Spring 2024

Big Bend Ecological Conservation

Integrating Earth Observations into Invasive Species Management Decisions in Big Bend National Park in Texas

DEVELOP Technical Report
March 29th, 2024

Kaitlyn L. Lemon (Project Lead)
Rebecca De Fazio
Chloe A. Marini
Margaret L. Birks

Advisors:
Dr. Jeffrey Luvall, NASA Marshall Space Flight Center
Dr. Robert Griffin, University of Alabama in Huntsville

Lead
Cristina Villalobos-Heredia

1. Abstract

Located in Brewster County Texas, U.S., along the Texas-Mexico border, Big Bend National Park is 3,243 square kilometers of desert, mountains, and rivers. NASA's MSFC Spring 2024 DEVELOP Team partnered with the National Park Service (NPS), to address the environmental concern of perennial invasive grasses in Big Bend National Park. Buffelgrass (*Cenchrus ciliaris*), introduced to the park in the 1940's, poses an ongoing threat, and causes habitat destruction for many of the park's native ecosystems. Buffelgrass amplifies fire risk in the park, aids in the destruction of historic structures, and alters stream channels. To address the rising concern of Buffelgrass presence, unique advanced spatial data methods were applied to construct a habitat suitability model and perform a comprehensive fire risk assessment. A habitat suitability model was developed considering climate, vegetation, and phenological variables, in addition to physical and topographical variables. Subsequently, a fire risk model was developed, taking into account fire history data, accessibility factors, climate trends and predictions, along with developed areas. Multi-Source Land Surface Phenology (LSP) Sentinel-2 and Landsat 8 Operational Land Imager (OLI) imagery were used to predict Buffelgrass hotspot locations throughout the park. These analyses allowed the identification of optimal Buffelgrass habitat and hotspot locations, as well as park zones that reflect the greatest risk for future Buffelgrass invasion and fire risk. The collective results of the habitat suitability model, fire risk assessment, and Buffelgrass hot spot identification will allow the NPS to facilitate efficient mitigation measures and management strategies, and improved resource allocation where it's most needed.

Key Terms

remote sensing, NDVI, fire risk, invasive species, National Park Service, phenology, Buffelgrass

2. Introduction

2.1 Background

In 1944, Congress established Big Bend National Park, located in Brewster County, Texas, to preserve a portion of the Chihuahuan Desert. In 1976, the park gained the International Biosphere Reserve Designation from the United Nations Educational, Scientific, and Cultural Organization (UNESCO), for additional ecological preservation and to keep the park accessible for current and future generations (NPS, 2024). As the 15th largest national park in the United States, Big Bend National Park encompasses 3,243 sq km and is situated along 315 km of the Rio Grande Wild and Scenic River. Known for its rich geologic and biological diversity, Big Bend National Park (Figure 1) provides ample opportunities for biological and archeological research, along with cultural and recreational activities (NPS, 2024).

In the early 1900's, resource managers introduced invasive perennial grasses into the arid ecosystems of Big Bend National Park in the Southwest for cattle foraging and erosion control (Innes, 2022). As foraging within the park was eliminated, these non-native grasses began to outcompete native vegetation (Leavitt et al., 2010). Within Big Bend National Park, the park managers have identified three dominant invasive perennial grasses of concern. Of these, the African Buffelgrass (*Cenchrus ciliaris*) is considered the most threatening of invasive plant species (Leavitt et al., 2010). With the ability to alter natural ecosystems and succession, invasive grasses directly contribute to the loss of biodiversity within native plant communities (Leavitt et al., 2010). Invasive grasses also increase fire risk and disturb natural fire regimes by increasing fuel load and creating degraded landscapes that allow for a competitive advantage for invasive grasses to establish post burn, creating a positive feedback loop (Young and Scott, 2014). Buffelgrass fuel loads have shown to be 2 to 4,000 times greater than native grasses, at 1-4 tons per acre. The elevated fuel load can increase average fire temperature ranges from normal expectation of 88-399 degrees Celsius to a much higher range of 704-871 degrees Celsius, resulting in greater ecosystem damage when a wildfire occurs (NPS, 2019).

The National Park Service (NPS) estimated in 2005 that non-native plants were established in over 11,000 sq km of national parks, including 65 known exotic species capable of colonizing within Big Bend National Park (Young et al., 2013). Mitigation and restoration efforts have mainly been in the field, with reliance on established roads and trails to access known invasive species locations. Due to the limited accessibility via roads throughout the park, coupled with the vast size and diversity of terrain, most of the park has not been field surveyed for invasive plants. Ground-based surveys across large landscapes require resource managers to invest huge time commitments and are cost prohibitive. Additionally, for ground-based surveys to be successful, surveys must be completed at regular intervals to ensure species inventories are comprehensive (Young et al., 2013). Due to these limitations, coupled with the diverse phenological characteristics and site suitability associated with differing invasive species, mitigation needs and high-risk zones for habitat suitability and fire risk are unknown.

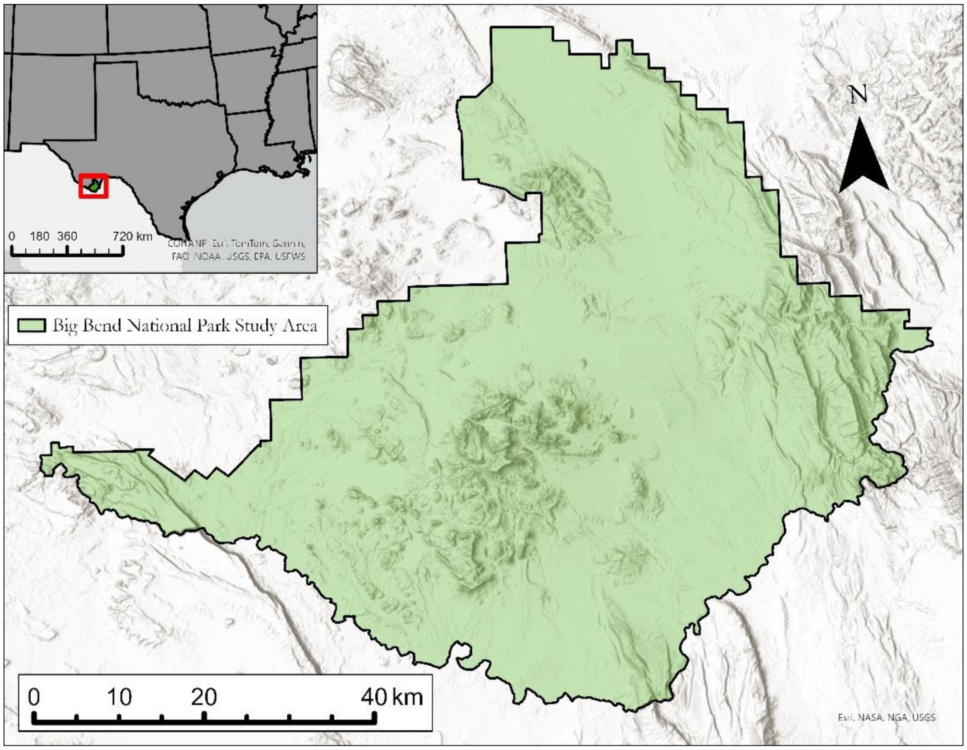

Figure 1. Study area (3,243 km^2) of the boundaries of Big Bend National Park in Brewster County, Texas. Map compiled with ArcGIS Pro software.

2.2 Project Partners and Objectives

In partnership with the National Park Service (NPS), our DEVELOP team's project aims to comprehensively assess and locate the invasive flora species Buffelgrass within Big Bend National Park, as well as identify areas in the park that are at risk for enhanced fire risk. The NPS is committed to improving their mitigation strategies and efforts to protect the diverse ecosystems that exist within the park boundaries. These analyses were performed to provide our partners with an enhanced understanding of the threat Buffelgrass poses to the environment, as well aid the identification of locations that are experiencing exacerbated fire risk due to anthropogenic, environmental, and climatic variables. This project's objectives were focused on our partner's need to identify where their land management resources can be most efficiently allocated. These prime locations were identified for our partners through the implementation of advanced spatial analysis using ArcGIS Pro software and assorted satellite imagery.

