

## Sonoran Desert Ecological Conservation Identifying and Mapping Category 1 Invasive Species in the Sonoran Desert in Southern Arizona Using Harmonized Landsat and Sentinel Data

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**Abstract:** Buffelgrass (*Cenchrus ciliaris*) is an invasive perennial grass that is especially pervasive in the Sonoran Desert, located in the southwestern United States and northern Mexico. Saguaro National Park, Tumacácori National Historical Park, and the surrounding Pima and Santa Cruz Counties in Arizona are managing large-scale infestations of buffelgrass, which outcompete native vegetation and increase the risk and severity of wildfires, damaging the ecosystem and threatening the local community. This project aims to test the feasibility of using remote sensing to predictively map the spread and distribution of buffelgrass, as an alternative to other costly and time-consuming methods. We used Multi-Source Land Imaging (MuSLI) data for 2016-2019 and Normalized Difference Vegetation Index (NDVI) & Modified Soil Adjusted Vegetation Index 2 (MSAVI2) data derived from Harmonized Landsat-Sentinel (HLS) imagery to identify buffelgrass locations after significant rain events from 2016-2024. In addition, we created two habitat suitability models that may help identify where buffelgrass exists, and where it could spread. Our study showed no relationship between green-up identified using HLS-based MuSLI, NDVI, and MSAVI2 images and known locations of buffelgrass. More research and robust data are needed to determine the feasibility of multispectral imagery to be used as a method of identifying buffelgrass. Our Saguaro National Park suitability model aligned well with known buffelgrass points. The mean suitability values of the known points were 7.13, on a scale of 1-10. Both habitat suitability models of the park and entire study area, will allow partners to identify areas most susceptible to buffelgrass infestations, which may support ongoing management efforts to control buffelgrass.

**Key Terms:** buffelgrass, MuSLI, green-up, Harmonized Landsat and Sentinel-2, habitat suitability model, Saguaro National Park, NDVI, MSAVI2

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## 1. Introduction

Since ranching began in the Southwestern United States, many non-native species have been introduced to the region, as cattle and other livestock increased demand for grazing rangeland. Buffelgrass (*Cenchrus ciliaris*) was introduced in the 1930s and became a desirable choice for livestock grazing and erosion control, (Ines, 2022; Brooks et al., 2004; Drake et al., 2016; Hovanes et al., 2023; Elkind et al., 2019). These perennial grass species were appealing to land managers due to their ability to produce three times as much foraging biomass for livestock as native grasses, thereby increasing the land's carrying capacity (Martin et al., 1995). While this was beneficial for livestock grazing, the conversion of deserts into managed rangeland for the purpose of livestock grazing in the 20<sup>th</sup> century has had unintended consequences that are still being felt today. With the removal of cattle and focus on desert conservation, buffelgrass has become one of many invasive species in the region that has grown out of control (U.S. Department of the Interior, 2011).

Buffelgrass has become highly invasive in North America and has proven difficult to remove. Land managers call buffelgrass the “archenemy of the Sonoran Desert” due to its ability to outcompete native species and increase the risk of wildfires (U.S. Department of the Interior, 2024; U.S. Department of the Interior, 2011). Buffelgrass' ability to outcompete native species may be due to its deep roots (up to 2.5 meters) that can access water supply both faster and for a longer period of time than native plants (Marshall et al., 2012). Studies in Australia found the presence of buffelgrass had a negative correlation with species richness, which supports the idea that buffelgrass infestations reduce biodiversity (Clarke et al., 2005; Jackson, 2005). Buffelgrass increases susceptibility to wildfires and benefits from the fires themselves, creating a positive feedback loop for the species. Its presence in desert landscapes increases the risk of wildfires due to the sheer surface area that it covers, eliminating the fire breaks that naturally occur in a desert ecosystem. This, combined with its ability to rebound quickly after fires, sets it apart from native species in an ecosystem that is not adapted to fires. Furthermore, buffelgrass infestations create high fuel loads and higher fire temperatures than those observed in other grassland ecosystems, leading to greater habitat destruction (McDonald & McPherson, 2016). As a result, buffelgrass is locally known as a Category 1 invasive species; which is defined as having rapid ecosystem conversion potential (F. Foley, personal communication, February 13<sup>th</sup>, 2025; Van Klinken, Friedel, & Grice, 2006).

Given buffelgrass's ability to rapidly transform desert into grassland, land managers must work quickly to both map and treat buffelgrass infestations to prevent future spread. Current control options for buffelgrass include manual removal, applied herbicides, controlled burning, and controlled animal grazing (Marshall et al, 2012). The most time-effective and cost-effective way of treatment is herbicidal treatments, but it has time constraints, as herbicide is only effective when buffelgrass green-up is at least 50% (Rosenblatt et al, 2023). Additionally, some studies show that buffelgrass must be treated three times before the herbicide is effective (McDonald & McPherson, 2013). To support this work, we are partnering with the National Park Service (NPS), the United States Fish and Wildlife Service (USFWS), and the United States Geological Survey (USGS). Our study area includes Saguaro National Park, Tumacácori National Historical Park, and the surrounding Pima and Santa Cruz Counties.

Previous research within Saguaro National Park employed remote sensing data to train satellite models by detecting and mapping buffelgrass using DigitalGlobe WorldView-2 satellite imagery acquired between 2013 and 2015 and Unmanned Aerial Vehicle (UAV) imagery to help land managers monitor the spread of buffelgrass and prioritize areas for control (Elkind et al., 2019; Brenner, Christman, & Rogan 2012). Our partners at Saguaro National Park conducted aerial surveys of the park via helicopter in 2019, and field surveys have continued, yet both have proven to be costly and time-consuming (F. Foley, personal communication, January 29<sup>th</sup>, 2025). To address gaps in data collection, our DEVELOP team's project aimed to map the spread and distribution of buffelgrass throughout our study area using NASA Earthdata products in combination with ancillary datasets provided by partners (Figure 1).

Our goal was to create a buffelgrass distribution time series from 2016-2024 to identify the distribution and spread of buffelgrass using vegetation green-up, habitat suitability, and in situ data. We created a habitat

suitability model to identify the areas that are most susceptible to buffelgrass infestations. By providing the distribution of buffelgrass and identifying areas that are susceptible to future infestations, we aimed to create a resource that allows our partners to determine if their management plans are in alignment with the current spread of buffelgrass throughout the study area and prioritize areas for treatment. Based on the success of these methods, this project could serve as a template for future invasive species assessments via remote sensing.

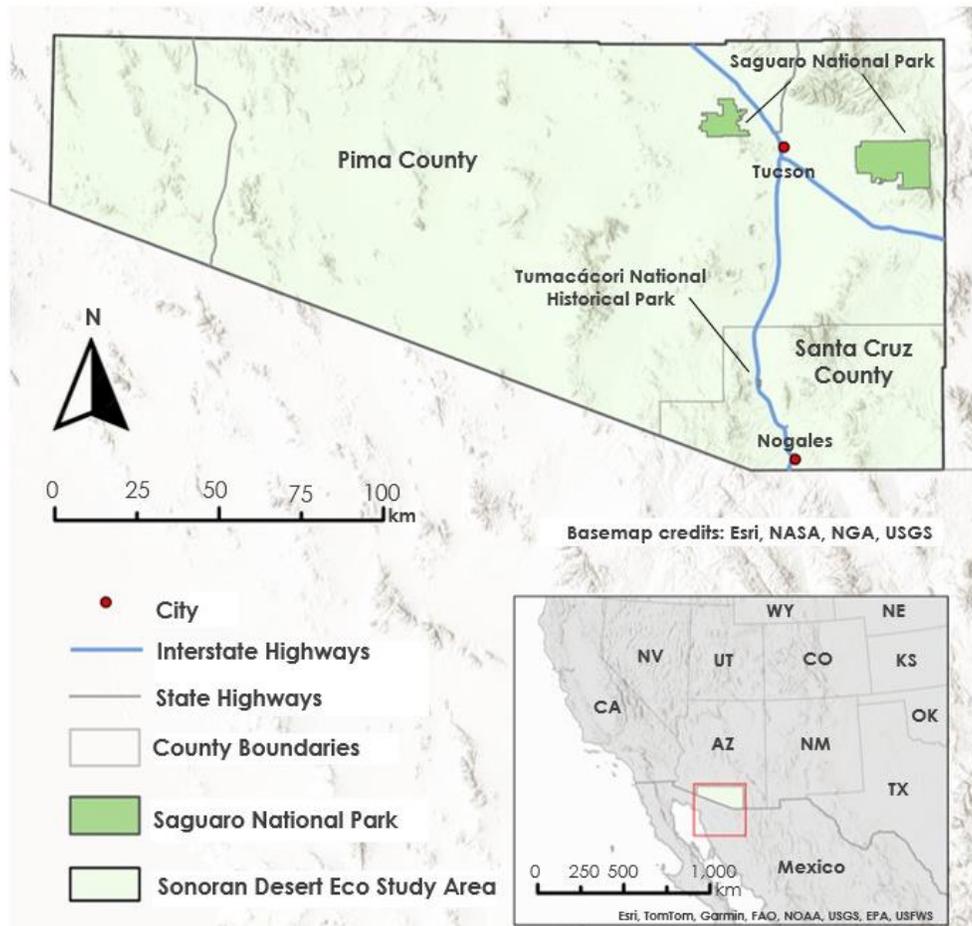


Figure 1. Study area map indicates Pima and Santa Cruz counties in Arizona (27,004 km<sup>2</sup>), encompassing Saguardo National Park and Tumaacacori National Historical Park. Saguardo National Park is split into two regions divided by the city of Tucson, the Tuscon Mountain District (West) and Rincon Mountain District (East).

## 2. Methodology

### 2.1 Data Acquisition

#### 2.1.1 Remotely Sensed Data

To identify buffelgrass in our study area, we gathered Harmonized Landsat Sentinel-2 (HLS) Multi-spectral Instrument Surface Reflectance Daily Global 30m v2.0 from NASA's Earthdata search (Masek et al., 2021). From this dataset we downloaded the red band (labeled as B04) and the near infrared band (labeled as B05). These specific bands were used to calculate the Normalized Difference Vegetation Index (NDVI) and the second Modified Soil Adjusted Vegetation Index (MSAVI2). We also downloaded the Fmask layer to mask values that interfered with an accurate reading, such as cloud cover, rain, and snow. The data was split into the European Space Agency's Sentinel-2 tiling system which itself is a slightly modified version of the Military

Grid Reference System (MGRS). MGRS is based on the UTM projection. It has five character tile designations for which the two digits at the beginning represent the UTM zone, the first character after that represents the latitude band, and the last two letters correspond to individual tiles that are a little over 100 km on a side (<https://hls.gsfc.nasa.gov/products-description/tiling-system/>). Seven of these tiles covered our study area. These grid designations are 12RVV, 12RWV, 12STA, 12SUA, 12SVA, 12SVB, and 12SWA. We selected specific dates to download from National Oceanic and Atmospheric Administration's (NOAA) National Weather Service (NWS) Data platform, NowData for the years 2016, 2018-2020, 2024 that corresponded to significant rain events, which were defined as greater than or equal to one inch of rain over a 3–5-day period (National Park Service, 2019). We downloaded images one week before, three weeks after and seven weeks after significant rain events. Images were not always available exactly three or seven weeks after significant rain events, or with minimal cloud cover, so the clearest and closest images to that timeframe were downloaded. We gathered these images to assist in the creation of our vegetation distribution time series.

