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Glacier National Park Climate

Utilizing NASA Earth Observations to Quantify Landscape Disturbances Related to a
Changing Climate in Glacier National Park from 1999-2016

DEVELOP Technical Report

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1. Abstract

National parks face an increasing number of threats from climate and biotic stressors, which lead to both major and minor landscape disturbances. The effects of disturbance are wide-ranging (e.g., changing species composition, altering nutrient flow and biodiversity, and landscape alterations) and impact numerous ecosystems within the park. While disturbance is part of the ecological history of a region, the major drivers and magnitude of disturbance change over time. In this project, the team quantified and mapped landscape disturbances in Glacier National Park from 1999 to 2016 (for the months of June – September). Landsat data were used to detect and map biotic stress from pathogens (primarily the mountain pine beetle), fires, avalanche tracks, and landslides by using a threshold-based decision tree classification scheme similar to the work of Goodwin and others. Based on this methodology, and cross referencing results with insect Aerial Detection Surveys from the US Forest Service, it was observed that pathogen presence is adequately represented by a negative change in NDMI of 600-4,000, with potential “green attack” phases of pathogen attack being represented by negative changes in NDMI of 250-600. Abrupt disturbances such as landslides, floods, and avalanches are represented by changes in NDMI of greater than 4,000. These results show the potential for improvement in using NASA Earth observations to detect landscape disturbance and will aid the National Park Service in natural resource management by predicting a multitude of landscape disturbances in response to climate change.

Keywords

Remote Sensing, Landsat, disturbance, pathogens, fire, avalanche, landslide, time series

2. Introduction

2.1 Background Information

Glacier National Park (GNP), located within the larger Crown of the Continent ecosystem, encompasses one million acres of northern Rocky Mountain wilderness in northwestern Montana (Figure 1). Considered one of the last “intact and pristine wilderness” areas in the contiguous United States, this area is home to many species of flora and fauna that have, unlike much of the American continent, remained unchanged since the arrival of European settlers two hundred years ago. Bisected longitudinally by the Continental Divide, the Crown of the Continent ecosystem is also home to the headwaters of three of North America’s largest rivers: the Columbia, the Missouri, and the Saskatchewan (Waldt, 2004). It’s unique beauty, diversity, and scale has led it to be classified as an International Biosphere Reserve, UNESCO World Heritage Site, and an International Peace Park in conjunction with Waterton Lakes National Park in Alberta, Canada. Despite its pristine nature, the park has been subject to various landscape changes over the past 100 years, primarily driven by a warming climate (Hall and Fagre, 2003). Within GNP, park managers have noted that the specific time period of 1999-2016 has been characterized by climatic extremes (Potter, 2016), the ramifications of which are poorly understood. Geographic Information Systems (GIS) and remote sensing tools have been used in the past to observe temporal vegetation change in other forested ecosystems (Goodwin et al., 2008; Vogelmann, et al., 2012; Banskota et al., 2014; Potter, 2016); however, these methods have been infrequently applied to GNP.



Figure 1: Inset map of Waterton Glacier National Park. U.S. Map courtesy of geology.com.

2.2 Project Partners & Objectives

This project partnered with Richard Menicke, Geographer for the National Park Service (NPS) at Glacier National Park and Dr. Christopher Potter, Senior Research Scientist for the National Aeronautics and Space Administration (NASA) Biospheric Branch at Ames Research Center. Richard Menicke was interested in quantifying and mapping landscape disturbances in GNP, so that park managers can better understand the changing landscape to improve future resource management decisions. Additionally, such projects are expected to provide the groundwork for future research endeavors in the park, including but limited to: the relationship between fire and pathogen spread, increased pathogen disturbance near surface water bodies, and growing risk of avalanches and landslides due to receding ice and snowmelt. As Chief Geographer at GNP, Mr. Menicke assisted the team by providing background information related to the park, such as specific ecological and disaster events in the park's history and other areas of the park that are of particular interest. Dr. Christopher Potter was interested in the methodological development to quantify and differentiate moderate-level landscape disturbances, caused primarily by pathogens, using NASA Earth observations. His past research using NASA Earth observations to map and quantify temporal vegetation change caused by fire and his direct counsel has helped with various aspects of this project throughout the term. He aims to apply this project's methodology to future remote sensing research related to fire and disturbance ecology.

This project falls under the Climate Application Area of NASA's Applied Sciences Program and will help scientists, park staff, and land managers better understand the impacts of a changing climate on forested ecosystems. In this study, we propose a methodology for quantifying and mapping landscape disturbances related to a changing climate in Glacier National Park, specifically focusing on the time period of 1999-2016. The project uses a decision tree based threshold technique to differentiate the major drivers of disturbances using the Normalized Difference Vegetation Index (NDVI) and the Normalized Difference Moisture Index (NDMI). These disturbances include attack and subsequent desiccation of pine forest by White Pine Blister Rust and the Mountain Pine Beetle, avalanches and landslides, and fire. To date, such techniques have not been applied to quantify and map disturbance in GNP.

3. Methodology

3.1 Data Acquisition

Richard Menicke and Glacier National Park provided the team with a variety of website links to geospatial data (Appendix 1). The team downloaded satellite and aerial imagery, a GNP boundary layer shapefile, forest insect and disease polygons from the U.S. Department of Agriculture's Aerial Detection Surveys (ADS), and a

vegetation land cover classification map layer. The vegetation coverage map was developed by the USGS and the NPS vegetation mapping program using aerial imagery from 1997-1999 and extensive field surveys. In addition to this data, Menicke provided Landsat and survey based shapefiles delineating fire perimeters, fire extent, and burn severity within GNP.

The bulk of the satellite data collected by the team was downloaded from the United States Geological Survey Earth Science Processing Architecture (USGS ESPA) website. The USGS makes all data available to the public and downloadable via online request. USGS National Gap Analysis Program (GAP) and Landsat surface reflectance data for the time period of 1999-2016 were downloaded. The reflectance data includes satellite images from Landsat 5 Thematic Mapper (TM), Landsat 7 Enhanced Thematic Mapper (ETM+), and Landsat 8 Operational Land Manager (OLI). The team also ordered NDVI and NDMI indices computed for each image in our time series of Landsat surface reflectance data using the ESPA Ordering Interface. Since GNP experiences high snow and cloud cover in most of the park for October through May, only data for the months of June through September were downloaded to reduce inaccuracies in surface spectral signatures.

The team accessed total precipitation and snow water equivalent (SWE) data averaged by year for four weather stations (Many Glacier, Flat Top Mountain, Pike Creek, and Emery) within and adjacent to GNP via the National Resources Conservation Service (NRCS) Snow Telemetry data set.