3. Methodology

3.1 Data Acquisition

3.1.1 Big Bend National Park Data

In a thorough analysis of Big Bend National Park, various data types and formats were collected to suit the scope of the research. We acquired numerous bulk datasets from the NPS online DataStore. These datasets included infrastructure data such as roads, trails, buildings and campsites, and field data from their vegetation data mapping project. We used these larger datasets to extrapolate out known invasive species locations, along with dominant co-species and vegetation cover types. The project partners contributed additional fire location data, sensitive areas, and cattle trespassing shapefiles.

We used a plant database from the United States Department of Agriculture (USDA) to gather various data on phenology, habitat preferences, common co-species, and preferred climate variables to comprehend alternative methods of detecting the location of Buffelgrass. The database additionally provided weather parameters for precipitation and temperature ranges required for green-up to be calculated. We also utilized the USDA Fire Effects Information System (FEIS) to gain a better understanding of the historical and current approaches to Buffelgrass management and fire ecology.

3.1.2 Spectral Imaging

We acquired raster datasets of plant phenology through a National Aeronautics and Space Administration (NASA) product titled Multi-Source Land Surface Phenology Yearly North America 30 meter (MSLSP30NA) or referred to as Multi-Source Land Imaging (MuSLI) (Friedl, 2021). The data encompassed US phenology at 30-meter resolution from 2016 to 2019. Additional datasets for 2020-2023 were supplied by MuSLI upon request. The United States was split into a grid system, with Big Bend falling within the 13RFN grid code file and included datasets for onset greenness. We selected the Onset Greenness Maximum (OGMx) datasets based upon Buffelgrass green-up parameters.

We acquired Landsat 8 Operational Land Imager (OLI) images through United States Geological Survey (USGS) Earth Explorer to calculate the Normalized Difference Vegetation Index (NDVI) for Buffelgrass. Selecting specific dates for 2013, 2017-2019, and 2023 (Table 1). Landsat 8 imagery was selected due to the increase in NDVI value representation for vegetation cover found in low vegetation ecosystems (Xu & Guo, 2014).

Table 1

Collection of Landsat 8 OLI images used for NDVI, from 2013, 2017-2019, and 2023, with IDs.

Satellite Sensor	Collection Category	Collection Number	Land Cloud Cover	Date Acquired	Earth Explorer Product ID
Landsat 8 OLI_TIRS	T1	2	4.23	08/20/2013	LC08_L1TP_030040_20130820_20200912_02_T1
Landsat 8 OLI_TIRS	T1	2	2.37	06/28/2017	LC08_L1TP_030040_20170628_20200903_02_T1
Landsat 8 OLI_TIRS	T1	2	0.44	10/05/2018	LC08_L1TP_030040_20181005_20200830_02_T1
Landsat 8 OLI_TIRS	T1	2	3.25	01/25/2019	LC08_L1TP_030040_20190125_20200830_02_T1
Landsat 8 OLI_TIRS	T1	2	0.11	09/01/2023	LC08_L1TP_030040_20230901_20230911_02_T1

3.1.3 Environmental Variables

To understand the topographical patterns of the land, we chose to use the 30-meter Digital Elevation Model (3DEM) from the USGS. The area encompassing Big Bend was broken into and downloaded as 64 TIFF files. We mosaiced the 64 different raster datasets into one file to encompass Big Bend National Park. We then clipped the dataset to its bounds to shave off excess data.

We acquired historic precipitation and temperature data from the National Oceanic and Atmospheric Administration's (NOAA) National Weather Service (NWS) Data platform NowData. We identified four known weather stations within and in proximity to the park; Castolon, Lajitas, Chisos Basin, and Panther Junction. Each station was used to obtain data from 2016 to 2023 and prioritized based on elevation and location within the park and if the datasets were fully populated.

We collected precipitation and temperature data from the WorldClim data site. These datasets contained future projections of 30 seconds spatial resolution monthly average maximum temperatures (C) and monthly total precipitation (mm) for the years 2021 to 2040 and 2041 to 2060. The climate data were obtained from the global climate model GISS-E2-1G, developed by NASA's Goddard Institute for Space Studies (GISS), for the Shared Socioeconomic Pathway (SSP) 245. SSP 245 is a moderate emission scenario representing intermediate greenhouse gas concentrations and emissions, and the associated climate change.

3.2 Data Processing

3.2.1 Big Bend National Park Data

Our partners at Big Bend National Park provided known visible vegetation coordinates for native and invasive species along with a fine-scale vegetation classification map. We utilized this information to aggregate specific known points of the vegetation creating a presence timeline from 2010 to 2018. We used information in these known plot locations to determine the dominant co-species associated with Buffelgrass and to identify the dominant vegetation cover type where Buffelgrass was found. Any species or vegetation type associated with 2% or more of known Buffelgrass plots was classified as dominant.

We extracted relevant Big Bend National Park infrastructure data from larger datasets to accurately display roadways and infrastructure within the park. These datasets included current roads, trails, and campgrounds, and park buildings and facilities. To ensure the accuracy of fire presence data, we removed controlled treatments from the dataset to prevent skewing fire association with invasive species. Additionally, we separated fire presence by incident type. These extracted shapefiles were overlaid onto the study area shapefile as a preliminary first step for analysis.

3.2.2 Multispectral Data Products

MuSLI is an off-the-shelf deliverable dataset that provides images that have undergone cloud cover removal. Moreover, all green-up statistics were precalculated within the MuSLI images. Using the Make NetCDF Raster Layer file in ArcGIS Pro, we selected the OGMx variable from within the dataset. Integrating precipitation and temporal trends allowed us to further define potential greening timelines specific to Buffelgrass and extract the dates of detected occurrence. For the habitat suitability model, OGMx was extracted and used to find the quick green-up dates in Big Bend for 2017 to 2019. 2016 to 2019 OGMx data was then combined with 2020 to 2023 OGMx to create the Buffelgrass detection map.

We utilized Landsat 8 (OLI) raster files from known potential green-up timelines to calculate NDVI and validate known invasive species location points for 2013 and 2017. Additionally, images from 2017-2019 and 2023 were implemented to calculate NDVI as part of the Habitat Suitability Model. We calculated NDVI in ArcGIS Pro using the NDVI equation (1). NDVI values for shrub and grassland ecosystems can range from 0.2 to 0.3 based on early growing season Landsat data (Weier and Herring, 2000). We further buffered the NDVI value range to 0.15 to 0.35 to specifically target Buffelgrass in Big Bend National Park (Olsson et al., 2011).

$$NDVI = \frac{(NIR-Red)}{(NIR+Red)} \quad (1)$$

3.2.3 Environmental Variables

We used historic precipitation and temperature tables to determine potential greening timeframes for Buffelgrass. The Buffelgrass species necessitates rain events with 19.05 mm or more of rainfall between a two-to-five-day timeframe for successful green-up (NPS, 2019). Additionally, Buffelgrass requires consistent daily temperatures of 10 degrees Celsius or greater (NPS, 2019). We calculated all potential green-up timelines for 2016-2023. These timelines along with in situ data were used to select OGMx data for the habitat suitability model and Buffelgrass detection map.

We actively collected and applied projected climate variables, including monthly average maximum temperature in degrees Celsius and monthly total precipitation in mm, from 2021-2040 and 2041-2060 in the thorough analyses of assessing fire risk and identifying optimal Buffelgrass habitat and hotspots. To perform the fire risk assessment, it was essential to identify the least and greatest changes in precipitation and temperature. We calculated the change in temperature by identifying the average monthly temperature change between 2021 to 2040 and 2041 to 2060, then further averaging the change over all 12 months. This process provided a raster of average projected change in monthly maximum temperatures across the study area. We then utilized ArcGIS Pro's raster calculator to calculate the average change in total monthly precipitation by determining the monthly change in total precipitation, and further averaging the 12 months of data, creating a raster of predicted precipitation change across Big Bend National Park. To construct the habitat suitability model, we calculated the sum of summer (June to September) monthly total precipitation with ArcGIS Pro's raster calculator using the projected dataset for 2021 to 2040. Additionally, we utilized ArcGIS Pro's raster calculator to find the average maximum monthly temperature from 2021 to 2040. These changes in temperature allow for further analysis into the environmental impacts of worsening drought conditions or impacts of temperature variations that are causing changes in the risks these invasive species pose on Big Bend National Park.