Table 1

*Collection of HLS Sentinel-2 images used for NDVI, from 2016, 2018-2020, and 2024 with IDs*

Satellite Sensor	Collection Category	Collection Number	Date Acquired
HLS.L30	T1	2	01/21/2016
HLS.L30	T1	2	02/20/2016
HLS.L30	T1	2	02/07/2018
HLS.L30	T1	2	04/10/2018
HLS.L30	T1	2	11/26/2019
HLS.L30	T1	2	12/19/2019
HLS.L30	T1	2	01/05/2020
HLS.L30	T1	2	01/30/2020
HLS.L30	T1	2	02/04/2020
HLS.L30	T1	2	03/05/2020
HLS.L30	T1	2	03/30/2020
HLS.L30	T1	2	01/10/2024
HLS.L30	T1	2	02/18/2024
HLS.L30	T1	2	03/13/2024

We also made use of a Landsat-based phenology data set known as the MuSLI (Multi-Source Land Imaging) Multi-Source Land Surface Phenology Yearly North America 30 m V011 (MSLSP30NA) that is available on EarthData for 2016-2019. This data set provides phenological metric images that display green-up statistics. Green-up statistics are displayed by the day that the vegetation reaches a certain percent of greenness. MuSLI has been used previously for identifying buffelgrass in other studies (Lemon, 2024) but is not necessarily indicative of current conditions, due to the dynamic environmental conditions in the Sonoran Desert that can vary in conjunction with precipitation patterns.

We gathered MuSLI data from NASA Earthdata search website (Friedl, 2021). This data describes plant phenology at 30-meter resolution from 2016 to 2019. These data were split into a grid, and our study area spanned 11 of these grids. We selected the following grid code files from the MGRS system to encompass our area; 12SVA, 12SWB, 12SUB, 12SWA, 12SUA, 12SVB, 12STB, 12STA, 12RVV, 12RUV, 12RWV. These images have undergone cloud cover removal. These data were split into a grid, and our study area spanned 11 of these grids. We selected the following grid code files to encompass our area; 12SVA, 12SWB, 12SUB, 12SWA, 12SUA, 12SVB, 12STB, 12STA, 12RVV, 12RUV, 12RWV. We also gathered these data to assist in

the creation of our vegetation distribution time series. We downloaded these data as NetCDF files and converted them to TIFF files to process in ArcGIS Pro v3.3.2.

### *2.1.2 National Park Data*

We acquired most of our feature data from the NPS online DataStore and from ArcGIS Living Atlas. We used park boundaries (2025) and trails (2019) from the National Park DataStore and the surrounding cities, road network, streams, and county boundaries from ArcGIS Living Atlas. Our partners shared field data for Saguaro National Park, including buffelgrass treatment data, vegetation classes, and washes data. We received additional known buffelgrass points in Saguaro National Park from iNaturalist. We also added a hydrologic soil group layer, which was provided by Idaho State University from the Soil Survey Geographic Database. To better understand the topography of the study area, we downloaded the one arc-second Digital Elevation Model (DEM) from USGS at a 30-meter spatial resolution (USGS Science Data Catalog, 2021).

We gathered historical precipitation data from the NOAA's National Weather Service (NWS) data platform NowData (National Weather Service, 2016-2024). This provided us with a list of weather stations in southern Arizona, with historic precipitation tables for each weather station. We selected three of these weather stations to create a triangle that would roughly cover our study area to measure widespread rain events. These station names are "TUMACACORI NM", "Tucson Area" and "SAGUARO NATIONAL PARK". From each station we gathered precipitation in inches during 2016-2024. We used these historic precipitation tables to create a potential green-up timeline for buffelgrass. We specifically gathered data during the following months to target winter green-up periods: January, February, March, November, and December. We compiled a timeline of significant rain events for every weather station. To target rain events that covered our whole area, we only selected rain events that had precipitation greater than one inch in all three of our weather stations. This gave us one significant rain event for 2016, 2018-2020, and 2024. The years 2017, 2021, 2022 and 2024 did not have any significant rain events that would cause a green-up, so we excluded these years. Further, we used this weather station data to determine if we should use Daymet precipitation data (Thornton, 2022) or GPM IMERG data, downloaded from Giovanni. We chose Daymet because it aligned more closely to the climate station data and had a finer spatial resolution at 1 km, compared to GPM IMERG.

## **2.2 Data Processing**

### *2.2.1 Habitat Suitability Processing*

Our team computed two buffelgrass habitat suitability models, one encompassing the entire study area and another specific to Saguaro National Park. We developed both models using the suitability modeler tool in ArcGIS Pro v3.3.2. These models use weighted overlays to calculate suitability with a suitability value ranging from 1, least suitable for buffelgrass, to 10, most suitable for buffelgrass. Both models included the following criteria: aspect, elevation, slope, average annual precipitation, hydrologic soil groups, and distance from valleys. Vegetation class data was limited to Saguaro National Park, so this suitability model included an extra variable.

The aspect, slope, and elevation criteria were all derived from the USGS 30-meter Digital Elevation Model (Figures A1, B1, & C1). We used the aspect tool in ArcGIS Pro v3.3.2 to show aspect values made by a geodesic method. These values ranged from -1 (flat), to 360. Knowing that buffelgrass prefers south facing aspects, we added this layer to our habitat suitability model giving south, southeastern, and southwestern aspects the highest values, with values decreasing as aspects turn northward. Flat values were given a value of 6 (Figure C2; Innes, 2022). We created the elevation criteria by directly adding the USGS 30-meter Digital Elevation Model to our suitability model. We set the ideal value of buffelgrass elevation at between 650 meters above sea level and 1400 meters above sea level, with suitability values falling above or below those thresholds (Figure A2; Innes, 2022). The slope variable was derived using the slope tool on ArcGIS Pro

v3.3.2 and are reported as a percentage. We added the layer into the habitat suitability model with ideal values ranging from 25% to 34% slope (Figure B2; Innes, 2022).

We calculated the sum of precipitation from each of our study periods available years (2016-2023), then averaged those sums together to get an average annual precipitation throughout our study years. After these files were downloaded, we mosaiced them together, and clipped them to our study area to remove excess data. We assigned high suitability values to have a range of 375 - 750 millimeters annually (Figures E1 & E2; Innes, 2022).

Given that buffelgrass can cause soils to have high runoff potential (Innes, 2022), we added a hydrologic soil group layer which groups soils into low to high runoff potential from A-D. We gave higher suitability values to hydrologic soil groups that fit these parameters. Hydrologic soil groups with lower runoff potential and unknown groups had their value decrease respectively (Figures F1 & F2).

Washes provide ideal growing conditions for buffelgrass, so factoring in buffelgrass's proximity to washes was added to our models upon recommendation from our partners. The washes data provided by our partners did not fit our whole study area, so we used it as a reference to compare to a geomorphon landform layer created from our USGS 30-meter Digital Elevation Model. This geomorphon landform layer is classified into nine landforms: flat, peak, ridge, shoulder, spur, slope, hollow, footslope, valley, and pit areas. By running zonal statistics, we saw that most of the washes occur within the valley class, and we set a distance accumulation from the valleys. Pixels that were closer to the valleys received a higher suitability value, compared to pixels further away (Figures D1, D2, & D3).

We added vegetation class data to our Saguario National Park Suitability Model but not our Study Area Model due to limited vegetation data for areas other than in the national park. We gave maximum suitability values to vegetation classes buffelgrass commonly invades and gave minimum values to classes it does not invade. Buffelgrass preferred desert/shrubland classes (commonly containing brittle bush, acacia, spiny hackberry, Arizona mimosa, honey mesquite, creosote bush, saltbush, triangle bur ragweed, desert ironwood, yellow paloverde, and saguaro cacti; Figures G1 & G2; Innes, 2022).

### *2.2.2 Vegetation Distribution Time Series Processing*

After downloading MuSLI data, we then mosaiced the TIFF files to represent our study area. We used the data during the given years and selected the Onset Greenness Maximum (OGMx) and OGMx2 settings to analyze the first and second period of 90% greenness increase. Then, we selected the 50PCGI (Wallace et al., 2016) and 50PCGI2 settings to find the first and second period of 50% greenness increase. Moreover, we selected the Onset Greenness Minimum (OGMn) setting to analyze the first cycle of 85% greenness decrease for the whole study area to target specifically areas with buffelgrass greenness decrease.

We utilized HLS images to compute NDVI (Kriegler, 1969; USGS, 2024) and MSAVI2 (Qi et al, 1994) changes that correlated to our precipitation timeline gathered from NOAA. We also downloaded these images to assess our habitat suitability model by looking for an increase in either vegetation index to detect buffelgrass presence, and to create a vegetation distribution time series. We selected NDVI and MSAVI2 to measure the greenness of a 30m pixel. MSAVI2 minimizes the effect of bare soil (Esri, 2025), which we expected to assist in buffelgrass identification. To calculate the vegetation indices, we used surface reflectance from the near-infrared band labeled B05 (NIR), and the red band labeled B04 (RED), from HLS.

Two python scripts were written in version 3.13. The first script calculated NDVI, using the NDVI equation (1), and removed any pixel that contained clouds, water, snow, rain shadow, and rain shadow adjacent using the Fmask band. This program was also modified to process data using the MSAVI2 equation (2) using the

same variables as NDVI. The second program mosaiced the processed HLS tiles together and clipped them to our study area.

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

$$MSAVI2 = \frac{1}{2} \times \left( 2(NIR + 1) - \sqrt{(2 \times NIR + 1)^2 - 8(NIR - RED)} \right) \quad (2)$$

## 2.3 Data Analysis

### 2.3.1 Buffelgrass Habitat Suitability Model

After the suitability models were displayed with all layers, we ran a sensitivity analysis to determine which weights should be used. A sensitivity analysis was done by testing each criterion in both models at different weights. We determined which weights to use by assessing the modeling results with our known buffelgrass points. At first, the average annual precipitation data was given the most weight in both suitability models because buffelgrass greens-up following large rainfall events. Weighting the model like this gave high suitability values to high elevation areas. The issue with this approach is that we had no validation data in these higher elevation locations. We also recognized that precipitation events were highly variable across our study area. Because of this, precipitation was given the lowest weight in the model. Vegetation classes were given the highest weight as 88% of known buffelgrass points aligned with the shrubland class in our vegetation class layer. All other variables' weights were adjusted to better align with our validation points of known buffelgrass points. Partners gave some input on which data layers they thought were most important, but the weights were ultimately decided by comparison to ground truthed points.

