Using cloud-based remote sensing to estimate Hurricane Impacts on Vegetative Cover in Carolina Bays in North Carolina

By

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Submitted to the Graduate Faculty of
North Carolina State University
in partial fulfillment of the
requirements for the Degree of
Master of Environmental Assessment

Raleigh, North Carolina

2018

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04/26/18

ABSTRACT

Schager, Sara, Masters of Environmental Assessment, Using cloud-based remote sensing to estimate Hurricane Impacts on Vegetative Cover in Carolina Bays in North Carolina

Carolina Bays are unique geographically isolated wetlands that provide critical habitat to several species of plants and animals in the southeastern United States. These areas, due to their inland location, unique vegetation, and shallow inundation of water, can experience strong effects from hurricanes. Hurricanes' high winds, and large amounts of precipitation could affect these shallow, inland wetlands. Carolina Bays have not been well studied, and the impacts of hurricanes on them have been even less evaluated. I utilized a cloud-based remote sensing approach to examine the effects of hurricanes on the vegetative cover of Carolina Bays. Using Climate engine, I utilized the normalized difference vegetation index (NDVI) as a measure of vegetation status. I evaluated seven hurricanes and 32 sites to determine if hurricanes affected vegetative cover in Carolina Bays. Out of the 32 sites and seven hurricanes examined, five sites showed statistically significant effects to vegetation from hurricanes. Site 6 had a higher NDVI value (0.909) before the hurricane than it did during the same time period the year after the hurricane occurred (0.755). Additionally, Site 6 was 60% agricultural field. This site showed that Climate Engine is capable of detecting changes in NDVI values on Carolina Bay sites. Four sites affected by Hurricane Fran had a significantly lower NDVI the month after the hurricane occurred than they did the month before the hurricane. Hurricane Fran was a larger hurricane event and probably had bigger vegetative impacts than the smaller hurricane events. My research suggests that NDVI values obtained from Climate Engine are capable of determining vegetative impacts on Carolina Bays, especially changes to NDVI of Carolina Bays during bigger hurricanes. While Climate Engine makes large amounts of remote sensing data easily accessible, in our case the remote sensed data did not show very strong impacts of smaller hurricane events on Carolina Bays. This is probably due to the fact that the actual impacts on the ground are limited due to the dynamic nature of the Carolina Bays themselves, rather than limitations of Climate Engine. Limitations such as cloud cover during evaluation windows, resolution of satellite photography (30 x 30 m pixels), and the fact that NDVI cannot pick up on species composition changes or changes caused by fallen debris may have hindered evaluation. Future research on Carolina Bays should focus on changes in depth of water due to precipitation and fallen debris, which may uncover additional impacts to these ecosystems from hurricanes.

ACKNOWLEDGEMENTS

I would like to thank my thesis advisor, Dr. Marcelo Ardon Sayao of the College of Natural Resources at North Carolina State University. Dr. Ardon was always available to answer my questions, provide guidance and suggestions to improve my research and continually steered me in the right direction.

I would also like to thank Cam McNutt of the Division of Water Quality, North Carolina Department of Environmental and Natural Resources for providing assistance in locating map layers of Carolina Bays in North Carolina.

I would like to thank I would also like to acknowledge Dr. Barry Goldfarb of the College of Natural Resources at North Carolina State University and Mrs. Linda Taylor of the College of Natural Resources at North Carolina State University for their support evaluating this research and providing feedback to improve the direction of this paper.

Finally, I would like to thank my husband and children for their continuous support, encouragement and understanding as I worked to complete this degree and paper. This process would never have been possible without them. Thank you.

Sara Schager

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Introduction

Carolina Bays are a unique habitat type that occur in the Coastal Plain area of the southeastern United States. They are small elliptical wetlands that are arranged in the landscape from a northwest to southeast direction (Prouty, 1952). These depressions are oriented from northwest to southeast and are not connected to other wetlands (Linde et. al., 1995). Carolina Bays also incorporate a sand rim on the southeastern edge (Prouty, 1952). They receive most of their water input from precipitation in the spring and fall and also tend to dry out during the summer months (South Carolina Department of Natural Resources, 2015). Currently there are estimated to be between 10,000 and 20,000 Carolina Bays in existence (Richardson and Gibbons, 1993), with many areas that were historically Carolina Bays drained for agricultural uses.

There have been several theories about how Carolina Bays formed. However, recent research has pointed toward Carolina Bays being the remains of glacier ice boulders which were thrown off a meteorite. This created seismic shock waves which when they impacted the Earth created liquified ground that was subsequently impacted by pieces of ice from the boulders. The meteorite is believed to have impacted the Laurentide Ice Sheet (Zamora, 2017). The orientation of these wetlands in a northwestern to southeastern direction was caused by this single impact event (Zamora, 2017).

Carolina Bays provide a unique habitat for vegetation that is not seen in other habitats. They have a fluctuating hydrologic regime that responds to rainfall seasonality (Sharitz and Gibbons, 1982 and Schalles and Shure 1989). Carolina Bays have a larger species richness in their seed banks than has been noted in other types of wetlands (Kirkman, 1996). Additionally, they are a habitat for several rare herbaceous flowering plants (Bennett and Nelson, 1990 and Knox and Sharitz, 1990). Finally, Carolina Bays are important to overall water quality and carbon sequestration (Sullivan et. al., 2017). This set of unique characteristics makes them a valuable part of the landscape.

Wetlands, in general, perform important functions by exchanging materials and energy with the surrounding environment (Cohen et. al., 2015). They fulfill necessary functions such as providing vital habitat for dependent organisms, acting as retention areas for sediment and nutrients, and reducing the severity of flooding events downstream of their location. (Cohen et. al., 2015). Carolina Bays are important because they offer critical habitat to rare plants and animals. Research on Carolina Bays has largely focused on how they were formed, their hydrologic impacts, and on the unique plants and animals that utilize them. However, vegetative impacts to Carolina Bays from hurricanes have not been well studied. Hurricanes, with high winds and large amount of rainfall that occur, could easily impact Carolina Bays by creating changes in vegetative cover within the Carolina Bay itself and the surrounding area.

Hurricanes produce two main types of impacts on wetlands, wind effects and precipitation effects. Wind effects include wind damage to trees and vegetation. Hurricanes can also impact Carolina Bays by changing hydroperiod and impacting vulnerable plant and animal habitat (by increasing forest floor litter near geographically isolated wetlands, thereby increasing suitable habitat).

Research on hurricanes has shown than they have a largely varied path after landfall. Previous research has studied the width of the storm path, the effects of the storm, what happens to coastal habitats because of them and even the flooding events they cause (Doyle 2009, Avery et.al., 2014, Rodgers et. al., 2009 and Conner et. al., 2014). A map created by the National Oceanic and Atmospheric Administration (NOAA) provides the paths of all the recorded hurricanes that have impacted the southeastern United States. Additionally, Bianchette (Liu et. al., 2016) found that hurricane Isaac (a landfalling hurricane) had the biggest impacts 70 km to the east of the exact storm path. Due to the general rotational direction of hurricane winds, 70 km to the east of the actual hurricane's path would conceivably receive the most severe impacts. Hurricane winds are one of the forces that expose wetlands to damage in numerous ways. The main impact to wetlands from hurricane winds is wind damage to vegetation. A study of wetlands in Virginia found that tree damage caused by high winds increased with increasing soil salinity and proximity to the Atlantic Coast (Middleton, 2016).

In addition to the impacts discussed above, it is important to note that inland geographically isolated wetlands (GIW's), such as Carolina Bays, may be more sensitive to hurricanes than coastal wetlands, because they do not experience hurricanes on a regular basis and thus might not be adapted to deal with high winds and rainfall. A study in 2016 found that the impact on vegetation from hurricanes can be extremely variable, however, in general, saltwater wetlands are more resilient than freshwater wetlands (Medeiros et al. 2016). This suggests that inland GIW's may experience different effects than coastal wetlands due to the lack of storm surge, but may experience other impacts such as vegetative damage due to hurricane winds (Medeiros et al. 2016).

Remote sensing has been used to determine human impacts of hurricanes in populated areas (Kelmas, 2009), but not specific to wetlands or Carolina Bays. Additionally, researchers found that a canopy foliage index (CFI), which was created by transforming satellite optical data, showed a large decrease in canopy cover following a storm event for a wetland area in southern Louisiana following Hurricane Katrina (Ramsey et al. 2009). Additionally, Rodgers et. al. 2009, found declines of up to 49% on the normalized difference vegetation index (NDVI) on coastal emergent wetlands impacted by Hurricane Katrina using Landsat 5 satellite images before and after the hurricane to determine impacts. However, to my knowledge no work has been done on using remote sensing to estimate the impacts of hurricanes on the vegetation of Carolina Bays.

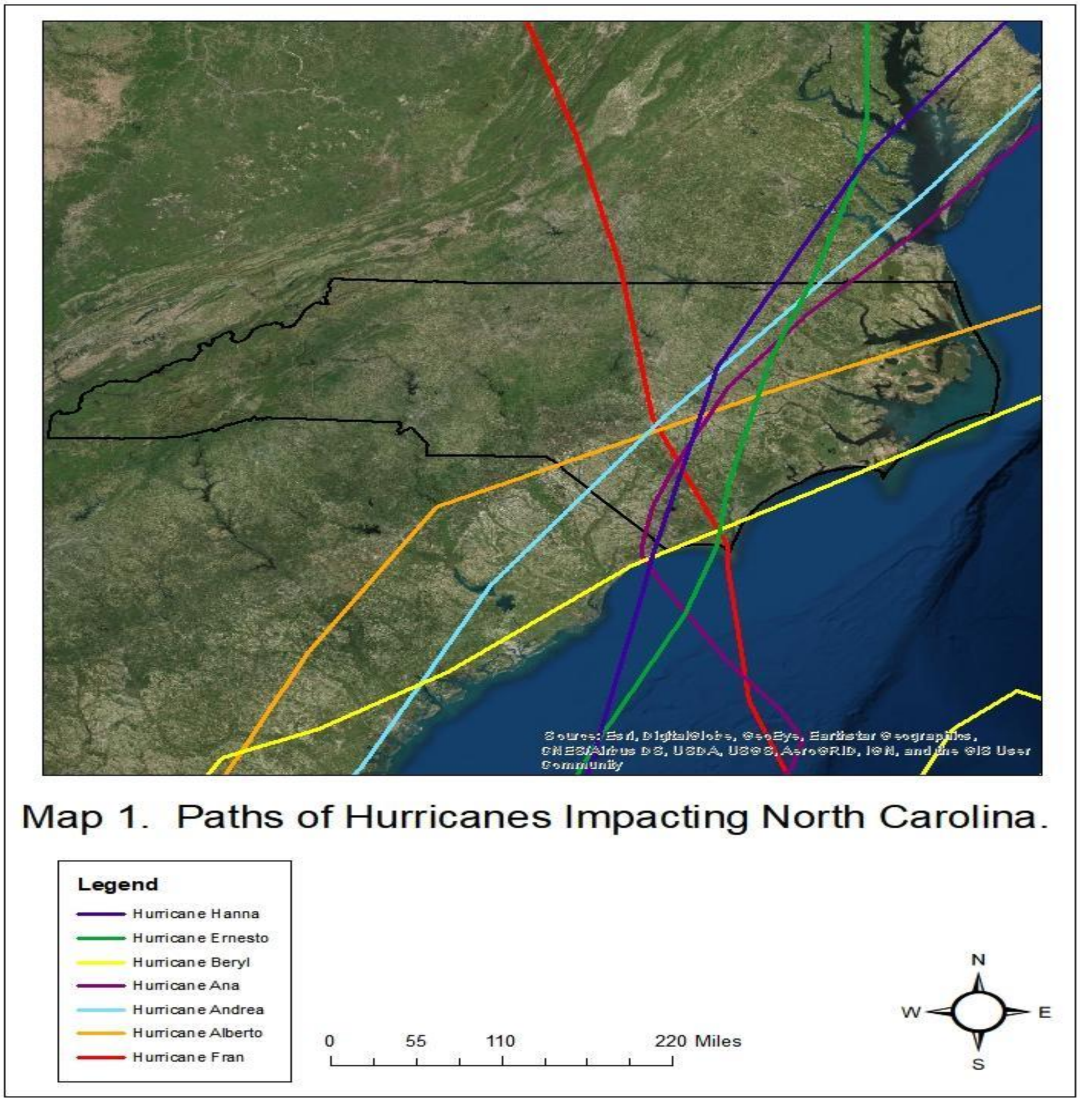
In this study, I used the NOAA Hurricane Paths Map to identify hurricanes that might have impacted Carolina bays. I used Landsat images to estimate the Normalized Difference Vegetation Indices (NDVI) to determine if hurricanes had notable vegetative impacts on Carolina Bays. I obtained the Landsat images from Climate Engine (http://clim-engine.appspot.com/). Climate Engine is an online cloud-based tool that utilizes Google Earth and Google Cloud to allow satellite and climate data to be processed for research purposes (Huntington et al. 2017). Climate Engine makes freely available all Landsat images and can be used to download timeseries of NDVI indices for a particular area using a point and click interface. Climate Engine has the potential to serve as a valuable tool for natural resource managers, given the large amount of climate and remote sensing data that has now become freely accessible (Huntington et al. 2017). The NDVI is an index that measures vegetative cover using satellite imagery. NDVI values range between 0 and 1 and the higher the indices, the more green vegetative cover the satellite imagery observed at the given date.

Our ability to study the impacts of hurricanes may become increasingly important as climate change could increase the frequency of hurricanes that make landfall in North Carolina and expose Carolina Bays to high wind and precipitation events.