3.3 Data Analysis

3.3.1 Geospatial Park Zoning

Preliminary analysis of Big Bend National Park exposed a need for the implementation of a zoning structure for the 3,243 sq km of land it contains. This preliminary analysis was performed in ArcGIS Pro by visualizing the Big Bend National Park Boundary Shapefile in combination with a classified DEM raster, and the Big Bend National Park roads and trails shapefiles provided by the NPS. A 2-mile buffer was placed on the roads to identify areas within the park that were least accessible to ensure every zone could be accessed by an intersecting road. Another major factor included in the analysis was the identification of major elevation gradient differences. A visual analysis of these factors, including recommendations from the partners, allowed for the construction of a zoning system consisting of 20 individual zones within the park. These zones were produced in ArcGIS Pro by creating a feature class and a series of polygons snapped to either the boundary file, specific roads, or follow along major elevation gradients. These parameters were used to determine the zones seen in Figure 2, which were specifically requested as part of the deliverables package by the project partners. The zoning map was additionally designed to aid cross agency departments in communicating risks and issues within regions of the park.

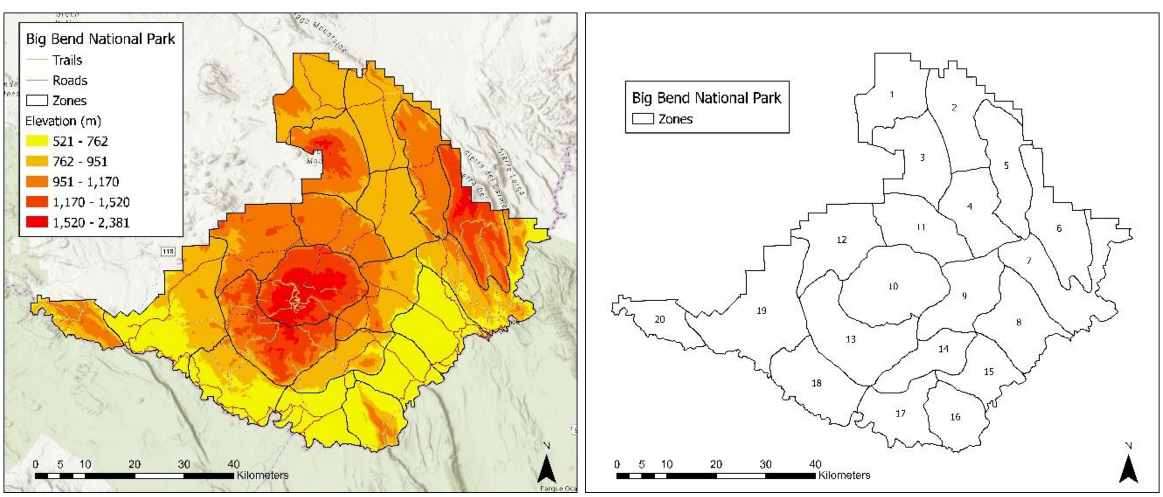

Figure 2. Elevation was used as a primary variable along with road and trail access for creating a Zoning map of Big Bend National Park. Created in ArcGIS Pro.

3.3.2 Habitat Suitability

We performed an analysis of multiple phenological, topographical, and climate datasets aided in the creation of a habitat suitability model. To identify the areas in Big Bend National Park that were the most suitable habitat for the invasive grass species, an aggregated NDVI/green-up dataset was analyzed in ArcGIS Pro in combination with elevation data, vegetation cover type, and known species locations. A major factor considered in the habitat suitability analysis is the average precipitation in each zone, due to the specific precipitation and moisture preferences of Buffelgrass. Along with these major variables, temperature averages and locations of dominant co-species were used to further identify suitable habitat for these species.

3.3.3 Fire Risk Assessment

The fire risk assessment of Big Bend National Park was performed via zonal statistical analysis, by combining and weighing several variables that maximize or minimize fire risk in any given zone (Table F1). These variables were all rescaled and weighted based on the potential for fire risk. The Rescale by Function tool in ArcGIS Pro assigned values of zero to areas with the lowest or no fire risk, and a one to those values that signify maximal fire risk. Two of the primary variables considered in the fire risk assessment are the projected average change in maximum temperature between 2021-2040 and 2041-2060, and the average change in precipitation from 2021-2040 and 2041-2060 with a "middle of the road" climate change and pollution mitigation strategy (SSP245). We rescaled the temperature from [0,1], where 0 signifies either the greatest decrease or lowest increase in average maximum temperatures, and 1 signifies the greatest increase in average maximum temperatures. This rescaling of values creates a more controlled scale of lowest to greatest risk that the zone's temperature change poses regarding fire risk. The average precipitation values were then rescaled from [1,0] signifying that the greatest decrease in precipitation would lead to increased fire risk due to potential dry/drought conditions in the given zone. Other variables considered in this analysis included cattle trespass counts by zone [0,1], percentage of protected area in each zone [0,1], and a combination of habitat suitability considerations and fire history data.

3.3.4 Buffelgrass Detection Map

We used variables from the habitat suitability model to determine an optimum habitat map for Buffelgrass, including NDVI, vegetation cover type and elevation data as inputs to the model. A confusion matrix was done to analyze our confidence in the optimum habitat map (Figure E1). The confusion matrix used predicted values for Buffelgrass presence (value 1 = positive) and absence (value 0 = negative) and known values of Buffelgrass presence (value 1 = positive) and absence (value 0 = negative). Areas with positive predicted values and positive actual values were classified as true positives (TP) and areas with negative predicted values and positive actual values were classified as false negatives (FN). Further areas with positive predicted values and negative actual values were classified as false positives (FP) and areas with negative predicted values and negative actual values were classified as true negatives (TN). We then calculated the accuracy using equation (2) (Ragan, 2018).

$$\frac{TP+TN}{TOTAL\ SUM} \quad (2)$$

We proceeded to analyze the OGMx green-up data for each of the eight years spanning from 2016-2023. Utilizing specific green-up timelines obtained from all four weather stations, we identified periods when Buffelgrass was likely to experience significant green-up events (Table G1). Subsequently, each year of OGMx data underwent rescaling, with 0 denoting no green-up and 1 indicating the presence of a green-up. The rescaled data from each year where then aggregated to establish a presence threshold. To visually represent locations where green-up occurred in one or more years, a gradient color scheme was applied. This representation was subsequently clipped to the optimal habitat map to delineate the most probable locations of Buffelgrass.

4. Results & Discussion

4.1 Analysis of Results

4.1.1 Buffelgrass Habitat Suitability

The Buffelgrass habitat suitability model (Figure 3) identified zone 8, zone 15, and zone 19 in Big Bend National Park as the areas that are most suitable for Buffelgrass presence. These zones face a greater risk of Buffelgrass spread, significantly impacting the park's native ecosystems. The habitat suitability map offers the NPS a valuable resource to incorporate into their Buffelgrass management strategies.

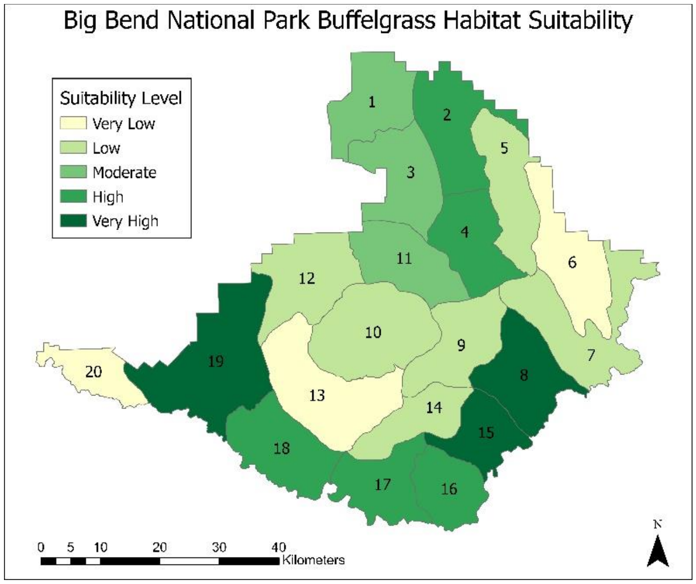

Figure 3: Map of Big Bend National Park with habitat suitability ranked per zone based on the following: climate trends, vegetation and phenological variables, and physical and typographical variables.