3.2 Data Processing

LANDSAT 5, 7, 8 (1999-2016 for months: June to September)

Each Landsat scene was clipped to the minimum bounding box of a 4 kilometer buffered park boundary, to include areas of interest directly outside Glacier National Park's administrative boundaries in our analysis. Percent cloud cover was calculated for each image, and only images with less than 30% cloud coverage were selected for further analysis. Clouds, water, and snow were masked from Landsat scenes using each scene's "cfmask" layer. Using a target date of July 21st, the resulting "NoData" pixels were filled in with the temporally closest Landsat scenes available within that year's month range. Since NDMI is sensitive to changes in moisture that can be affected by seasonality, it was important to keep these composited Landsat scenes as close to the target date as possible. The reference date was selected because it occurs during the middle of the growing season at Glacier National Park. The yearly composited NDMI images were then used for subsequent analyses. NDMI was selected because of its recognized sensitivity to detect pathogen disturbance (Goodwin et al., 2008). The index is calculated with the following equation:

$$NDMI = \frac{(NIR - MIR)}{(NIR + MIR)}$$

where, *MIR*= surface reflectance mid-infrared band
and, *NIR* = surface reflectance near infrared band

NDMI values range from -1 to 1. The team used a scale factor of 10,000 to convert the data to integer format, so values for pixels in NDMI images range from -10,000 to 10,000 and values for pixels in interannual Δ NDMI images range from -20,000 to 20,000. Figure 2 shows the interannual periods that were selected based on data availability as well as data attributes such as fire occurrence and percentage of clouds detected which were accounted for by masking our images.

<i>InterAnnual Period</i>	<i>Sensor used to create cloud free composites</i>	<i>Recent Fire Occurrences (>100,000 acres)</i>
<i>1999-2000</i>	<i>Landsat 5; Landsat 7</i>	<i>Present</i>
<i>2000-2001</i>	<i>Landsat 5; Landsat 7</i>	<i>Present</i>
<i>2001-2002</i>	<i>Landsat 5; Landsat 7</i>	<i>Present</i>
<i>2002-2003</i>	<i>Landsat 5; Landsat 7</i>	<i>Present</i>
<i>2003-2004</i>	<i>Landsat 5</i>	<i>Present</i>
<i>2004-2005</i>	<i>Landsat 5</i>	<i>Present</i>
<i>2005-2006</i>	<i>Landsat 5</i>	<i>Present</i>
<i>2006-2007</i>	<i>Landsat 5</i>	<i>None</i>
<i>2009-2010</i>	<i>Landsat 5</i>	<i>None</i>
<i>2010-2011</i>	<i>Landsat 5</i>	<i>None</i>
<i>2013-2014</i>	<i>Landsat 8</i>	<i>None</i>
<i>2014-2015</i>	<i>Landsat 8</i>	<i>None</i>
<i>2015-2016</i>	<i>Landsat 8</i>	<i>None</i>

Figure 2: Table shows the interannual periods used in this study. Data gaps include the years of 2008 and 2011, therefore, interannual periods from 2007-2008, 2009-2009, 2011-2012, and 2012-2013 were not examined.

3.3 Data Analysis

In order to classify the yearly NDMI images, we applied a decision tree approach using threshold values. These thresholds were determined by comparing histogram overlap for areas within GNP affected by pathogens and healthy forest areas (Figure 3).

Images were first analyzed by comparing Normalized Difference Moisture Index (NDMI) for dates before and during known pathogen disturbance in the same area. Areas were chosen by referencing ADS polygons, which are analyst produced maps that delineate pathogen disturbance via fly-over. Healthy forest polygons were mapped in Google Earth Engine API (GEE) using true-color NAIP imagery and NDVI derived from Landsat for individual years. These areas of healthy forest were restricted to areas identified as pine species within the NPS vegetation classification, and excluding areas of known pathogens.

The team determined the threshold values by comparing NDMI histograms of healthy pine forest polygons with NDMI histograms from areas characterized as “pathogen infested” by ADS for both years which make up an interannual period. In both cases, areas were labeled as “healthy forest” or as “disturbed” only if they were classified in these categories for both years that make up the interannual period. Histograms were examined for overlap and compared to precipitation and SWE averages in order to assess whether drought caused uncertainty in the classification scheme. Misclassification was also compared to SNOTEL data using a regression analysis to examine the impact of drought on our classification scheme. Years that experienced precipitation and snow water equivalent levels that were similar in degree to a normal year as compared to our pre-determined baseline year of 1995 were used to determine threshold values. A high value for Δ NDMI, reflecting a high amount of disturbance, corresponds to roughly two standard deviations from the mean of histogram overlap and was selected for minimal overlap between the histograms (Figure 4). After masking-out burned areas, this threshold value was used to map pathogen disturbance temporally from 1999-2015 across Glacier National Park, similar to the work of Goodwin and others (2008) (Figure 5). Abrupt disturbance was classified as Δ NDMI values less than -4000, the range of -450 and -4000 was classified as high disturbance, -250 and -450 as moderate disturbance, 0 to -250 as low disturbance, 0 to 650 as healthy vegetation and values above 650 were regeneration. The team chose to label these categories generally as “Disturbance” due to the uncertainty concerning whether a decrease in NDMI is due to drought,, pathogens, or other landscape factors. All interannual maps are viewable through the link provided in Appendix 2.