Methods

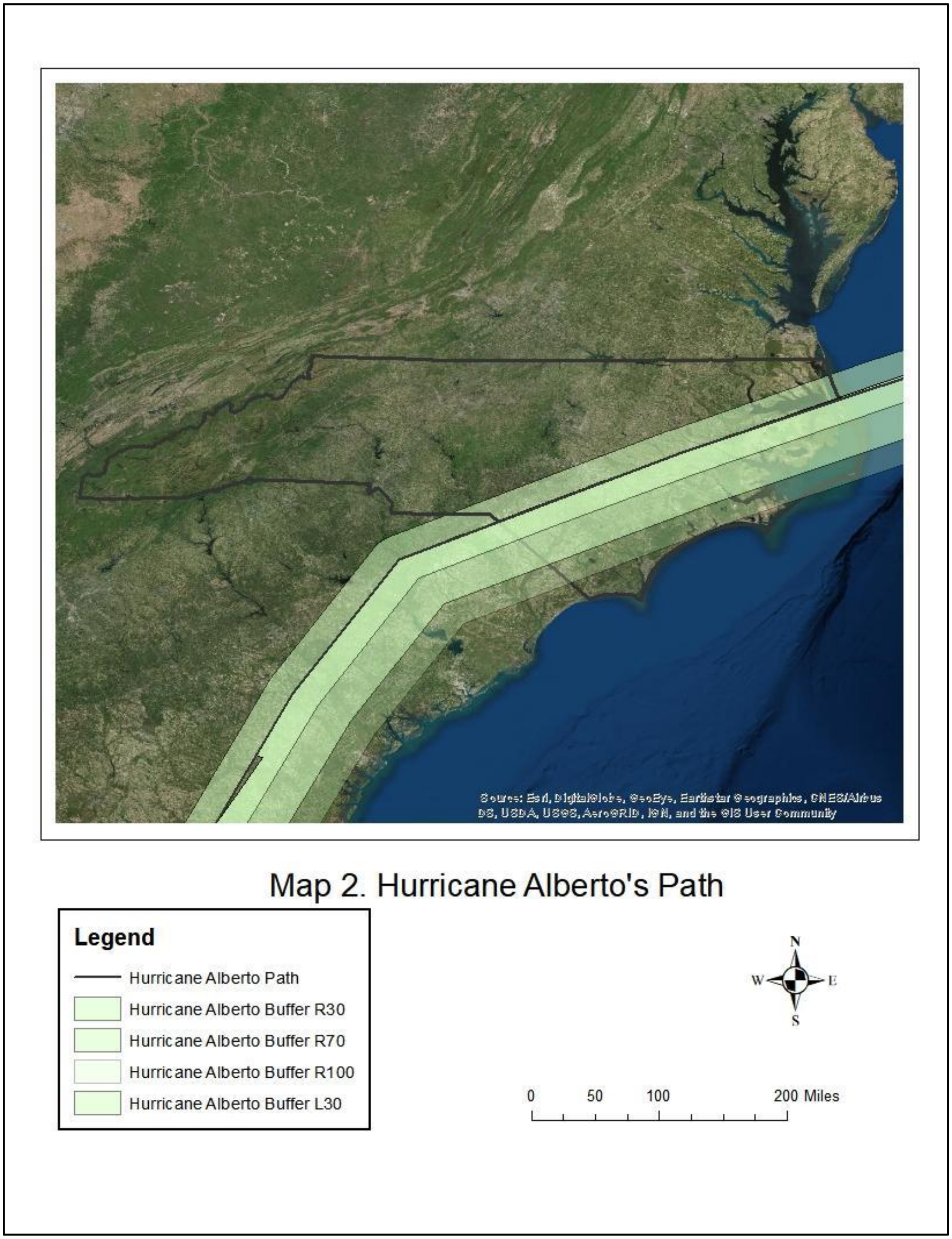
In order to examine the impacts of hurricanes on Carolina Bay vegetation, I generated maps of seven hurricanes that made landfall in North Carolina between 1996 and 2015 by downloading the information from the National Oceanic and Atmospheric Administration (NOAA, https://coast.noaa.gov/hurricanes/). The NOAA Historical Hurricanes Tracks web tool was used to determine where each of the studied hurricanes impacted North Carolina. The coordinates for each hurricane path were then downloaded into ArcMAP. Map 1 shows the ArcMAP image of the hurricane paths that were used to select study sites in this project.

Map 1. Paths of Seven Study Hurricanes Impacting North Carolina in the years 1996-2015.

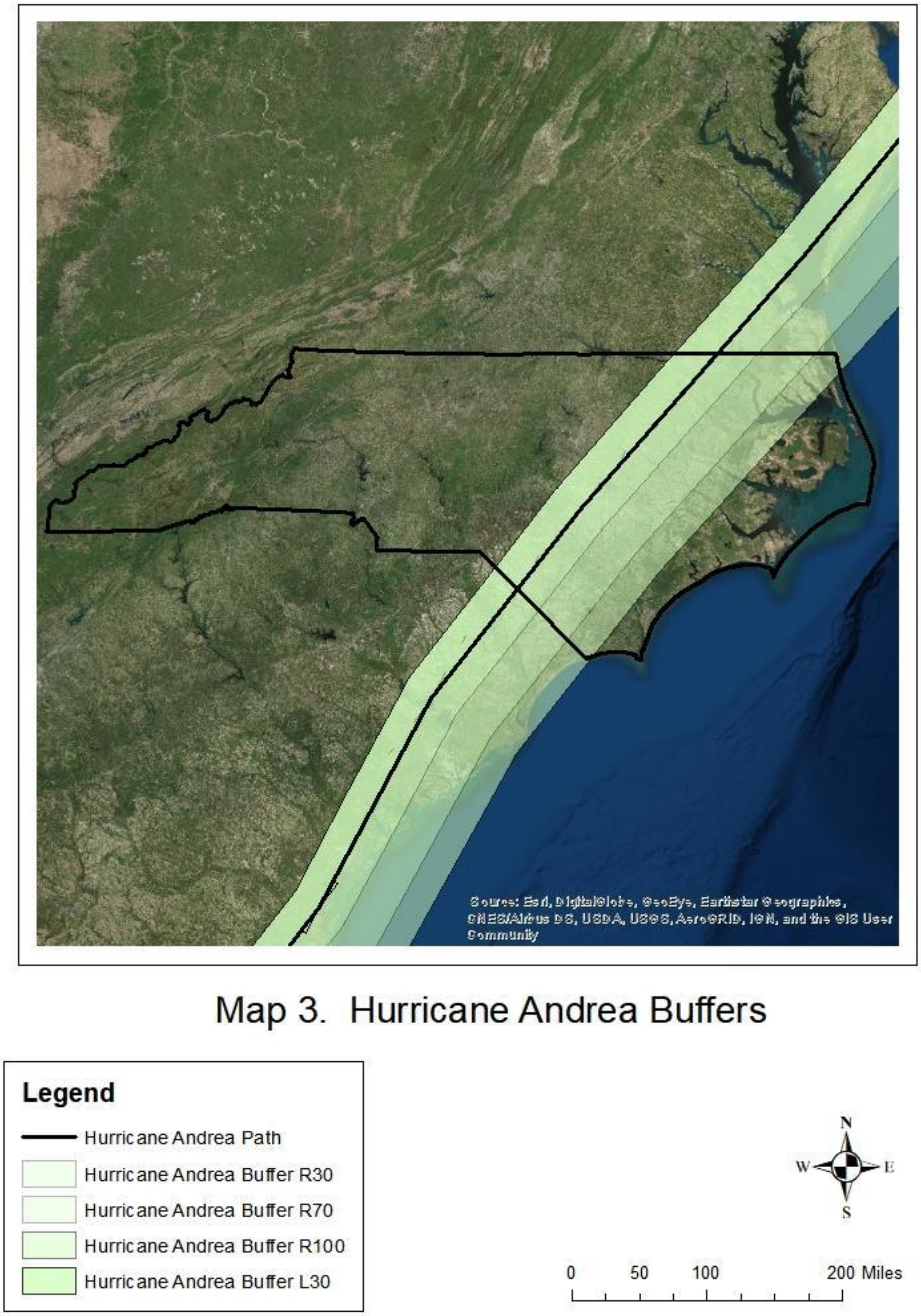


Hurricanes with different wind speeds and strengths were studied to see if the strength of the hurricane impacted the vegetation differently. I created buffers around each of the hurricane paths at 30 km to the west, 30 km to the east, 70 km to the east and 100 km to the east (see the ArcMAP Procedure Log from Appendix B for details). These distances were chosen to evaluate impacts of hurricanes on Carolina Bays because they give an even distribution of impacts from the actual path of the hurricane. Maps 2-8 show the buffer zones for each hurricane.

