAGCA would be to increase the federal land leasing rate for grazing. While increasing the grazing fee may be unfavorable to some ranchers, a rate increase would not be unprecedented, especially when adjusting for inflation. In 1981, when the federal government first authorized the BLM to lease public lands for grazing, the leasing rate was set at $2.31 per AUM. This amount is equal to $8.61 today when adjusted for inflation (Bureau of Labor Statistics, 2025). Furthermore, the current grazing fee is miniscule compared to the cost of leasing private lands for grazing. In 2024, the average grazing fee on private lands in the United States was $23.40 per AUM, ranging from $10.50 in Oklahoma to $35.50 in South Dakota (with the value for each state being equivalent to the average monthly lease rate on private, non-irrigated grazing land within that state (United States Department of Agriculture National Agricultural Statistics Service [USDA NASS], 2025).

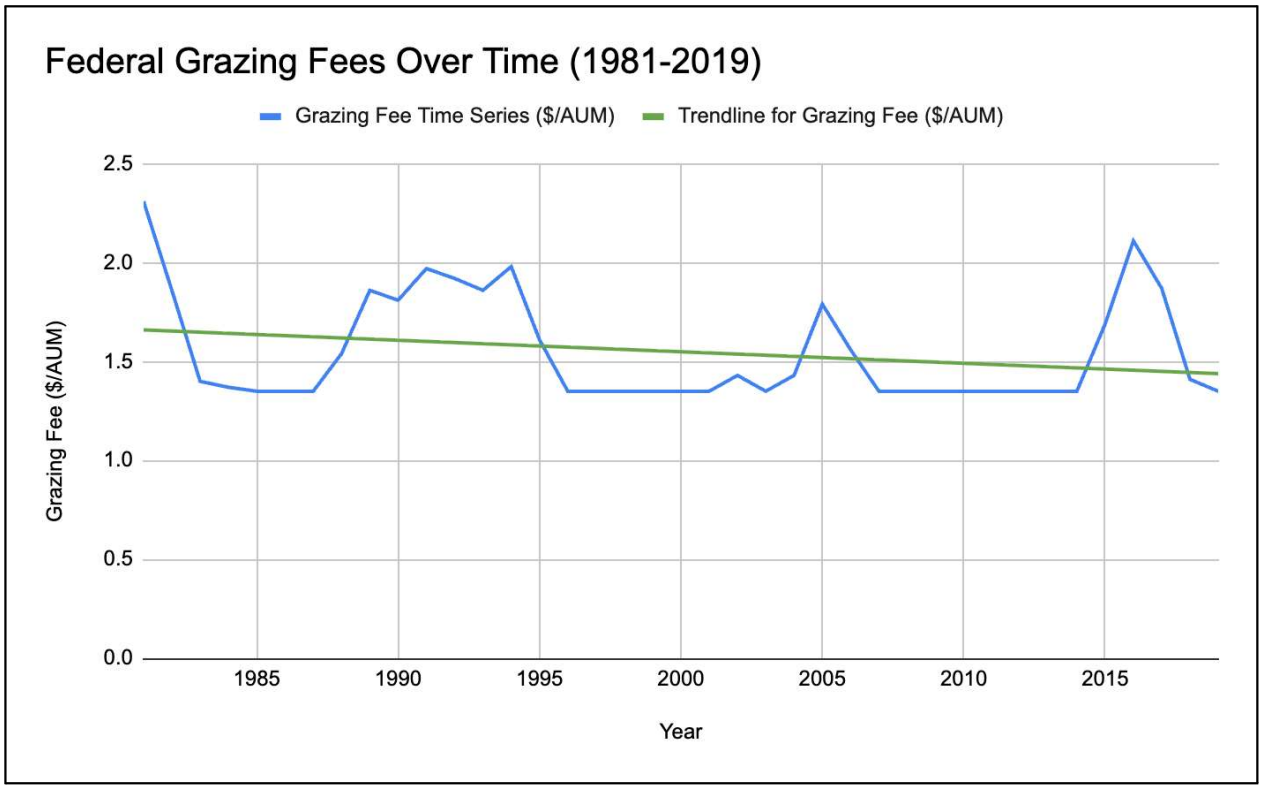


Figure 6.8. *Annual grazing fees from 1981 to 2019 (Vincent, 2019). The trendline is the line of best fit for the data, indicating the overall downward trend of federal grazing fees from 1981 to 2019.*

The low rate of public land leasing for grazing, which functions as a large subsidy, has negative consequences for both the sustainability and equity of the ranching industry. An investigative study (Olale & Tobias, 2025) found that over half of all livestock grazing on federally-leased land is controlled by only 10% of ranchers, indicating that grazing on public lands is heavily dominated by large-scale operations. Combined with decreases in BLM and Forest Service oversight of the environmental impact of grazing, this has led to significant land degradation from overgrazing, as large-scale ranchers are able to rent vast amounts of public land for relatively small amounts of money, especially given that the fees they pay through this program are an insignificant portion of their overall revenue due to economies of scale.[79] Thus, the low rate of grazing on federal land results in taxpayer-funded subsidies that disproportionately benefit wealthy, large grazing operations at the expense of ecosystem health and the longevity of natural resources.

A number of groups have advocated for increases in the federal leasing rate in order to implement conservation measures on grasslands. In 2005, the Center for Biological Diversity (CBD), along with several other conservation groups, petitioned the BLM and the U.S. Forest Service to raise the leasing rate for grazing to $7.64 per AUM on BLM lands in order for the

[79] Economies of scale refer to the reduction of costs to produce each unit of a good due to the spreading of fixed costs over larger amounts of units. Larger businesses typically benefit from economies of scale.

federal government to break even with the amount it spends on maintaining public rangeland, as well as to limit environmental degradation on these lands (Nokkentved, 2005). When the agencies did not respond, the CBD sued the Department of the Interior, a matter that was elevated to the United States Supreme Court (Vincent, 2019). While these efforts were ultimately unsuccessful, this initiative demonstrates that increasing the grazing fee has been sought by groups in the past. Additionally, many ranchers are aware of the intimate connection between their livelihoods and the health of grassland ecosystems, as grassland conversion to cropland directly decreases rangeland area. For example, the Lesser Prairie-Chicken Landowner Alliance (LPCLA), a new coalition formed in 2025, has significant representation from the ranching industry. Stacy Hoeme, one of the leaders of the coalition, stated: “By conserving these prairie-chickens, I know my ranch will always stay a ranch” (On Land, 2025). Other coalition members echoed this sentiment, citing major decreases in the profitability of ranching over their lifetimes, driven in part by grassland decline. Additional support for this increase from ranchers may be spurred by public education about its use for grassland conservation as a means of ensuring the longevity of the ranching industry.

On the other hand, smaller ranching operations depend heavily on federal subsidies in the form of cheap grazing land to maintain their livelihoods. One solution discussed in the Olale and Tobias (2025) study is to issue differentiated leasing rates according to an income-based metric. This step would result in smaller, less well-off ranchers maintaining access to the low rates of land leasing while limiting wealthier producers’ access to these subsidies. Thus, while a rigorous analysis of grazing operation sizes and other factors would need to be carried out to draw productive conclusions about what differentiated grazing fee brackets should look like, we recommend further work in this realm. As a starting point, we look at increasing the overall grazing rate for all graziers using public land, but a future study should modify the tool provided in Appendix F to include possible levels of subsidy that inversely vary with ranching operation size and wealth.

Per its current design, NAGCA would appropriate, on average, $92.5 million annually for the grant program, the North American Grasslands Conservation Council, research on native seed crop systems, and administrative costs (NAGCA, 2024). According to estimates cited in Kauffman et al. (2022), approximately 14 million AUMs of federal land in the United States are rented for grazing annually. Using these numbers and assuming that none of the revenue currently generated by public lands grazing is to be used to pay for NAGCA, we calculated the leasing rate increase per AUM necessary to cover the costs associated with NAGCA each year (see Appendix F for code and documentation). We present the result of this calculation in the Recommendations section of this chapter. Figure 6.9 presents other possible rate increase scenarios and the respective additional federal revenue that these scenarios would generate.