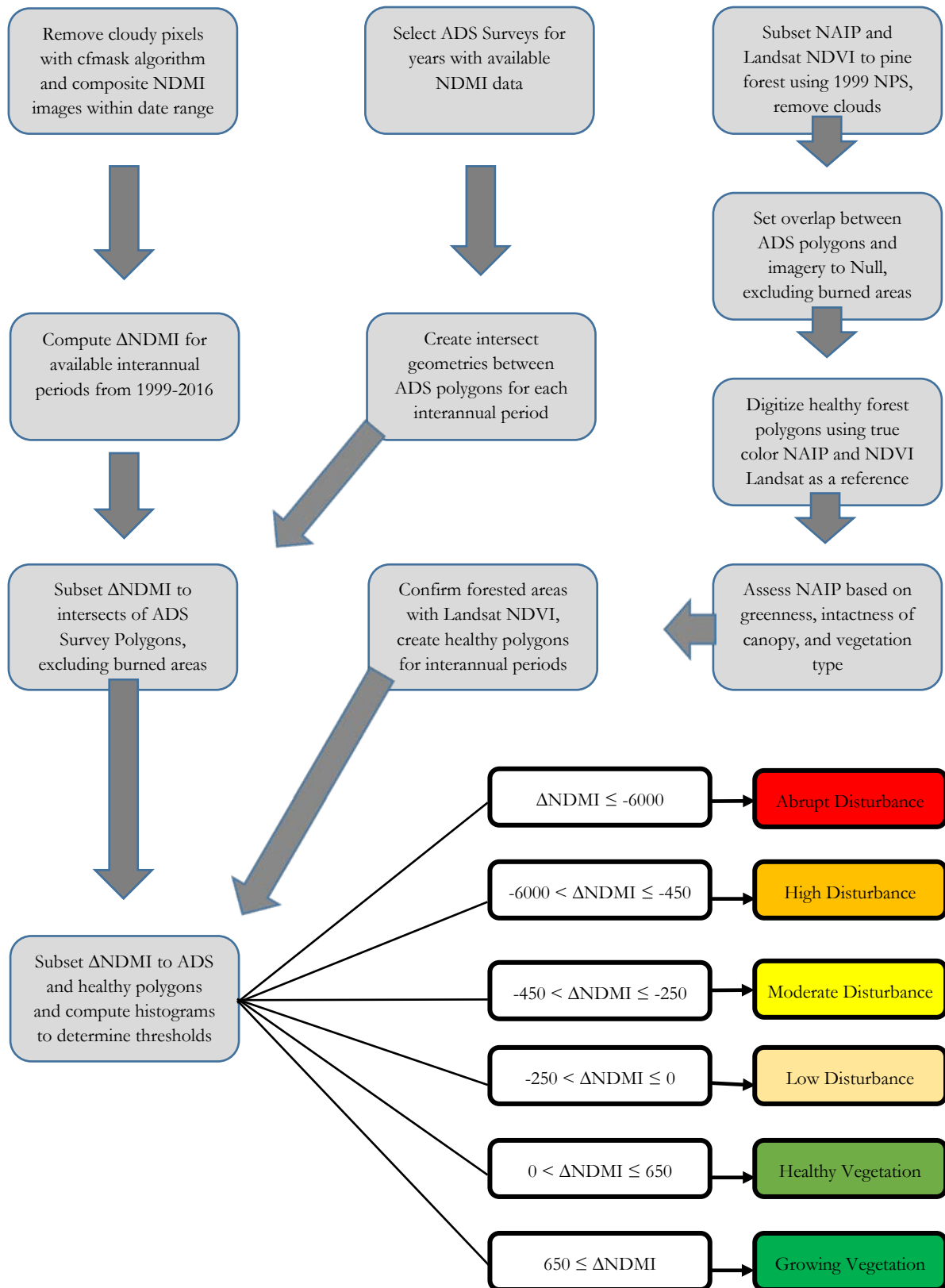


Figure 3: Decision tree for categorizing disturbances within Glacier National Park. Classes reflect the degree of deviation from the mean of the normal distribution of the ΔNDMI histogram within pathogen polygons and the histogram within forest polygons.

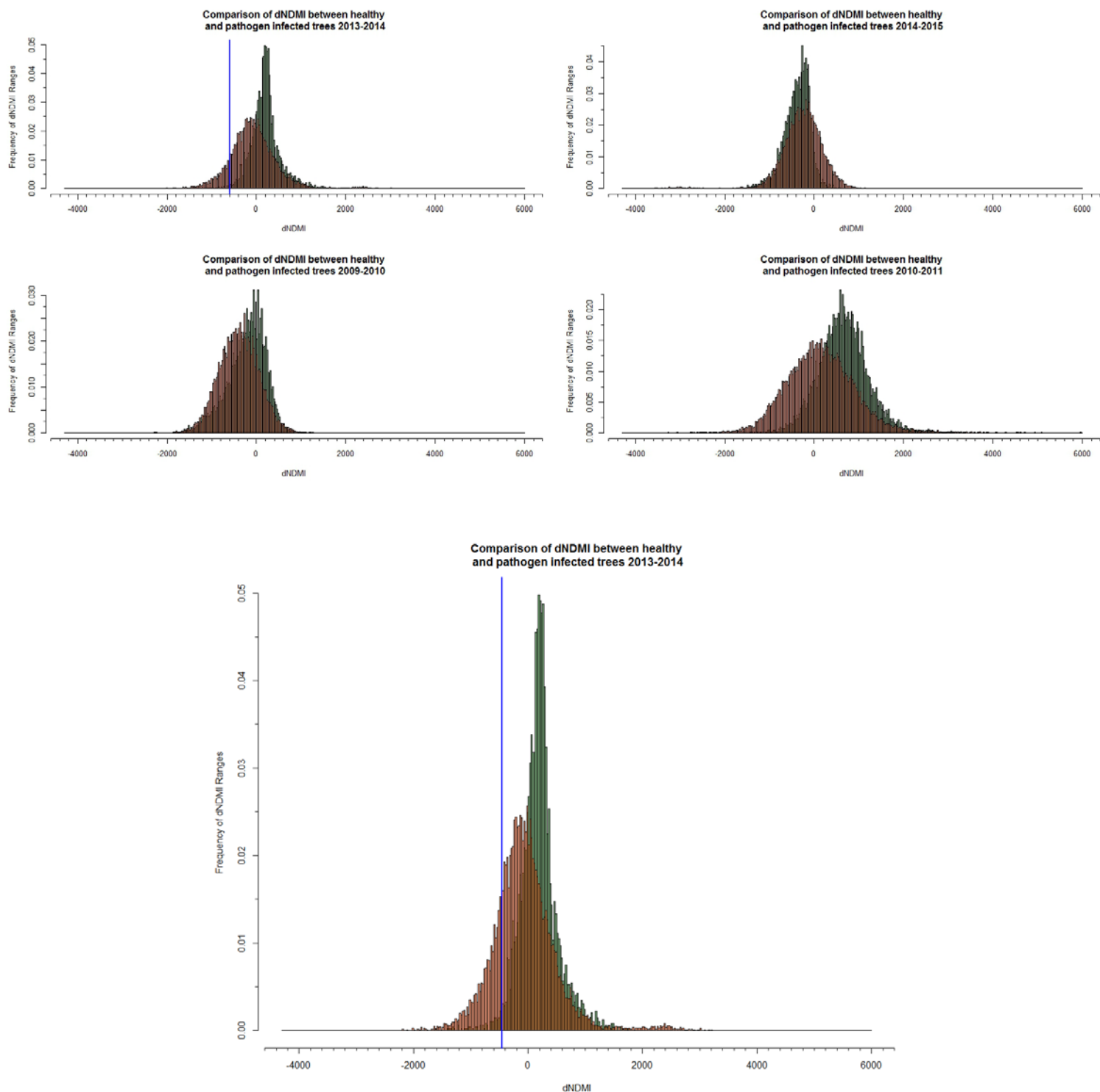


Figure 4: NDMI histograms for ADS polygon in orange and healthy vegetation sample in green. The top image displays the histograms for four interannual periods. 2014-2015 and 2009-2010 are years that experienced significant drought and thus Δ NDMI poorly distinguishes healthy vegetation from disturbed vegetation. The blue line represents the threshold value for detecting High Disturbance ($-6000 < \Delta$ NDMI ≤ -450).