4.1.2 Fire Risk Assessment

The zonal fire risk assessment of Big Bend National Park determined that zone 8, zone 10, and zone 19 are the areas at the greatest risk for future fires (Figure 5). Fire risk values from 0-.24 indicated low risk, values .25-.28 indicate medium low risk, .29-.35 indicated a medium risk, .36-.48 indicate a high risk, and values of .49 and greater indicate a high risk of fire within that region of Big Bend (Figure 4). This model has equipped the NPS with a prediction tool to use in their mitigation efforts and to help facilitate a more systematic implementation of park policies to reduce the threat within the park.

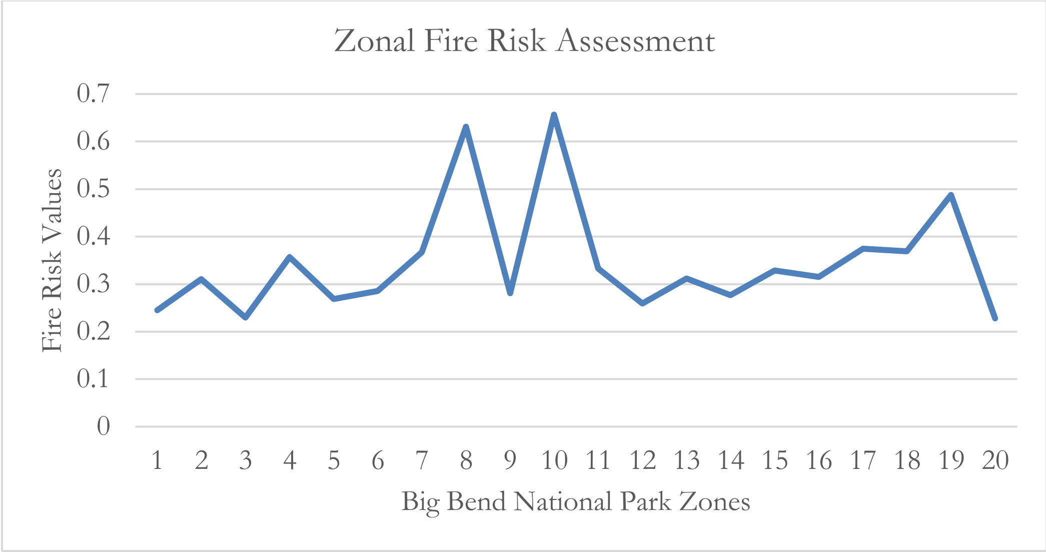

Figure 4: Identifies high risk fire values for the 20 zones within the park based upon a weighted zonal statistic analysis.

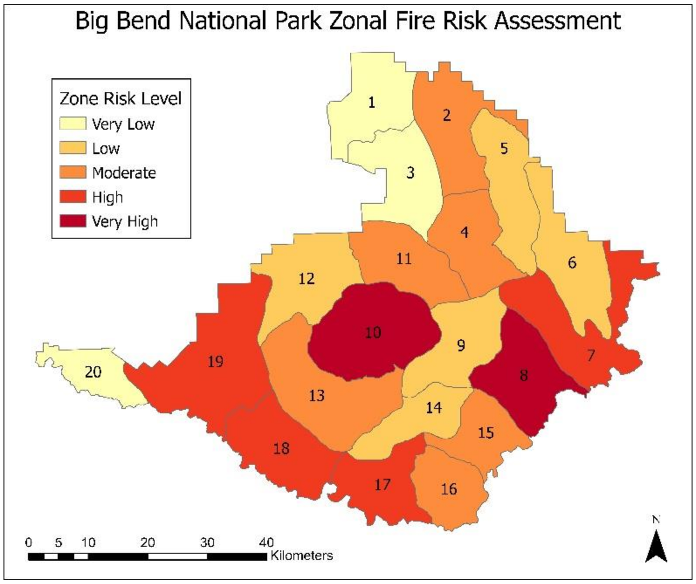

Figure 5: Map of Big Bend Park zonal fire risk analysis based on the following: climate history and trends, vegetation variables, trails and roads, cattle trespass points, and protected areas.

4.1.3 Buffelgrass Hot Spot Identification

The final maps (Figure 6; FigureD1) show the combined calculation of OGMx green-ups and the optimum habitat map. The optimum habitat suitability map was established with an 81% accuracy using the confusion matrix. OGMx results are visible only within the optimum habitat range. The map shows veins of bright orange and red areas with increased probability of Buffelgrass. The presence probability shows values for 1-8 occurrences of overlapping green-ups. Low values represent 1 to 2 co-occurrences, medium values represent 3 to 5 co-occurrences, high indicates an area with 6 occurrences or more.

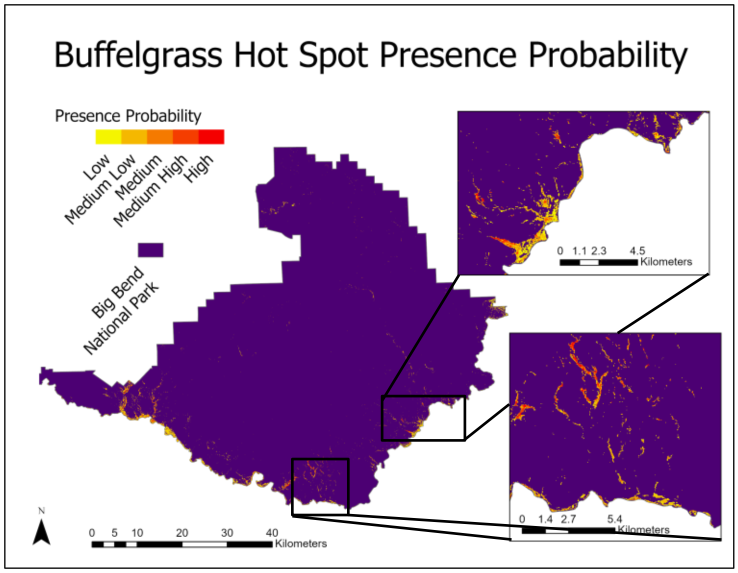

Figure 6: Map of Big Bend Park with Buffelgrass presence ranked based on spectral imaging and habitat suitability. High occurrence levels increase the probability of Buffelgrass presence within the park. Purple indicates areas with zero occurrences, or areas within the park outside of the known habitat elevation range.

4.2 Errors and Uncertainties

The climate model used in this analysis contains uncertainties in projections, potentially skewing data due to inaccuracies in representing future conditions. Selecting SSP245 aimed to maintain proximity to the current US emission scenario, but significant changes in emissions could introduce uncertainties or errors into the data. Additionally, the Buffelgrass hotspot detection map failed to include roads and trails, which could skew data along major seed transport routes, impacting the analysis. Moreover, NDVI ranges may be subject to error or uncertainty that could be due to issues with input reflectance data such as unmasked clouds and cloud shadows. These factors highlight the need for caution in interpreting and utilizing the data and the importance of ongoing refinement and validation efforts to improve the accuracy and reliability of future assessments.

4.3 Feasibility for Partner Use

We created the project's models to make them reproducible for the partners at Big Bend National Park. We utilized information provided by the NPS from previous projects to craft a species profile and datasets that highlighted the locations where Buffelgrass would most likely thrive and grow. However, limitations and feasibility issues arose when acknowledging that in situ data of known Buffelgrass plot locations had been extracted from a larger vegetation survey project. The last dates of acquired data were from March of 2018, and no Buffelgrass-specific vegetation survey had been conducted within the park.

The green-up timelines were created by compiling data from four different weather stations within Big Bend National Park territories, all at different elevations and locations. This was partly to compensate for variations and incomplete data from each weather station. Also, we used the four weather stations to account for variations in elevation and spatial extent of the park. Temperature and precipitation measurements often varied between the four weather stations, creating limitations in assuring accurate green-up timelines throughout the entirety of the park

MuSLI was used to highlight potential hotspots and validate known Buffelgrass locations. MuSLI is no longer publicly produced meaning that data from 2020 to 2023 had to be requested directly from the PI, Mark Friedl from Boston University, on the project. The suitability model had the MuSLI data weigh on the potential hotspot areas, so future reproducibility will need to either go without the supplied MuSLI dataset or need to be acquired from the PI.