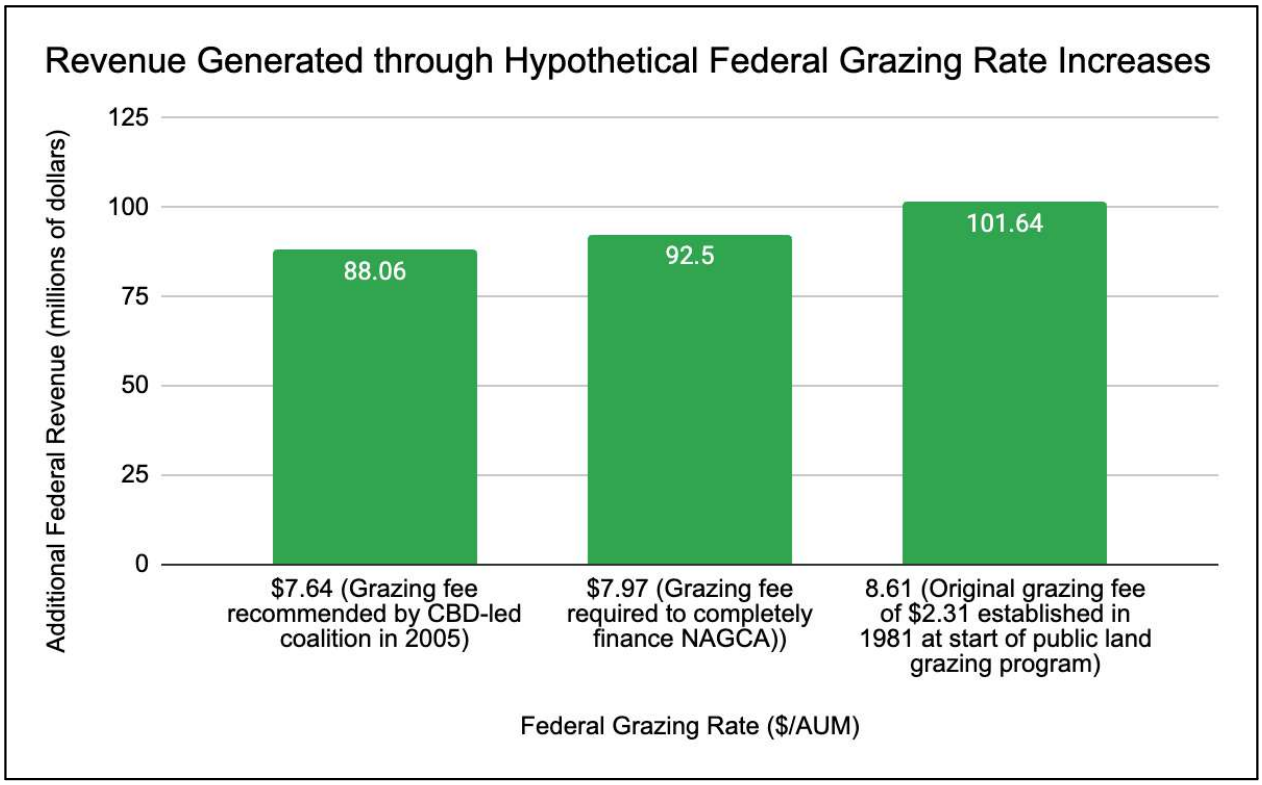


Figure 6.9. *Public lands grazing rate increase scenarios. The grazing rates represented in this table were derived from the CBD petition, the necessary rate to finance NAGCA, and the inflation-adjusted initial grazing fee of $2.31, respectively.*

6.6 Recommendations

Using the analyses conducted in this chapter, we recommend the following actions to ensure that NAGCA is feasible to implement, highly effective, attractive to U.S. Senators and Representatives, and accessible to the greatest possible number of users. We also outline several steps for further study that would be useful for future project teams to undertake.

6.6.1 Create a Universal Set of Metrics for Grassland Performance in the United States

Firstly, a unified set of metrics should be established to measure grassland performance. Specifically, these metrics should reflect the effectiveness of conservation and restoration efforts by creating a comprehensive image of grassland performance before and after the implementation of conservation and restoration interventions. These could include, for example, measurements of habitat connectivity for keystone species, as these species play a strong role in other aspects of grassland performance (see Buller & Hennessy (2026) for examples of habitat connectivity metrics for grassland species that could be adapted to be federally applicable). These metrics should be created with participation from a range of stakeholders, including farmers and ranchers, for whom grassland performance may be defined in particular ways relevant to their industries; local, State, and federal government representatives who may have a broader understanding of grassland ecosystem functions for the public good; and Indigenous

Peoples, many of whom are key stewards of grasslands. Recipients of grassland conservation grants through NAGCA should use these metrics to report on the success of their initiatives. Technical assistance should be provided, for example by the regional councils established in NAGCA, with conducting these evaluations in order to prevent imposing excessive burdens on those seeking to take on grassland conservation projects and thus discouraging them from applying for NAGCA grants. The data gathered from these metrics can also inform the federal grassland conservation strategy that NAGCA would initiate.

6.6.2 Reduce Application Requirements and Provide Assistance to Applicants

Our second recommendation is to reduce the labor required for NAGCA grant applications. As stated by stakeholders using already existing federal conservation incentive programs (see Section 6.3.2 of this chapter), the time and labor needed to fill out applications for these programs can act as a deterrent to their participation. Entities seeking funding through NAGCA are likely to already have full-time professional responsibilities, leaving little space for taking on an intensive application process. Federal representatives, such as members of the regional councils established through NAGCA, should take on the role of the agricultural consulting companies mentioned in Section 6.3.2, specifically by providing consulting services to applicants. This way, this assistance could be provided for free as part of the responsibilities assigned to these councils, removing the financial burdens imposed by paying for services from private consulting firms and thus opening the possibility of participation to a wider range of potential applicants.

6.6.3 Increase the Federal Leasing Rate to Finance NAGCA

Finally, we recommend increasing the federal land leasing rate for grazing from $1.35 per AUM to $7.97 per AUM and using the additional funds generated through this increase to cover all costs associated with NAGCA. Since Executive Order 12548, put forth in 1986, prohibits changes in grazing fees exceeding 25% of the previous year's level, we recommend increasing the grazing fee by 25% each year until the $7.97 target is reached (see Table 6.5 for the resulting annual grazing rates if this proposal were implemented). Since the number of animals on grazing land is not a static number, the leasing fee for grazing should be re-evaluated every year using the programming tool provided in Appendix F in order to ensure that the revenue from grazing continues to be sufficient to finance NAGCA. Furthermore, the grazing rate is subject to annual change, so if the grazing rate is no longer $1.35 at the time of NAGCA's passage, the code provided in Appendix F should be modified to reflect the new grazing rate.

Table 6.5. *Grazing fees over time if our recommendation of a 25% annual increase were implemented, where Year 1 is the time of implementation and Year 0 is the prior year, assuming the current grazing rate still applies.*

Year	0	1	2	3	4	5	6	7	8	9
Grazing Rate ($/AUM)	1.35	1.68	2.10	2.62	3.27	4.08	5.09	6.36	7.95	7.97

6.6.4 Avenues for Further Work

As mentioned in the previous section, future studies should consider possible differentiation of grazing fees on public lands by location, operation size, and operator income. In locations with more expensive private grazing fees, larger operators may be charged higher rates in order to fund NAGCA, while smaller operations should remain heavily subsidized in order to improve the equity dimension of the ranching industry. However, in any given location, caution should be taken to maintain public grazing fees for all operators that are lower than the respective private grazing fee, as meeting or exceeding the threshold of private grazing fees would disincentive grazing on public lands, resulting in less federal revenue for financing NAGCA.