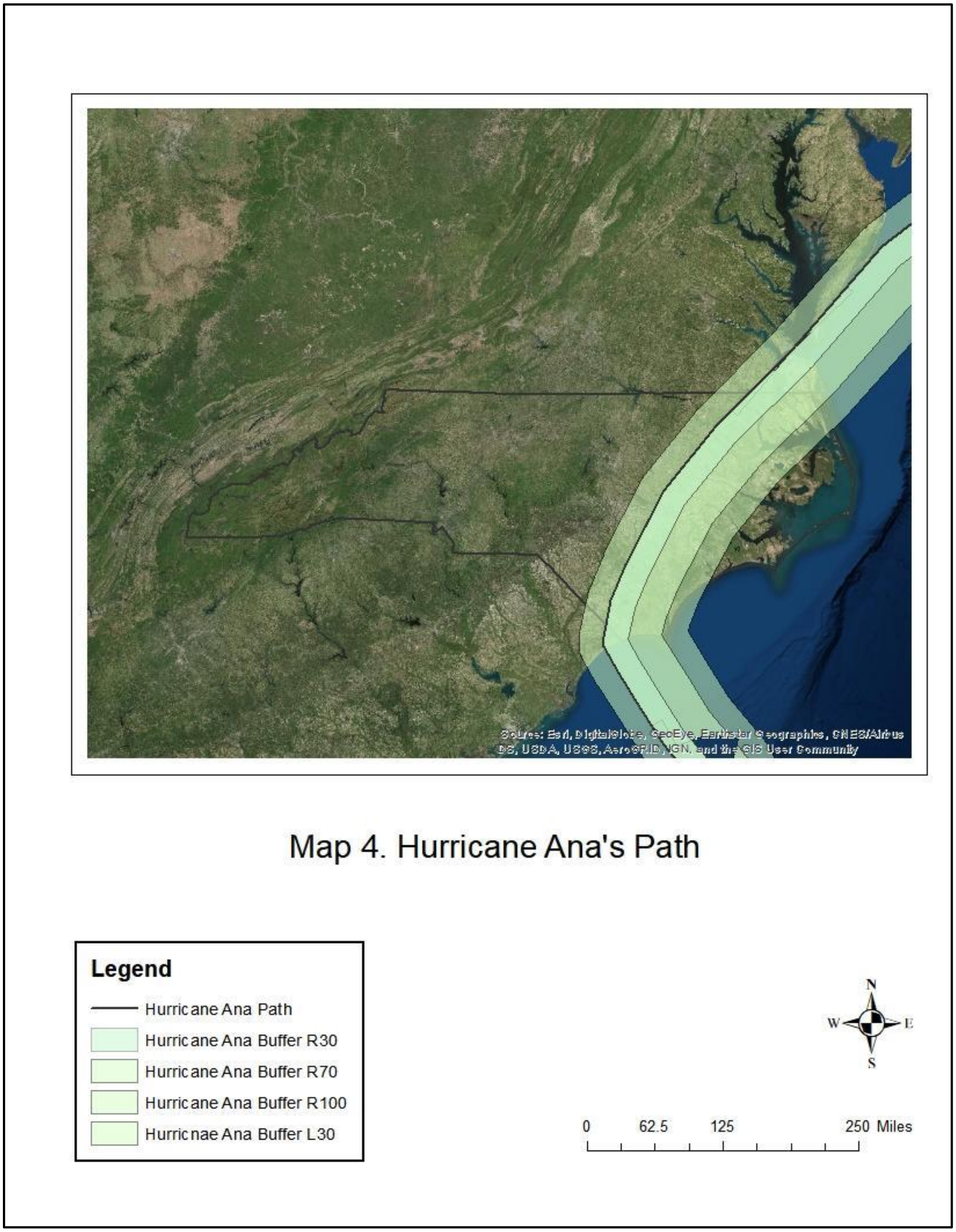
Map 2. Hurricane Alberto Buffers



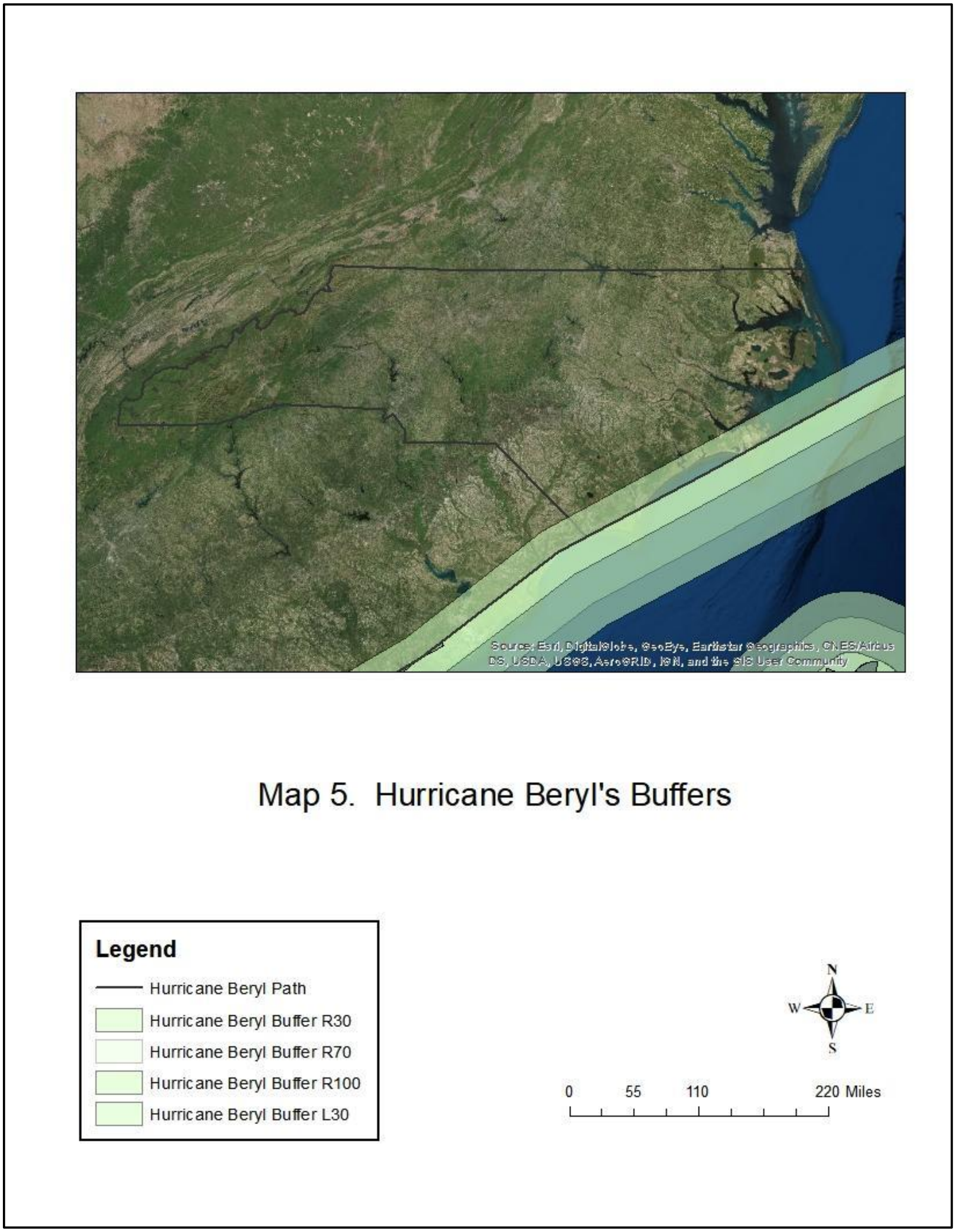
Map 3. Hurricane Andrea Buffers



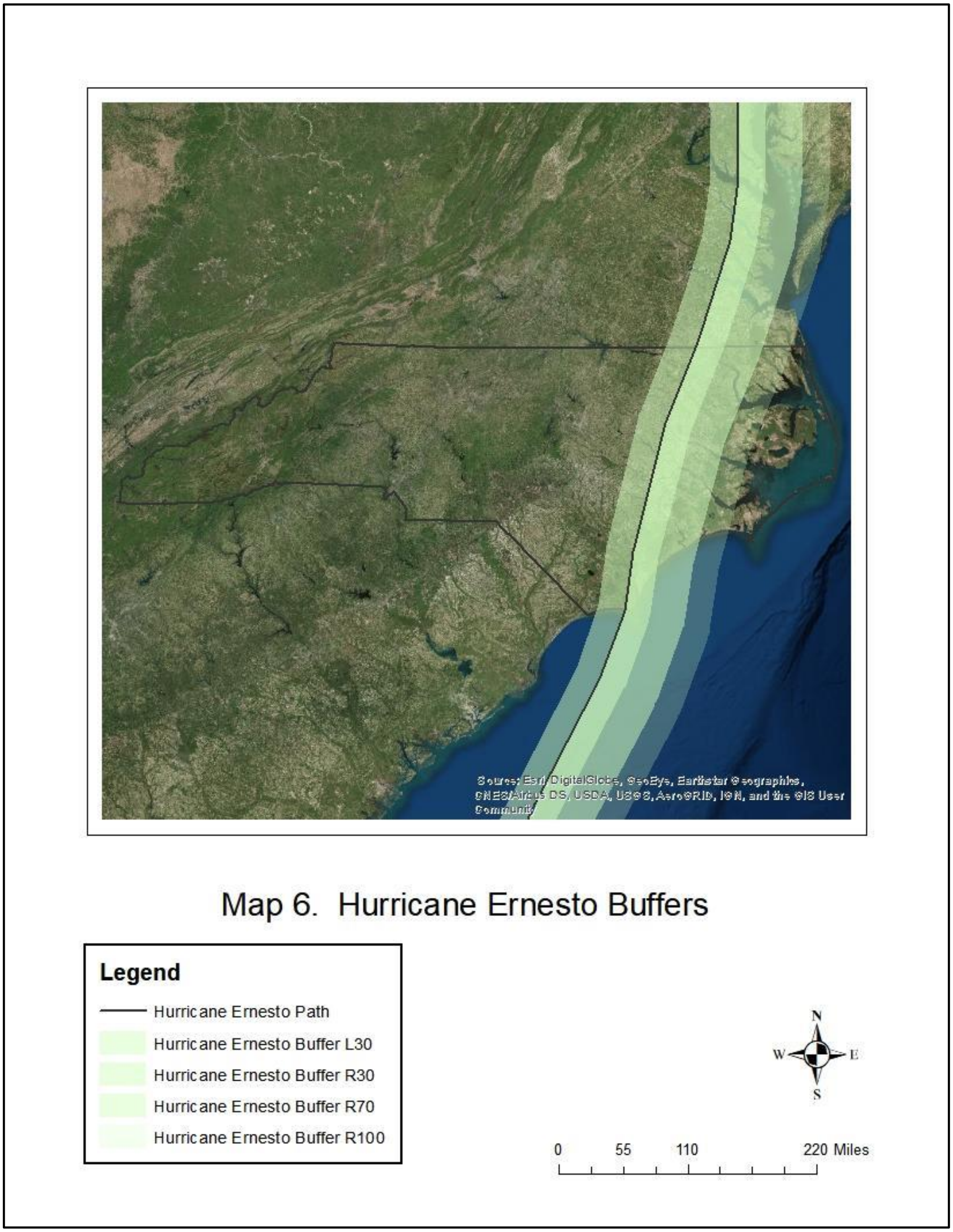
Map 4. Hurricane Ana Buffers



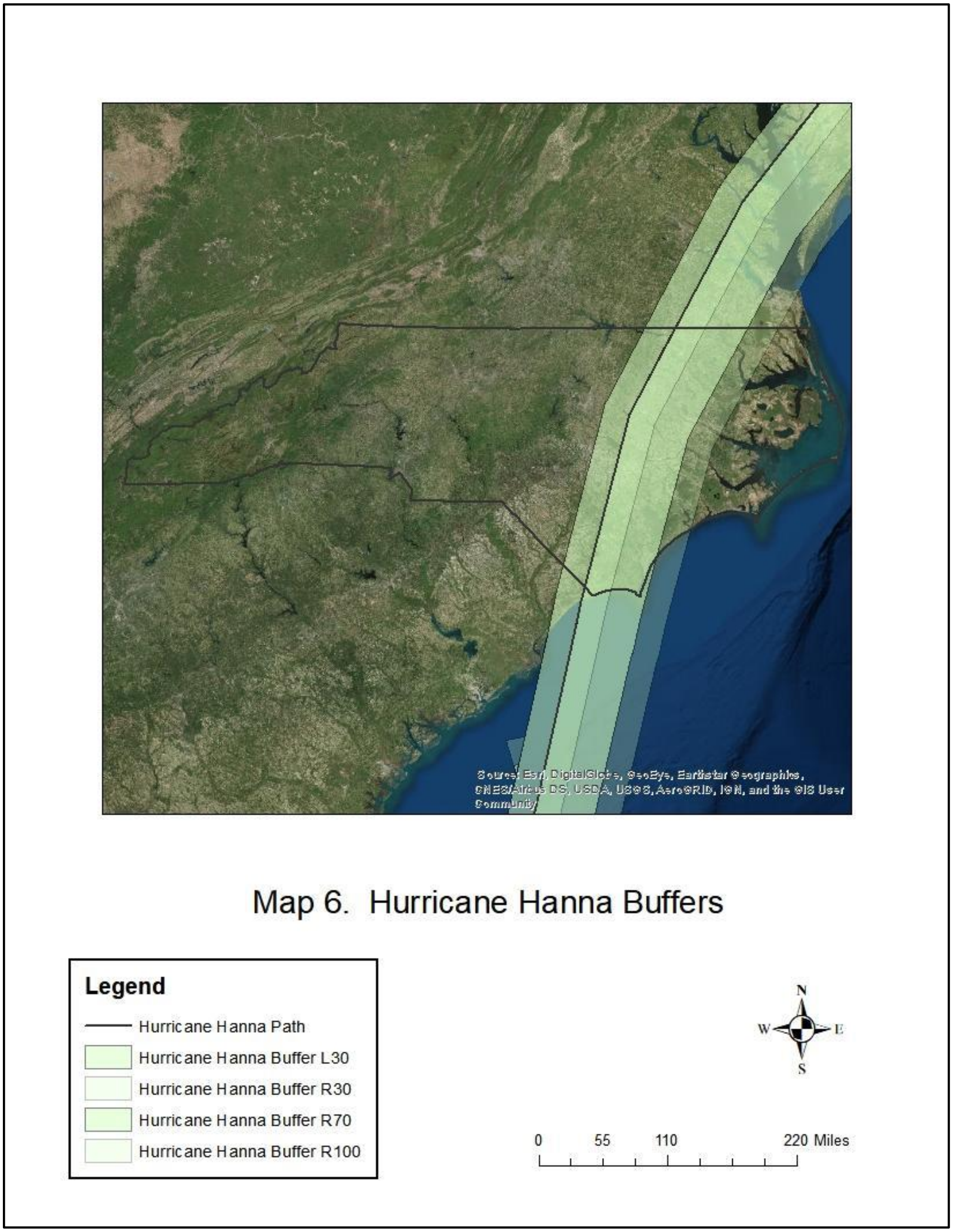
Map 5. Hurricane Beryl Buffers



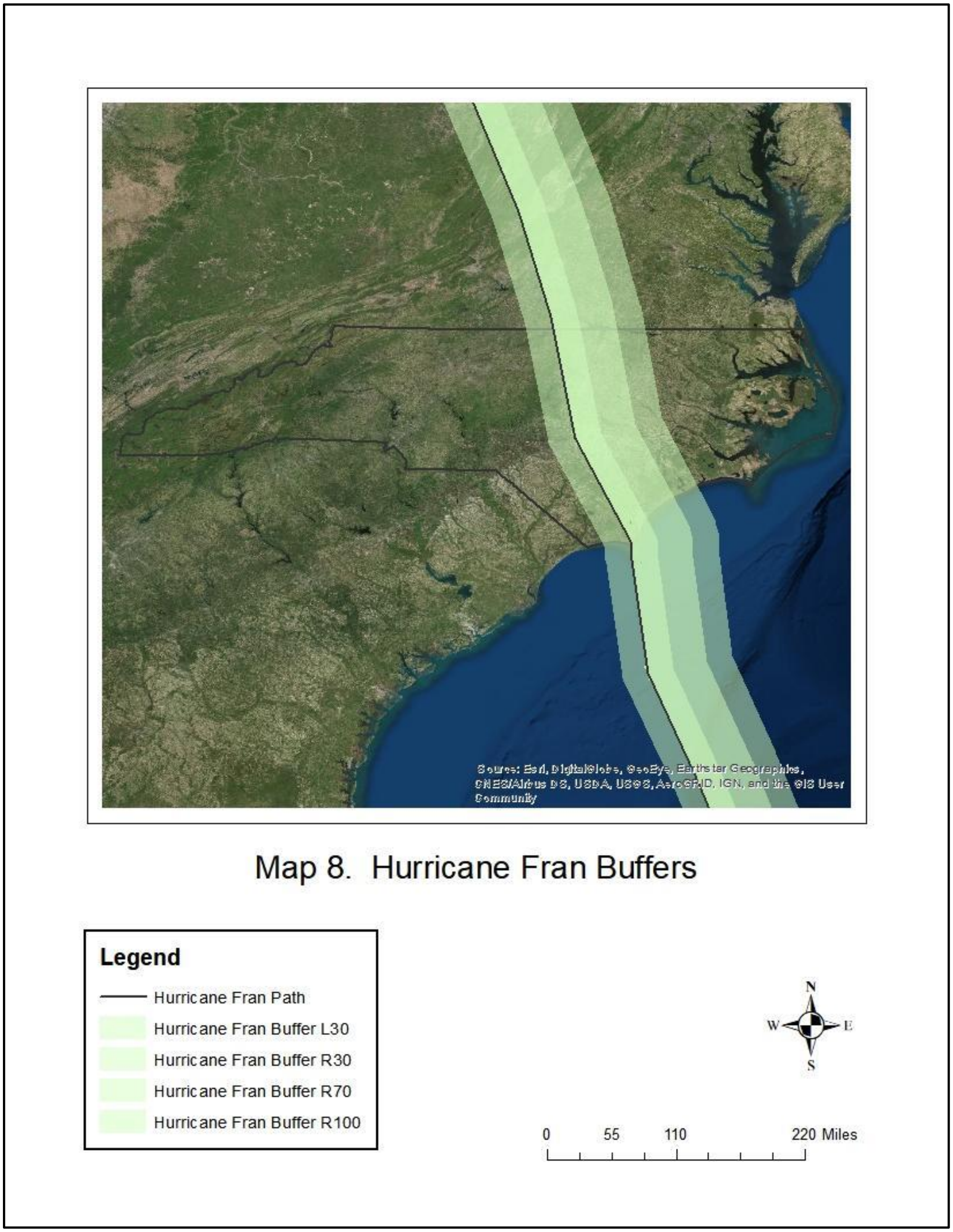
Map 6. Hurricane Ernesto Buffers



Map 7. Hurricane Hanna Buffers



Map 8. Hurricane Fran Buffers

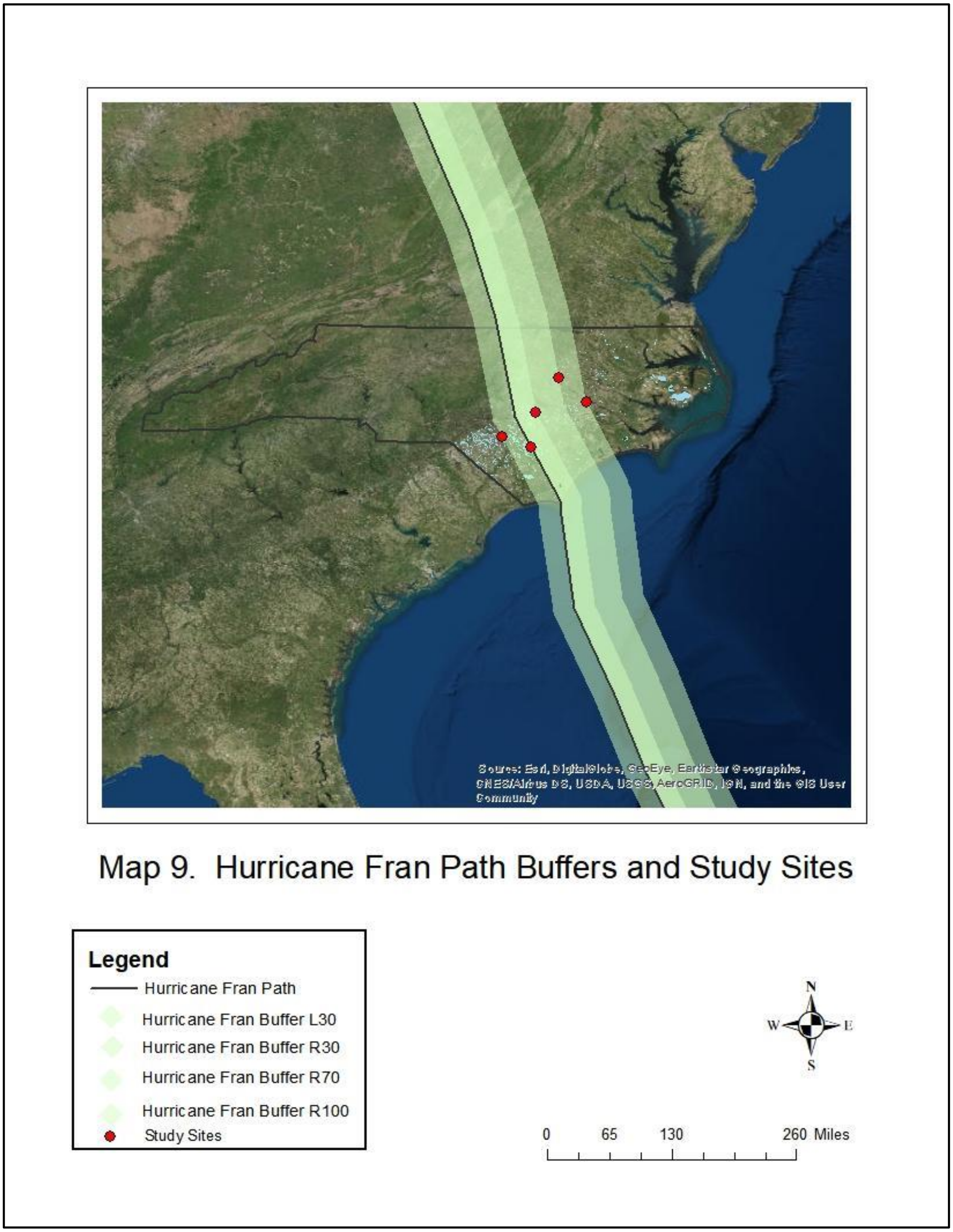


Next, a map of Carolina Bays in North Carolina (http://georgehoward.net/NCBays.KMZ) was overlaid on the buffered hurricane path map and five Carolina Bay sites were selected for each hurricane (30 km west of the hurricane path, the hurricane path, 30 km east of the hurricane path, 70 km east of the hurricane path and 100 km east of the hurricane path). The Carolina Bay's GIS file was verified and Carolina Bay study sites were determined to have the appropriate size and orientation using this map and satellite imagery. Map 9 shows the buffered hurricane path for Hurricane Fran, along with the selected sites for this hurricane.