Table 2

*Saguaro National Park Suitability Model weighted values*

Criteria	Weighted Percent
Aspect	20%
Elevation	15%
Slope	15%
Average Annual Precipitation	5%
Hydrological Soil Group	5%
Distance From Valleys	15%
Vegetation Class	25%

Table 3

*Study Area Suitability Model weighted values*

Criteria	Weighted Percent
Aspect	20%
Elevation	20%
Slope	20%
Average Annual Precipitation	10%
Hydrologic Soil Group	10%
Distance from Valleys	20%

We used the buffelgrass field data to verify the accuracy of both of our two habitat suitability models. We ran the extract multi-value tool in ArcGIS Pro v3.3.2 to give suitability values to each point of buffelgrass in the Saguaro National Park Suitability Model. This added the suitability value of each buffelgrass point in the layer's attribute table. We created histograms for both models, where the x-axis displayed the suitability value of the buffelgrass points, and the y-axis displayed the number of buffelgrass points. We used a visual comparison to examine the differences between the two models. We calculated a 95% confidence interval for both histograms to identify a range for the true mean of buffelgrass in our study area. We overlaid our suitability model with our confidence interval suitability values, to show areas in the model that were above the lower bound of the confidence interval.

### *2.3.2 Vegetation Distribution Time Series Analysis*

We analyzed the 2016-2019 MuSLI phenology data products OGMx, OGMx\_2, 50PCGI, 50PCGI\_2, and OGMn by cross comparing the raster cells with our known locations of buffelgrass. We used the Extract Multi Value Tool in ArcGIS Pro v3.3.2 to add the respective MuSLI values to the known buffelgrass attribute table. To help visualize our data, the results were displayed as histograms in ArcGIS Pro.

Using maps of calculated NDVI and MSAVI2 of our study area, we calculated the change in NDVI and change in MSAVI2. First, we imported NDVI and MSAVI2 layers created from the python scripts into ArcGIS Pro v3.3.2. We added the NDVI and MSAVI2 raster images for our study area three weeks post rainfall, seven weeks post rainfall, and before the rainfall. We then subtracted the three-week and seven-week sample of NDVI and MSAVI2 from the NDVI and MSAVI2 before the rainfall. This was done using the Raster Calculator tool in ArcGIS Pro v3.3.2. This gave us a total of four raster files that showed the change of both NDVI and MSAVI2 three weeks and seven weeks after a significant rain event. After looking at the change in both vegetation indices three and seven weeks after rainfall in a histogram in ArcGIS Pro v3.3.2, we found more large positive changes in both indices three weeks post rainfall. A large positive change in either vegetation index would indicate a greenness increase. Since there were more positive changes in both NDVI and MSAVI2 three weeks after rainfall compared to seven weeks after rainfall, we used the change in NDVI and MSAVI2 three weeks after rainfall for further analysis.

To examine the relationship between the change in NDVI and MSAVI2 values and suitable buffelgrass habitat, we imported the NDVI and MSAVI2 rasters into our habitat suitability model. We used the Con tool in ArcGIS Pro v3.3.2 to remove any 30m pixels in both vegetation indices that did not display a substantial positive change three weeks after rainfall. We then used the extract multi-value to points tool to obtain the suitability values that substantial changes occurred over.

## **3. Results**

### ***3.1 Analysis of Results***

#### *3.1.1 Buffelgrass Habitat Suitability Models*

The habitat suitability model for our entire study area (Figure 2) displayed more suitable habitat for buffelgrass in the eastern half of our study area. Putting our known buffelgrass points into our model gave each point a suitability value based on its location in the study area. We calculated the mean and median of the suitability values. The mean was 6.46 and the Median was 6.69, with a Standard Deviation of 1.43. We found that 846,800 acres, or 14.62% of the entire study area, had suitability values over the mean of 6.46. We ran a 95% confidence interval, and it gave us a lower bound of 3.65 and an upper bound of 9.26. This tells us with a 95% confidence rate that the true mean of all buffelgrass in the area falls in regions of our map with suitability values between 3.65-9.26. This translates into 5,223,875 acres, or 78.69% of the entire study area, had suitability values above the lower bound of 3.65.

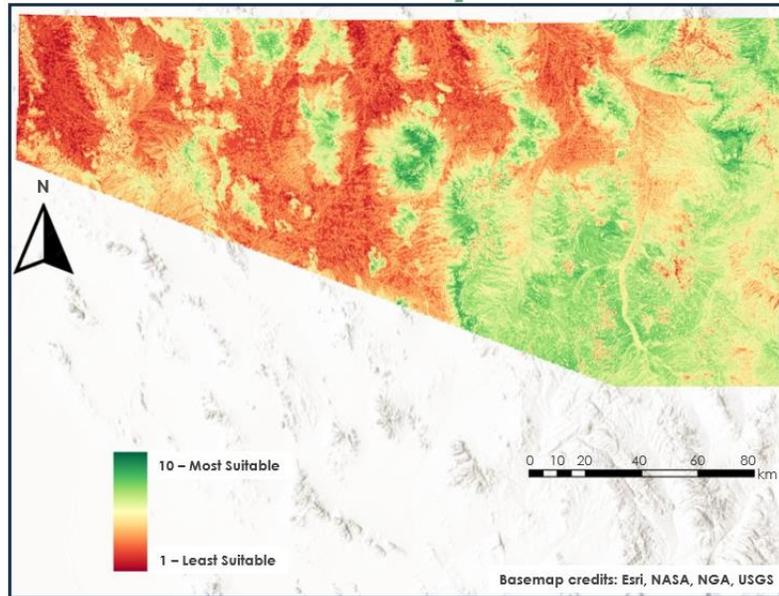


Figure 2. Habitat Suitability Model for study area

Since we received more data from partners for Saguaro National Park, our Saguaro National Park suitability model (Figure 3 & H1) provided more detail and opportunity for analysis. Overlaying our known buffelgrass points with our suitability model allowed us to assess our model. We then made a histogram of the suitability values of our known points (Figure 3). The mean was 7.13 and the median was 7.34, with a standard deviation of 1.34. We found that 15,631 acres, or 20.47% of Saguaro National Park, had suitability values over the mean of 7.13. Our 95% confidence interval for this model gave a lower bound of 4.5 and an upper bound of 9.8. This tells us with a 95% confidence rate that the true mean of all buffelgrass in the areas falls in regions of our map with suitability values between 4.5- 9.8. We determined that 56,834 acres, or 61.8% of Saguaro National Park, had suitability values above the lower bound of 4.5.

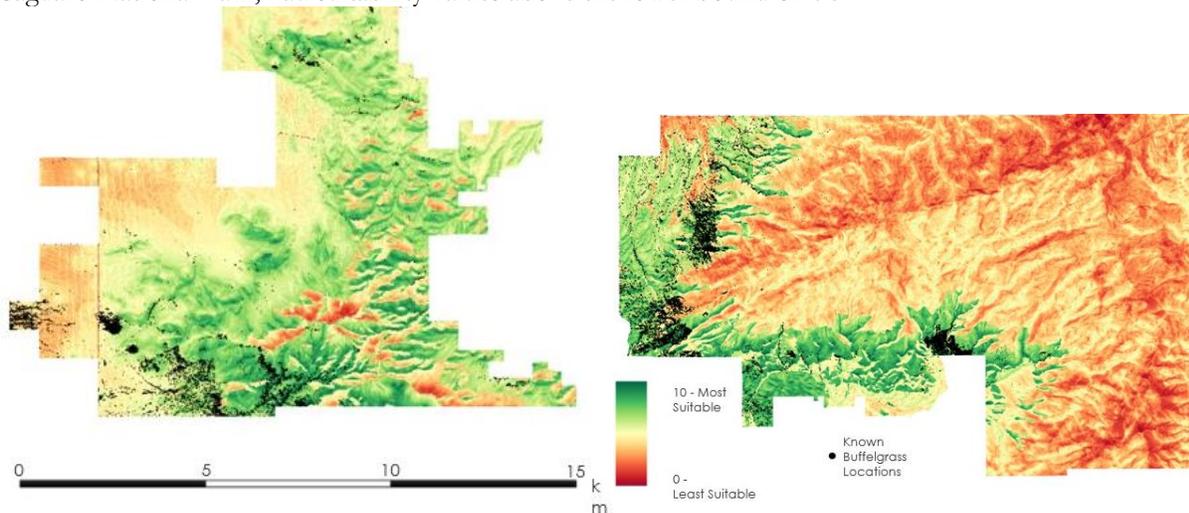


Figure 3. Habitat Suitability Model for Saguaro National Park showing Tuscon Mountain District (left) and Rincon Mountain District (right) with known buffelgrass locations (Both images are of the same scale)

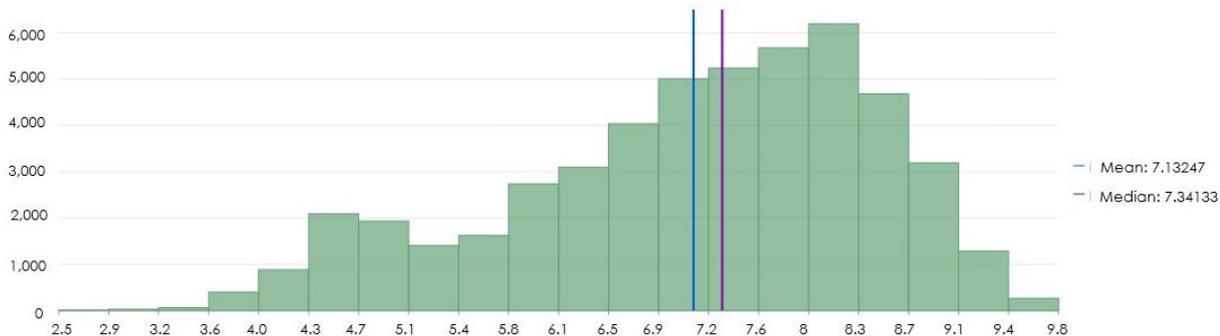


Figure 4. Histogram displaying suitability values from Saguaro National Park Suitability Model for known buffelgrass points

### 3.1.2 Vegetation Distribution Time Series Results

When analyzing the histogram of OGMx of our study area (Figure 5), we found the majority of the 30m pixels that displayed a 90% green-up did not occur during the months we were looking for buffelgrass. OGMx\_2, 50PCGI, 50PCGI\_2, and OGMn histograms showed similar results to the OGMx histogram. The OGMx of our known buffelgrass points provided by partners (Figure 6) showed that days of 90% greenness increase did not occur within the same timeframe. This histogram showed that buffelgrass points greened-up at different times throughout the year. OGMx\_2, 50PCGI, 50PCGI\_2, and OGMn histograms also showed similar results to Figure 5.