Additional limitations included both time and accessibility to commercial datasets and other satellite imagery. The lack of validation through high resolution imagery prohibited us from validating predicted Buffelgrass locations further. Moreover, only one Landsat 8 OLI imagery scene was used to calculate NDVI, which did not cover a small western section of the park, resulting in an inaccurate NDVI, and subsequent optimal habitat suitability assessment of that region of the park (zone 20).

4.4 Future Work

Future analysis would benefit from a comprehensive invasive species survey of the park. Ideally utilizing a combination of on the ground surveys and unmanned aerial vehicle (UAV) surveys. Areas surveyed based on the Buffelgrass detection map would allow advancements in the accuracy of the habitat suitability model and fire risk assessment and define precision of predicted areas using additional confusion matrix equations. The project would benefit from additional analysis incorporating high resolution multi-spectral imaging. With a combination of UAV and ground surveys, coupled with higher resolution multispectral imagery, these models could successfully be applied to other destructive and fire escalating invasive grass species within the park.

5. Conclusions

We created park zones that allowed for a systematic method of analysis for calculating habitat suitability and fire risk. The park zones also created an internal structure that will allow for a clearer understanding of problematic locations in the park, including the ability to prioritize restoration and mitigation methods regionally. The habitat suitability model identified areas most at risk for Buffelgrass infestation. We found out that predicting Buffelgrass was made easier using Landsat-based NDVI and green-up data due to the specific phenological characteristics of the grass's green-up and senescence phases. The Buffelgrass detection map computed from these data had an overall 81% accuracy rate compared to reference data. Additionally, habitat preferences played a big role in determining optimal habitat suitability hotspots, specifically vegetation cover type, elevation, and accessways such as trails and roads.

Big Bend National Park may continue to use maps and models from this project in their strategies concerning invasive flora species. The development of a zoning map for the park will enable park management personnel to more effectively guide and distribute their resources, including conservation teams and mitigation practices, to specific areas delineated within the park's newly established zoning system. Big Bend National Park may use the reproducible habitat suitability and fire risk models to further identify hotspots within their new zones that need to be assessed and managed in the future. The park zones, habitat suitability model, the fire risk assessment and the Buffelgrass hot spot detection map may help Big Bend National Park further advocate for more invasive species management funding and resources to continue protecting the park and its native ecosystems.

6. Acknowledgements

The MSFC Huntsville Ecological Conservation Team thanks our project partners the National Park Service (NPS). We are grateful to Dr. Jeffery Luvall, Dr. Robert Griffen, Eric Anderson and Dr. Kent Ross for advising and guiding us, as well as Dr. Mark Friedl and Helen Parache for helping us to acquire and interpret specific data necessary to the success of this project. The Big Bend Ecological Conservation project was led by Cristina Villalobos-Heredia (MSFC) with documentation edited by Maya Hall (ARC).

This material contains modified Copernicus Sentinel data (2013, 2016, and 2023), processed by ESA.

This work utilized data made available through the NASA Commercial Smallsat Data Acquisition (CSDA) program.

Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Aeronautics and Space Administration.

This material is based upon work supported by NASA through contract 80LARC23FA024.

7. Glossary

Buffelgrass (*Cenchrus Ciliaris*) – a perennial grass that is native to Africa, southern Asia, southern Iran and Sicily; it is used as erosion control in semi-arid regions and pasture grass in tropical regions
Digital Elevation Model (3DEM) – a 3D computer graphics representation of elevation data to represent terrain or overlaying objects, commonly of a planet, moon, or asteroid
Earth observations – Satellites and sensors that collect information about the Earth's physical, chemical, and biological systems over space and time
Geospatial – relating or denoting data that is associated with a particular location
Green-up – the period in which plants, shrubs, and trees begin to flower and leaf out after breaking dormancy
International Biosphere Reserve Designation – a designation given to a natural protected are within the framework of UNESCO's Man and the Biosphere Program
Landsat 8 Operational Land Imager (OLI) – a remote sensing instrument on the Landsat 8 satellite that measures the Earth's surface in the visible, near infrared, and short wave infrared spectral bands
Multi-Source Land Surface Phenology (LSP) – a product that uses satellite-based data to describe seasonal changes in vegetation greenness and leaf area at the landscape scale
Multi-Source Land Surface Phenology Yearly North America 30-meter (MSLSP30NA)/Multi-source Land Imaging (MuSLI) – this product provides a Land Surface Phenology product for North America derived from Harmonized Landsat Sentinel-2 (HLS) data
National Oceanic and Atmospheric Administration (NOAA) – a federal agency responsible for monitoring weather, atmospheric occurrences, coasts, fishing and wildlife policies, and climate monitoring in relation to the atmosphere and oceans.
National Park Service (NPS) – a federal agency that manages the more than 400 national parks in the United States with the mission to preserve that natural and cultural resources of the National Park System
National Weather Service (NWS) – a federal agency that provides weather, hydrologic and climate forecasts and warnings for the United States, its territories, and ocean areas
NetCDF – a file format that stores multidimensional scientific data, such as temperature, humidity, pressure, wind speed, and direction
Normalized Difference Vegetation Index (NDVI) – a remote sensing method that measures the density and healthy of vegetation in an area
Onset Greenness Maximum (OGMx) – When the plant species undergoes a 90% maximum greening (green-up) increase, meaning it has reached its peak level of greenness, increased by 90% from previous levels (dormancy), due to response in favorable growing conditions
Phenology – the study of cyclic and seasonal natural phenomena, especially in relation to climate and plant and animal life
Sentinal-2 Multisource Instrument (MSI) – a high-resolution imaging sensor on the European Space Agency's (ESA) Sentinel-2 series of satellites; the MSI measures the Earth's reflected radiance across 13 spectral bands
United Nations Educational, Scientific and Cultural Organization (UNESCO) – an agency that promotes international cooperation in education, science and culture
United States Geographical Survey (USGS) – an agency within the Department of the Interior that collects data in multiple fields, like environmental, resource management, and public safety, to help further science-based policy
United States Department of Agriculture (USDA) – the federal executive department responsible for developing and executing federal laws related to farming forestry rural economic development and food
Unmanned Aerial Vehicle (UAV) – Commonly referred to as a drone, UAV's are aerial flying vehicles that do not carry a human operator and are piloted remotely
WorldClim – An open-source database with historical and future climate datasets, containing average, maximum, and minimum temperatures and precipitation information.

64 TIFF file – a tagged image file format file that uses 64-bit offsets instead of the 32-bit offsets used in standard TIFF files