Map 10 shows a close up image of the Carolina Bay map layer and the satellite imagery to show how a site was selected. In general, the Carolina Bays selected had to be located correctly, and be covered in vegetation (this was determined by overlaying satellite imagery provided in ArcMAP onto the map of hurricane paths and Carolina Bay locations). However, as controls, one site was selected that was suburban and one that showed standing water. These two sites were selected to determine if any observed changes to the NDVI were occurring on these sites, indicating a different cause than hurricane damage.

Map 11 shows the same study site without the Carolina Bay map layer to exhibit how by zooming to a closer view, I was able to select sites that were exactly on Carolina Bay sites. Map 12-18 show the selected study sites for the studied hurricanes.

Map 9. Hurricane Fran Path Buffers and Study Sites.



Map 10. Hurricane Alberto Study Site #3 Close Up

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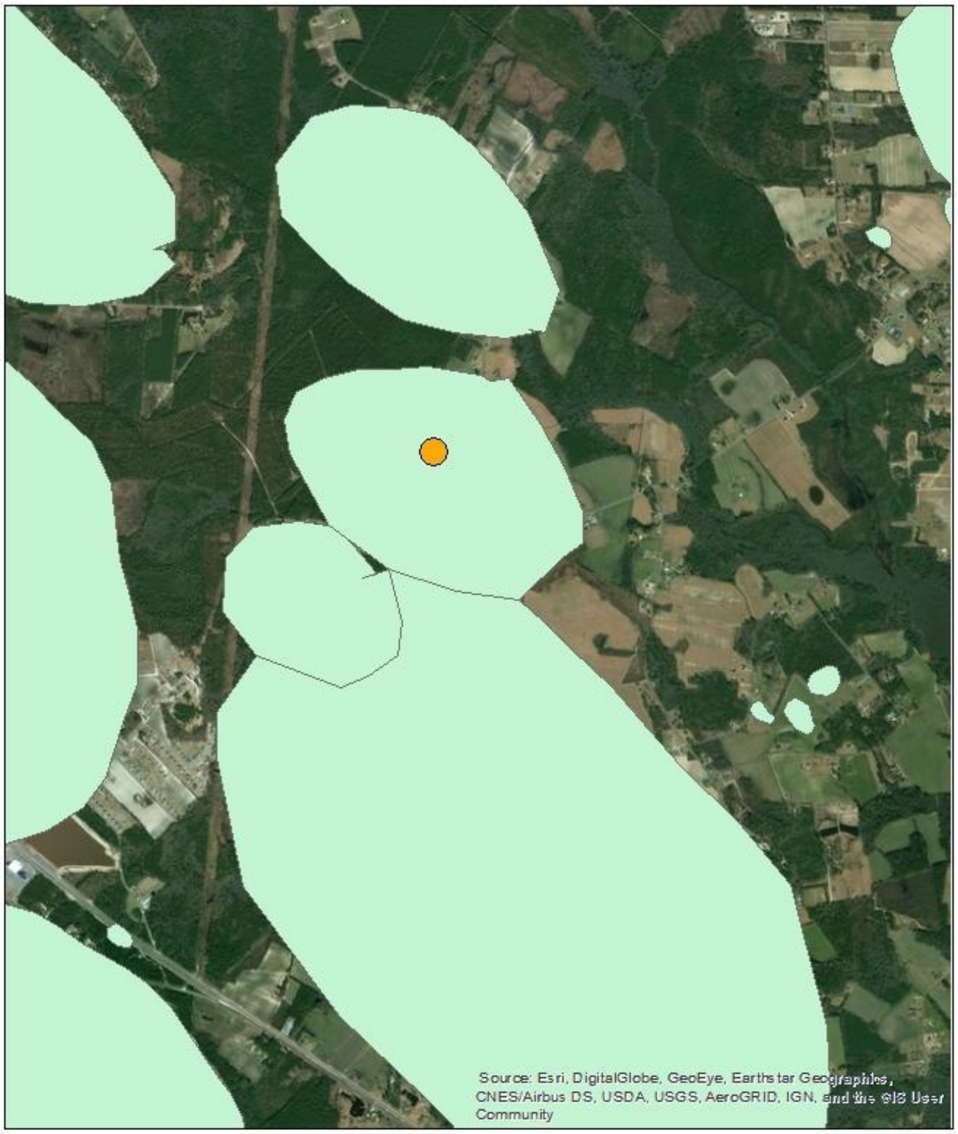
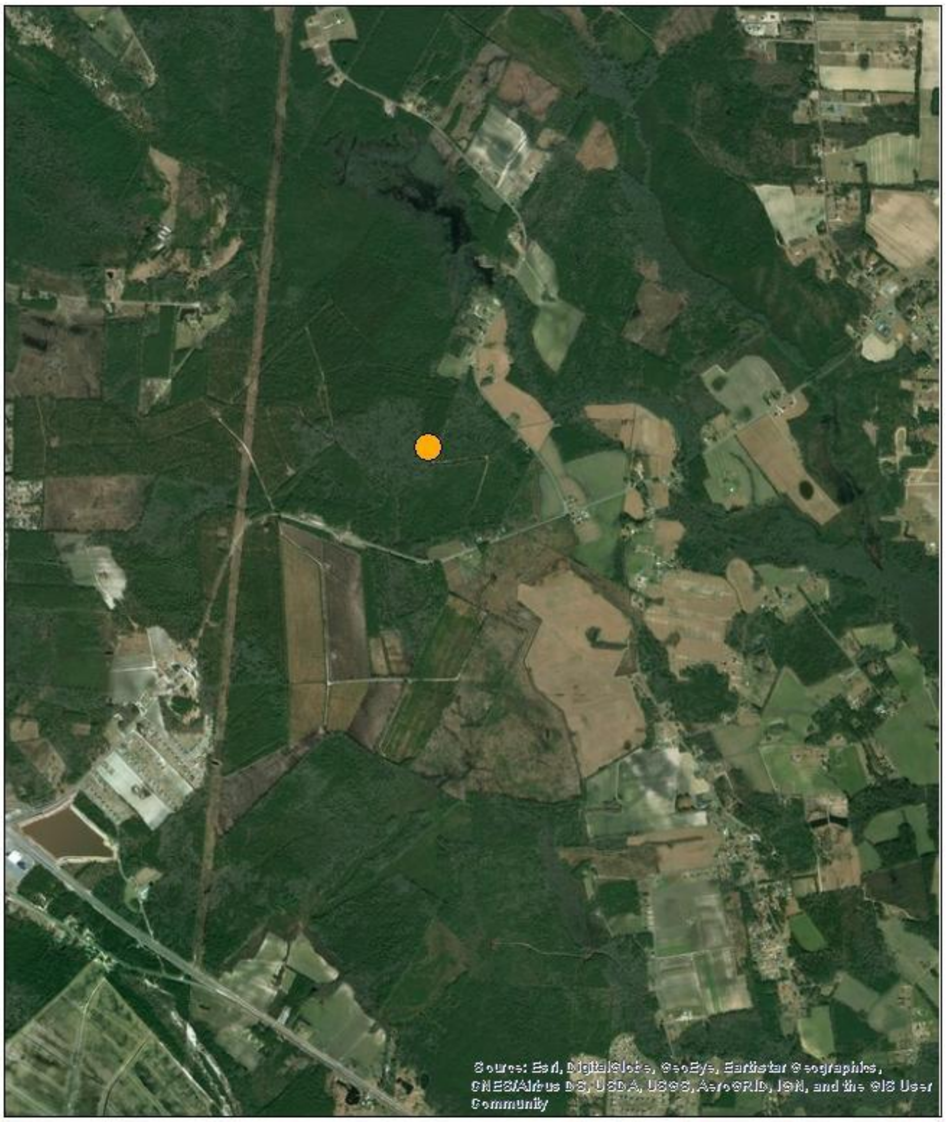
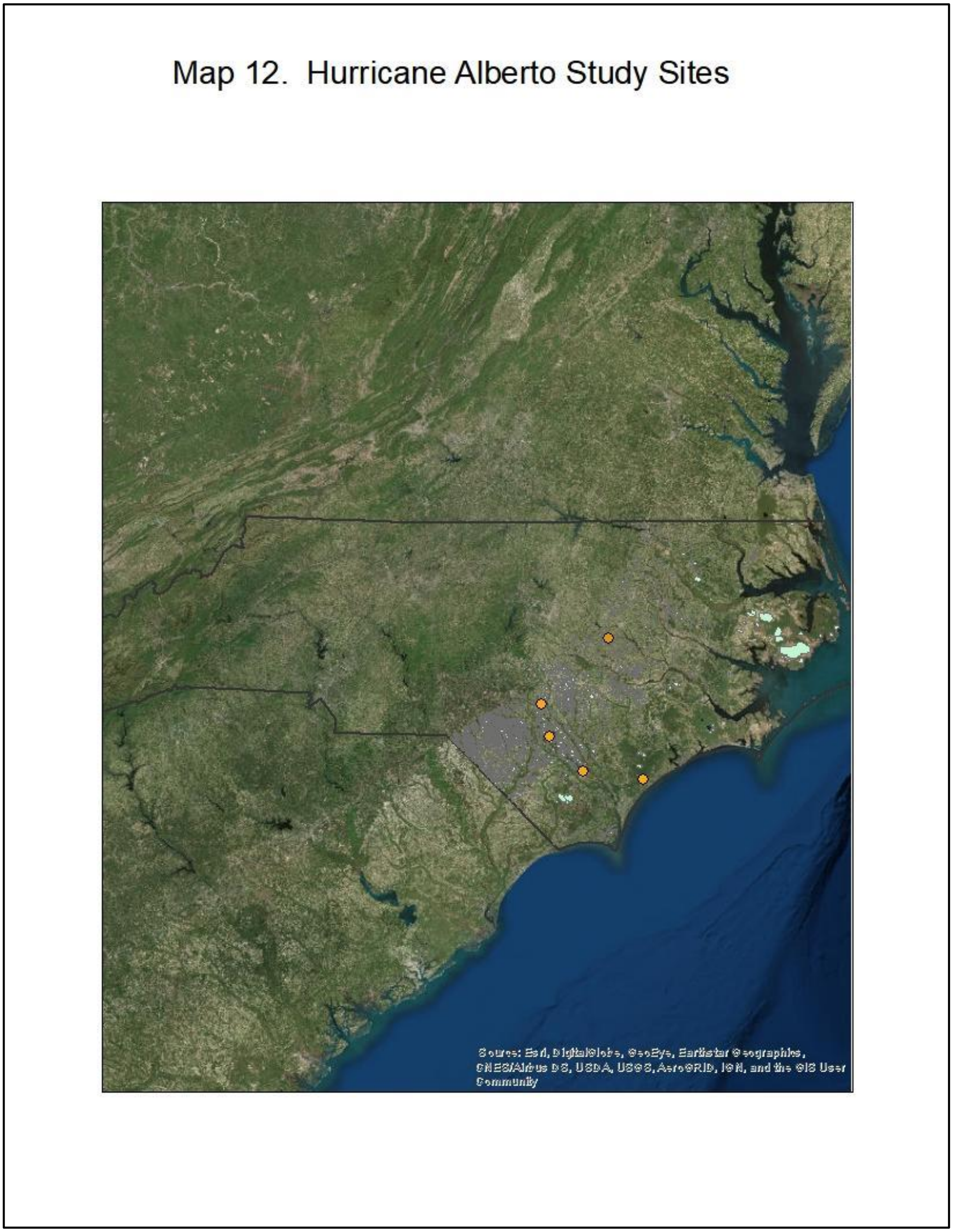