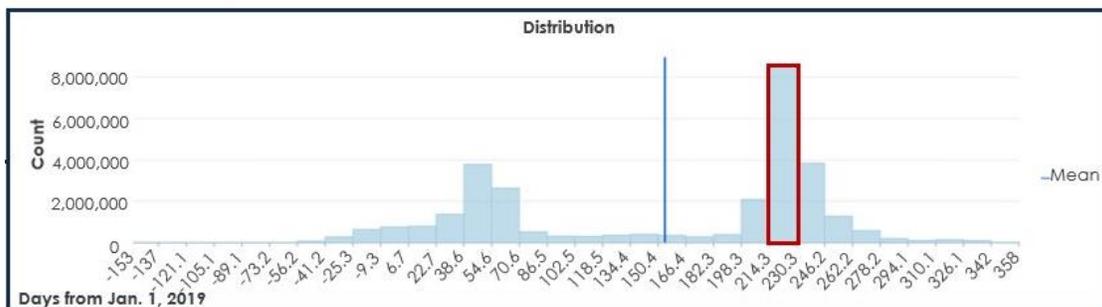


Figure 5. Green-up 90% 2019 OGMx entire study area

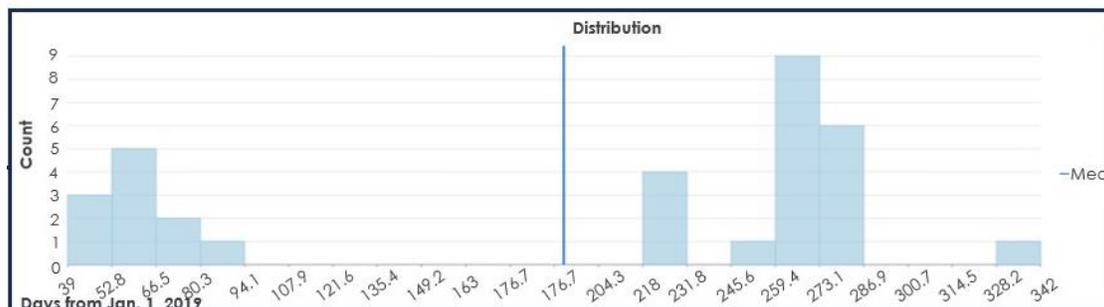


Figure 6. Green-up 90% OGMx Esri – only for known buffelgrass locations

The histogram displaying the change in NDVI across our habitat suitability model, (Figure 7), showed that most of the points of NDVI change three weeks after rainfall did not occur in areas that were highly

suitability for buffelgrass. Similarly, the histogram displaying the change in MSAVI2 across our habitat suitability model (Figure 8), showed that most of the points of MSAVI2 change three weeks after rainfall did not occur in areas that were highly suitability for buffelgrass.

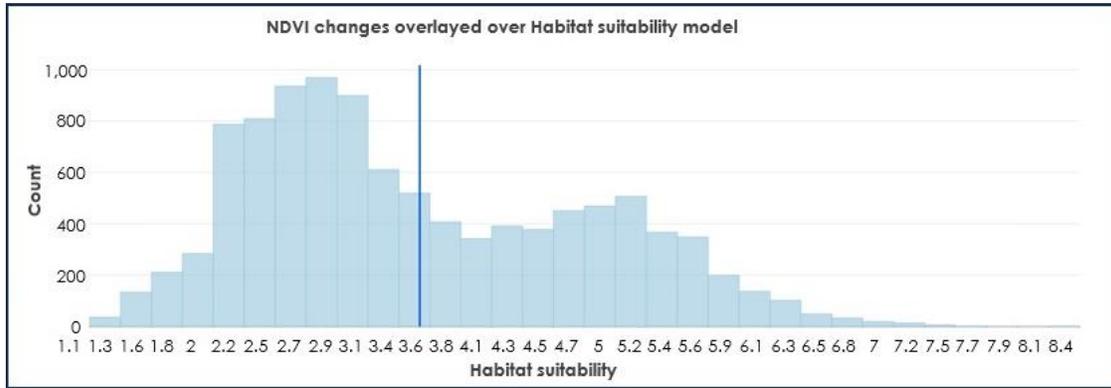


Figure 7. Histogram of NDVI changes overlaid with habitat suitability model, where the blue line indicates the mean.

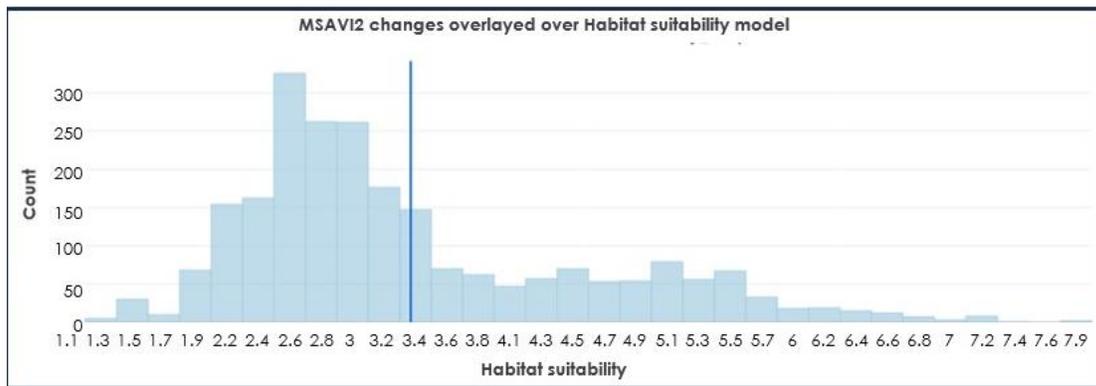


Figure 8. Histogram of MSAVI2 changes overlaid with habitat suitability model, where the blue line indicates the mean.

### 3.2 Errors & Uncertainties

#### 3.2.1 Habitat Suitability

Our habitat suitability models did not have a buffer for roads, which may have impacted our model results. Our ability to verify our model results was limited by availability of known buffelgrass points, which were only in Saguaro National Park. Furthermore, we did not have known absence points for buffelgrass, and we didn't know if certain areas of the park with no buffelgrass points have yet to be surveyed or if they have been surveyed and do not contain buffelgrass. The buffelgrass points used to create our model were also used to verify our model, which is a dependent form of validation, and may result in an overfit model. In the future, a better approach may be to use half of the points to create the model and the other half to verify the model, as an independent form of validation.

#### 3.2.2 Buffelgrass Distribution Time Series

With our study area being so large, multiple scenes were required to capture our entire study area. The East and West sections of the park had a few days difference between calculated vegetation index values (NDVI and MSAVI2). Cloud-masking resulted in large portions of the NDVI and MSAVI2 raster files being obscured. This outcome may be changes by using data with a higher temporal resolution (such as MODIS).

Sparse precipitation in the study area also caused some uncertainties - even large rain events did not cover our whole study area. This means we would not see an increase in NDVI and MSAVI2 uniformly across the study area. It is possible also that use of higher temporal resolution imagery in deriving spectral index-based indices may help in terms of generating cloud-free maps for the times of year that are most important in the identification of buffelgrass dominated areas.

## 4. Conclusions

### 4.1 Interpretation of Results

#### 4.1.1 Habitat Suitability

Our habitat suitability model for Saguaro National Park matched well with known buffelgrass points. The similarity between mean 7.13 and median 7.34 indicates a relatively normal distribution. However, our data is somewhat left-skewed due to a cluster of buffelgrass points falling within an area on the outskirts of the Tucson Mountain District deemed to be less suitable by our model. This can likely be attributed to a nearby canal in this area that is infested with buffelgrass, providing the opportunity for its spread in an area that would otherwise not be suitable for buffelgrass. The Study Area Suitability Model was less detailed in comparison to the Saguaro National Park Suitability Model due to a lack of data outside of the national park.

#### 4.1.2 Buffelgrass Distribution Time Series

We demonstrated two separate geospatial methods to detect buffelgrass using multispectral imagery. MuSLI data showing green-up and green-down did not correspond visually with the locations of our known buffelgrass points. It also showed us that our known buffelgrass points did not green-up on a similar timeline. Since there was not uniform green-up with our known buffelgrass points, we could not use this method to detect buffelgrass in our area. When looking at the change in NDVI and MSAVI2, most of the substantial changes in both vegetation indices were in unsuitable buffelgrass habitat. Since neither method provided us with a way to detect buffelgrass, we were unable to construct a buffelgrass distribution time series for our study area. While our methods to detect buffelgrass using multispectral were infeasible, the incorporation of higher spectral and/or temporal resolution imagery plus more robust ancillary data should be considered in future research.

### 4.2 Feasibility & Partner Implementation

#### 4.2.1 Habitat Suitability Model

Our habitat suitability models will allow partners to identify areas most susceptible to buffelgrass infestations. Partners can use and recreate this model to support management efforts of buffelgrass. The habitat suitability model provides estimates of where buffelgrass is most likely to occur, which can be integrated into our partner's knowledge of the study area and save time when conducting field surveys. The data provided to the partners will allow them to recreate our models, if desired, to add more variables and refine the models as they continue their work. More robust field data and more environmental variables, such as temperature, is recommended for future models. It would also be beneficial to run a separate analysis for the two park districts, Rincon Mountain District (East) and Tucson Mountain District (West), given their geographical differences. The next term of this project will be focusing on mapping stinknet in the study area, and similar methods can be employed in the creation of the next habitat suitability model. Providing the next term with our work will serve as a template for their project.

#### 4.2.2 Buffelgrass Distribution Time Series

While our methods to identify buffelgrass using two kinds of Landsat-based multi-spectral image products were infeasible, more research is needed to further research the feasibility of detecting buffelgrass via other remote sensing using different approaches. Given that our multi-spectral imagery was limited to a 30-meter resolution and an irregular temporal resolution, diversifying methods and incorporating higher spectral imagery with better spatial resolution should be considered, along with higher temporal resolution multispectral imagery relative to Landsat data. Another approach could be focusing on gathering higher resolution elevation and topographic data. When working with vegetation indices, we had difficulty using MuSLI and the change in NDVI and MSAVI2 during the winter months, but extending the time period of

analysis or using data with a higher temporal resolution may be more successful when looking at green-down. Unless MuSLI products are available beyond 2019, this tool will be limited in its usability for future research into this invasive plant mapping application. The study area for the current project was for a large area. The next term of this project may benefit from focusing on a smaller study area and should attempt similar remote sensing methods using time series of HLS NDVI and MSAVI2 but also incorporate higher spatial resolution data like Planet or Maxar data instead of retrying MuSLI to diversify their methods. NAIP ortho rectified aerial imagery may also be of value as a multispectral data source. It may also be useful to try using high temporal resolution (daily) imagery for satellite sensors such as MODIS, VIIRS, and OLCI to pinpoint the times of years that buffelgrass is spectrally distinct compared to adjacent cover types, such as those with native grasses.

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## 6. Glossary

**50 Percent Greenness Increase (50PCGI)** – when a plant reaches a 50% greenness increase, meaning they have reached a middle point between maximum and minimum greenness, due to the first appearance of favorable growing conditions. 50PCGI\_2 represents the second highest 50PCGI cycle.

**Buffelgrass (*Cenchrus ciliaris*)** – A perennial grass native to Africa, Asia, and most of the Middle East. It is highly invasive to areas in Australia, North America, South America, and Pacific Islands. It is especially problematic in the Southwestern United States.

**Category 1 Invasive Species** – refers to species that pose a serious threat to native ecosystems by outcompeting native plants and escalating fire risk.

**Daymet** – a processed data source that uses statistical modeling to determine daily weather and climatology variables from ground-based observations. Data is gridded into a 1km x 1km format. Daymet was made by the Environmental Sciences Division at Oak Ridge National Laboratory, Oak Ridge, TN, and is supported by NASA.

**Digital Elevation Model (DEM)** – a 3D representation of the earth’s surface showing the elevation of the land. DEM’s are created by light detection remote sensors.