Another key item for further work is examining other ways to finance NAGCA. NAGCA's funding amount increases each year for the five years that the bill would last. If this pattern continues, it may no longer be feasible to increase grazing fees to the amount needed to cover future iterations of the bill, possibly necessitating the use of other federal revenue streams. One emerging and promising avenue for financing is increasing land leasing rates for solar, wind, geothermal, and other renewable energy generation. While federal lands have been leased for energy production such as oil and gas drilling since 1920, the practice of leasing federal lands for renewable energy production began with the Federal Land Policy and Management Act of 1976, which authorized the BLM to grant federal rights-of-way to selected solar and wind energy projects (Bank, 2011). Since then, over 200 solar, wind, and geothermal projects have been approved on public lands, with a total generation capacity of over 30,000 megawatts (MW) (BLM, 2024). Each project is charged rent consisting of the greater value between the acreage rent (dollars per acre multiplied by project acreage) and the capacity fee (dollars per megawatt multiplied by generation capacity in megawatts), both of which vary by state. Research into how the federal government utilizes funding collected through these projects can inform whether some of this revenue can be used to finance NAGCA. Further options for financing could also be explored if deemed necessary or useful by BNGA.

Another subject for further work is standardizing the metrics for habitat connectivity referred to in this chapter and discussed in further detail in Buller & Kelly (2026) and Hennessy & Buller (2026) for use across the United States. These metrics should be tailored to reflect the values of as broad a range of stakeholders as possible, as mentioned above, and to facilitate data collection by NAGCA grantees, who may not always have training in using conventional scientific methods or tools. Thus, a citizen science approach should be adopted in the development of these standardized metrics.

A set of educational materials on the benefits of grassland conservation to the ranching industry should also be prepared for dissemination to ranching interest group members to accompany notice of an increase in the federal grazing fee. These materials can be used to promote support of the fee increase proposed in Section 6.6.3 of this chapter.

Finally, we have initiated Freedom of Information Act (FOIA) requests for information to the agencies administering the programs described in Table 6.4 (for programs administered by federal agencies), with the goal of obtaining information on organizations that have been funded or otherwise assisted through these programs. This will provide insight into which groups have access to, or are prioritized by, the federal government for grassland conservation purposes. See Table 6.6 for information on these requests. Some responses to these requests have been received and processed (see Appendix G), and we will follow up with BNGA once we receive the rest of the responses. See Appendix H for general instructions for submitting additional FOIA requests.

Table 6.6. *In-progress FOIA requests for information regarding programs described in Table 6.4.*

Administering Agency	Program	Request Number	Date Submitted	Contact for Follow-Up
U.S. Fish and Wildlife Service	Partners for Fish and Wildlife	2788001	March 9, 2026	Erik Germain 805-701-5734 erik_germain@fws.gov
U.S. Fish and Wildlife Service	Western Big Game Seasonal Habitat and Migration Corridors Fund	2788231	March 9, 2026	Erik Germain 805-701-5734 erik_germain@fws.gov
U.S. Fish and Wildlife Service	Pittman-Robertson Wildlife Restoration Act	2788036	March 9, 2026	Erik Germain 805-701-5734 erik_germain@fws.gov
Agricultural Conservation Easement Program	USDA Natural Resources Conservation Service	2788066	March 9, 2026	Patrick McLoughlin (202) 590-6168 patrick.mcloughlin@usda.gov
U.S. Forest Service	Bankhead-Jones Tenant Act	2788076	March 9, 2026	Margaret Scofield sm.fs.wofoia@usda.gov
USDA Farm Service Agency	Conservation Reserve Program	2788091	March 9, 2026	Patrick McLoughlin (202) 590-6168 patrick.mcloughlin@usda.gov
USDA Farm Service Agency	Grassland Conservation Reserve Program	2788141	March 9, 2026	Patrick McLoughlin (202) 590-6168 patrick.mcloughlin@usda.gov
USDA NRCS	Conservation Stewardship	2788101	March 9, 2026	Patrick McLoughlin (202) 590-6168

Administering Agency	Program	Request Number	Date Submitted	Contact for Follow-Up
	Program			patrick.mcloughlin@usda.gov
USDA NRCS	Conservation Technical Assistance Program	2788106	March 9, 2026	Patrick McLoughlin (202) 590-6168 patrick.mcloughlin@usda.gov
USDA NRCS	Environmental Quality Incentives Program (EQIP)	2788126	March 9, 2026	Patrick McLoughlin (202) 590-6168 patrick.mcloughlin@usda.gov
USDA NRCS	Joint Chiefs' Landscape Restoration Partnership	2788156	March 9, 2026	Patrick McLoughlin (202) 590-6168 patrick.mcloughlin@usda.gov
USDA NRCS	Regional Conservation Partnership Program	2788181	March 9, 2026	Patrick McLoughlin (202) 590-6168 patrick.mcloughlin@usda.gov
USDA NRCS	Working Lands for Wildlife Initiative	2788246	March 9, 2026	Patrick McLoughlin (202) 590-6168 patrick.mcloughlin@usda.gov
National Park Service	Land and Water Conservation Fund	2788171	March 9, 2026	Nicholas A. Banco (202) 641-1621 npsfoia@nps.gov

6.7 Conclusion

Grasslands in the United States should be a priority ecosystem for conservation due to both their severe decline in acreage and their importance to Native Nations, federal, State, and local governments, and private interests. While various policy initiatives in the United States to conserve grasslands have been enacted, many of these are closely tied to agriculture, a primary driver of grassland conversion to cropland. Thus, without more flexible federal conservation policies that cover a more comprehensive set of grasslands, the preservation of unconverted grasslands will continue to be sporadic and exist mainly in the form of projects taken on by various entities at their own expense, significantly limiting the number and diversity of such projects.

The North American Grasslands Conservation Act (NAGCA) is a promising avenue for grassland conservation due to its incentive-based approach, high level of flexibility, and its accompanying North American Grasslands Conservation Strategy, which can help facilitate collaboration between and otherwise support existing efforts. NAGCA is currently in the Subcommittee on Conservation, Research, and Biotechnology of the Congressional Committee on Agriculture, with a major barrier to implementation being the question of how to finance it. In this chapter, we sought to increase Congressional support for NAGCA by providing a financing strategy and highlighting the economic and cultural benefits of grassland restoration. Toward this goal, we determined streams of private and public revenue from grasslands and recommended increasing the leasing rate for grazing on BLM-managed public lands from $1.35 per animal unit month (AUM) to $7.97 per AUM and using the additional generated revenue to finance NAGCA. We also suggested several further actions to ensure that NAGCA has as broad a reach and as high an effectiveness as possible, namely providing assistance with the grant application process through the regional councils NAGCA would establish and standardizing metrics for grassland conservation.

Increasing grazing fees from public lands to $7.97/AUM will provide enough additional federal revenue to fully finance all expenditures that would be appropriated through NAGCA, per the current text of the bill. However, more diversified funding may be needed, for example if pushback from rancher lobbying groups prevents the entire extent of the recommended increase from being implemented. To this end, future studies should explore other possibilities, such as federal land leasing for renewable energy. Further work should also be done on standardizing metrics for grassland conservation for use both across federal agencies and by NAGCA grantees, perhaps in collaboration with NAGCA regional councils. In order to ensure that these metrics represent a wide range of interests, values, and ecosystem functions, a diversity of stakeholders should be involved in their establishment, including but not limited to Indigenous organizations, farming and ranching representatives, and local and State governments.

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Appendices

Appendix A: Standard Operating Procedures

BNGA-SEAS Master's Project, 2025 - 2026

Objective: To validate publicly available geospatial data of roads, water bodies, bison wallows, land cover, soil texture, and elevation in the field using GPS techniques; and to understand the extent to which fencing is present along roads and property boundaries, what types of roads are typically accompanied by fencing, and whether the types of fences present are hazardous to pronghorn or likely to obstruct their movement.

Scope: Applicable for validating GIS layers with up to 30m resolution with on-the-ground points.