Map 11. Hurricane Alberto Study Site #3 Close Up Polygons Removed

Map 11. Hurricane Alberto Study Site #3 Close Up Polygons Removed



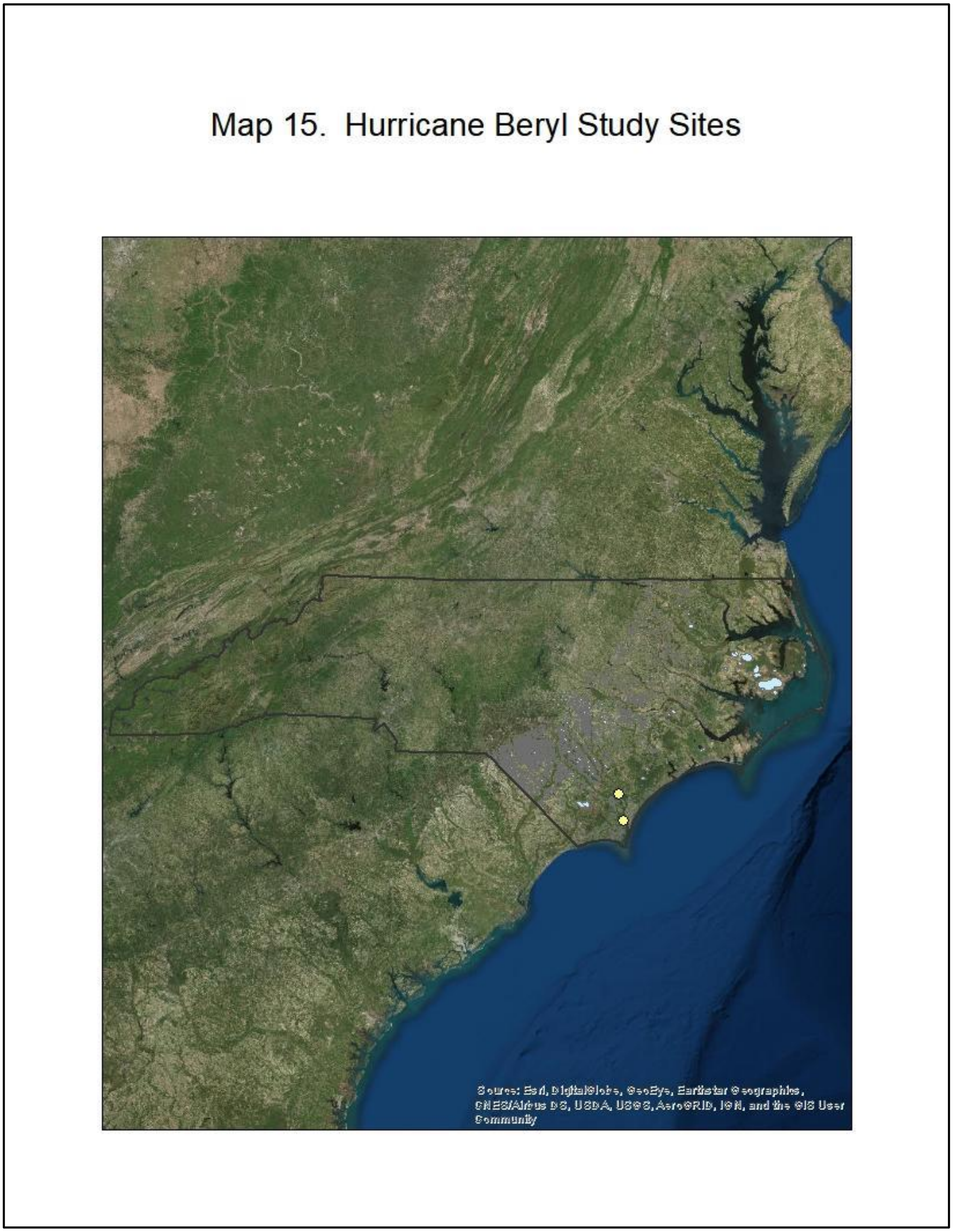
Map 12.   Hurricane Alberto Study Sites



Map 13. Hurricane Andrea Study Sites

Map 14. Hurricane Ana Study Sites

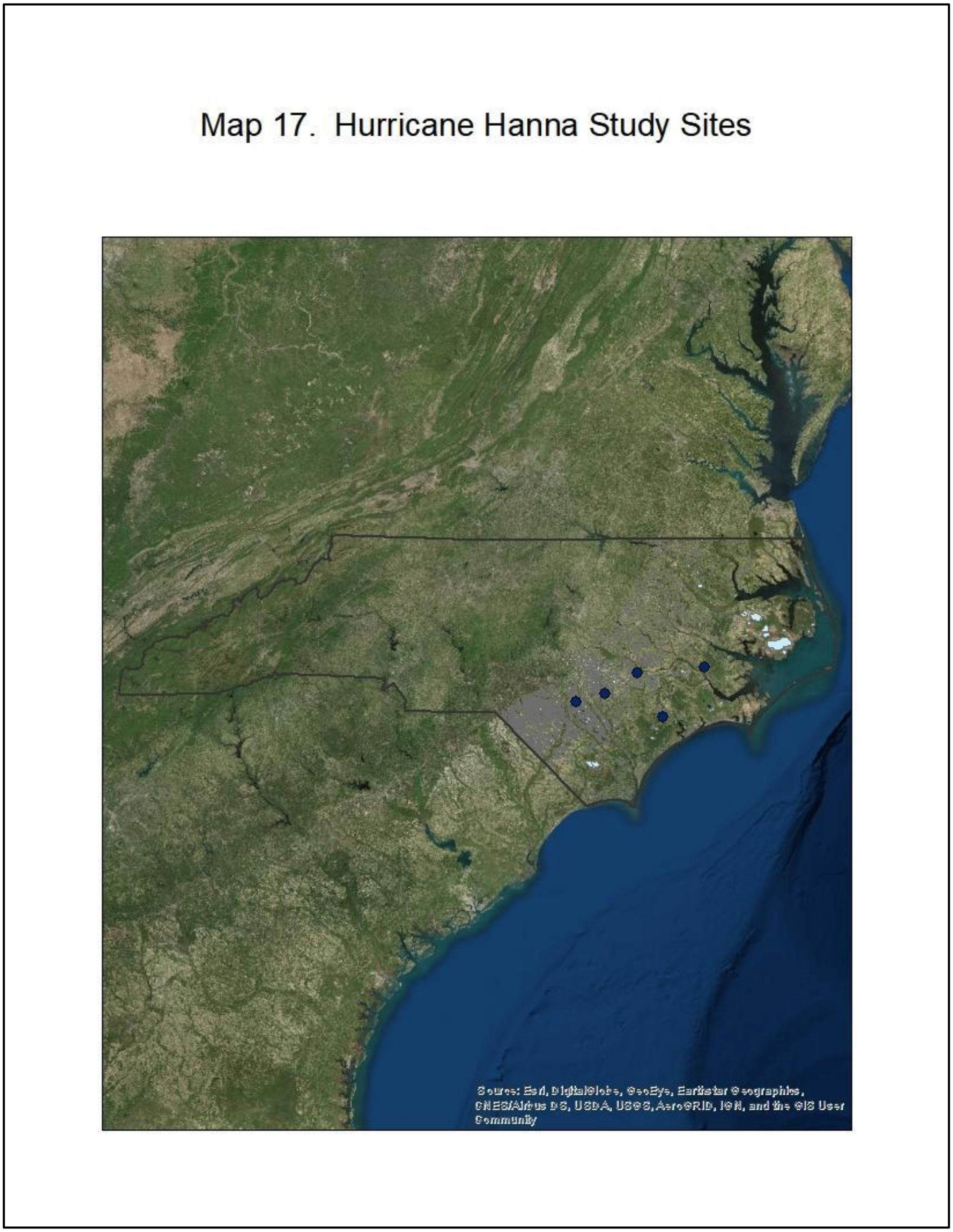
Map 15. Hurricane Beryl Study Sites



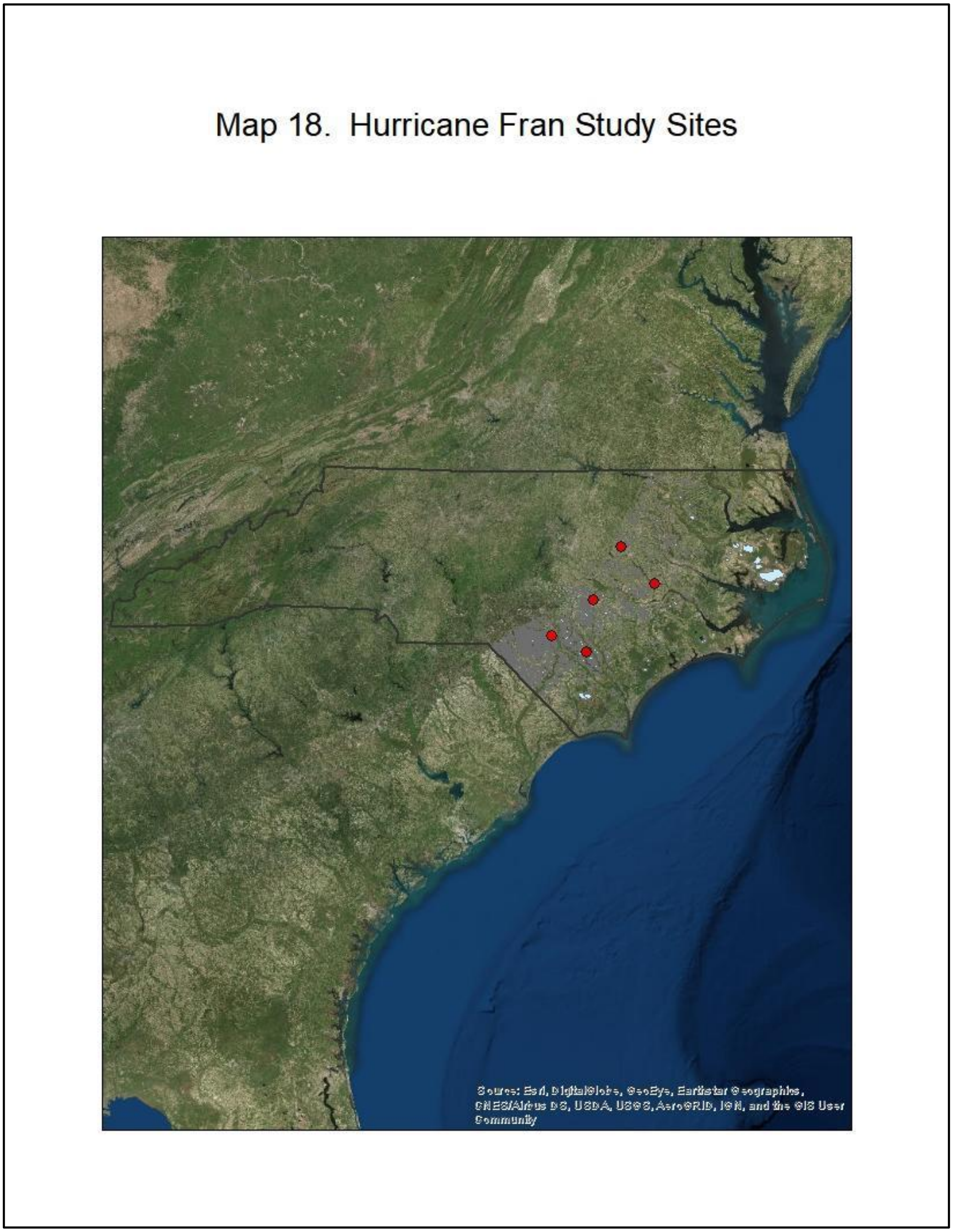
Map 16. Hurricane Ernesto Study Sites

Map 16. Hurricane Ernesto Study Sites

Map 17. Hurricane Hanna Study Sites



Map 18. Hurricane Fran Study Sites



Next, the latitude and longitude were determined for each study site. This was done by going into the ArcMap program, selecting the study site with the identify feature, and clicking on each Carolina Bay study site. This brought up a table that identifies information about the site selected (the study site). On this table is a location tab. Clicking on the button to the right of this information provides coordinates in Degrees Decimal Minutes. (See Appendix B for GIS Procedure Log). The output is then the latitude and longitude information for that study site. This information is one of the pieces of data entered into Climate Engine.

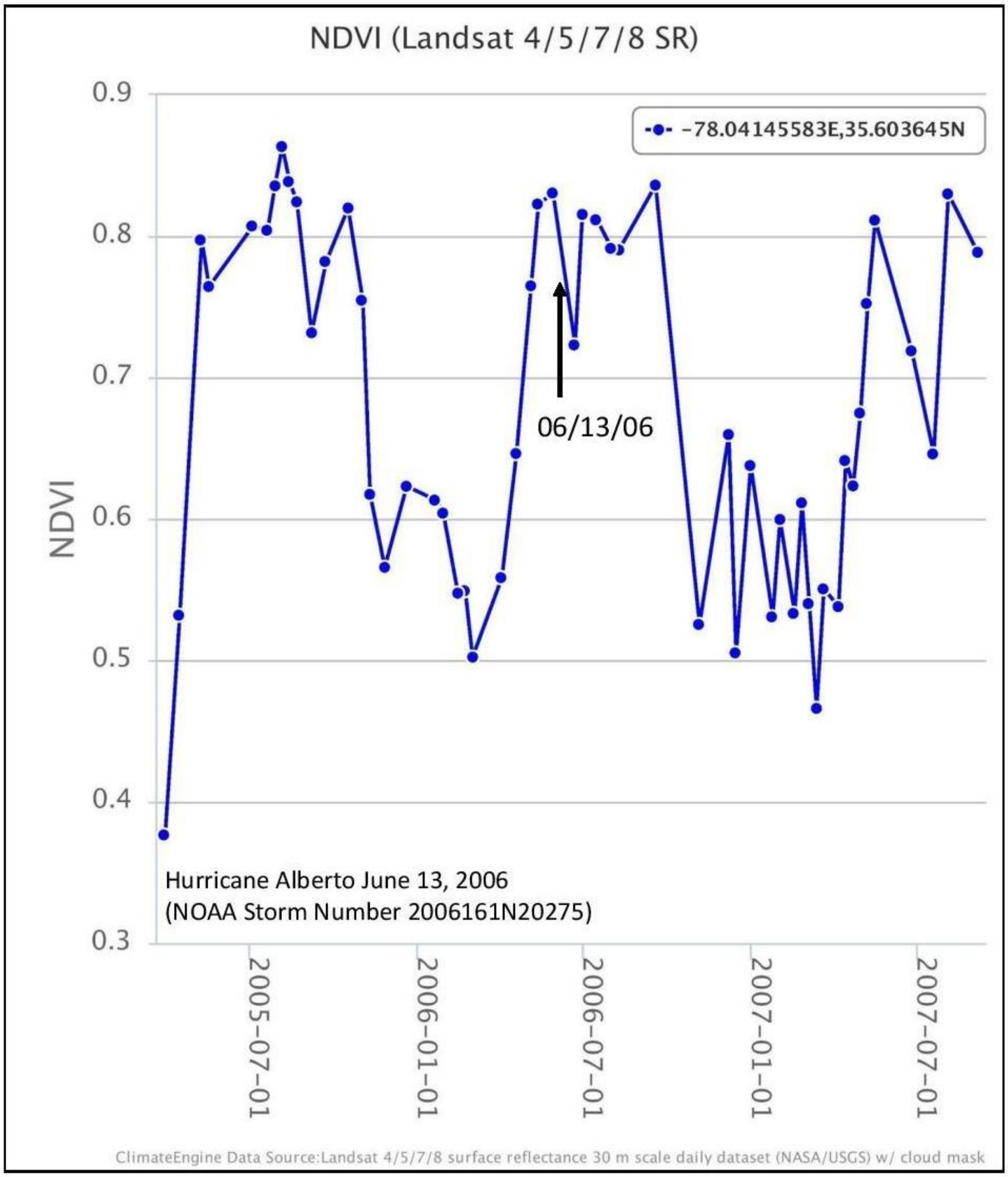
Climate Engine (http://clim-engine-development.appspot.com/) was then used to obtain time series of NDVI data about each site selected. Once the Climate Engine site is opened, I selected the "Make Graph" tab at the top left of the page. Table 1 shows the variables selected for each site to obtain the NDVI data for that study site within the Climate Engine website.