Vegetation Disturbances in Glacier National Park

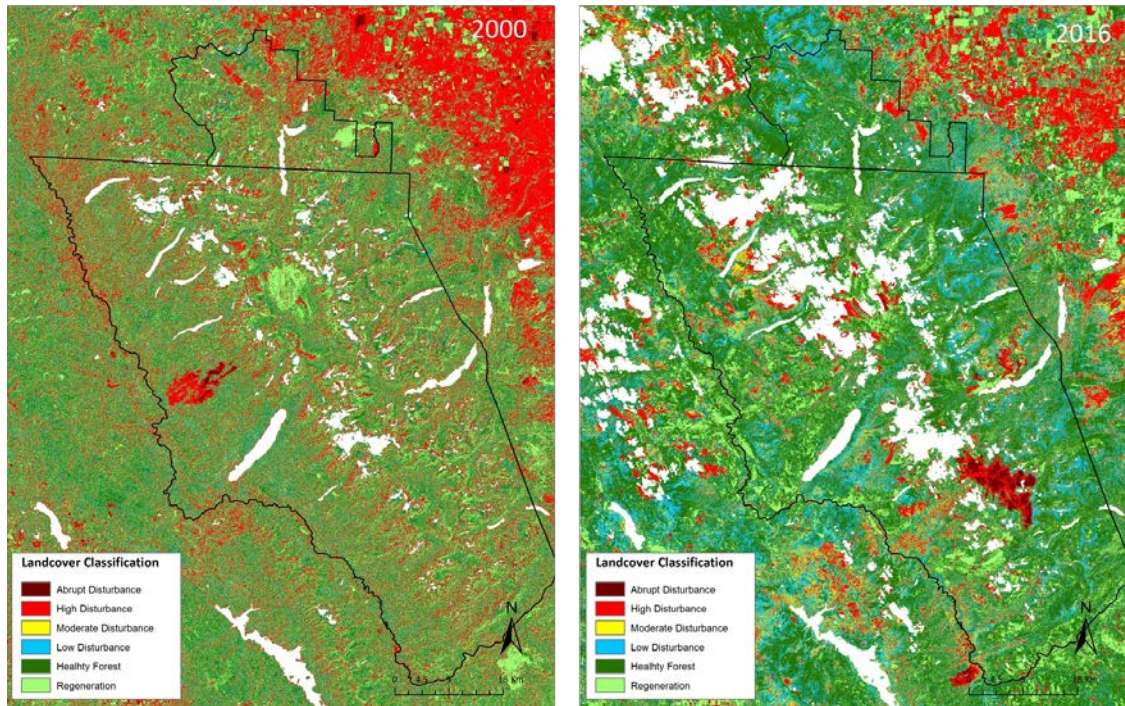


Figure 5: Classified Disturbance maps based on changes in NDMI for Glacier National Park. For full list of maps in 1999-2016 date range, see Appendix 2.

Next, the classified interannual Δ NDMI maps were grouped into sets of five interannual periods (Table 2) and frequency maps were created to reflect persistent high disturbance (Appendix 3). These frequency maps were computed on a rolling basis, so that 11 maps in total were produced. Figure 6 illustrates the process used to create these frequency maps. Cloud-free Landsat images were absent for the years 2008 and 2012, so in some cases, these five year time periods were extended to contain the most whole sequence of five interannual periods. These frequency maps provide evidence of persistent pathogen presence, since the mountain pine beetle attacks generally follow a five year time span: from green attack, when beetles first enter a tree, to red attack when foliage begins to redden due to dryness, then to gray attack when all foliage moisture is completely absent and needles fall off (Wulder et al., 2006).

Frequency Year Range	Interannual Periods Aggregated for Frequency
1999-2004	1999-2000, 2000-2001, 2001-2002, 2002-2003, 2003-2004
2000-2005	2000-2001, 2001-2002, 2002-2003, 2003-2004, 2004-2005
2001-2006	2001-2002, 2002-2003, 2003-2004, 2004-2005, 2005-2006
2002-2007	2002-2003, 2003-2004, 2004-2005, 2005-2006, 2006-2007
2003-2010*	2003-2004, 2004-2005, 2005-2006, 2006-2007, 2009-2010
2004-2011*	2004-2005, 2005-2006, 2006-2007, 2009-2010, 2010-2011
2005-2014*	2005-2006, 2006-2007, 2009-2010, 2010-2011, 2013-2014
2006-2015*	2006-2007, 2009-2010, 2010-2011, 2013-2014, 2014-2015
2009-2016*	2009-2010, 2010-2011, 2013-2014, 2014-2015, 2015-2016

Table 2: Interannual Periods used to create frequency maps. Asterisk indicates Frequency ranges with gaps due to missing interannual period data, which in turn could not be computed due to lack of cloud free images during the years 2008 and 2012.

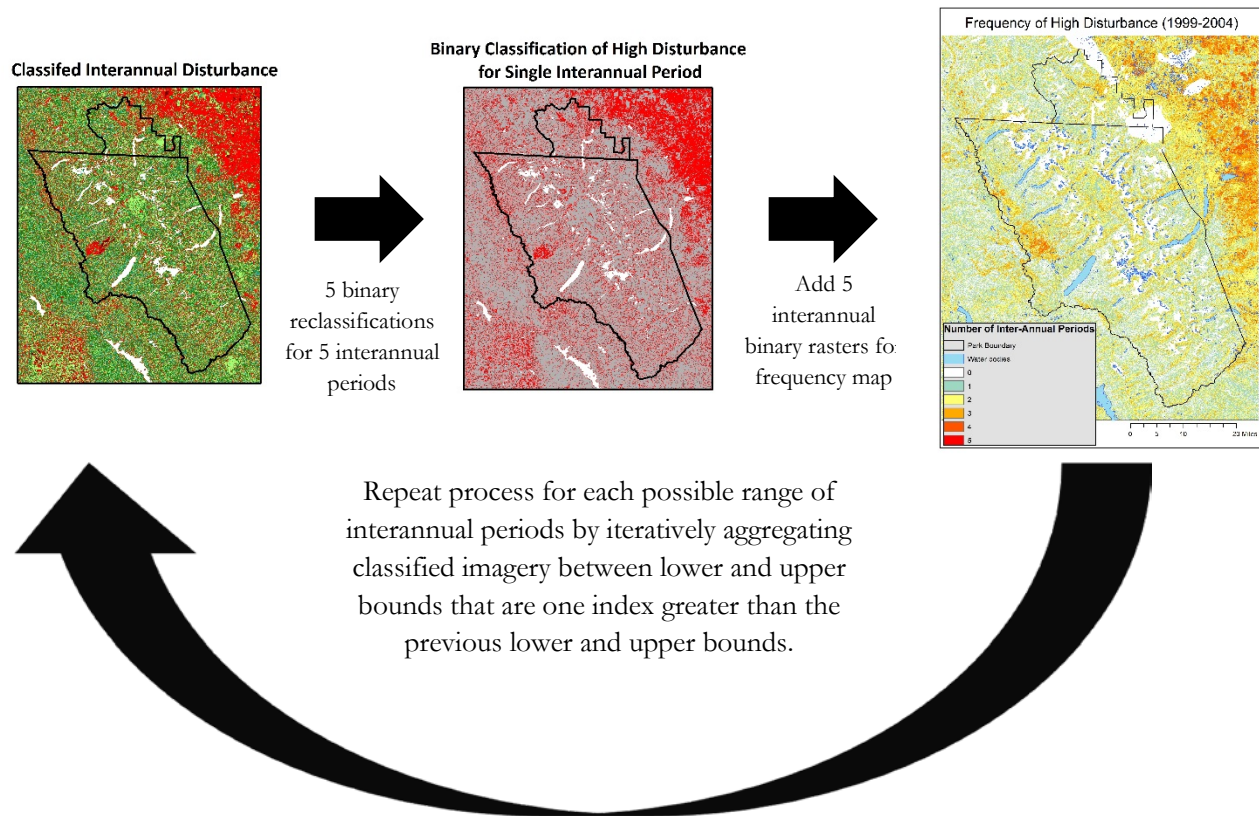


Figure 6: Workflow for creating eleven frequency maps of high disturbance. Frequency map shows, per pixel, for how many interannual periods an area was classified as High Disturbance.