Materials/Tools:

- GPS receiver or cell phone with bluetooth-enabled GPS
- 50m transect tape
- 1m quadrat
- Meter stick(s)
- Bottle of water or spray bottle
- Small shovel or garden trowel
- Pocket Penetrometer
- High-vis vests
- Field data collection app (e.g., ArcGIS Field Maps)
- Laser rangefinder

Method:

A. **Preparation**
   a. Identify transect starting points along roads (as many as possible, including different road types, different land cover and soil types, and different terrain features), so that transects are at least 30m apart.
   b. Prepare data collection workflow in ArcGIS Field Maps, including the attributes listed below:

Attribute Field	Description
Surveyor Full Name	First and last name of the person recording the point/line
Date and Time of Sample	Date and time that the point/line/polygon is recorded
Property Owner	Name of the person/entity that owns the land on which the sampling is happening
Access Granted to Site	Whether or not access was granted to the sampling site

Attribute Field	Description
Authorization	Name of the person/entity that granted access to the sampling site
Site Name	Name of the sampling site
Sample ID	Sample ID
Sampling Method	Method used to collect the sample (transect, etc.)
Elevation	Elevation (meters) of the sample
Slope	Slope (percentage) of the sample
Aspect	Aspect (direction) of the sample
Temperature	Temperature (in °F) at the time of sampling
Weather	Weather at the time of sampling
Noise Type	Type of noise at the sampling site (natural, anthropogenic, no noise)
Noise Level	Noise level at the sampling site (low, moderate, high)
Road Access	Whether or not a road is accessible from the sampling site
Distance to Road	If a road is accessible, distance to the road from the sampling site (meters)
Road Surface Type	If a road is accessible, road surface type (dirt, paved)
Trail Access	Whether or not a trail is accessible from the sampling site
Distance to Trail	If a trail is accessible, distance to the trail from the sampling site (meters)
Soil Texture	Soil texture at the sampling site, following USDA NRCS "Soil Texture By Feel" guidelines/flowchart
Soil Penetration	Depth to soil penetration (centimeters), using a soil penetrometer
Land Cover	Land cover type, following LANDFIRE existing vegetation type reference data

Attribute Field	Description
Vegetation Community	Vegetation community type, following LANDFIRE existing vegetation type reference data
Vegetation Height	Vegetation height (centimeters)
Percent Vegetation Cover	Visual estimate of the percentage of the sampling site that is vegetated
Distance to Wallow	If a bison wallow is present, distance to the wallow from the sampling site (centimeters).
Diagnostic Vegetation	If a bison wallow is present, type of dominant diagnostic vegetation also present, following LANDFIRE existing vegetation type reference data
Fence Condition	If a fence is present, condition of the fence (good, neutral, poor)
Fence Height	If a fence is present, height of the fence from ground to top wire/rail (cm)
Fence Gap Height	If a fence is present, height of the gap from ground to bottom wire/rail (cm)
Top Wire Type	If a fence is present, material type of the top wire/rail (barbed, smooth, other)
Bottom Wire Type	If a fence is present, material type of the bottom wire/rail (barbed, smooth, other)
Wildlife Types	Wildlife observed at the sampling site
Distance to Water	If water is nearby, distance to the water body from the sampling site
Water Body Type	If water is nearby, type of water body (perennial stream, ephemeral stream, lake, wetland, river)
Water Body Audible	If water is nearby, whether or not the water body is audible from the sampling site
Photos	Photos of the sampling site (North, South, East West, Above - canopy/sky above site, Below - ground at the site, Site - aerial

Attribute Field	Description
	view of the site)
Additional Notes	Any additional notes/observations not captured in the workflow.

c. Ensure that the GPS equipment is working properly, is charged, etc.

B. Data Collection

a. Navigate to the *starting point* of the transect.
b. Record a GPS point. Take photos in all directions at the edge of the road. Record the road type (paved, dirt, etc.)
c. Roll out the transect tape to 50 meters, beginning from the starting point and moving outward in one direction.
    i. At each sample point (10m intervals along this 50m transect):
        1. Put down the 1m quadrat and take photos in all directions.
        2. Record a GPS point at the center of the quadrat.
        3. Measure the maximum vegetation height within the quadrat with the meter stick, in cm.
        4. Identify the dominant land cover type and vegetation community type within the quadrat, and estimate the percent cover.
        5. Measure soil attributes at the center of the quadrat.
        6. Fill in the other attributes from the above table.
d. Continue the transect as far as possible, safe, and permitted. If a fence is encountered:
    i. Take photos in all directions, including a good photo of the fence.
    ii. Record a GPS point.
    iii. Measure/record fence attributes as prompted in the field maps app.

C. Data Processing

- Upload the field data into the chosen mapping software to visualize it (e.g., ArcGIS Pro)
- Calculate accuracy metrics (RMSE, confusion matrix) for each variable.
- Back-up the field data to a second location (e.g., DropBox, Google Drive, etc)

Appendix B: Cost Analysis to Reproduce the Fieldwork Methods

Item	Average unit cost	Recommended quantity	Total ($)	Source	Notes
Cell phone with Bluetooth capability	800	1	800		Price varies depending on phone make/model/year, as well as new vs used versions.
Trimble Catalyst DA2 Antenna Kit	430	1	430	Seiler Geospatial	
Trimble DA2 Fabric Carry Pouch	30	1	30	Seiler Geospatial	
Trimble DA2 Single Battery	65	2	130	Seiler Geospatial	
Trimble 2-Meter Carbon Fiber Range Pole	395	1	395	Seiler Geospatial	
Trimble Catalyst Subscription	55	1	55	Seiler Geospatial	
Garmin eTrex SE	150	1	150	Garmin	We used a Garmin eTrex 10, which has been discontinued. The eTrex SE is the most up-to-date model.
50 meter transect tape	50	1	50	Grainger	
1 meter quadrat	50	1	50	Forestry Suppliers	
Meter stick	35	1	35	Forestry Suppliers	

Item	Average unit cost	Recommended quantity	Total ($)	Source	Notes
Spray bottle	6	1	6	Home Depot	
Small shovel	10	1	10	Home Depot	
Pocket penetrometer	53	1	53	AMS Samplers	
High-vis vest	10	1	10	Home Depot	
Waterproof notebook	10	1	10	Rite in the Rain	
Laser rangefinder	100	1	100	TecTecTec	Optional, but helpful to get distance to road/water.
Trimble Mobile Manager app		1	0		Use with Trimble Catalyst subscription log-in.
ArcGIS Field Maps app		1	0		Price varies - included with Esri license.
		GRAND TOTAL	**$2,314**		

Appendix C: Table of Available Patch and Class Metrics Computed by 'landscapemetrics' R Package

Name	Description	Patch- or Class-based
Contiguity Index	Shape metric; assesses the spatial connectedness of cells in patches	Patch
Core Area	Core area metric; the area within a patch that is not on the edge of it. A cell is defined as core area if the cell has no neighbor with a different value than itself	Patch
Core Area Index	Core area metric; the percentage of a patch that is core area, that is the cell has no neighbor with a different value than itself. This metric describes patch and shape simultaneously (more core area when the patch is large and the shape is compact) and is comparable among patches with different area	Patch
Euclidean Nearest Neighbor Distance	Aggregation metric; the distance (measured edge-to-edge) to the nearest neighboring patch of the same class. This metric is a simple way to describe patch isolation	Patch
Fractal Dimension Index	Shape metric; this index is based on the patch perimeter and patch area, and describes patch complexity	Patch
Number of Core Areas	Core area metric; this metric counts the disjunct core areas	Patch
Patch Area	Area and edge metric; the area of each patch in hectares	Patch
Patch Perimeter	Area and edge metric; the perimeter of the patch including the edge to the landscape boundary. This metric describes patch area (larger perimeter for larger patches) and also patch shape (large perimeter for irregular shapes)	Patch
Perimeter-Area Ratio	Shape metric; this metric describes the patch complexity. For example, a patch with a higher perimeter-area ratio will have a more complex, meandering shape	Patch
Radius of Gyration	Area and edge metric; the distance from each cell to	Patch