**Geomorphon Landforms** – a tool in ArcGIS Pro v3.3.2 that requires an input DEM to create a representation of the landscape based on elevation differences between the target cell and surrounding cells. Landforms are classified into 10 common types: flat, peak, ridge, shoulder, spur, slope, hollow, footslope, valley, and pit.

**Green-up** – the period in which plants break dormancy after winter and start new growth. Greenness increases and green-up are interchangeable terms and are often measured by the percentage of maximum greenness a plant reaches.

**Harmonized Landsat and Sentinel-2 (HLS)** – A product meant to produce a seamless surface reflectance record by combining results measured by the Operational Land Imager (OLI) aboard Landsat 8, and the Multi-Spectral Instrument (MSI) aboard Sentinel-2.

**Integrated Multi-satellitE Retrievals for Global Precipitation Measurement (GPM IMERG)** – a product derived from a constellation of satellites used to estimate precipitation over the Earth with a 10 km x 10 km resolution.

**Landsat 8 Operational Land Imager (OLI)** – a remote sensing instrument aboard the Landsat 8 satellite used for imaging Earth’s surface and collects data in the visible, near infrared, and short wave infrared spectral bands.

**Modified Soil Adjusted Vegetation Index 2 (MSAVI2)** – a vegetation index meant to improve the accuracy of NDVI by minimizing the influence of bare soil.

**Multi-Source Land Surface Phenology Yearly North America 30-meter (MSLSP30NA)/Multi-Source Land Imaging (MuSLI)** – a land surface phenology product derived from Harmonized Landsat and Sentinel-2 data. It describes changes in vegetation greenness by displaying the dates a pixel reaches a certain amount of greenness.

**NASA Earthdata** – an open access earth science database created by the National Aeronautics and Space Administration.

**National Oceanic and Atmospheric Administration (NOAA)** – a federal agency that studies and reports on scientific findings focused on the ocean, atmosphere, and coastal regions.

**National Park Service (NPS)** – a bureau of the US Department of the interior that manages over 400 national parks, monuments, and historical sites. The mission of the NPS is to preserve the country's national and cultural heritage.

**NetCDF** – a file format for storing multidimensional scientific data such as temperature, wind speed, and humidity.

**Normalized Difference Vegetation Index (NDVI)** – a measure of vegetation health and density derived from satellite imagery. It uses the difference between near-infrared and red bands to calculate a remote sensing-based indicator of vegetation greenness.

**Onset Greenness Maximum (OGMx)** – when a plant reaches a 90% greenness increase, meaning they have reached their peak greenness due to favorable growing conditions. OGMx\_2 represents the second highest OGMx cycle.

**Onset Greenness Minimum (OGMn)** – when a plant reaches an 85% greenness decrease, meaning they have reached their lowest greenness levels due to unfavorable growing conditions. OGMn\_2 represents the second lowest OGMn cycle

**Remote Sensing** – the process of gathering information about the Earth remotely from a distance, typically using satellites, by using sensors to measure reflected and emitted radiation.

**Sentinel-2 Multi-Spectral Imager (MSI)** – a remote sensing instrument aboard the European Space Agency's Sentinel-2 satellite. Its combination of spectral bands makes it especially useful for monitoring vegetation, soil, and water cover.

**TIFF** – a file format that stores high quality raster images.

**Unmanned Aerial Vehicle (UAV)** – devices that can fly without a pilot on board, also known as drones.

**United States Fish and Wildlife Service (USFWS)** – a federal agency within the Department of the Interior meant to protect wildlife, fish, plants, and their habitats.

**United States Geological Survey (USGS)** – a federal agency within the Department of the Interior that provides scientific data in many fields such as; topography, natural hazards, water, energy, ecosystems, and climate change. The USGS aims to make scientific data available to help the public understand the Earth.

**WorldView 2** – a commercial satellite launched by DigitalGlobe offering extremely high imagery resolution.

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## 8. Appendices

### Appendix A: Elevation data

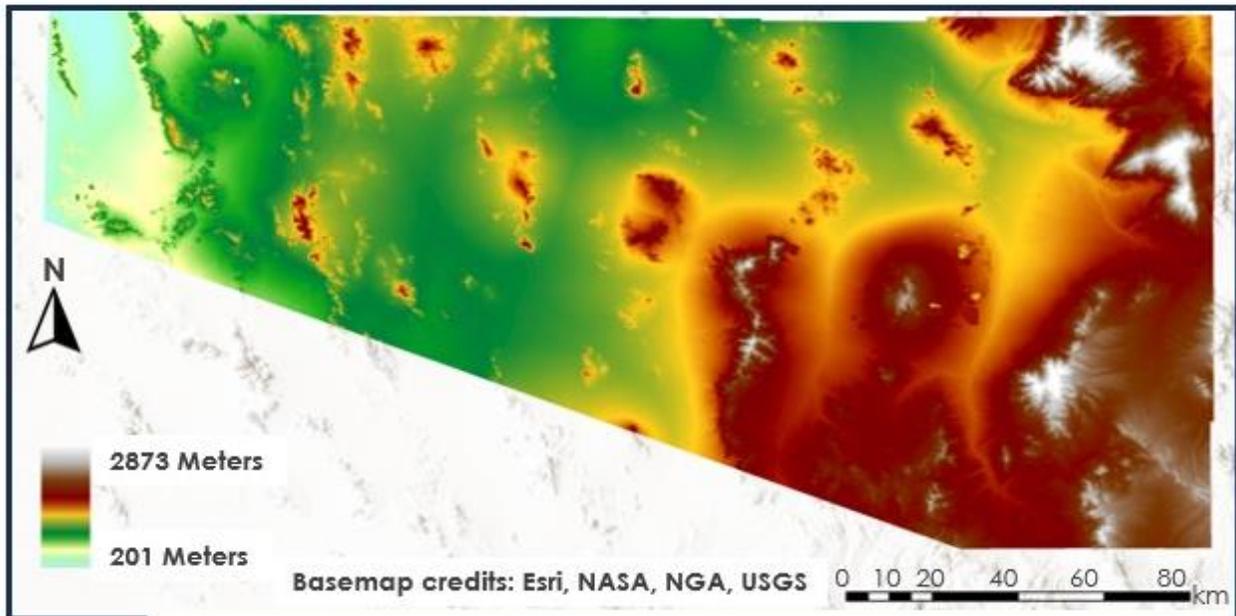


Figure A1. USGS Topographic Digital Elevation Model (DEM) with 30-meter resolution.

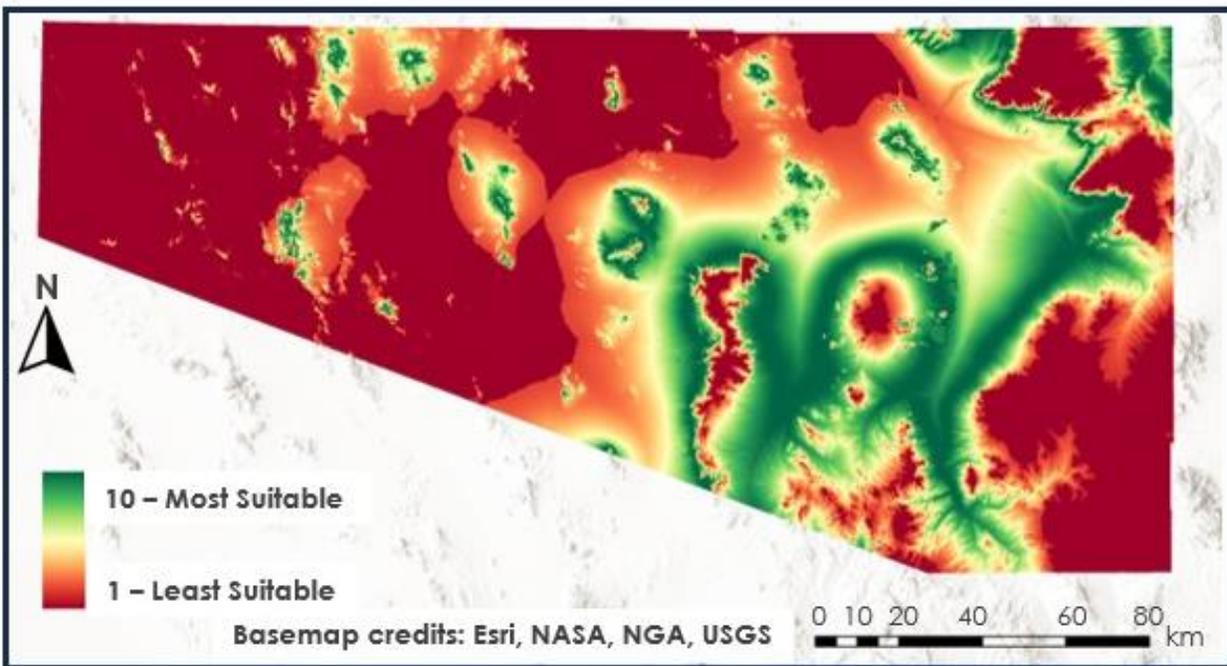


Figure A2. Elevation values transformed to suitability values. The most suitable values were between 650 and 1400 meters above sea level.

Appendix B: *Slope data*

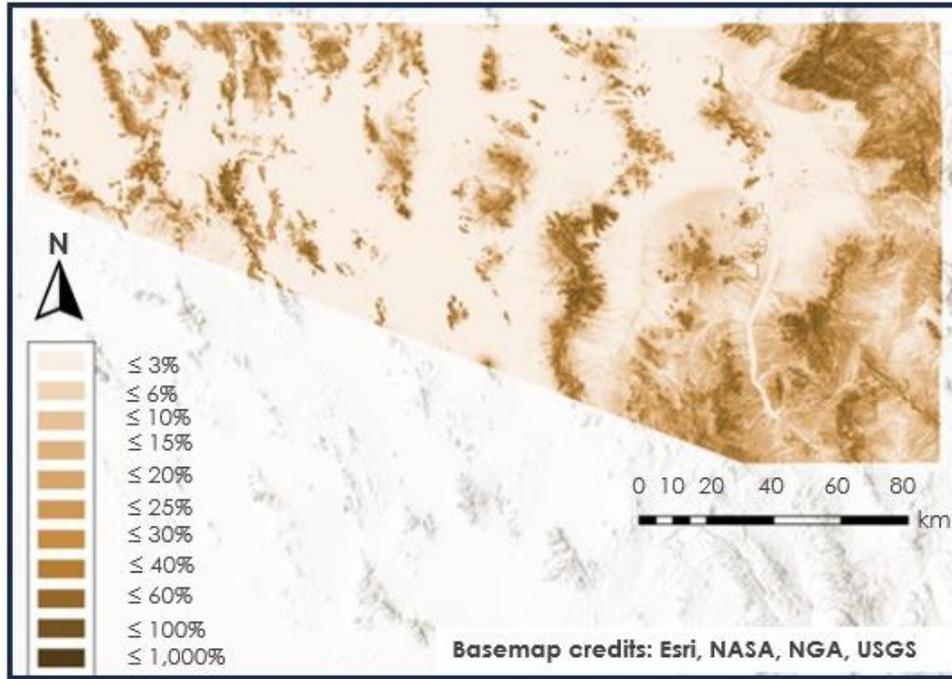


Figure B1. Slope values derived from 30-meter USGS Topographic Digital Elevation Model (DEM).