3.4 Evaluation

The ADS maps damage due to defoliation, mortality, discoloration, dieback, top kill, branch breakage, main stem broken or uprooted, and branch flagging. We assume these disturbances fall within the abrupt, high, and moderate categories mapped in the project. Post-classification, the percent of each disturbance category within the ADS polygons was calculated and threshold values used here were evaluated for correspondence to pathogen polygons. Misclassification within ADS polygons was analyzed using a Pearson's correlation between forest categories and precipitation data averaged for four weather stations within or adjacent to GNP.

4. Results & Discussion

Classified Disturbance Compared to ADS Areas

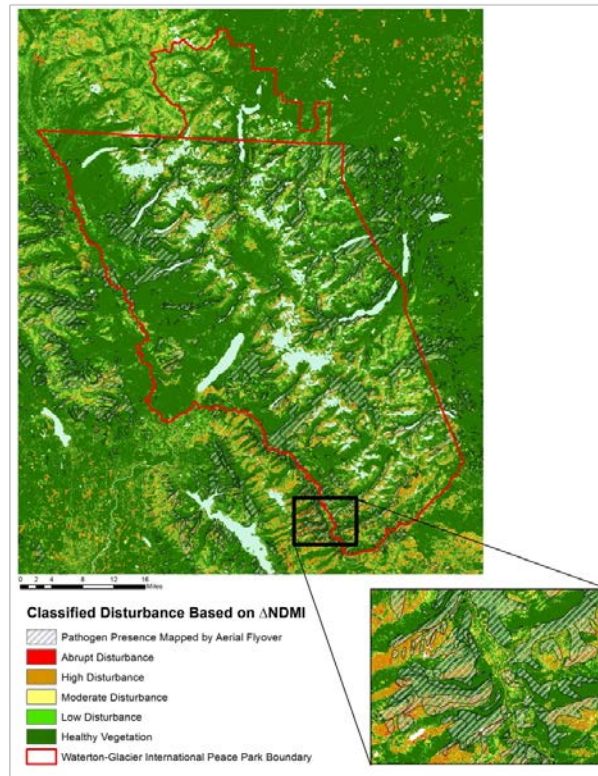


Figure 7: Our classified disturbance classifications compared to Aerial Detection Survey (ADS) pathogen presence areas.

Frequency of High Disturbance

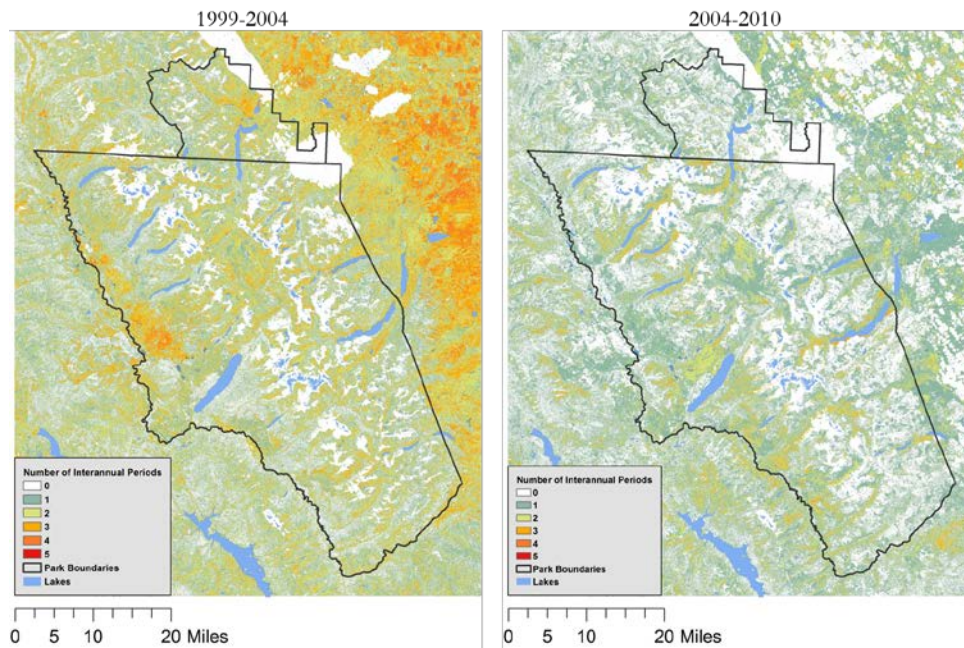


Figure 8: Disturbance frequency maps for the time periods 1999-2004 and 2004-2010. These maps illustrate how often certain areas are affected by high disturbance levels of NDMI change.

4.1 Analysis of Results

Disturbance maps created have correlations with both fire and pathogens for years that follow years with average or above average precipitation. Figure 5 illustrates how our disturbance maps of Δ NDMI are capable of picking up burned areas, shown by the large patch of high and abrupt disturbance area classified on the western side of the park in 2000. This classified area aligns with the fire polygons given to us by the park service. The ability to delineate the extent of fire is also noted for other years where large fires were present within the park (Appendix 2). Areas classified as high to moderate disturbance also correlate with boundary areas mapped by Aerial Detection Survey for insect and disease presence (Figure 7). Although not exact, it can be seen that there is significant overlap in some areas between areas mapped by this method, and our threshold classification.

By looking at disturbance frequency maps (Figure 8), certain geometries stand out as being affected by persistent disturbance for three to five years. Due to this timespan being similar to the lifespan of the mountain pine beetle, it can be assumed that these areas have a chance of being proxies for detecting presence of mountain pine beetle infected forests. Disturbances such as fire, floods, avalanches, and landslides will conversely show up as only having been disturbed for one year, as these disturbances are characterized by drastic interannual change in NDMI which does not leave much forest structure to be further disturbed. It is also possible that these areas have been perennially disturbed due to drought or other slower acting biologic stressors, rather than pathogens. Nevertheless, we expect that these rolling frequency maps are better predictors of emerging areas of disturbance compared with maps of a single instance of interannual change, as they reduce some of the noise in the data from yearly fluctuations in climatic variables.

It was also observed that portions of the study location to the northeast of the park are consistently under disturbance. This is most likely due to the fact that these are agricultural lands where irrigation and crop growing have significant impacts on the NDMI values. This, coupled with the fact that these are not forested lands, leads us to suggest that our threshold scheme should not be applied to those areas.