After the proper variables were selected, I chose the Get Time Series Button. The data range for each site was selected from 13 months before the hurricane impacted the study site to 13 months after the hurricane impacted the site, so that I could compare NDVI numbers from before the hurricane hit the study site, to after the hurricane hit the study site. This created a time series of NDVI for each site. Figure 1 shows the graph for Site 1. See Appendix C for each study sites' NDVI graph.

Table 1. Variables selected to obtain time series NDVI values for the study sites from the Climate Engine online tool (https://clim-engine.appspot.com/).

Region	Point (input latitude and longitude site data into drop down menu)
Time Series Calculation Drop Down Menu #1	Daily Data
Time Series Calculation Drop Down Menu #2	One Variable Analysis
Variable #1 Type	Remote Sensing
Variable #1 Dataset	Landsat 4/5/7/8 Surface Reflectance
Variable #1 Variable	NDVI (Vegetation Index)
Variable #1 Computation Resolution (Scale)	30 <
Time Period Season	Custom Date Range
Time Period State Date	Enter date that is 1 year and 3 months before the hurricane
Time period End Date	Enter date that is 1 year and 9 months after the hurricane

Figure 1. NDVI graph for study site 1, Hurricane Alberto: June 13, 2006.



These graphs were then used to to obtain NDVI numbers for 13 months before the hurricane impacted the study site, 11 months before the hurricane impacted the study site, 1 month before the hurricane impacted the study site, 1 month after the hurricane impacted the study site, 11 months after the hurricane impacted the study site and 13 months after the hurricane impacted the study site. This time frame was chosen because it allowed me to compare NDVI numbers from the same time of year both before and after a hurricane had impacted the study site. This allowed me to account for any seasonal changes in the NDVI that might occur and compare like times of year in our analysis.

Statistics were then obtained from the NDVI numbers using SAS Enterprise Guide software and SAS JMP software. A Distribution Analysis was run on the data to compare NDVI numbers for each hurricane. Average and one standard deviation were calculated for each study site. Finally, JMP software was utilized to run ANOVA's which determined differences across the means of the NDVI numbers, and Tukey's Post hoc tests which were performed to show which of the tested means were statistically different.

Results

Thirty two study sites were evaluated to determine changes to NDVI numbers in Carolina Bays associated with seven hurricanes.

Hurricane Alberto (NOAA Storm Number 2006161N20275) impacted North Carolina on June 13, 2006. It was a Tropical Depression over South Carolina earlier that day but was losing strength as it proceeded over North Carolina. I evaluated five study sites from Hurricane Alberto (Sites 1-5). Table 19 in Appendix D shows the site information for Sites 1-5.

Hurricane Andrea (NOAA Storm Number 2013157N25273) impacted North Carolina on June 7, 2013. It also was a Tropical Depression over South Carolina earlier that day but was losing strength as it proceeded over North Carolina. I evaluated five study sites from Hurricane Andrea (Sites 6-10). Table 20 in Appendix D shows the site information for Sites 6-10.

Hurricane Ana (NOAA Storm Number 2015126N27281) impacted North Carolina on May 10, 2015. It was a Tropical Storm when it made landfall on the South Carolina coast. As it proceeded inland over North Carolina it began to weaken and impacted North Carolina as a Tropical Depression. I evaluated five study sites from Hurricane Ana (Sites 11-15). Table 21 in Appendix D shows the site information for Sites 11-15.

Hurricane Beryl (NOAA Storm Number 2012147N30284) impacted North Carolina on May 30, 2012 as a Tropical Storm. Due to the path that Hurricane Beryl took (it was so close to the North Carolina coast), the sites to the right of the hurricane were located in the ocean and had no Carolina

Bays to select as study sites. Therefore only two study sites were evaluated from Hurricane Beryl (Sites 16 and 17). Table 22 in Appendix D shows the site information for Sites 16 and 17.

Hurricane Ernesto (NOAA Storm Number 2006237N13298) impacted the North Carolina on September 1, 2006 as a Tropical Storm. It weakened to a Tropical Depression near Raleigh, NC as it proceeded through the state. I evaluated five study sites associated with Hurricane Ernesto (Sites 18-22). Site 22 is an aquatic Carolina Bay, rather than a vegetated site, that was utilized as a type of control to make sure the Climate Engine Data was collected and evaluated correctly. Table 23 in Appendix D shows the site information for Sites 18-22.

Hurricane Hanna (NOAA Storm Number 2008241N19303) impacted North Carolina on September 6, 2008 as a Tropical Storm. I evaluated five study sites associated with Hurricane Hanna (Sites 23-27). Site 24 is a suburban Carolina Bay, rather than vegetated site. It shows up as Carolina Bay site on the satellite photography (the characteristic elliptical shape can be seen), however, on closer examination it can be seen that the sites is currently in a housing development with suburban vegetation such as lawn and yard. This site was also used as a control site to see if changes in the NDVI numbers that may be noticed were due to season rather than hurricane wind impacts. Table 24 in Appendix D shows the site information for Sites 23-27.

Hurricane Fran (NOAA Storm Number 1996237N14339) impacted North Carolina on September 6, 1996 as a Category 3 storm. As it moved through North Carolina, it weakened to a Category 1 storm over Fayetteville. I evaluated five study sites associated with Hurricane Fran (Site 28-32). Table 25 in Appendix D shows the site information for Sites 28-32.

The NDVI numbers for each study site were obtained for 13 months before the hurricane, 11 months before the hurricane, 1 month before the hurricane, 1 month after the hurricane, 11 months after the hurricane and 13 months after the hurricane. . This allowed for changes due to time of year/seasonal changes in vegetative cover to be negated. It allowed me to focus on any changes that occured only because of the hurricane’s impacts.

Table 3. Summary statistics of study sites for Hurricane Alberto during specific time periods

	13 months before the hurricane	11 months before the hurricane	1 month before the hurricane	1 month after the hurricane	11 months after the hurricane	13 months after the hurricane
Mean	0.78635	0.7287	0.83525	0.785125	0.761425	0.73655
Standard Deviation	0.02643	0.18185	0.02678	0.78275	0.04372	0.059
Median	0.7832	0.81215	0.8245	0.02218	0.7704	0.7495
Variance	0.000699	0.03307	0.000717	0.000492	0.00951	0.00348

Table 4. Summary statistics of study sites for Hurricane Ana during specific time periods

	13 months before the hurricane	11 months before the hurricane	1 month before the hurricane	1 month after the hurricane	11 months after the hurricane	13 months after the hurricane
Mean	0.7203	0.8401	0.77395	0.83934	0.755	0.8525
Standard Deviation	0.06389	0.04018	0.10956	0.05314	0.887	0.895
Median	0.6925	0.85	0.81825	0.865	0.725	0.8587
Variance	0.00408	0.00161	0.012	0.00282	0.892	0.79

Table 5. Summary statistics of study sites for Hurricane Andrea during specific time periods

	13 months before the hurricane	11 months before the hurricane	1 month before the hurricane	1 month after the hurricane	11 months after the hurricane	13 months after the hurricane
Mean	0.8097	0.74828	0.81326	0.655	0.8173	0.755457
Standard Deviation	0.0555652	0.023838	0.06964248	0.042713441	0.067394	0.056432
Median	0.7925	0.8	0.795	0.775	0.7955	0.729
Variance	0.1348066	0.280132	0.15129671	0.186725613	0.169904	0.003725

Table 6. Summary statistics of study sites for Hurricane Beryl during specific time periods

	13 months before the hurricane	11 months before the hurricane	1 month before the hurricane	1 month after the hurricane	11 months after the hurricane	13 months after the hurricane
Mean	0.6275	0.60215	0.64125	0.687	0.6725	0.7003
Standard Deviation	0.05303	0.03981	0.06541	0.08202	0.08556	0.10932
Median	0.6275	0.60215	0.64125	0.687	0.6725	0.7003
Variance	0.00281	0.00158	0.00428	0.00673	0.00732	0.01195

Table 7. Summary statistics of study sites for Hurricane Ernesto during specific time periods

	13 months before the hurricane	11 months before the hurricane	1 month before the hurricane	1 month after the hurricane	11 months after the hurricane	13 months after the hurricane
Mean	0.62926	0.62276	0.67064	0.57524	0.63578	0.5505
Standard Deviation	0.38897	0.43212	0.32656	0.43338	0.36716	0.52927
Median	0.7925	0.8	0.795	0.775	0.7955	0.729
Variance	0.1513	0.18673	0.10664	0.18782	0.13481	0.28013

Table 8. Summary statistics of study sites for Hurricane Hanna during specific time periods

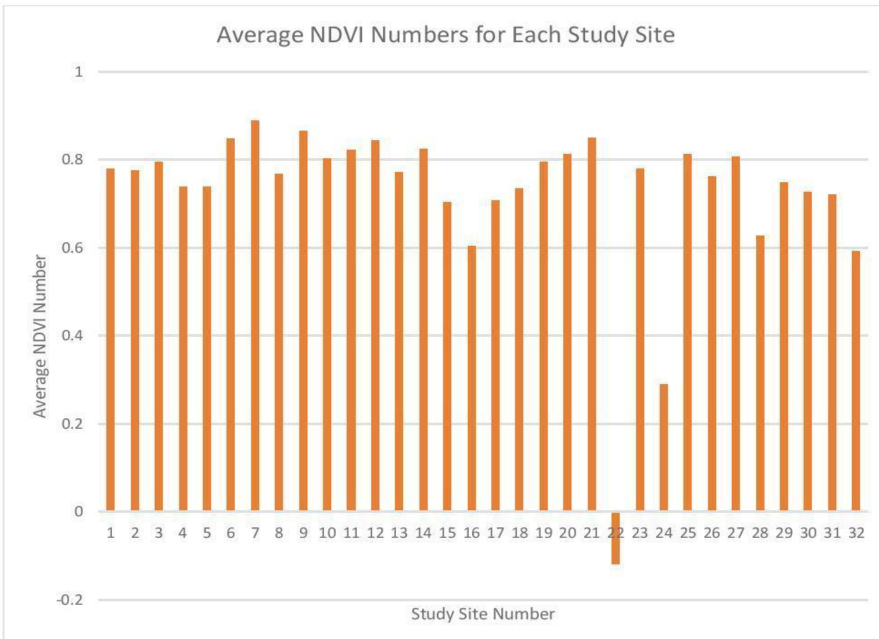
	13 months before the hurricane	11 months before the hurricane	1 month before the hurricane	1 month after the hurricane	11 months after the hurricane	13 months after the hurricane
Mean	0.70942	0.67724	0.70528	0.64966	0.72016	0.67754
Standard Deviation	0.23261	0.22759	0.21474	0.23567	0.22231	0.23977
Median	0.826	0.76	0.7983	0.7345	0.8325	0.772
Variance	0.05411	0.0518	0.04611	0.05554	0.04942	0.05749

Table 9. Summary statistics of study sites for Hurricane Fran during specific time periods

	13 months before the hurricane	11 months before the hurricane	1 month before the hurricane	1 month after the hurricane	11 months after the hurricane	13 months after the hurricane
Mean	0.729	0.6455	0.7084	0.58364	0.7217	0.7063
Standard Deviation	0.08044	0.1539	0.04736	0.08933	0.06897	0.06668
Median	0.7675	0.735	0.725	0.5832	0.755	0.72
Variance	0.00647	0.02369	0.00224	0.00798	0.00476	0.00445

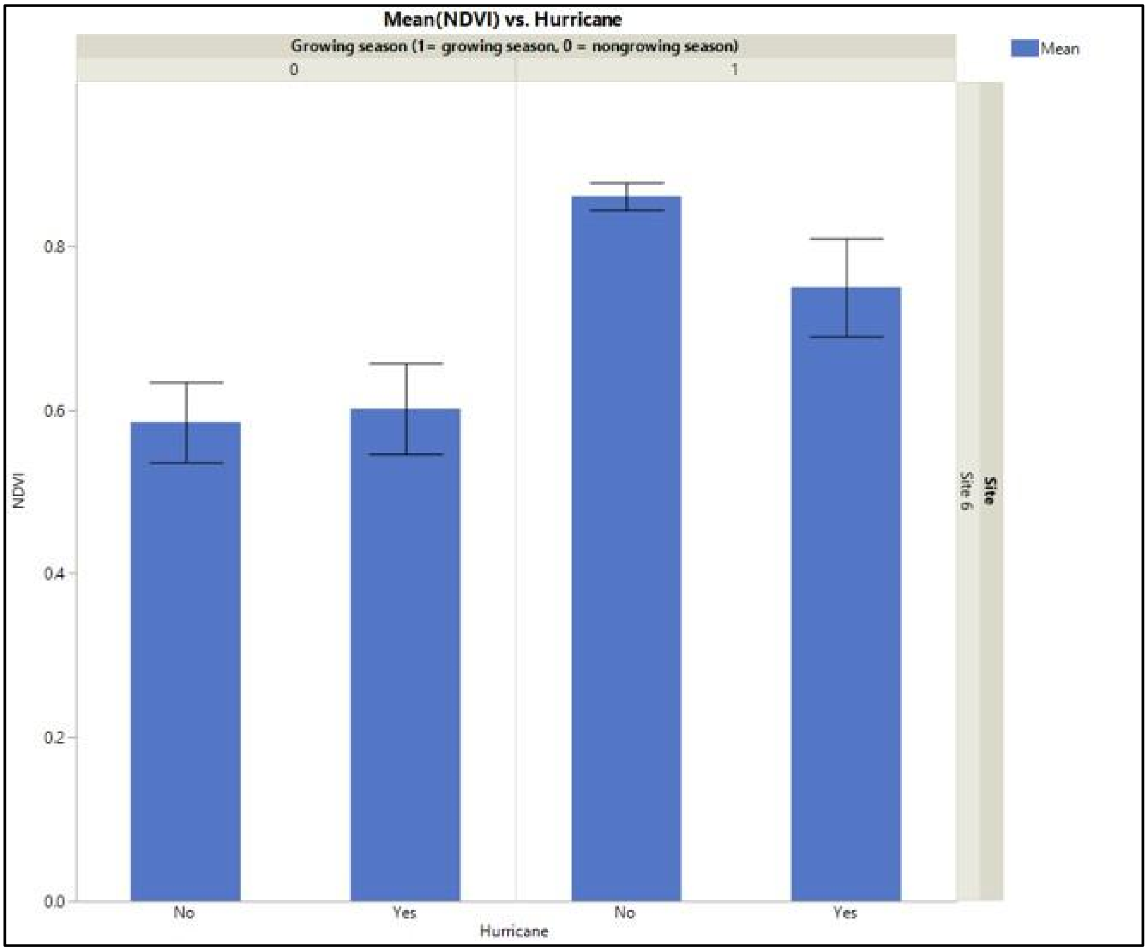
Tables 3-9 show the statistical summaries of of all sites NDVI values separated by when the NDVI measurement was taken in relation to when the hurricane occurred. These statistics were used to create Figure 2. Values ranged from 0.65 to 0.85, except for the site that contained standing water (site 22, which had an average NDVI value of -0.15) and the site that contained a housing development (site 24, which had and NDVI value of 0.25, Figure 2). Figure 2 shows the average NDVI number for each study site. Checking satellite imagery in ARCMAP revealed that approximately 60 % of Site 6 is an agricultural field. Additionally, Sites 28-32 are Hurricane Fran study sites.