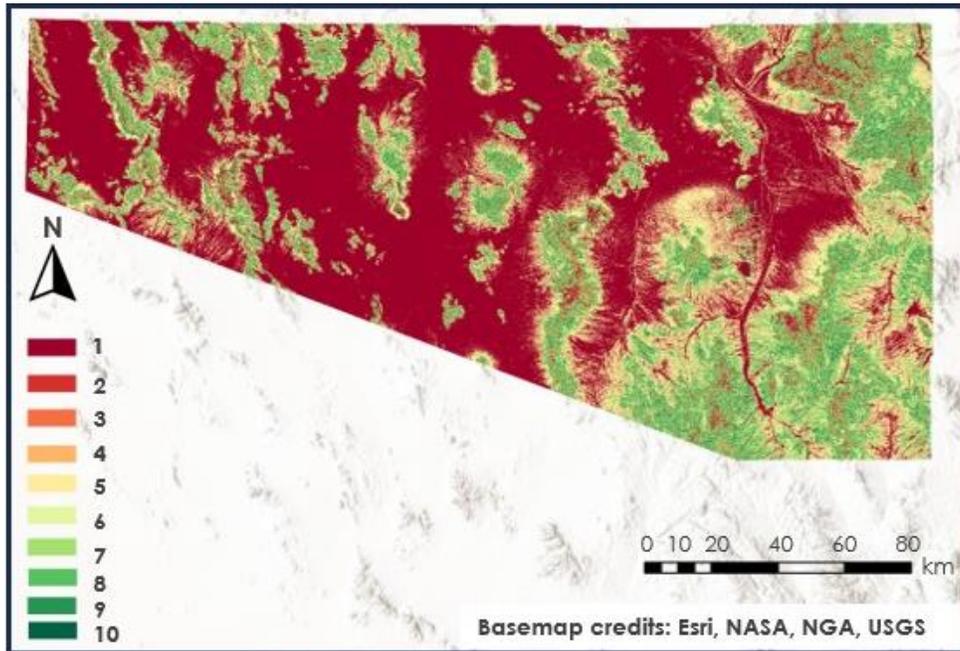


Figure B2. Slope values transformed to suitability values with ideal growing conditions for buffelgrass being between 25% and 34% slopes.

Appendix C: Aspect data

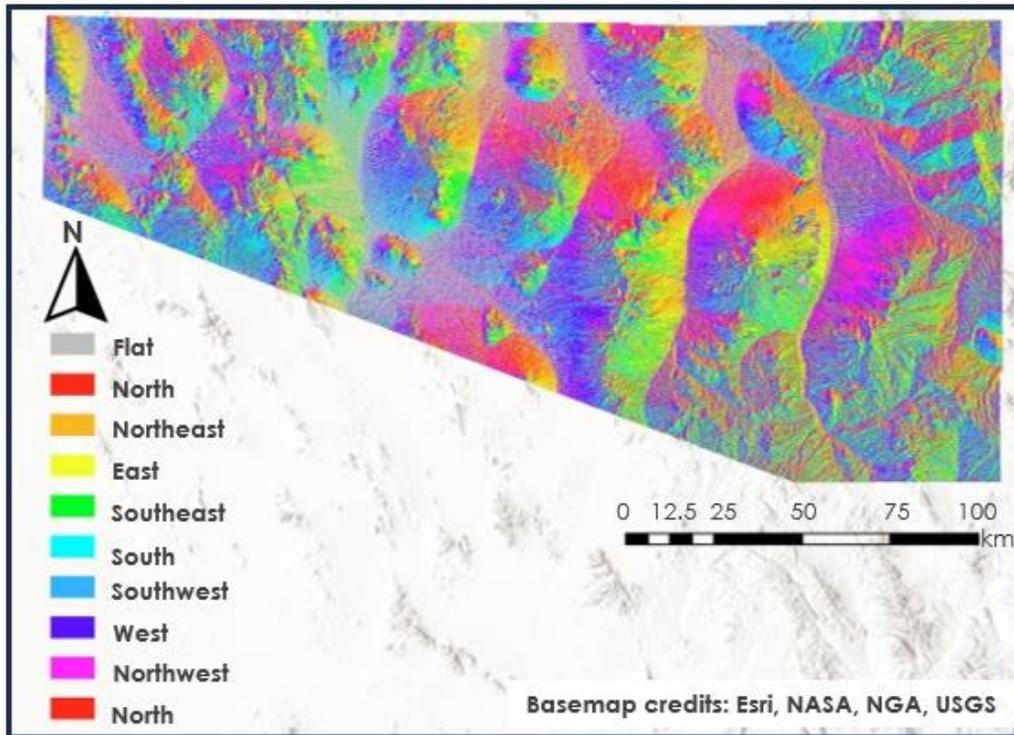


Figure C1. Aspect values derived from 30-meter USGS Topographic Digital Elevation Model (DEM).

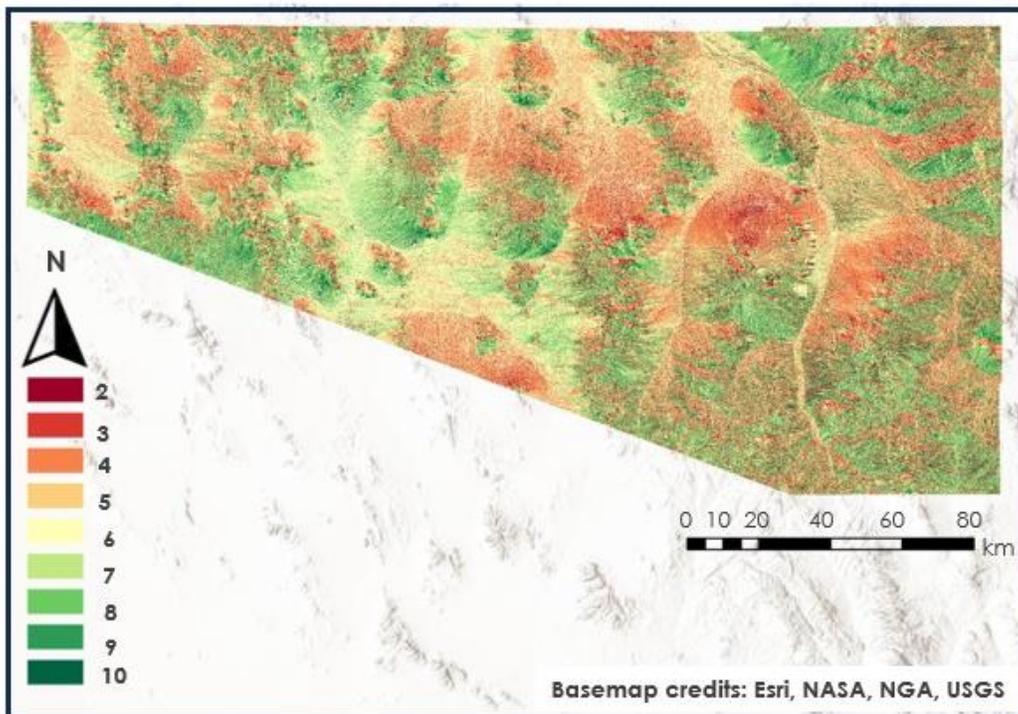


Figure C2. Aspects values transformed to suitability values, ranging from 2 to 10. Buffelgrass prefers growing on south facing slopes in dark green.

Appendix D: *Landform and washes data*

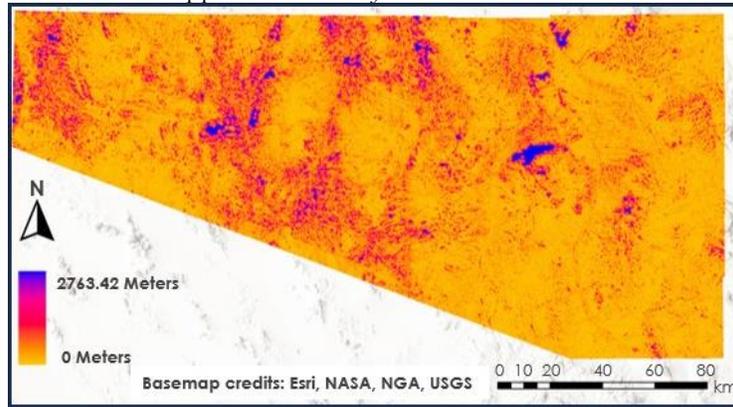


Figure D1. Map that shows distances from valleys. Buffelgrass prefers areas closer to valleys.

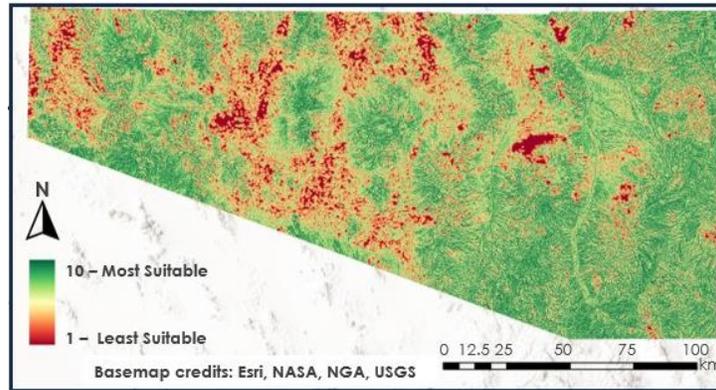


Figure D2. Distance from valleys layer integrated into suitability model. Green values are areas closer to valleys.

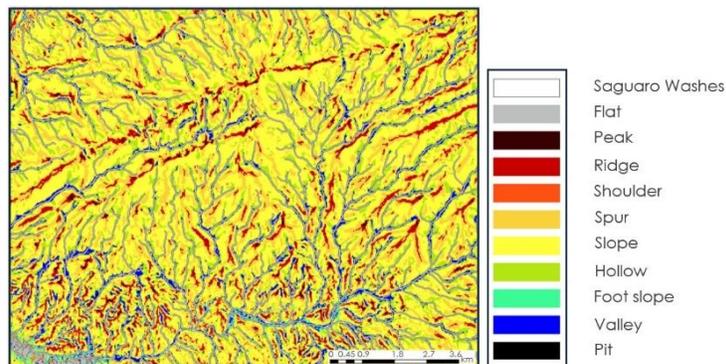


Figure D3. Geomorphic Landforms example. The area shown is in the middle of the Rincon District in Saguaro National Park. This layer was used to derive valley locations from washes to create the distance from valleys layer in our habitat suitability models.