The histograms for pathogen presence (mapped by ADS) and healthy forest display a great degree of overlap (Figure 2). While abrupt change is clearer with little overlap to healthy forest, high disturbance related to possible pathogen presence (threshold values from -450 to -4000) is more difficult to distinguish. At the lower thresholds for moderate and low disturbance, there is a high degree of overlap for the two histograms and it is not possible to discriminate these low-level disturbances from healthy forests. Due to the nature of aerial surveys, it is possible that healthy forest could occur within areas mapped as pathogen-presence. A possible solution to provide more discriminatory power would be to ground-truth a segment of the pathogen-infested areas. We expect this narrower range of Δ NDMI for pathogen-infested regions would display a smaller overlap with healthy forest regions.

4.2 Sources of Error

NDMI, being highly sensitive to changes in moisture, is also highly sensitive to precipitation variations from year to year. Therefore, years following 'drought years' show a much more pervasive presence of disturbances within the study area (Figure 9). Due to these findings, we suggest our model be used with caution in years following drought years, and if possible, be restricted to being used following years with average or above average precipitation. This will eliminate areas being falsely identified as pathogen infected, when in reality they are distressed from drought conditions.

SNOTEL Precipitation Data for Glacier National Park

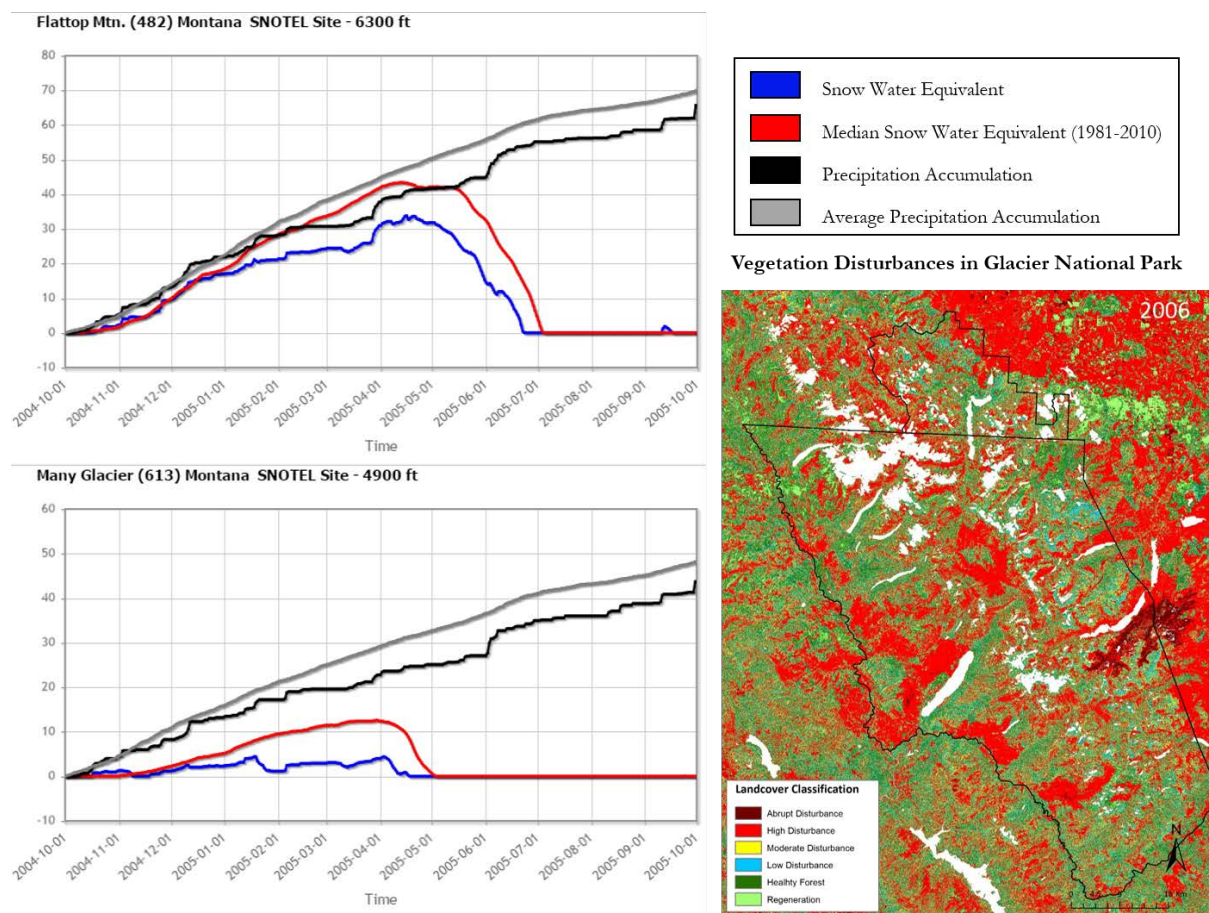


Figure 9: SNOTEL moisture data for water year 2005: October 2004 through October 2005. This is compared to a NDMI threshold map of disturbances for 2006. Due to drier conditions, there is an increase in high disturbance areas. For more SNOTEL data, see Appendix 4.

Error was also assessed by calculating the percentage of each disturbance category within ADS mapped polygons. Because we assumed that the ADS polygons map abrupt, high, and moderate disturbance, any pixels within the ADS polygons that instead truly represent a different category introduce another source of potential error. The range for misclassification of ADS polygons in the healthy forest and regeneration categories combined varied from 10 to 60% over the time period. Correlation analyses between average total precipitation for the four climate stations and combined healthy forest plus regeneration misclassification shows a strong association ($R^2 = 0.28$; $p=0.048$, $n=14$; Figure 11). Thus in wetter than normal years, there is a higher chance of classifying healthy forest and regeneration as disturbance within ADS polygons (Figure 10). In contrast, for drier than average years, the proportion of the ADS polygons classified as disturbance categories increases; however, some of the disturbance may be related to drought and not necessarily pathogen vectors. Furthermore, the ADS polygons do not measure the severity of disturbance and include portions of forest near pathogen infected stands that are not infected, introducing further error. Therefore, these results should be interpreted cautiously, taking into consideration that the frequency maps will not eliminate all noise from the data.