Figure 2. Average NDVI number for each Study Site.



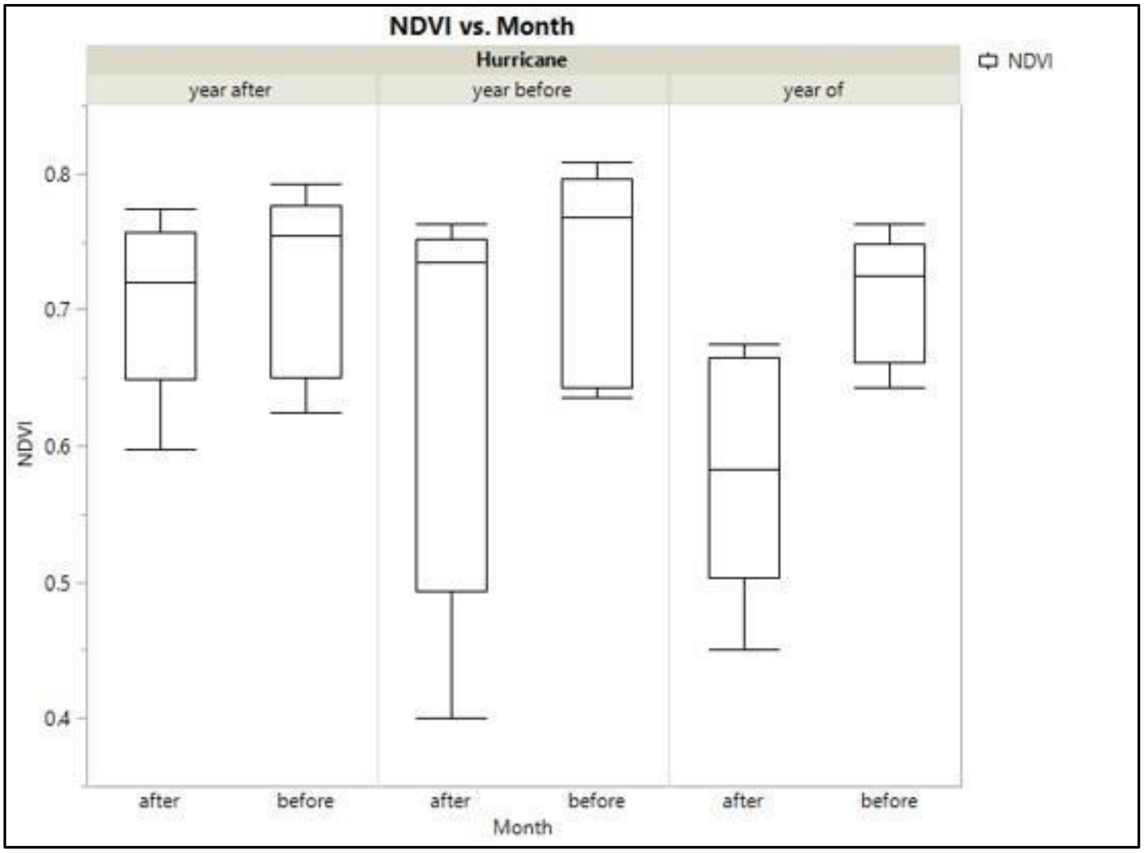
Next, utilizing SAS's JMP software an ANOVA was run to determine differences across the means for the study sites. Following the ANOVA, Tukey's Post Hoc test was run to determine the which of the study sites means were statistically different from the average. Site 6 and 4 of the 5 Hurricane Fran study sites (Sites 28-30 and 32) has statistically significant different means than the average. We created a figure that shows the results for Site 6's mean NDVI value before and after the growing season in years with and without a hurricane (Figure 3).

Figure 3. Hurricane Andrea Site 6 Mean NDVI Before and After the Growing Season in years with and without a hurricane.



Finally, we created a figure that showed the results for Hurricane Fran's sites (Sites 28-32). NDVI numbers differed significantly before and after the hurricane the year the hurricane occurred, when compared to the years without a hurricane (Figure 4).

Figure 4. ANOVA Results for the NDVI Numbers for study sites from Hurricane Fran (Sites 28-32 combined) one month before and after Hurricane Fran, the year before Hurricane Fran, the year of Hurricane Fran and the year after Hurricane Fran.



Hurricane Fran's study sites and study site 6 were the only sites that showed significant differences in the NDVI values before and after the hurricane event.

Discussion

Statistically significant changes to Carolina Bay's vegetation were detected using the NDVI data available on Climate Engine in study site 6, 28, 29, 30 and 32. The sites that showed statistically significant lower values of NDVI after the hurricane were Site 6 (Hurricane Andrea, 30km to the left of the hurricane path) and Sites 28, 29, 30, and 32 (Hurricane Fran sites).

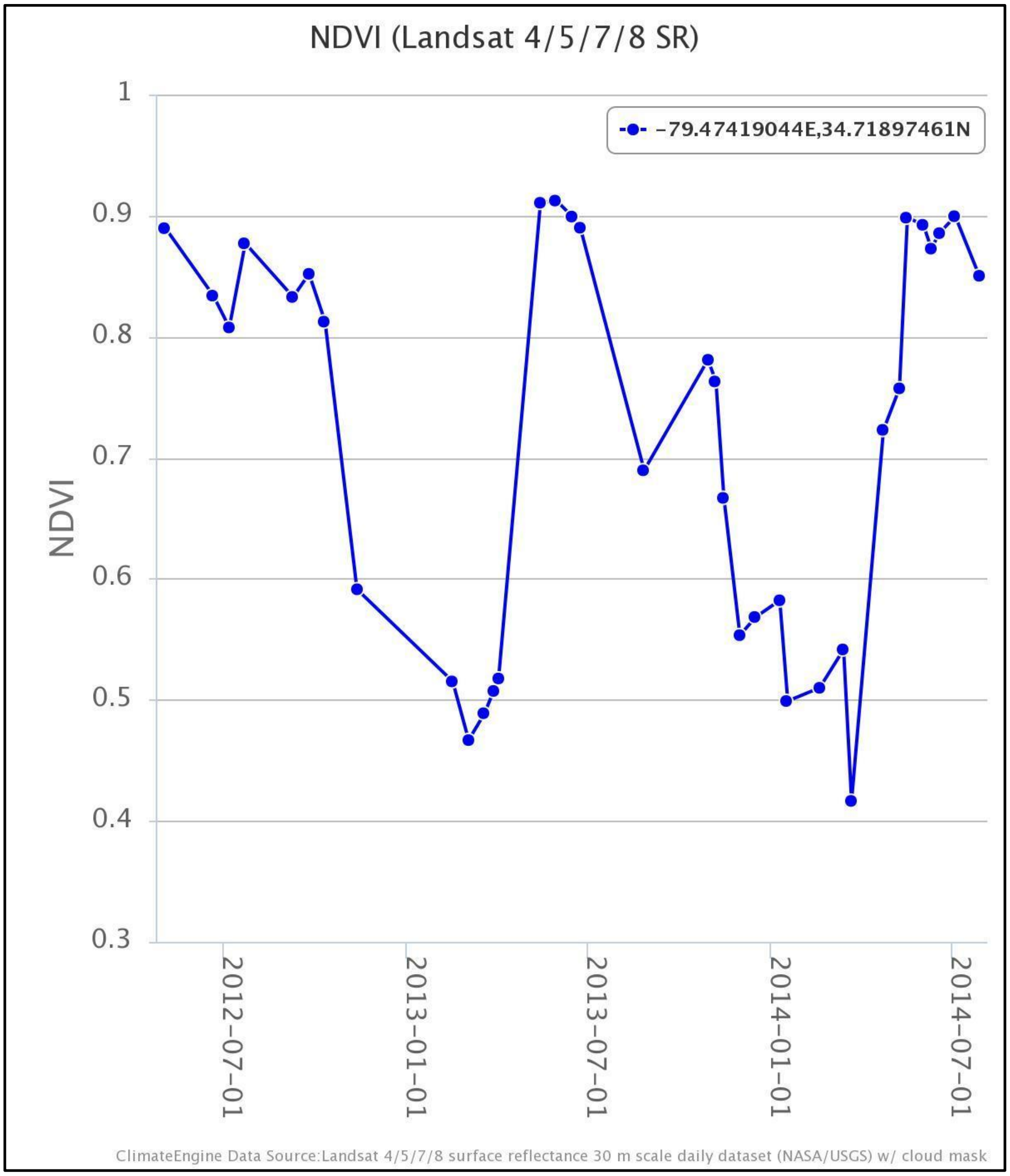
Site 6 is located 30 km to left of the path of Hurricane Andrea. Hurricane Andrea hit South Carolina as a Tropical Depression and continued to weaken as it moved over North Carolina. The NDVI graph is shown in Figure 4.. The hurricane event occurred on June 7, 2013.

Site 6 showed a change in the NDVI value between one month before the hurricane event and one month after the hurricane event. Looking at the NDVI graph (Figure 6), it can be seen that there is a difference between the NDVI one month before the hurricane event and the NDVI one month after the hurricane event. However, examining satellite imagery from ARCMAP (Map 19) shows, study site 6 is partly covered in an agricultural field. The seasonal trend in the changing NDVI number therefore is occurring in response to the agricultural use of the field rather than an impact from a hurricane event. For study site 6, seasonal changes in the NDVI value would be expected due to crop planting and harvest cycle harvest. Even though this entire site is not an agricultural field, enough of it is that we would expect to see a change in the NDVI value that would not be observed in the other Carolina Bay sites. This site served as a control in relation to the fact that the Climate Engine tool is capable of detecting changes in the vegetative cover of Carolina Bay sites. This allowed us to show in our study that Carolina Bays are not being significantly impacted by changes in vegetative cover unless the hurricane event is a large one. Site 6 and the changes in its NDVI numbers allowed us to understand that the Climate Engine tool is an effective tool for observing changes in vegetative cover on Carolina Bays. However, these vegetative cover changes are not occurring during the smaller hurricane events.

Looking at Site 28-30 and 32 (Hurricane Fran study sites) it can be further determined that there are statistically significant changes to the amount of vegetative cover in Carolina Bays when larger hurricanes pass over them, but not when smaller storm events occur.

Map 19. Study Site 6.

Figure 6: Timeseries of NDVI for site 6.



Sites 28-30 and 32 showed a decrease in the NDVI the month after the hurricane occurred when compared to the month before (Site 28 NDVI before the hurricane 0.635 and after the hurricane 0.5875, Site 29 NDVI before the hurricane 0.808 and after 0.735, Site 30 NDVI before the hurricane 0.7675 and after 0.7425, and Site 32 0.65 and 0.4). These changes do not take into account seasonal changes and Hurricane Fran occurred in September, meaning possible changes could be due to the end of the growing season.

These changes are not long term as recovery of the vegetative cover was observed the following year for the impacted sites. Additionally, Hurricane Fran was the largest and most powerful of the studied hurricanes, suggesting that impacts occurred to Carolina Bays from the stronger hurricanes. However, the fact that the impacts do not appear long term suggests that Carolina Bays may be resilient to the impacts from hurricanes due to the seasonal nature of the hydrologic impacts they are accustomed to encountering.

The distance of the study site from the actual hurricane path did not impact the NDVI. Study sites 30 kilometers left of the hurricane path, in the direct line of the hurricane path, 30 kilometers to the right of the hurricane path, 70 kilometers to the right of the hurricane path and 100 kilometers to the right of the hurricane path all showed the same result when their NDVI numbers were examined. They were not statistically significantly different before the hurricane when compared to after the hurricane event.

Alternatively, the size of the hurricane event did impact the NDVI for the study sites. Impacts from small hurricane/ tropical storms are not observable by examining an NDVI number for the site impacted. However, the vegetative impacts to the larger Hurricane Fran were observable in the NDVI numbers. This would suggest that vegetative impacts to Carolina Bays are observable using the NDVI as an assessment tool. However, the possible smaller impacts from small hurricanes/tropical storms are not detectable using NDVI.

One of the reasons that Climate Engine may not be able to detect vegetative impacts from the hurricanes on the NDVI are that the hurricanes studied (except for Hurricane Fran) were not large enough at the time they passed over the study sites. All the other hurricanes were studied were Tropical Storm force winds or lower (See Table 1.) With these smaller hurricanes impacts to vegetation may be non-existent. It maybe that only larger hurricanes like Fran are having actual vegetation impacts on Carolina Bays. This is supported by the fact that when changes are known to have occurred, as in study site 6, Climate Engine detected these changes and they were reflected in the NDVI numbers.

Table 18 shows the data, including lowest observed pressure, maximum recorded winds and the strength of each hurricane as it made landfall in North Carolina for the hurricanes associated with the study sites evaluated. Additionally, rainfall totals are shown in Table 18. Table 18. Hurricane Data Table

Hurricane Name	Dates of Hurricane	Lowest Observed Pressure	Maximum Winds (kts)	North Carolina Landfall Status	Rainfall Amount
Alberto	5/19-5/23 2012	995.0	50 kts	<Tropical Depression	5.64 inches at RDU airport
Andrea	6/5-6/8 2013	992.0	55 kts	<Tropical Depression	5.14 inches at RDU airport
Ana	5/6-5/12 2015	998.0	50 kts	Tropical Depression	5.13 inches at Leland, NC
Beryl	5/25-6/2 2012	992.0	60 kts	Tropical Storm	6.00 inches at Hyde County, NC
Ernesto	8/24-9/4 2006	985.0	60 kts	Tropical Storm	9.85 inches at Grifton, NC
Hanna	8/28-9/8 2008	977.0	70 kts	Tropical Storm	1.11 inches at Newport, NC
Fran	8/31-9/6 1996	946.0	105 kts	Category 3	8.80 inches at RDU airport

The main other study that was able to use NDVI to look at hurricane effects on wetlands was Rodgers et. al. 2009, who found a 49% decrease in the NDVI value between March (before the hurricane

Katrina hit) and September (after the hurricane hit) 2005. Although this study evaluated coastal wetlands and changes in the NDVI were attributed to increased salinity at the site, it led us to wonder if NDVI was a good method for examining changes to Carolina Bays due to hurricanes.