Name	Description	Patch- or Class-based
	the patch centroid. This metric characterizes both the patch area and compactness	
Related Circumscribing Circle	Shape metric; the ratio between the patch area and the smallest circumscribing circle of that patch. This metric characterizes the compactness of the patch and is comparable among patches with different areas	Patch
Shape Index	Shape metric; the ratio between the actual perimeter of the patch and the square root of the patch area. This metric is a simple measure of shape complexity	Patch
Aggregation Index	Aggregation metric; equals the number of like adjacencies divided by the theoretical maximum possible number of like adjacencies for that class	Class
Patch Area	Area and edge metric; summarizes each class as the mean of all patch areas belonging to a class. This metric describes the composition of the landscape and gives an idea of patch structure	Class
Total Class Area	Area and edge metric; sums the area of all patches belonging to a class. This metric shows if the landscape is dominated by one class or if all classes are equally present	Class
Core Area Index	Core area metric; summarizes each class as the core area index of all patches belonging to a class, resulting in the percentage of core area in relation to patch area	Class
Related Circumscribing Circle	Shape metric; summarizes each class by the related circumscribing circle of all patches belonging to a class. This metric describes the ratio between the patch area and the smallest circumscribing circle of the patches	Class
Clumpiness Index	Aggregation metric; the proportion of like adjacencies involving the corresponding class from the expected under a spatially random distribution	Class
Patch Cohesion Index	Aggregation metric; characterises the connectedness of patches belonging to a class. This metric can be	Class

Name	Description	Patch- or Class-based
	used to assess if patches of the same class are aggregated by location or isolated	
Contiguity Index	Shape metric; summarizes the spatial connectedness of each patch belonging to a class	Class
Core Area	Core area metric; summarizes the amount of core area of all patches belonging to a class	Class
Core Area Percentage of Landscape	Core area metric; equals the percentage of core area of a certain class in relation to the total landscape area	Class
Disjunct Core Area Density	Core area metric; equals the number of disjunct core areas per 100ha relative to the total area, where a disjunct core area is a "patch within a patch," containing only core cells	Class
Disjunct Core Area	Core area metric; summarizes each class by the amount of disjunct core areas belonging to a class	Class
Division Index	Aggregation metric; the probability that two randomly selected cells are not located in the same patch of a certain class. This metric is negatively correlated with the effective mesh size	Class
Edge Density	Area and edge metric; the sum of all edges of a class in relation to the landscape area. This metric describes the configuration of the landscape (e.g.: aggregation of the same class will result in low edge density) and is comparable across landscapes	Class
Euclidean Nearest Neighbor Distance	Aggregation metric; measures the distance to the nearest neighboring patch of the same class (edge to edge). This metric is easily comparable among different landscapes	Class
Fractal Dimension Index	Shape metric; summarizes each class by the fractal dimension index of all patches belonging to a class, where the fractal dimension index is based on the patch perimeter and the patch area and describes patch complexity	Class
Radius of Gyration	Area and edge metric; summarizes the radius of gyration of all patches belonging to a class, where	Class

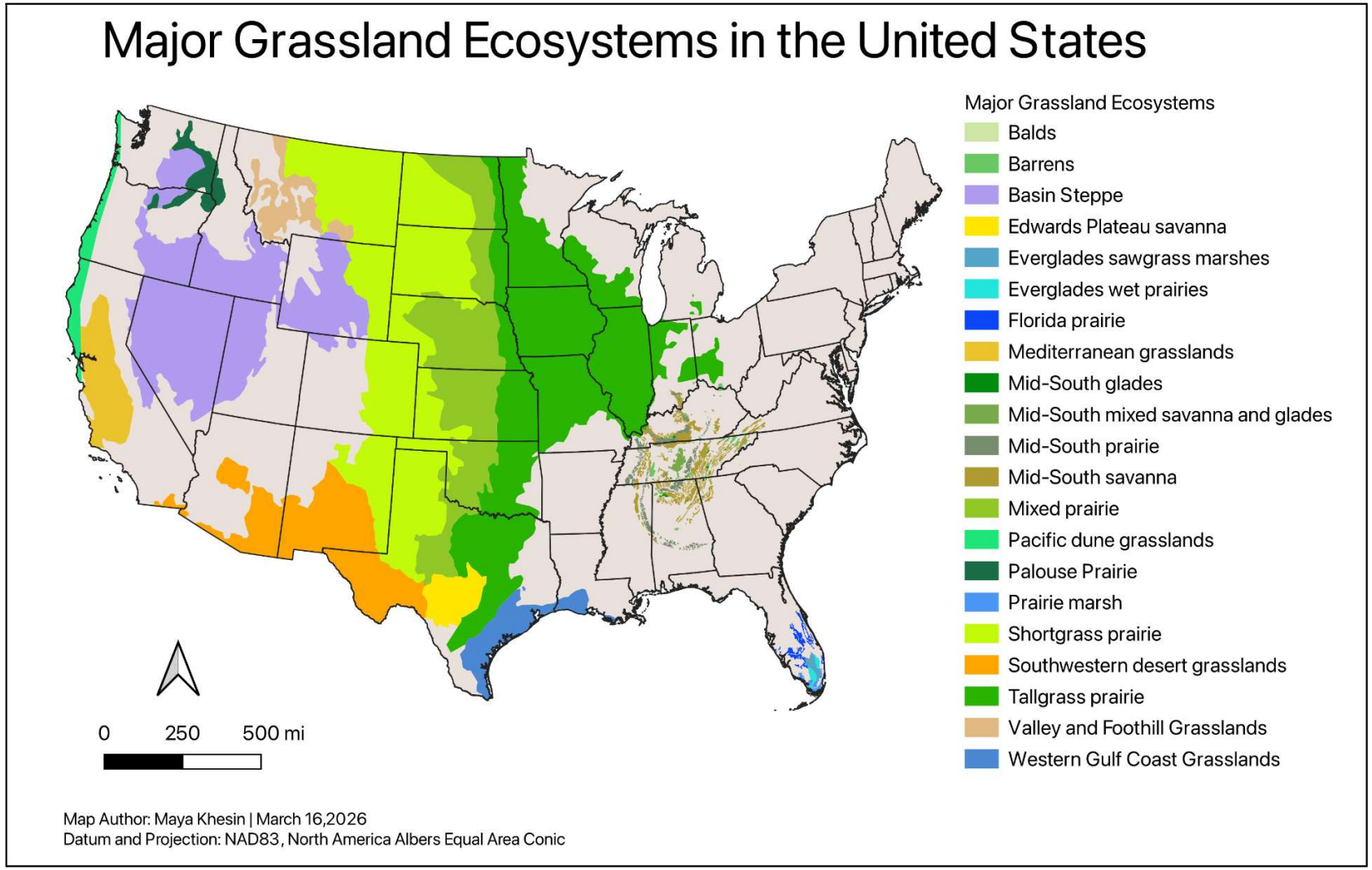
Name	Description	Patch- or Class-based
	the radius of gyration is a measure of the distance from each cell to the patch centroid	
Interspersion and Juxtaposition Index	Aggregation metric; describes the intermixing of classes	Class
Largest Patch Index	Area and edge metric; equal to the percentage of the landscape covered by the corresponding largest patch of each class. This metric is a simple measure of class dominance	Class
Effective Mesh Size	Aggregation metric; relatively measures patch structure across a class	Class
Number of Disjunct Core Areas	Core area metric; summarizes the number of disjunct core areas of all patches belonging to a certain class, where the disjunct core area is a "patch within a patch" that is composed only of core area and does not touch the perimeter	Class
Normalized Landscape Shape Index	Aggregation metric; describes the ratio of the actual edge length of a class in relation to the hypothetical range of possible edge lengths of the class	Class
Number of Patches	Aggregation metric; the number of patches belonging to a certain class. This metric describes the fragmentation of a class	Class
Perimeter-Area Fractal Dimension	Shape metric; describes the patch complexity of a class while being scale independent (i.e.: increasing the patch size while not changing the patch form will not change the metric)	Class
Perimeter-Area Ratio	Shape metric; summarizes each patch's perimeter-area ratio belonging to a certain class. This metric describes the patch complexity	Class
Patch Density	Aggregation metric; describes the fragmentation of a class. In comparison to the number of patches metric, patch density is standardized to the area and is able to be compared among landscapes with different total area	Class
Percentage of Like Adjacencies	Aggregation metric; calculates the frequency of how often patches of different classes than the focal class	Class