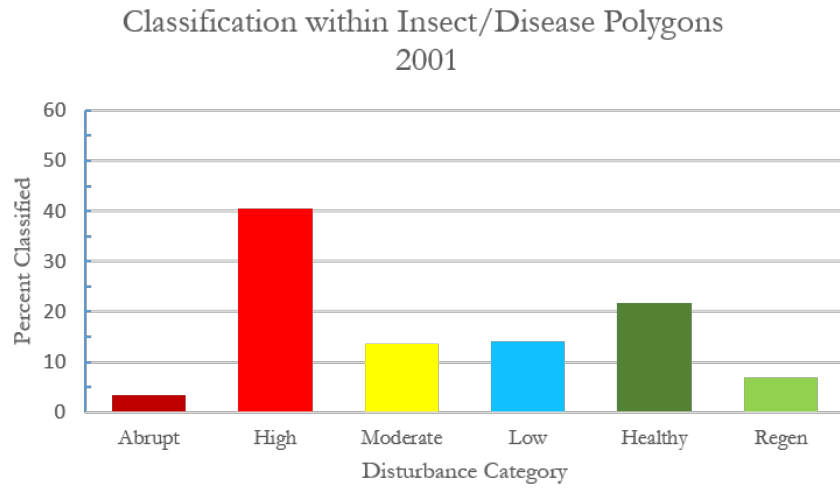
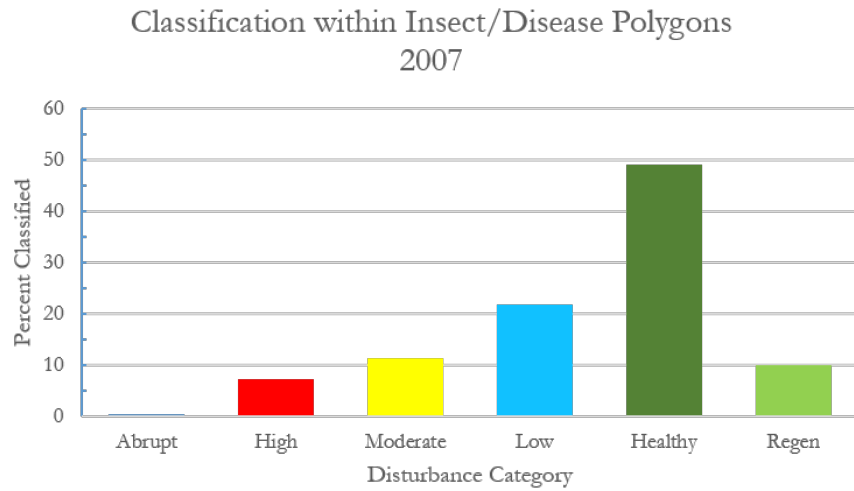


Figure 10: Histograms of disturbance classification within areas classified by Aerial Detection Survey (ADS) as having been affected by insect/disease.

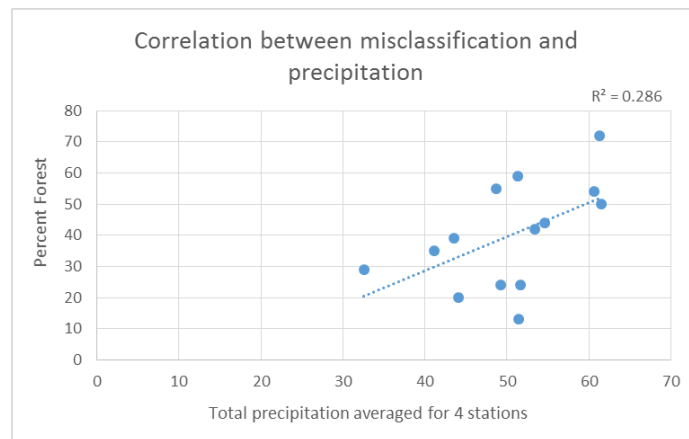


Figure 11: Correlation between classified forest categories within USDA ADS polygons and total precipitation averaged for 4 weather stations ($R^2 = 0.23$; $p=0.048$, $n=14$).

4.3 Future Work

Ideas for expanding upon this first term's work are as follows: use Δ NBR (Normalized Burn Ratio) to map recent and historical fire areas in Waterton Lakes National Park; leverage NASA's SRTM elevation data, land cover datasets, and disturbance frequency maps to understand how landscape characteristics affect disturbance; continue to work with area high school groups to develop ground truth data sets that will improve threshold determination and allow for an accuracy assessment of our frequency maps; explore the correlation between Mountain Pine Beetle presence and fire intensity, frequency, extent, and ignition.

5. Conclusions

Threshold based classification schemes provide a quick way of identifying and mapping landscape disturbances. Δ NDMI is very sensitive to changes in time of year and precipitation changes, therefore drought signatures can mimic pathogen disturbance signatures. It is for this reason that **our** Δ NDMI threshold classification is best applied to years with roughly average precipitation. Furthermore, by improving the accuracy of our Δ NDMI thresholds we will improve our predictions of pathogens across the landscape. We expect that we could improve these thresholds given more ground truth polygons that specifically delineate areas impacted by pathogens at different stages of green, red and grey attack, include attributes such as the percent of stand infected as a proportion of the overall stand, and by incorporating the fire polygons provided by the park service into how we determine the threshold for abrupt disturbance.

6. Acknowledgments

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- Dr. Kenton Ross, Science Advisor, NASA Langley Research Center
- Dr. Christopher Potter, Senior Research Scientist, NASA Ames Research Center
- Richard Menicke, Geographer, National Park Service
- The students and teachers of Whitefish and Columbia Falls High Schools

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7. References

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8. Content Innovation

Content Innovation #1

VPS video

Available on YouTube at: <https://www.youtube.com/watch?v=O5Foy-pWVaM&feature=youtu.be&list=PLJ.8pCbx5gnDaUglEO0269Lj95zp4r63V4>

Content Innovation #2

Glossary Viewer

- **Aerial Detection Surveys (ADS)** - provided by the U.S. Forest Service, Area Detection Surveys are a remote sensing technique used to detect forest changing events often attributed to insects and disease. These surveys are conducted using a small aircraft on which an observer visually gauges the extent of forest degradation. The observer will manually record his or her observations through sketches onto a map.
- **Columbia, Missouri, Saskatchewan Rivers**- Glacier National Park water can be considered the headwaters of rivers throughout the entire United States, including the three major rivers listed. The Columbia is one of the largest rivers in the Pacific Northwest and enters the Pacific Ocean. The Missouri River is the longest river in American and feeds into Mississippi River. The Saskatchewan is one of Canada's major rivers and empties several hundred miles away into Lake Winnipeg.
- **Crown of the Continent Ecosystem**- This encompasses Glacier National Park, Great Bear Wilderness, Bob Marshall Wilderness, and Scapegoat Wilderness. The term “Crown of the Continent” was coined by George Bird Grinnell, an early American explorer who heavily advocated for the protection and establishment of what is now GNP. (<https://www.nps.gov/glac/learn/historyculture/index.htm>)

“Far away in northwestern Montana, hidden from view by clustering mountain peaks, lies and unmapped corner- The Crown of the Continent.” –George Bird Grinnell (1901)
(<http://www.crownsience.org/topics/history/glaciernationalpark>)
- **Digital Elevation Models (DEM)**- in a generalized sense, Digital Elevation Models (DEM) depict topographic elevation of a study area. DEMs are usually raster datasets with each pixel value of the raster given a particular elevation height. On a map, a DEM will illustrate a terrain with what looks like hill shade, giving the overall image a 3-dimensional appearance.