8. References

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9. Appendices

Appendix A: Buffelgrass Detection Map

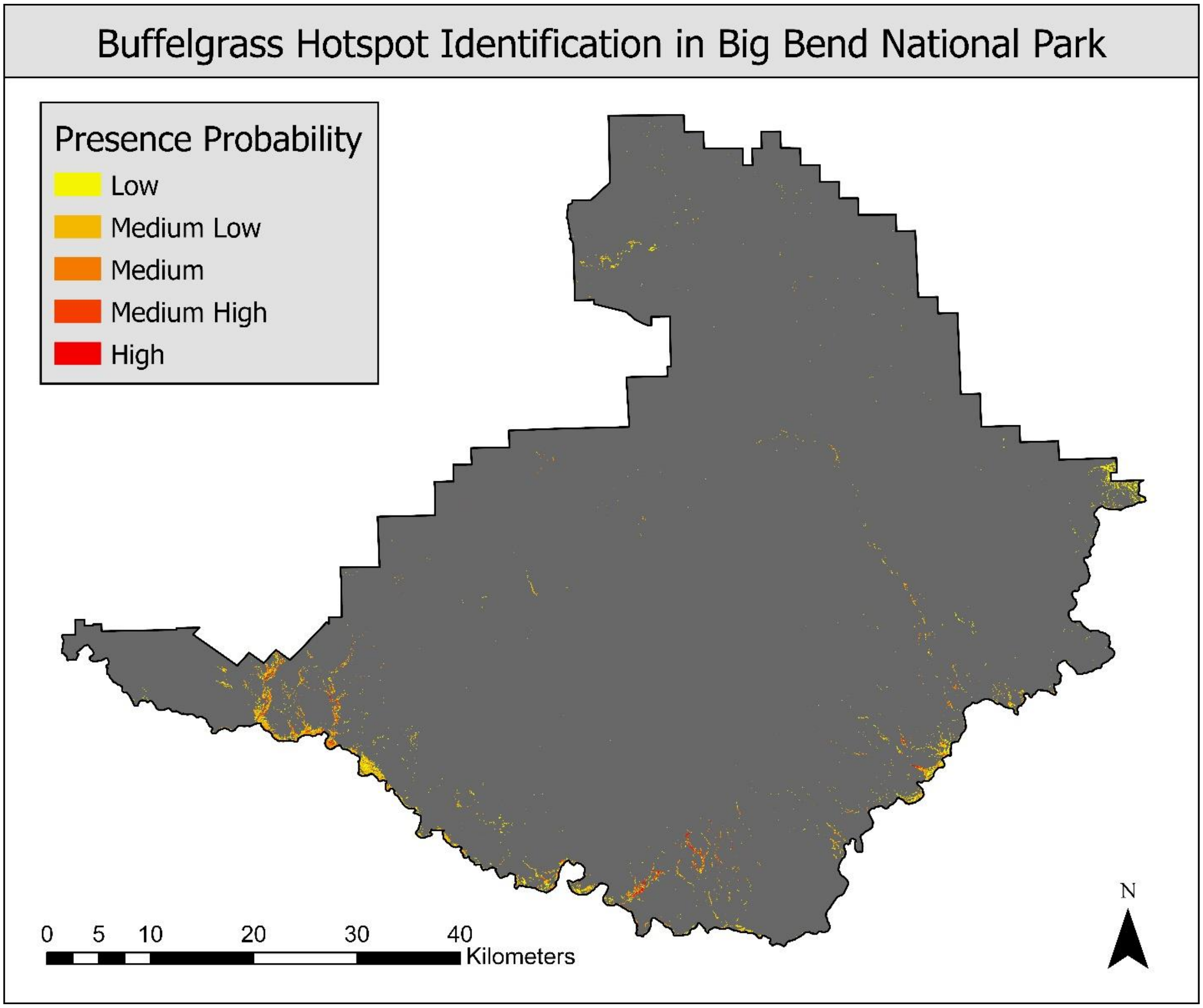

Figure A1: The Buffelgrass detection map, modified to the specifications of the project partners requests.

Appendix B: Buffelgrass Detection Map with Accessibility

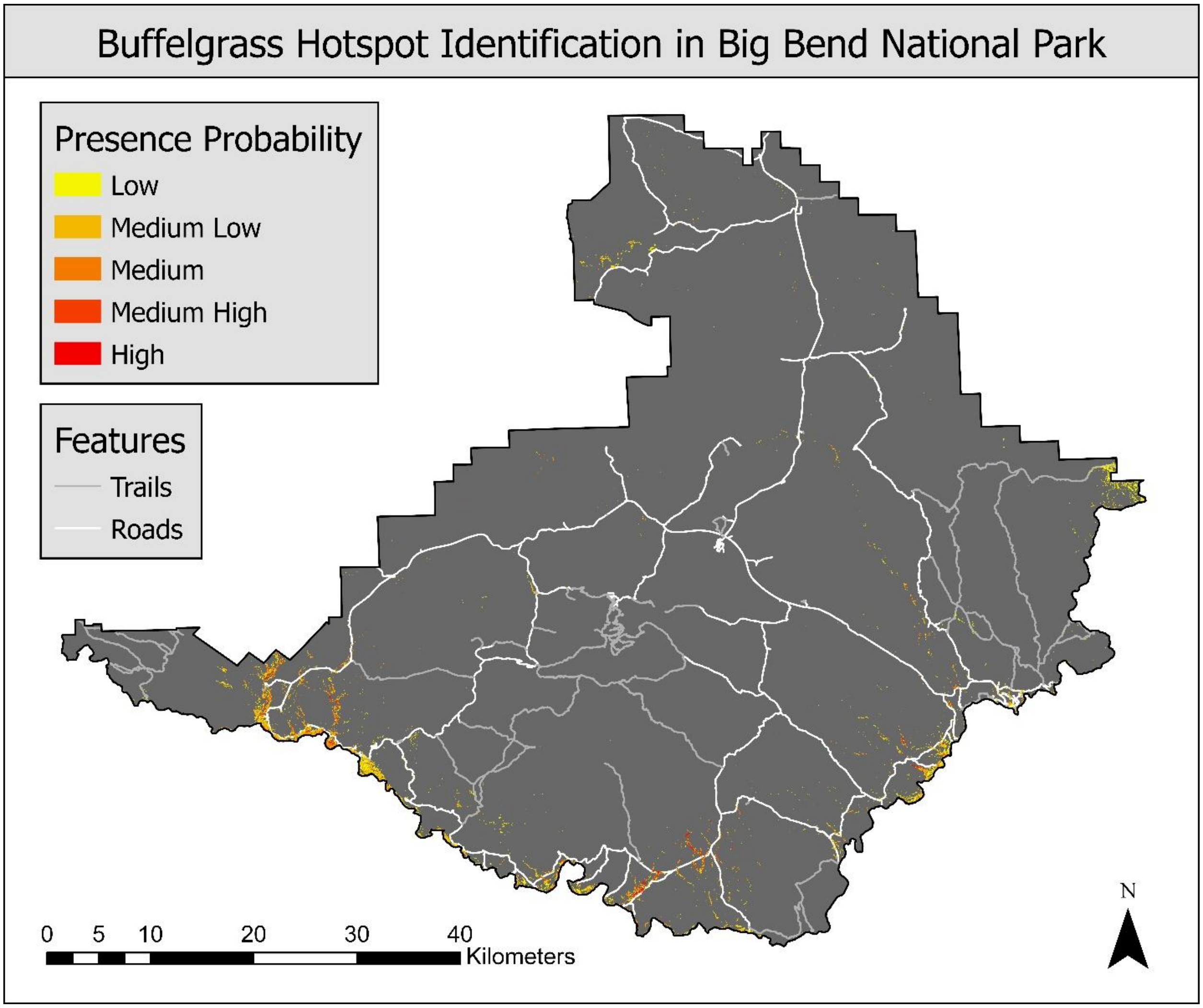

Figure B1: The Buffelgrass detection map, modified to the specifications of the project partners requests to include roadways and trails.