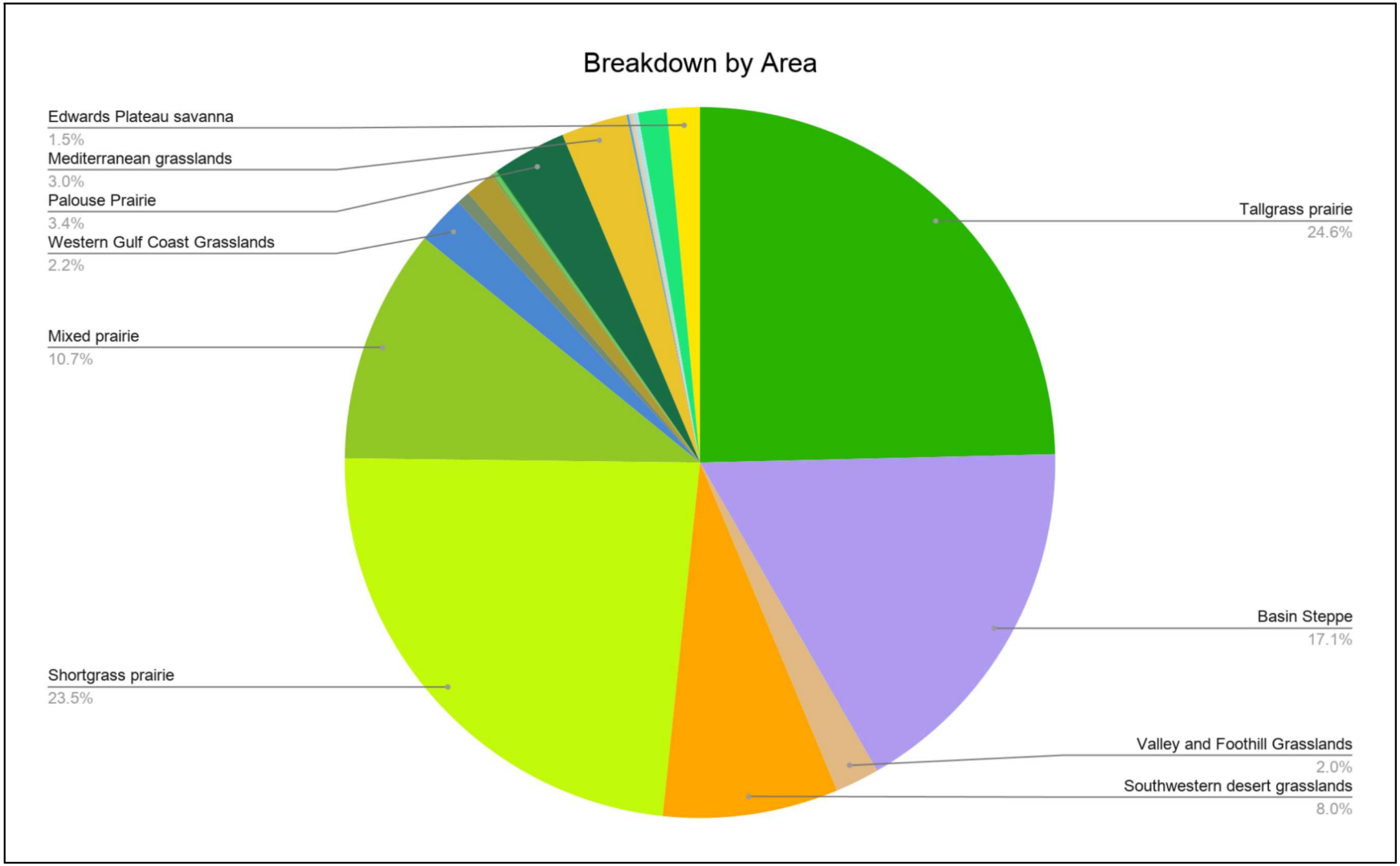
Name	Description	Patch- or Class-based
	are next to each other	
Percentage of Landscape	Area and edge metric; measures the percentage of the landscape belonging to a class. This metric is a measure of composition and is directly comparable among landscapes with different total areas	Class
Shape Index	Shape metric; describes the ratio between the actual perimeter of the patch and the square root of the patch area, summarized across all patches of a certain class	Class
Splitting Index	Aggregation metric; describes the number of patches if all patches of a certain class were divided into equally sized patches	Class
Total Core Area	Core area metric; equals the sum of core areas of all patches belonging to a certain class, where core area is defined as all cells that have no neighbor with a different value than themselves, thus all area in a patch that is not an edge	Class
Total Edge	Area and edge metric; sums all edges between a focal class and all other classes. This metric measures the configuration of the landscape, as a highly fragmented landscape will have many edges, however this metric is not easily comparable among landscapes with different total areas	Class

Appendix D: Table of All Reported Class Metrics for Grassland/Pasture Land Cover of the Three Areas of Interest

Metric	Value			Units
	Rocky Boy's Reservation	Hill	Chouteau	
Aggregation Index	88.25	91.11	88.65	N/A
Core Area Percentage of Landscape	27.04	36.10	31.72	Percent
Edge Density	57.25	55.28	67.10	Meters per hectare
Effective Mesh Size	3,340.29	64,637.88	49,154.41	Hectares
Euclidean Nearest Neighbor Distance (mean)	102.18	88.01	85.80	Meters
Interspersion and Juxtaposition Index	25.43	61.11	49.55	N/A
Largest Patch Index	26.75	29.57	16.89	N/A
Number of Patches	2,447	22,380	38,124	Number
Patch Area (mean)	7.17	15.11	11.87	Hectares
Patch Cohesion Index	99.59	99.91	99.89	N/A
Patch Density	5.33	3.09	3.73	Number per 100 hectares
Percentage of Like Adjacencies	88.05	91.06	88.61	Percent
Perimeter-Area Fractal Dimension	1.45	1.45	1.48	N/A
Perimeter-Area Ratio (mean)	0.10	0.11	0.11	N/A
Total Class Area	17,555.40	338,166.63	452,647.53	Hectares

Appendix E. Grasslands in the United States and Their Dominant Flora




Breakdown by Area
Edwards Plateau savanna
1.5%
Mediterranean grasslands
3.0%
Palouse Prairie
3.4%
Western Gulf Coast Grasslands
2.2%
Mixed prairie
10.7%
Shortgrass prairie
23.5%
Tallgrass prairie
24.6%
Basin Steppe
17.1%
Valley and Foothill Grasslands
2.0%
Southwestern desert grasslands
8.0%

Other values (slices too narrow to display percentage in figure above):

- Pacific Dune Grasslands: 1.3%
- Florida prairie: 0.2%
- Everglades sawgrass marshes: 0.1%
- Everglades wet prairies: 0.1%
- Prairie marsh: 0.1%
- Mid-South glades: ~0.0%
- Barrens: 0.2%
- Mid-South mixed savanna and glades: 0.1%
- Mid-South savanna: 1.3%
- Mid-South prairie: 0.6%

To see examples of characteristic flora for each ecosystem, please follow this link, zoom in until the US Major Grassland Ecosystems layer is visible (it has more and smaller polygons than the US Major Grassland Ecosystems) and click on the ecosystem polygons. Popups listing dominant grasses, forbs, and shrubs will appear.

Sources: Comer and Keeler-Wolf, 2011; Crawford, 2005; Estes et al., 2016; Evans, 2014; Faber-Langendoen, 2025; Florida Geographic Data Library, n.d.; Florida Natural Areas Inventory, 2009; Florida Natural Areas Inventory, 2010; Fowler and Beckage, 2019; Huffman, n.d.; Menard and Kindscher, 2011; National Ecological Observatory Network, 2021; Nielson, Reeves, and Thomas, 2010; Nordman et al., 2011; Noss, 2020a; Noss, 2020b; Pyne, 2014; Pyne and Teague, 2014; Schafale and Evans, 2014; Tisdale, 1982; Van Deelen, 1991a; Van Deelen, 1991b; Vanderhorst et al., 2015; West, Hall, and Schulz, 2015; Wishart, 2004.