- **Goodwin's *Estimation of insect infestation dynamics using a temporal sequence of Landsat data*** – This scientific paper helped guide our data analysis and decision making processes. The paper discussed NDMI disturbances based on pine beetle attack. Goodwin and his supporting authors established healthy and unhealthy vegetation thresholds. Healthy vegetation's NDMI pixel range was between 0 and 20,000, whereas unhealthy vegetation, based on pathogen presence, generally existed between 0 and -4,000.
- **Landsat 5 Thematic Mapper (TM)**- This satellite carries several sensors including the Thematic Mapper (TM) which uses seven spectral bands while scanning the Earth with a spatial resolution of 30 meters. Landsat 5 was launched by NASA in March of 1984. The Thematic Mapper sensor halted its imaging in
- **Landsat 7 Enhanced Thematic Mapper (ETM+)**- Landsat 7 satellite carrying the Enhanced Thematic Mapper (ETM+) sensor was launched by NASA in April of 1999. The sensor has eight spectral bands, a spatial resolution of 30 meters, and is still in use today. (<http://landsat.gsfc.nasa.gov/the-enhanced-thematic-mapper-plus/>)
- **Landsat 8 Operational Land Manager (OLI)**- Landsat 8 satellite carrying the Operational Land Manager (OLI) was launched by NASA in February 2013 and its still in operation today. The OLI has nine spectral bands and its spatial resolution in 30 meters. (<http://landsat.gsfc.nasa.gov/operational-land-imager-oli/>)
- **Minimum envelope geometry**- or referred to as a 'Minimum bounding geometry', is a tool used in ArcMap to delineate a polygonal area feature class based on chosen input classes.
- **NASA's Applied Sciences Program**- consists of nine areas of application: Water Resources, Oceans, Weather, Climate, Disasters, Energy, Agriculture, Ecological Forecasting, Health and Air Quality. These nine areas of applications are intended to address environmental and public policy issues by conducting projects that apply NASA's Earth Observations to community and environmental concerns. (<https://develop.larc.nasa.gov/projects.php>)
- **NASA Earth observations**- refers to NASA's fleet of satellites which circumnavigates the Earth collecting timely scientific data 24/7.
- **Normalized Difference Moisture Index (NDMI)**- This index is based on vegetation moisture. Wetlands or vegetation with high levels of moisture will receive a higher index value (fraction) which is calculated using the following equation:

$$\text{NDMI} = (\text{NIR} - \text{SWIR1}) / (\text{NIR} + \text{SWIR1}) \text{ (Goodwin et al, 2008)}$$

NIR refers to near-infrared spectral band, and SWIR1 refers to the higher frequency short wave infrared spectral band. The SWIR1 band wavelength ranges from 1.55-1.75 micrometers for Landsat 5 TM and 7 ETM+ and ranges from 1.57-1.65 micrometers for Landsat 8 OLI

- **Normalized Difference Vegetation Index (NDVI)**- This index gauges the vegetation density based on spectral band analysis using the following equation:

$$\text{NDVI} = (\text{NIR} - \text{VIS}) / (\text{NIR} + \text{VIS})$$

NIR stands for the near infrared wave, and VIS stands for the visible infrared wave. Like NDMI, larger fractions are areas with healthier vegetation. (<http://earthobservatory.nasa.gov/>)

- **Pathogen disturbances**- The pathogen disturbances analyzed in our project, using established vegetation indices, refer to both those known and unknown. Prevalent and growing in reoccurrence, Mountain Pine Beetle degradation and White Pine Blister Rust are some of the more familiar disturbances to GNP's park service.

-*Mountain Pine Beetles (Dendroctonus ponderosae)* are native to the area, however climate change is likely accelerating the impacts of their destructive nature. The beetles burrow holes into the exterior of pines, firs, and spruces, degrading the bark which ultimately leads to the death of the tree. Normally, a cold winter in the park will lower the Mountain Pine Beetle population, but because of steadily increasing temperatures, their populations are rising.

-*White Pine Blister Rust (Cronartium ribicola)* is a stem rust fungus present in white pine tree species. Once infected, the non-native disease immediately kills its host.
(<https://www.nps.gov/glac/index.htm>)

- **Surface reflectance data-** refers to data obtained using remote sensing techniques by satellites-carrying sensors.
- **Time series-** Satellite images, or scenes, taken over a particular time period
- **United States Geological Survey Earth Science Processing Architecture (USGS ESPA)-** This USGS operated website allows for bulk ordering and downloading of Landsat time series scenes for a study area.
- **USGS National Gap Analysis Program (GAP)-** This USGS funded program provides land cover spatial data, species data, and protected areas data to the public. For our project, we utilized GAP's land cover data which classifies land use and vegetation based on the NatureServe Ecological System Classification. (<http://gapanalysis.usgs.gov/gaplandcover/>)

November of 2011 and the satellite was later decommissioned in June of 2013.
(http://landsat.usgs.gov/about_landsat5.php)

- **WGIPP-** acronym standing for Waterton-Glacier International Peace Park (WGIPP) which includes the U.S.'s Glacier National Park and the adjacent Waterton Lakes National Park of Canada.

Content Innovation #3

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9. Appendices

Appendix 1: Data Download locations

USGS ESPA site for ordering Landsat Data

<https://espa.cr.usgs.gov/login?next=https%3A%2F%2Fespa.cr.usgs.gov%2F>

Digital Elevation Model (DEM) Data

<http://viewer.nationalmap.gov/basic/?basemap=b1&category=ned,nedsrc&title=3DEP%20View>

GAP Vegetation Classification Data

<http://gapanalysis.usgs.gov/gaplandcover/data/download/>

Glacier National Park Boundary

<https://irma.nps.gov/DataStore/Reference/Profile/1042581>

Glacier National Park Vegetation Classification Data

<http://science.nature.nps.gov/im/inventory/veg/project.cfm?ReferenceCode=1047714>

Forest Insect and Disease Aerial Detection Survey (ADS) Data

<http://science.nature.nps.gov/im/inventory/veg/project.cfm?ReferenceCode=1047714>

Glacier National Park Fire Perimeter Polygons Generated by Fire Management

<http://irma.nps.gov/DataStore/Reference/Profile/1048748>

Glacier National Park Fire Perimeter Polygons Generated from Landsat-based Burn Severity

<https://irma.nps.gov/DataStore/Reference/Profile/1048749>

Greater Crown of the Continent Ecosystem Fire Burn Severity Generated via Landsat

<http://irma.nps.gov/DataStore/Reference/Profile/2224656>

Natural Resources Conservation Service (NRCS) Snowpack Telemetry (SNOTEL) Data and Products

<http://www.wcc.nrcs.usda.gov/snow/>

Appendix 2: InterAnnual Disturbance Maps Based on Δ NDMI

<https://drive.google.com/open?id=0B7vo49iFoQEZVlFGVHYwbT'ZLaFk>

Appendix 3: Disturbance Frequency Maps

<https://drive.google.com/open?id=0B7vo49iFoQEZZTk5NTlZazdCMk0>

Appendix 4: NRCS SNOTEL Water Year Charts

<https://drive.google.com/open?id=0B7vo49iFoQEZT2FFdlhPZkNfdVU>

Appendix 5: ADS Polygon Disturbance Classification Histograms

<https://drive.google.com/open?id=0B7vo49iFoQEZZ0xPUk1xT3ZpZW8>