Appendix C: Buffelgrass Detection Map with Accessibility and Zones

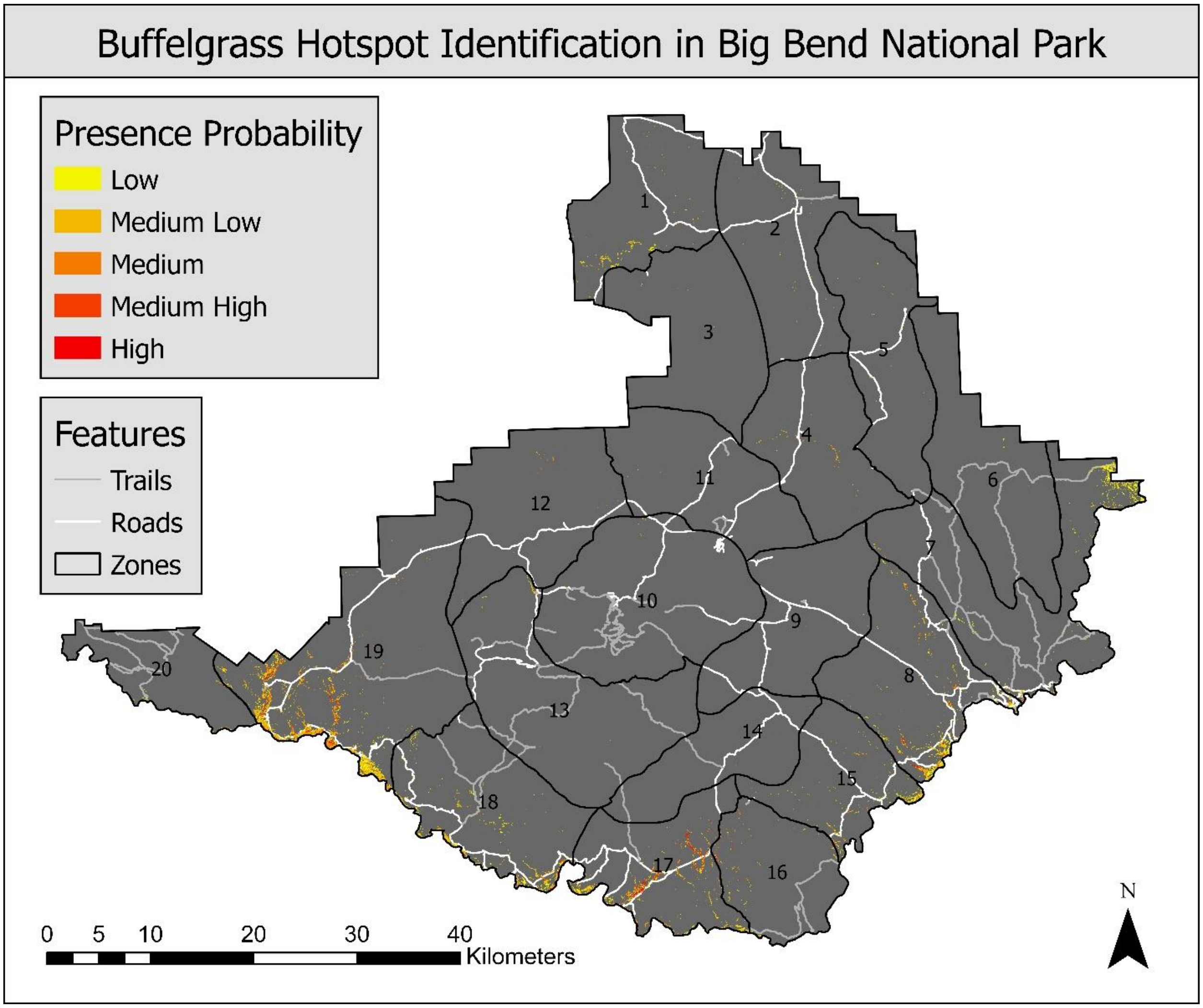

Figure C1: The Buffelgrass detection map, modified to the specifications of the project partners requests including accessibility and zonal overlay.

Appendix D: Large Region of High Presence Probability of Buffelgrass within the Park.

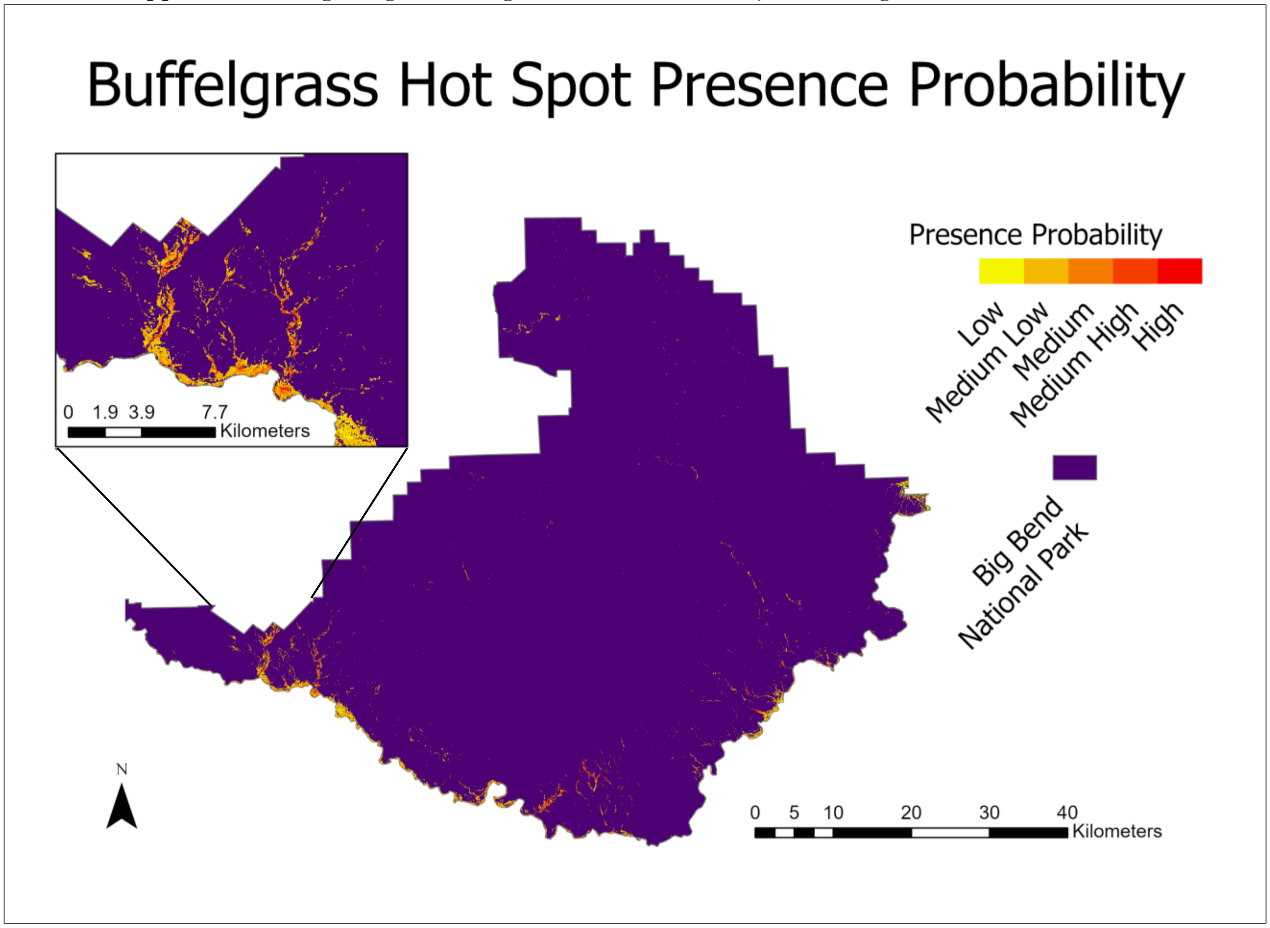

Figure D1: Outlines a region along the Southwest corner of the park with high probability of Buffelgrass presence. Due to this region being easily accessible, in-situ data was available and visual validation showed a strong correlation between the probability map and known Buffelgrass locations. The same in-situ data was also used as part of the Confusion Matrix calculations.