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Appendix F. Calculation Tool: Federal Revenue from Grazing Fee Increases

This tool calculates the necessary federal grazing fee to fully finance NAGCA (first block of code below), as well as additional federal revenue that can contribute to financing NAGCA from smaller rate increases (second block of code below). This code was based on the annual appropriation of $92,500,000 through NAGCA and an estimate of 14,000,000 AUM leased out from the federal government annually. To account for non-static numbers, please follow the instructions below:

- Number of AUM grazing on public lands per year: the print(calc_fees(14000000)) line should be changed to print(calc_fees(currentAUM)), where *currentAUM* is the user-inputted number of AUM of federal land.
    - To modify this number for the calc_revenue function, the print(calc_revenue(3, 14000000)) line should be changed to print(calc_revenue(3, currentAUM)).
- To test different scenarios using the calc_revenue function, the print(calc_revenue(3, 14000000)) line should be changed to print(calc_revenue(fee, currentAUM)), where *fee* is the grazing lease rate that the user wishes to test.
- To modify the base grazing fee in the calculation of projected grazing rates with a 25% annual increase in place:
    - The 1.35 value assigned to the *fee* variable should be modified to reflect the current grazing rate at the time of implementation
    - The value assigned to *target* should be modified to reflect the necessary grazing fee to finance NAGCA at the time of implementation, if it is different from the current value of $7.97.

Necessary Grazing Rate to Finance NAGCA

```
total_needed = 92500000 #total funding needed to pay for NAGCA (in dollars)
base_grazing_fee = 1.35 #current grazing fee per AUM

def calc_fees(aum): #calculates necessary grazing fee based on number of animals grazing on US public land each year
    revenue = 0 #additional revenue from leasing rate increase
    graze = base_grazing_fee
    while revenue < total_needed:
      revenue = (graze - base_grazing_fee) * aum
      graze += 0.01
    return graze

print(calc_fees(14000000))

base_grazing_fee = 1.35 #current grazing fee per AUM
```

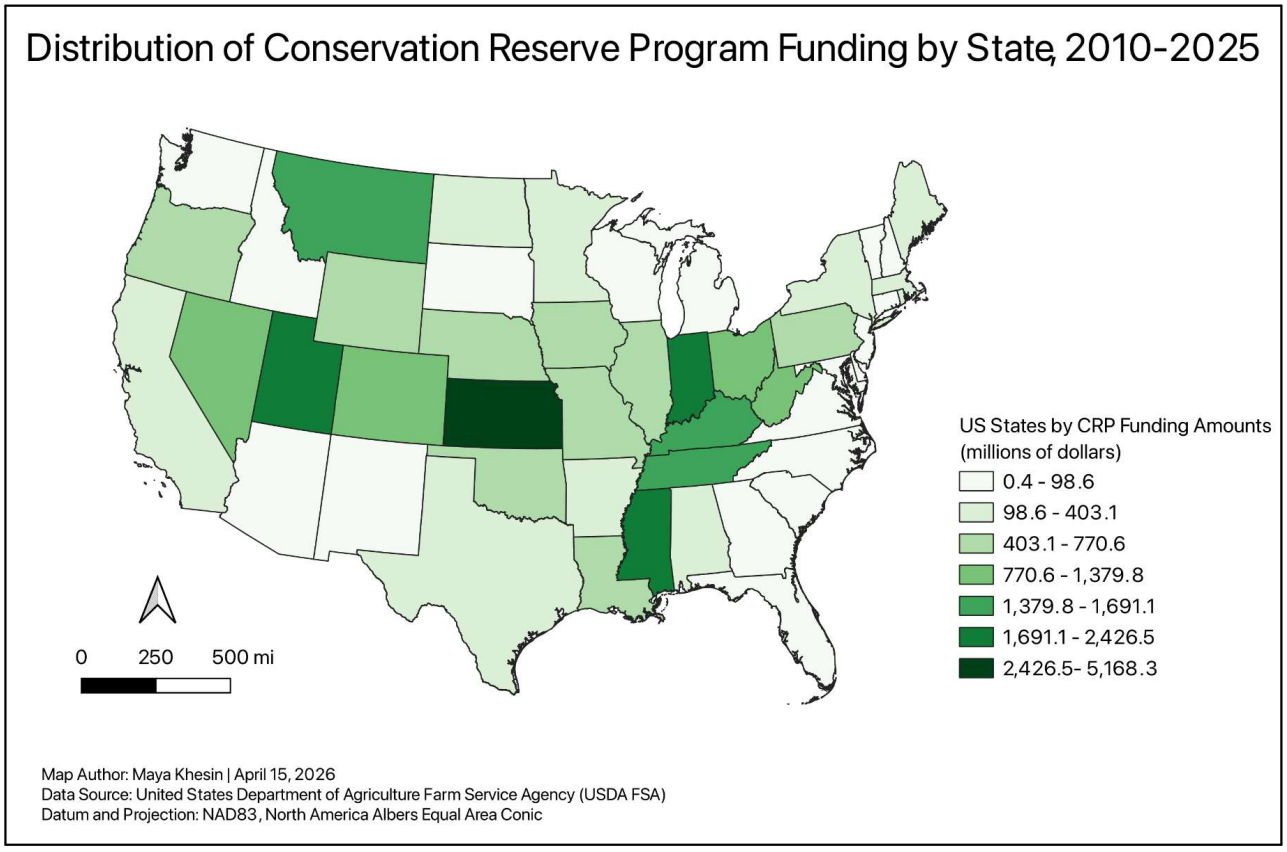
Additional Federal Revenue from Customized Grazing Rate Increase Scenarios

```
def calc_revenue(fee, aum): #calculates additional federal revenue from a given leasing rate based on annual number of animals grazing on federal lands.
    return (fee - base_grazing_fee) * aum
print(calc_revenue(3, 14000000))
```

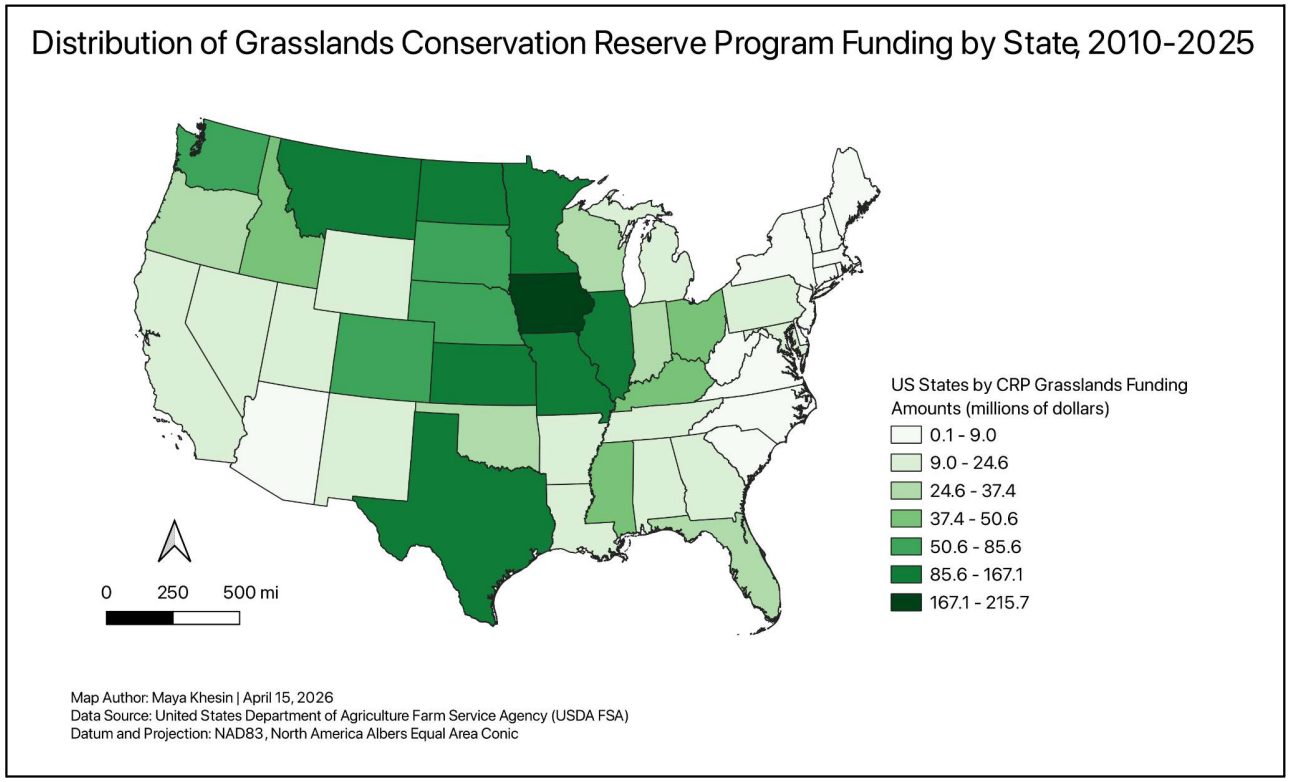
Projected Federal Grazing Fees Using 25% Annual Increase Rate