Appendix E: Annual precipitation data

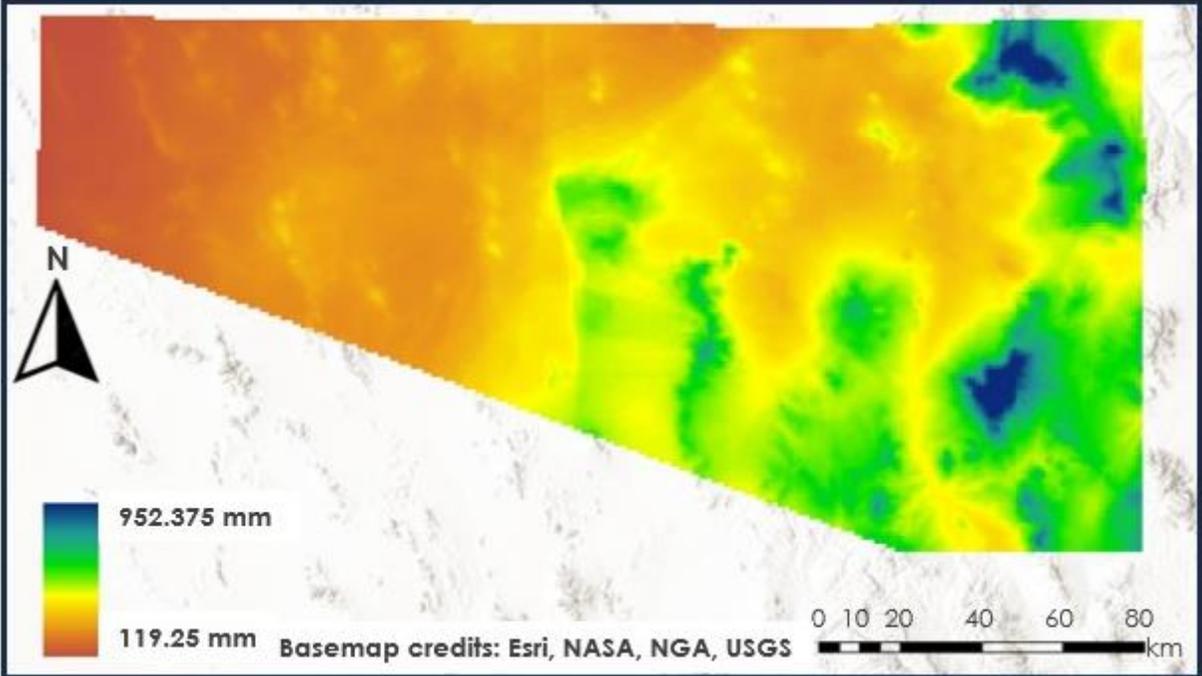


Figure E1. Average annual precipitation, from the years from 2016 to 2023.

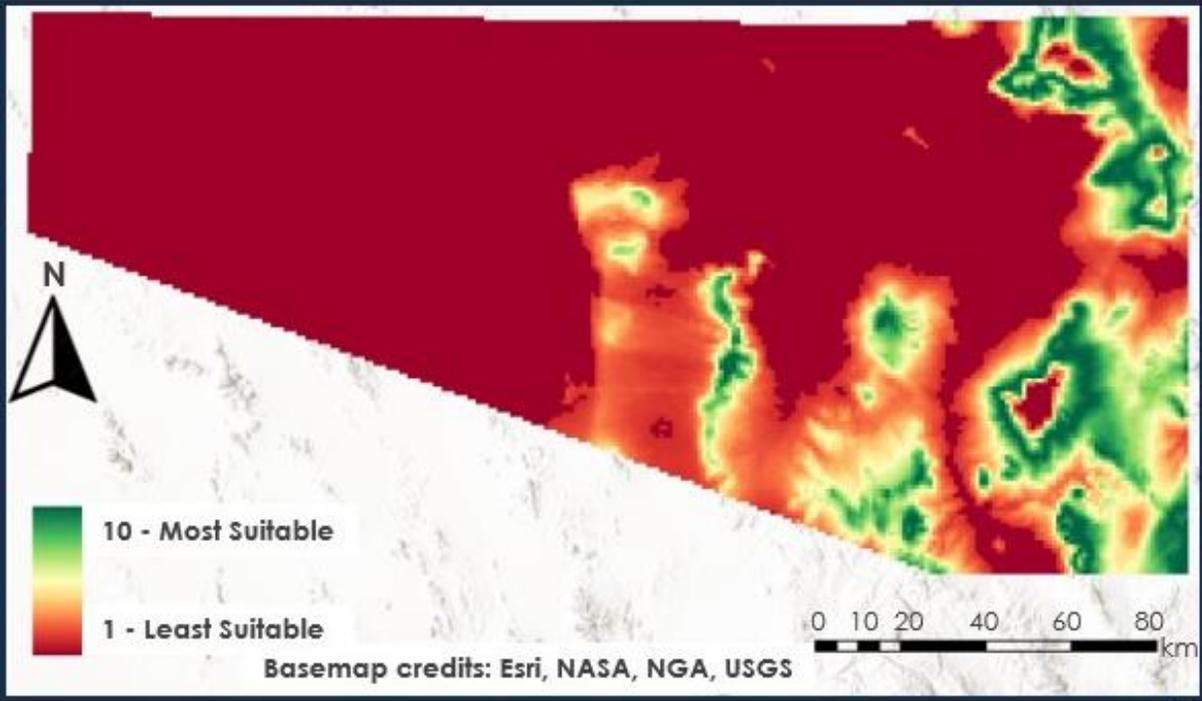


Figure E2. Annual precipitation values transformed to suitable values.

Appendix F: Hydrologic soil group data

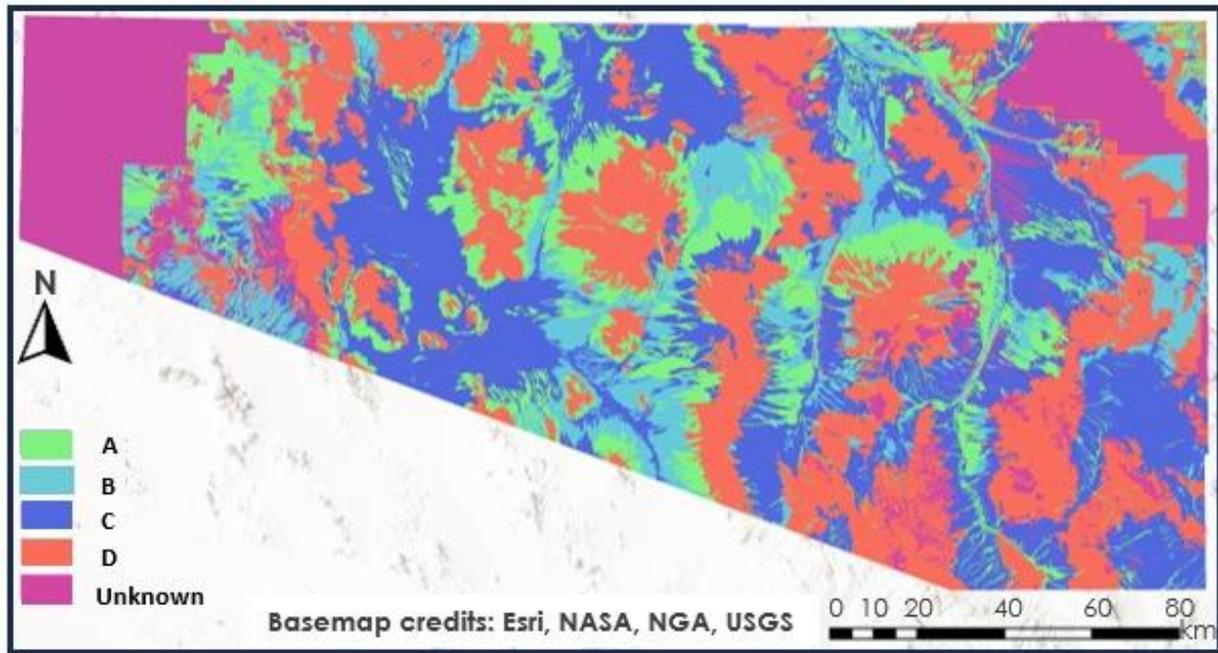


Figure F1. Hydrologic soil groups (D, C, B, A) ranked from highest runoff potential to lowest runoff potential.

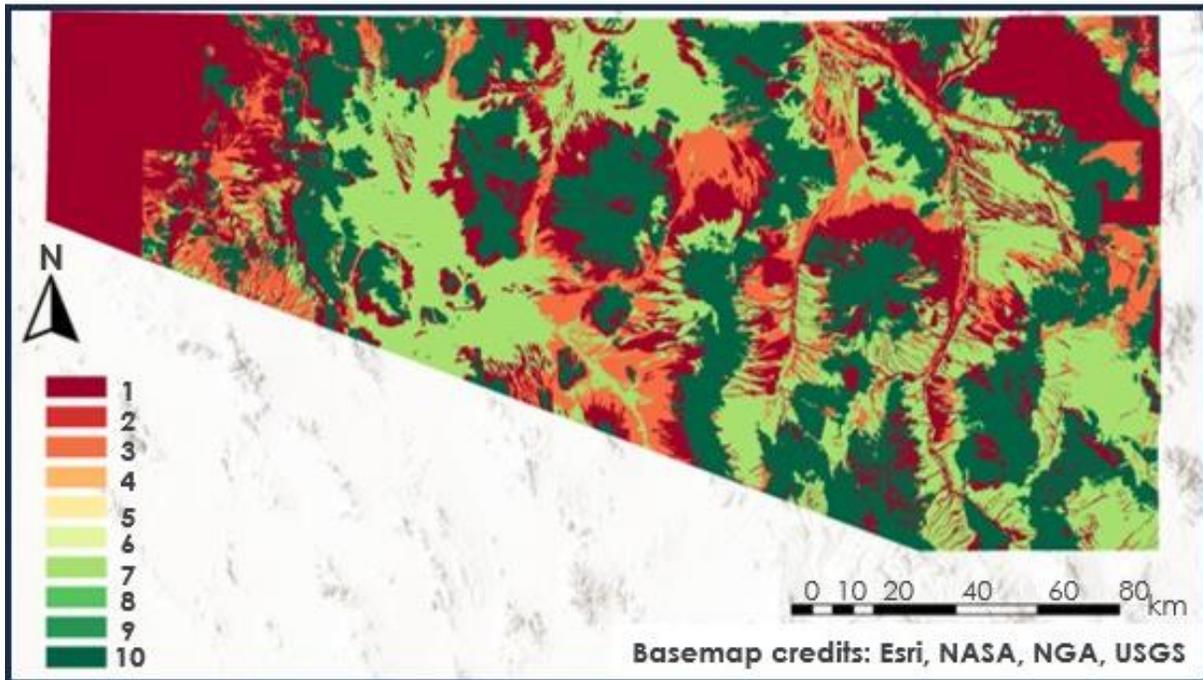


Figure F2. Hydrologic soil groups values transformed to suitable values. Hydrologic soil group D was given a high suitability value of 10.