Appendix E: Confusion Matrix

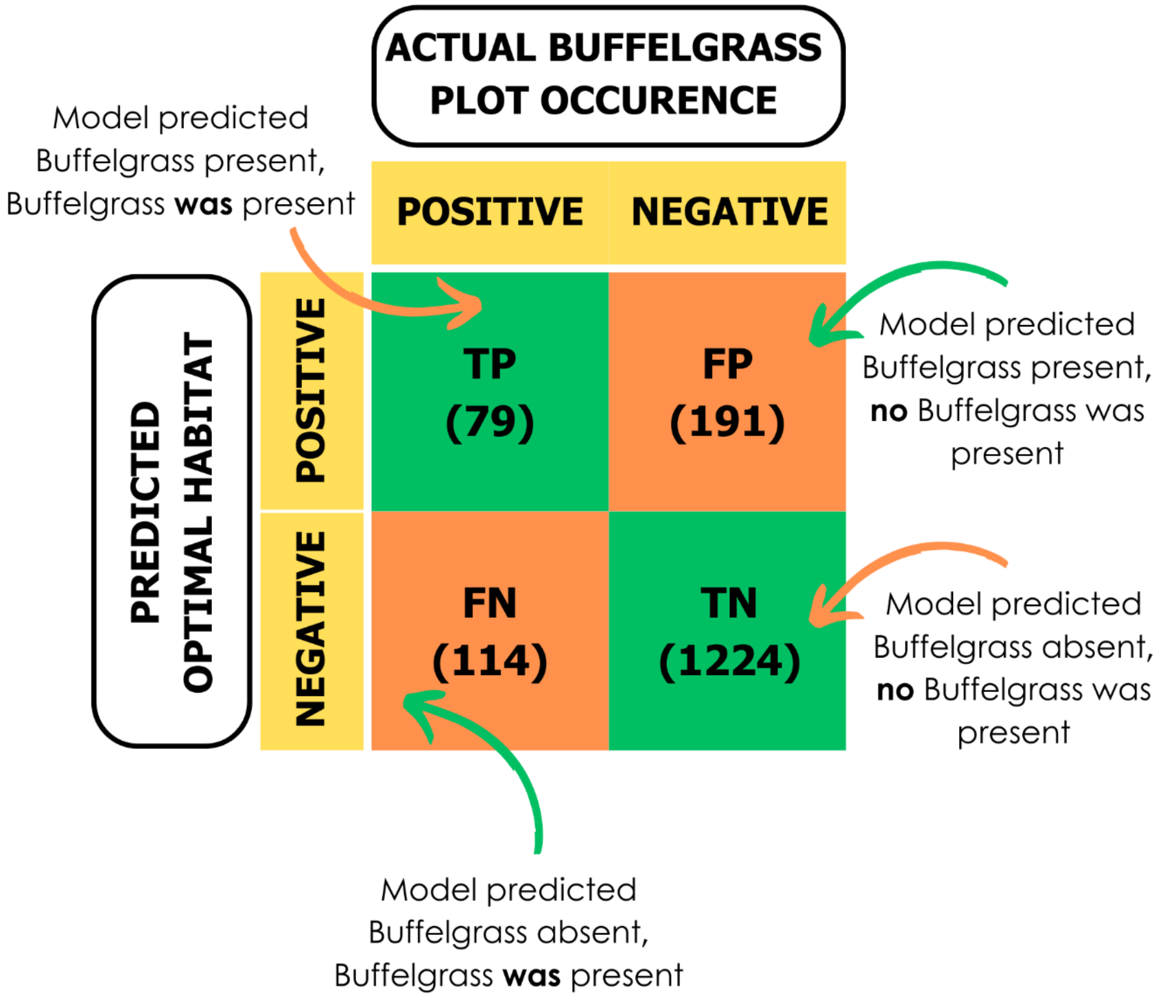

Figure E1: Shows the values used to determine the Confusion Matrix for Buffelgrass presence in the Buffelgrass detection map that determined an overall accuracy of 81%.

Appendix F: Analysis variables used for fire risk assessment

Table F1

Weighted variables used as part of the fire risk assessment with variable validation

Name	Variable	Rescale	Explanation	Weight
FirePt_FRA	Fire history points per zone rescaled from [0,1] where 0 indicates no prior fire history, and 1 indicated the zone with the greatest past fire history.	[0,1]	Greater fire history = greater risk for recurrence	1
Tmax_FRA	Average change in maximum monthly temperatures between 2021-2040 and 2041-2060 rescaled from [0,1] where 0 indicates the minimum increase in average maximum temperatures and 1 indicates the greatest increase in average maximum temperatures.	[0,1]	Greater temperature increase = greater fire risk	1
Precip_FRA	Average change in monthly precipitation between 2021-2040 and 2041-2060 rescaled from [1,0] where 1 indicates the greatest decrease or minimum increase of precipitation, and 1 indicates the maximum increase in average monthly precipitation.	[1,0]	Lesser precipitation increase = greater fire risk	1
HS_FRA	Numerical value assigned to each zone based on the habitat suitability rating for Buffelgrass. The value increases as the suitability for buffelgrass increases.	[0,1]	Greater suitability for invasive species = greater fire risk	1
Trails_FRA	The total length of trails that lie in each zone was calculated and rescaled from [0.1] where 0 indicates zones where there are no trail systems and 1 indicated the maximum length of trail systems in a given zone.	[0,1]	Greater accessibility via trail systems = greater fire risk	0.5
Roads_FRA	The total length of roads that lie in each zone was calculated and rescaled from [0.1] where 0 indicates zones where there are no roadways and 1 indicated the maximum length of roadway in a given zone.	[0,1]	Greater accessibility via roadways = greater fire risk	0.5
Camp_FRA	The cumulative sum of primitive campsites and developed campsites were calculated for each zone, then rescaled from [0,1] where 0 indicates no campsites within a zone, and 1 indicates the maximum number of campsites in a given zone.	[0,1]	Greater campsite occurrence = greater fire risk	0.75
Fac_FRA	The total area of developed facilities was calculated for each zone then rescaled from [0,1] where 0 indicates no developed facilities and 1 indicates maximum developed facility area in a given zone.	[0,1]	More developed areas = greater priority (increase risk)	1
Cattle_FRA	Livestock trespass survey point sums were calculated by zone to establish which zones experience maximized trespass traffic. The sums were rescaled from [0,1] where 0 indicates no known livestock trespass survey records, and 1 indicates the zone with the maximum trespass survey records.	[0,1]	Greater livestock trespass = greater fire risk (due to invasive grass species transport)	0.25
Grass_FRA	The total known points of Buffelgrass, Johnsongrass and Lehmann Lovegrass were combined and rescaled from [0,1] where 0 indicated there were no known grass species in the zone, and 1 indicated there were the greatest number of invasive grass species locations in the given zone.	[0,1]	Greater invasive grass occurrence = greater fire risk and fire fuel	1

Appendix G: Precipitation timeline table for four weather stations

Table G1

Precipitation timeline from 2016-2023 of potential green-up periods for Buffelgrass from the four weather stations.

			Lajitas		**Castolon**	
Year	**Green-Up Time Frame**	**OMGx Date Value**	**rainfall dates**	**rainfall mm**	**rainfall dates**	**rainfall mm**
2016	8/27 - 9/26	240-270	8/25-8/26	35.1	8/24-8/26	24.4
2017	5/20-10/22	140-295	5/30-5/31	27.4	5/22 & 5/30-5/31	64.8 & 32.8
			8/8	21.6	no data	NA
			9/20-9/24	23.9	no data	NA
2018	9/1-9/21	244-272	8/12-8/14	28.4	8/10-8/13	33.8
			9/19-9/21	25.4	9/2 & 9/7-9/8	48.3 & 22.4
2019	6/13-9/27	164-270	NA	NA	NA	NA
			7/7-7/8	20.3	7/7-7/9 & 7/18	26.9 & 23.4
			9/9-9/10	19.8	NA	NA
2020	9/25-10/11	269-285	9/9-9/14	29.7	9/9	32.5
2021	8/14-9/19	226-262	NA	NA	8/15-8/18	21.1
			NA	NA	NA	NA
2022	9/6-10/14	249-287	8/16-8/18	35.3	8/20-8/23	33
			9/1	35.3	9/1-9/3	37.6
2023	5/26-6/19	146-170	5/28	41.4	5/23	21.6
Year	**Green-Up Time Frame**	**OMGx Date Value**	**Chisos Basin**		**Panther Junction**	
2016	8/27 - 9/26	240-270	**rainfall dates**	**rainfall mm**	**rainfall dates**	**rainfall mm**
2017	5/20-10/22	140-295	8/11-8/14	94.7	8/18 - 8/20	41.9
			5/22	36.6	5/22	59.2
			8/13-8/14 & 8/18-8/20	27.9 & 33.8	8/15-8/16	21.8

2018	9/1-9/21	244-272	9/19-9/21	35.8	9/20-9/24	21.8
			8/11-8/15	53.1	8/11-8/14	41.7
2019	6/13-9/27	164-270	9/8-9/9 & 9/16-9/19	57.4 & 54.9	9/2 & 9/8	87.9 & 38.9
			6/10-6/11	21.3	6/3-6/4	23.6
			no data	NA	7/4-7/5	42.2
2020	9/25-10/11	269-285	9/21	80	9/21-9/22	37.3
2021	8/14-9/19	226-262	9/1-9/2 & 9/9-9/11	29.5 & 22.9	9/1 - 9.2 & 9/9-9/11	21.3 & 24.9
			8/2-8/5 & 8/12-8/13	65 & 33	NA	NA
2022	9/6-10/14	249-287	9/17	31	NA	NA
			8/29-8/30	23.4	8/20-8/23	33
2023	5/26-6/19	146-170	9/1-9/4	60.5	9/1-9/4	42.4
			5/28	48.3	5/28	33