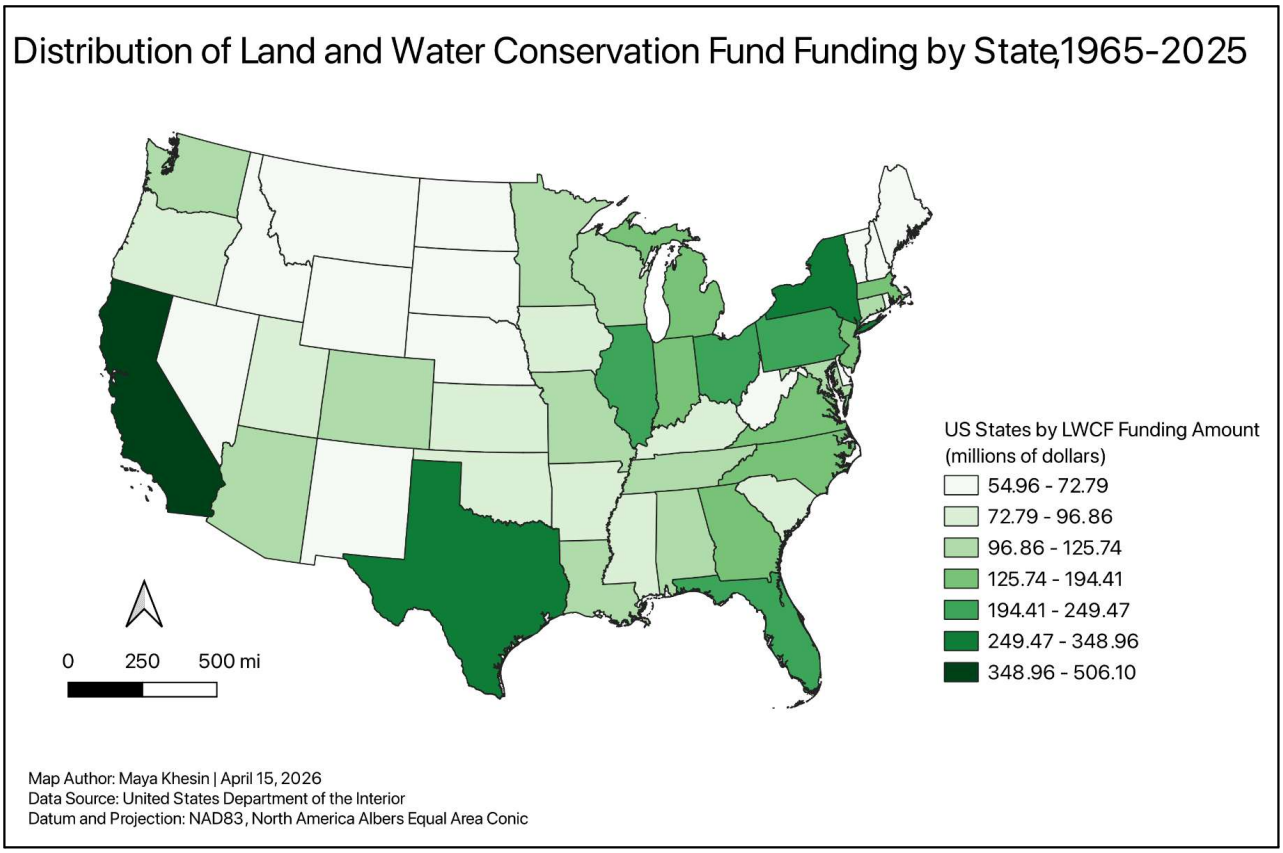
```
import math
year = 0
fee = 1.35 #current grazing fee per AUM
target = 7.97 #target grazing fee (based on amount needed to finance NAGCA)
while fee < target:
  fee = math.floor(fee*1.25*100)/100.0 #using floor function to round down to 2 decimal points
  year += 1
  print(year, fee)
```

The code and documentation for the tool can be found at this link: https://colab.research.google.com/drive/19rS7Wytq4hngk7y5ZRXMktyrO6giiHzX?usp=sharing.



Link to raw data





A zip file containing the raw data for the above two maps will be shared with BNGA as a separate file.

Other raw data obtained through FOIA requests (analysis was outside the scope of the project timeline):

- Bankhead-Jones Tenant Act Funding Distribution by State
- Conservation Stewardship Program (CSP): shared with BNGA as a separate file
- Environmental Quality Incentives Program (EQIP) Funding Distribution by State: shared with BNGA as a separate file
    - Includes data on Joint Chiefs Landscape Restoration Partnership and Working Lands for Wildlife Initiative

All other requests (outlined in Table 6.6) are still pending as of April 15, 2026.

Appendix H. Instructions for Freedom of Information Act (FOIA) Requests for Information

Background and Purpose:

The Freedom of Information Act (FOIA), enacted in 1967, requires disclosure of unreleased information held by the federal government upon request, with nine exceptions (categories of information that do not have to be released because they are considered particularly sensitive). These exceptions include: (1) information classified to protect national security; (2) information pertaining exclusively to agency personnel and practice; (3) information whose disclosure is prohibited by an existing law; (4) trade secrets or other confidential financial information; (5) confidential communication within or between agencies; (6) information whose disclosure would invade another individual's privacy; (7) law enforcement information whose release could interfere with law enforcement and justice proceedings, disclose the identity of a confidential source or invade an individual's privacy in any way, or create physical danger; (8) information concerning the supervision of financial institutions; and (9) geologic information on wells. All federal agencies are subject to FOIA, meaning that any citizen can request any information from any department or office within the federal government.

The purpose of this protocol is to provide instructions for submitting requests for information through FOIA. The following steps are intended to guide the user through the process of identifying to request information from, submitting the request for information, and gathering responses.

Procedure

1. Identify the agency from which you wish to request information. We provide several example categories with some of their respective relevant agencies below (as they appear in April 2026), but all agencies can be found here and are searchable by category.
   Example categories:
   a. Lands and Environment: Council of Environmental Quality, Department of Agriculture, Department of Energy, Environmental Protection Agency, Department of the Interior, Bureau of Land Management
   b. Housing: Department of Housing and Urban Development, Federal Housing Finance Agency
   c. Business: Department of Commerce, Farm Credit Administration, Federal Trade Commission, Antitrust Division
   d. Labor: Department of Labor, Equal Employment Opportunity Commission, Federal Labor Relations Authority, National Labor Relations Board
2. Find the FOIA request form for the agency from which you wish to request information. Clicking on an agency name link on this page will direct you to that agency's FOIA page.
   a. When you reach the agency page, click *"Continue the FOIA request process."*
   b. On the next page, read through the tips, and click *"Start FOIA request.*"

3. On the *"Make your request"* page, fill out the fields that appear. This includes your name, organization, contact information, and specific information you are requesting. There is also space to enter additional information that may provide context for the request or otherwise assist in the process. When you are finished inputting information, click *"Submit Request."*
4. Await response from the agency you have placed a request for information to. If the agency determines that this information is not classified or otherwise protected, you are required by law to receive the information. In the case that information is not disclosed, legal action may be taken to obtain it. FOIA request processing times vary by agency and request. During the waiting period, you may receive a call or email from a representative of the agency if the agency requires more information to carry out your request.
5. Your information will likely arrive in the form of a spreadsheet, which you will be able to open in Google Sheets, Microsoft Excel, or a different viewer/editor application. Statistical and/or geospatial analysis will likely be needed to make sense of the data.