Appendix G: *Saguaro national park different vegetation classes.*

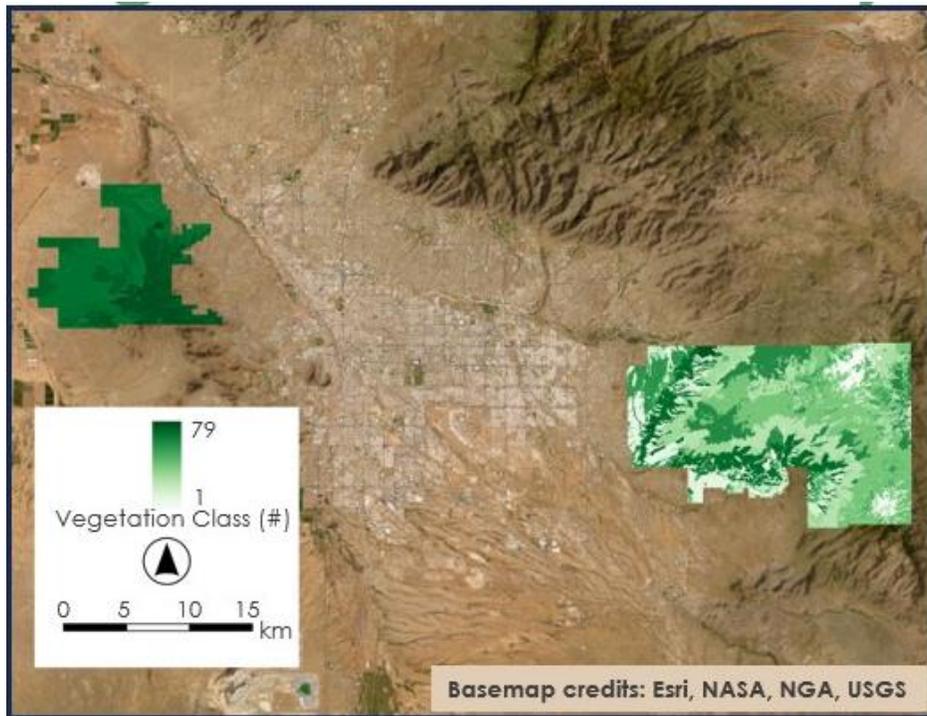


Figure G1. Different vegetation class types in Saguaro National Park.

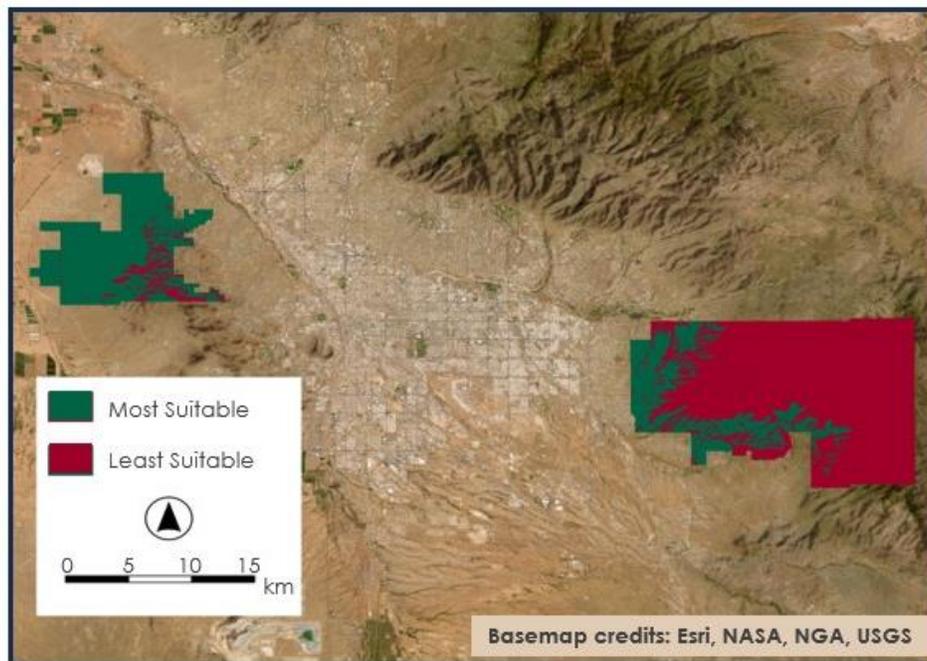


Figure G2. Most suitable areas in green are the vegetation classes that buffelgrass invades most often.

Appendix H: *Saguaro national park habitat suitability model includes Vegetation classes.*

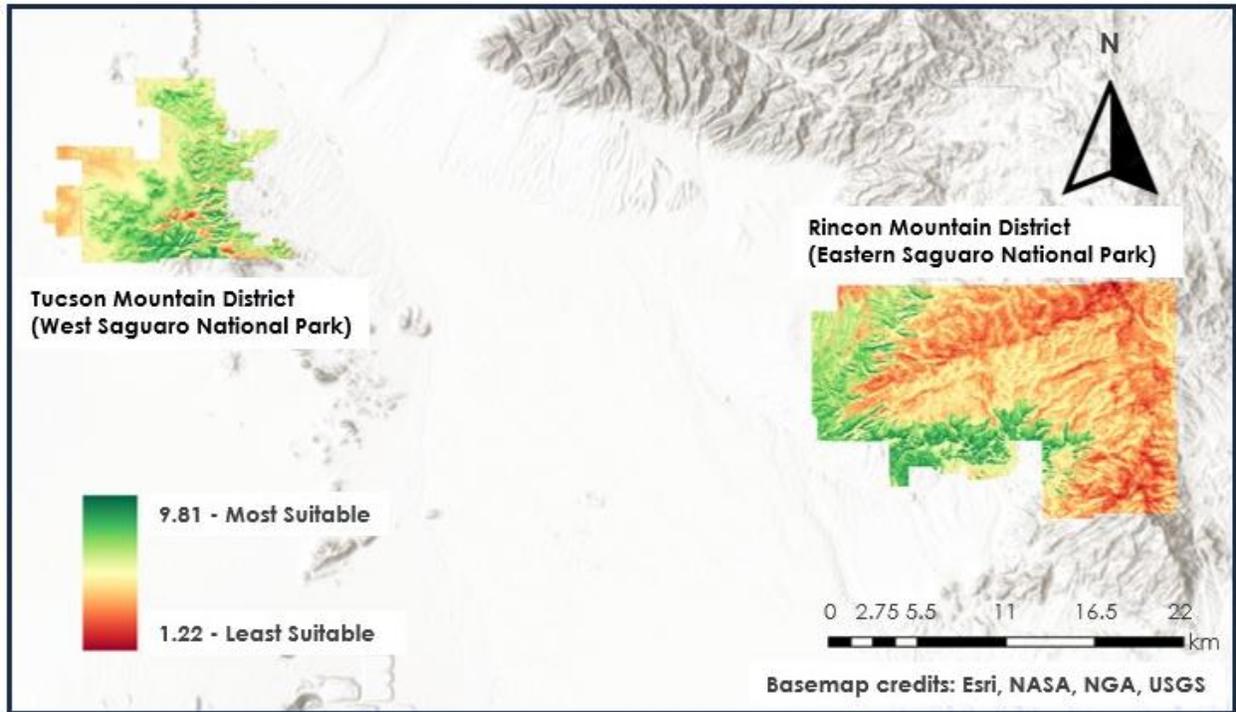
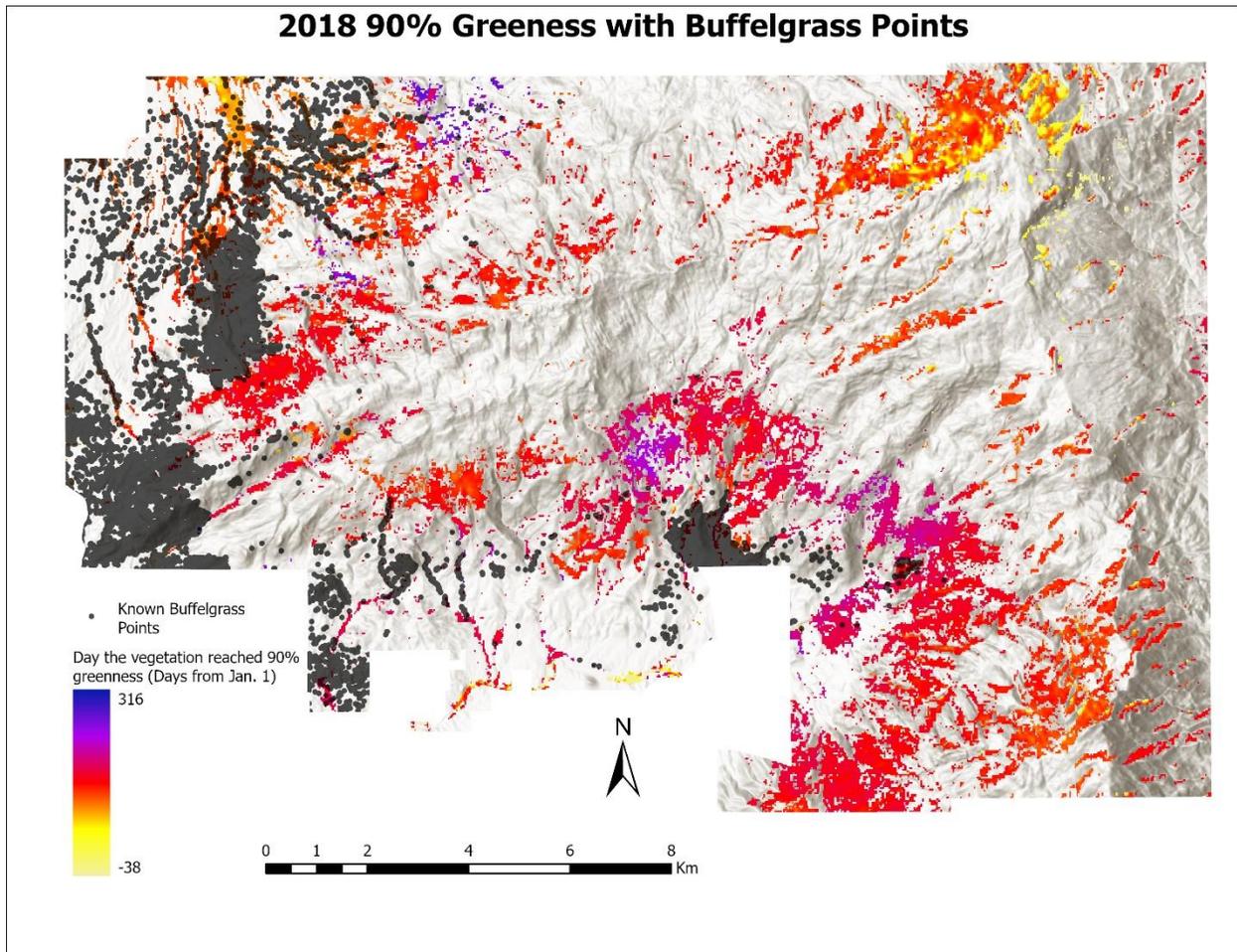


Figure H1. Saguaro National Park Suitability Model (Tucson Mountain District on the left, Rincon Mountain District on the right) with known buffelgrass points overlaid.



*Figure 11.* The map indicates the majority of buffelgrass points (in black) do not have any MuSLI data and those that do, are greening-up anywhere from day 203 (July 22<sup>nd</sup>) to 232 (August 20<sup>th</sup>), which is when most vegetation greens-up in the study area.