Carolina Bays are wetland areas that have adapted to seasonal changes in moisture and inundation levels. They host plant and animal life that are adapted to this transition. It makes sense that the types of vegetation that utilize Carolina Bays are also adapted to thrive in environments where change is constant and periods of severe weather are present.

As for the impacts of hurricanes on Carolina Bays, even when these impacts are observed, they appear to not be long term changes. This suggests that Carolina Bays are dynamic ecosystems that have evolved to tolerate changes to their environment and are often in an state of change. This idea is reinforced by what is known about Carolina Bays. They are environments that experience seasonal changes in their hydrologic cycle. The plants that exist in Carolina Bays are used to varying periods of water inundation. Therefore, the impacts of large amounts of precipitation may not be impacting Carolina Bay's vegetation like it would in a wetland that did not normally experience these changes in water levels.

Future studies should examine how vegetative species composition might change in response to hurricanes. The type of damage caused by hurricanes on Carolina Bays may be hard to detect using remote sensing because vegetation is mostly bushes, sedges and grasses. NDVI measures vegetative cover, and when bushes, sedges and grass are blown around by hurricanes the NDVI number may not be impacted because vegetation is still present in the Carolina Bay. The wind may injure these types of vegetation, but not remove them. This could be an avenue for species better adapted to disturbances to move into Carolina Bays, out competing species that do not favor disturbances.

The satellite data may not be able to distinguish changes in species compositions due to hurricanes. For example, hurricanes have been shown in some studies to change the species composition in wetlands. Wind damage to wetlands during hurricanes was observed as a major cause of the damage to two wetland study sites on the Delmarva Peninsula (Middleton, 2016). Hurricanes have been shown to affect forest woody plant species and their distribution (Middleton, 2009). Taxodium distichum L. Rich, (bald cypress) and Nyssa aquatic L., (water tupelo) tended to thrive in hurricane-impacted forests, because these species are less susceptible to wind damage than species such as *Acer rubrum* L., (red maple), *Quercus lyrata* (Walter), (overcup oak) and *Quercus nigra* (Aiton) Ashe, (water oak) (Middleton, 2009). The satellite data for Climate Engine and the NDVI would likely not be able to distinguish these types of changes if they are occurring in Carolina Bays.

Additionally, rainfall varied with each individual hurricane event and was unrelated to the impacts studied. However, future studies may find that rainfall amounts influence additional factors in Carolina Bays such as species composition and water quality.

The size and makeup of Carolina Bays may also affect the ability of the Climate Engine data to detect changes in their vegetative status. Due to the fact that Carolina Bays are often either smaller or shallow wetlands, the resolution of the photographic images may not be able to pick up the vegetation changes. Landsat images have a 30 x 30 m pixel size, so if the sites selected were smaller than the pixel size, the NDVI value might not be able to pick up vegetative changes. Additionally, the NDVI values may not include other land uses that were on a scale smaller than the Landsat resolution.

One of the sources of error in this study was that Climate Engine's effectiveness may have been impaired by cloud cover during the period when it was most important to observe the changes in Carolina Bay's vegetation due to the hurricane events. During the time period I was trying to analyze, cloud cover was present during each event. When cloud cover occurs, the satellite is unable to collect photographic data for NDVI. This caused an issue with missing data right around the time of the hurricane. This may have led to effects occurring in Carolina Bays that were not able to be picked up or observed using Climate Engine. This not only affected the frequency of images right around the time of the hurricane, but it affects the frequency of available images in Climate Engine as a whole.

Finally, NDVI values may be impacted by seasonal changes in the vegetative cover. These changes could very well occur during the same time period hurricanes occur in Carolina Bays. Separating out the change in NDVI due to hurricanes and the change in NDVI due to seasonal changes would be an interesting future research area.

Future research could find more effective ways to analyze this variable. While in our case, the data from Climate Engine proved to be capable of detecting large scale changes to vegetative cover of study sites like Carolina Bays, it did not prove to be very sensitive to possible smaller impacts from hurricanes. However, cloud based remote sensing holds great promise for resources managers. Landsat images that I used in this study used to cost around $500-$1000 each five to ten years ago. For each site, Climate Engine provided approximately 30-40 NDVI values, which are based on 30-40 Landsat images. That means that the kind of study I conducted, would have costed $15,000 to $40,000 per site before these images became freely accessible. Processing these kinds of images would have also required large amounts of computing time, which in my case was all done on servers hosted by Google. While Climate Engine might not have been the best tool to examine the effects of hurricanes on Carolina Bays, it is clear that this will be a tool that will continue to become more important for the rapid analyses of large remote sensing datasets.

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Appendix B. GIS Procedure Log

Procedure Log For Sara Schager's Professional Project GIS work Log

Data:

Storm.2005185N18273.ibtracs_all_lines.v03r09.shp file

Storm.2005249N26281.ibtracs_all_lines.v03r09.shp file

Storm.2005278N27280.ibtracs_all_lines.v03r09.shp file

Storm.2006161N20275.ibtracs_all_lines.v03r09.shp file

Storm.2006237N13298.ibtracs_all_lines.v03r09.shp file

Storm.2007151N18273.ibtracs_all_lines.v03r09.shp file

Storm.2007251N30288.ibtracs_all_lines.v03r09.shp file

Storm.2008201N32280.ibtracs_all_lines.v03r09.shp file

Storm.2008229N18293.ibtracs_all_lines.v03r09.shp file

Storm.2008241N19303.ibtracs_all_lines.v03r09.shp file

Storm.2009228N27277.ibtracs_all_lines.v03r09.shp file

Storm.2009308N11279.ibtracs_all_lines.v03r09.shp file

Storm.2010222N26277.ibtracs_all_lines.v03r09.shp file

Storm.2011197N31280.ibtracs_all_lines.v03r09.shp file

Storm.2011245N27269.ibtracs_all_lines.v03r09.shp file

Storm.2012140N33283.ibtracs_all_lines.v03r09.shp file

Storm.2012147N30284.ibtracs_all_lines.v03r09.shp file

Storm.2012176N26272.ibtracs_all_lines.v03r09.shp file

Storm.2013157N25273.ibtracs_all_lines.v03r09.shp file

Storm.2013204N11340.ibtracs_all_lines.v03r09.shp file

Storm.2014180N32282.ibtracs_all_lines.v03r09.shp file

Storm.2015126N27281.ibtracs_all_lines.v03r09.shp file

Storm.2015193N35285.ibtracs_all_lines.v03r09.shp file

Coordinate System>Data Frame Properties

WGS_1984_Web_Mercator_Auxiliary_Sphere

WKID: 3857 Authority: EPSG

Projection: Mercator_Auxiliary_Sphere

False_Easting: 0.0

False_Northing: 0.0

Central_Meridian: 0.0

Standard_Parallel_1: 0.0

Auxiliary_Sphere_Type: 0.0

Linear Unit: Meter (1.0)

Basemap World Topographic Map>Coordinate System >Data Frame Properties

WGS_1984_Web_Mercator_Auxiliary_Sphere

WKID: 3857 Authority: EPSG

Projection: Mercator_Auxiliary_Sphere

False_Easting: 0.0

False_Northing: 0.0

Central_Meridian: 0.0

Standard_Parallel_1: 0.0

Auxiliary_Sphere_Type: 0.0

Linear Unit: Meter (1.0)

To each hurricane line we will need to buffer the line twice…to the right of the line and to the left of the line. To create the buffer layer go to Geoprocessing>Buffer. Then each hurricane needs to be buffered to the right:

An Active X control on this page might be unsafe to interact with other parts of the page. Do you want to allow this interaction? Yes

And to the left:

An Active X control on this page might be unsafe to interact with other parts of the page. Do you want to allow this interaction? Yes

Change the colors of both buffers so that they match. This creates a buffer of each hurricane path that is 30 km to the right and 80 km to the left of the hurricane line. This was the chosen buffer width because (LOOK UP STUDY) indicated that the worst winds of a hurricane were seen at 70 km to the east or left of the eye of the hurricane (the line shown by the 2005 Cindy layer.

Buffer {2005 Cindy, 2005 Ophelia, 2006 Alberto, 2006 Ernesto, 2007 Barry, 2007 Gabrielle, 2008 Cristobal, 2008 Hanna, 2008 Fay, 2009 Ida, 2009 Claudette, 2010 Five, 2011 Lee, 2011 Brett, 2012 Beryl, 2012 Alberto, 2012 Debby, 2013 Andrea, 2013 Dorian, 2014 Arthur, 2015 Ana, 2015 Claudette}
Input Features: {2005 Cindy, 2005 Ophelia, 2006 Alberto, 2006 Ernesto, 2007 Barry, 2007 Gabrielle, 2008 Cristobal, 2008 Hanna, 2008 Fay, 2009 Ida, 2009 Claudette, 2010 Five, 2011 Lee, 2011 Brett, 2012 Beryl, 2012 Alberto, 2012 Debby, 2013 Andrea, 2013 Dorian, 2014 Arthur, 2015 Ana, 2015 Claudette}
Output Feature Class: {Hurricane Name Year_Buffer}
Distance: Linear Unit: 100 km
Side type: Right
End type: Round
Method: Planar
Dissolve Type: All

Buffer {2005 Cindy, 2005 Ophelia, 2006 Alberto, 2006 Ernesto, 2007 Barry, 2007 Gabrielle, 2008 Cristobal, 2008 Hanna, 2008 Fay, 2009 Ida, 2009 Claudette, 2010 Five, 2011 Lee, 2011 Brett, 2012 Beryl, 2012 Alberto, 2012 Debby, 2013 Andrea, 2013 Dorian, 2014 Arthur, 2015 Ana, 2015 Claudette}
Input Features: {2005 Cindy, 2005 Ophelia, 2006 Alberto, 2006 Ernesto, 2007 Barry, 2007 Gabrielle, 2008 Cristobal, 2008 Hanna, 2008 Fay, 2009 Ida, 2009 Claudette, 2010 Five, 2011 Lee, 2011 Brett, 2012 Beryl, 2012 Alberto, 2012 Debby, 2013 Andrea, 2013 Dorian, 2014 Arthur, 2015 Ana, 2015 Claudette}
Output Feature Class: {Hurricane Name Year_Buffer_left}
Distance: Linear Unit: 30 km
Side type: Left
End type: Round
Method: Planar
Dissolve Type: All

Create a Map of Each Hurricane with Buffers to enable site selection.

Example (Hurricane Hanna) for each Hurricane.

Open New Map

Blank Map

Add Data>Add Basemap>Imagery

Zoom Scale to 1:4,000,000

File>Add Data>Select Correct Shapefile

Buffer Storm track 30 Km to the left.

Select Geoprocessing>Buffer

An Active X control on this page might be unsafe to interact with other parts of the page. Do you want to allow this interaction? Yes

Input Features: Storm.2008241N19303.ibtracs_all_lines.v03r09

Output Feature Class: C:\Users\Schager\Desktop\EA 665\GIS Data\GIS Individual Hurricanes with buffers\Hanna_Buffer_L30.shp

Distance: Select Linear Unit

30 km

Side Type: Left

End Type: Round

Method:Planar

Dissolve Type: All

Select OK

Buffer Storm track 30 Km to the right.

Select Geoprocessing>Buffer

An Active X control on this page might be unsafe to interact with other parts of the page. Do you want to allow this interaction? Yes

Input Features: Storm.2008241N19303.ibtracs_all_lines.v03r09
Output Feature Class: C:\Users\Schager\Desktop\EA 665\GIS Data\GIS Individual Hurricanes with buffers\Hanna_2008_Buffer_R30.shp

Distance: Select Linear Unit
    30 km
Side Type: Right
End Type: Round
Method:Planar
Dissolve Type: All

Buffer the Storm track 70 km to the right.

Select Geoprocessing>Buffer

An Active X control on this page might be unsafe to interact with other parts of the page. Do you want to allow this interaction? Yes

Input Features: Storm.2008241N19303.ibtracs_all_lines.v03r09
Output Feature Class: C:\Users\Schager\Desktop\EA 665\GIS Data\GIS Individual Hurricanes with buffers\Hanna_2008_Buffer_R70.shp

Distance: Select Linear Unit
    70 km
Side Type: Right
End Type: Round
Method:Planar
Dissolve Type: All

Buffer the Storm track 100 km to the right.

Select Geoprocessing>Buffer

An Active X control on this page might be unsafe to interact with other parts of the page. Do you want to allow this interaction? Yes

Input Features: Storm.2008241N19303.ibtracs_all_lines.v03r09

Output Feature Class: C:\Users\Schager\Desktop\EA 665\GIS Data\GIS Individual Hurricanes with buffers\Hanna_2008_Buffer_R100.shp

Distance: Select Linear Unit

100 km

Side Type: Right

End Type: Round

Method:Planar

Dissolve Type: All

Clip Hurricane Buffer Right 100.

Geoprocessing<Clip

Input Feature Class: (Hurricane Name)_Buffer_R100

Clip Feature: (Hurricane Name)_Buffer_L30

Output Feature Class: Clipped_(Hurricane Name)_Buffer_R100

Erase Clip

Geoprocessing<ArcToolBox<Overlay<Erase

Input Feature Class: (Hurricane Name)_Buffer_R100

Erase Features: Clipped_(Hurricane Name)_Buffer_R100

Output Feature Class: Good_(Hurricane Name)_2013_Buffer_R100

Change Transparency of Buffers so they can be seen through to locate Carolina Bay study sites.

Right click on Data Layer>Layer Properties>Display>Transparent 50%

Apply>OK

File>Save As>Desktop>EA665>Hanna Buffers

Repeat for Hurricane Cindy, Hurricane Ernesto, Hurricane Hanna, Hurricane Beryl, Hurricane Andrea, Hurricane Anna.

Select sites on path and label each site with a point marker.

NDVI Input Data

Web address: http://clim-engine.appspot.com/

Choose Figure/Data

Time series Calculation: Daily Data

One Variable Analysis

Region: Points

Points: Input Latitude and Longitude Data

Variable 1:

Type: Remote Sensing

Dataset: Landsat 4/5/7/8 Surface Reflectance

Variable: NDVI (Vegetation Index)

Computation Resolution (Scale): 30 M

Time Period:

Season: Custom Date Range

Start Date: 3 months before hurricane date

End Date: 9 months after hurricane date

Appendix C. Graphs of NDVI data for Study Sites 1-32.

Figure 1. Site 1's NDVI Graph.

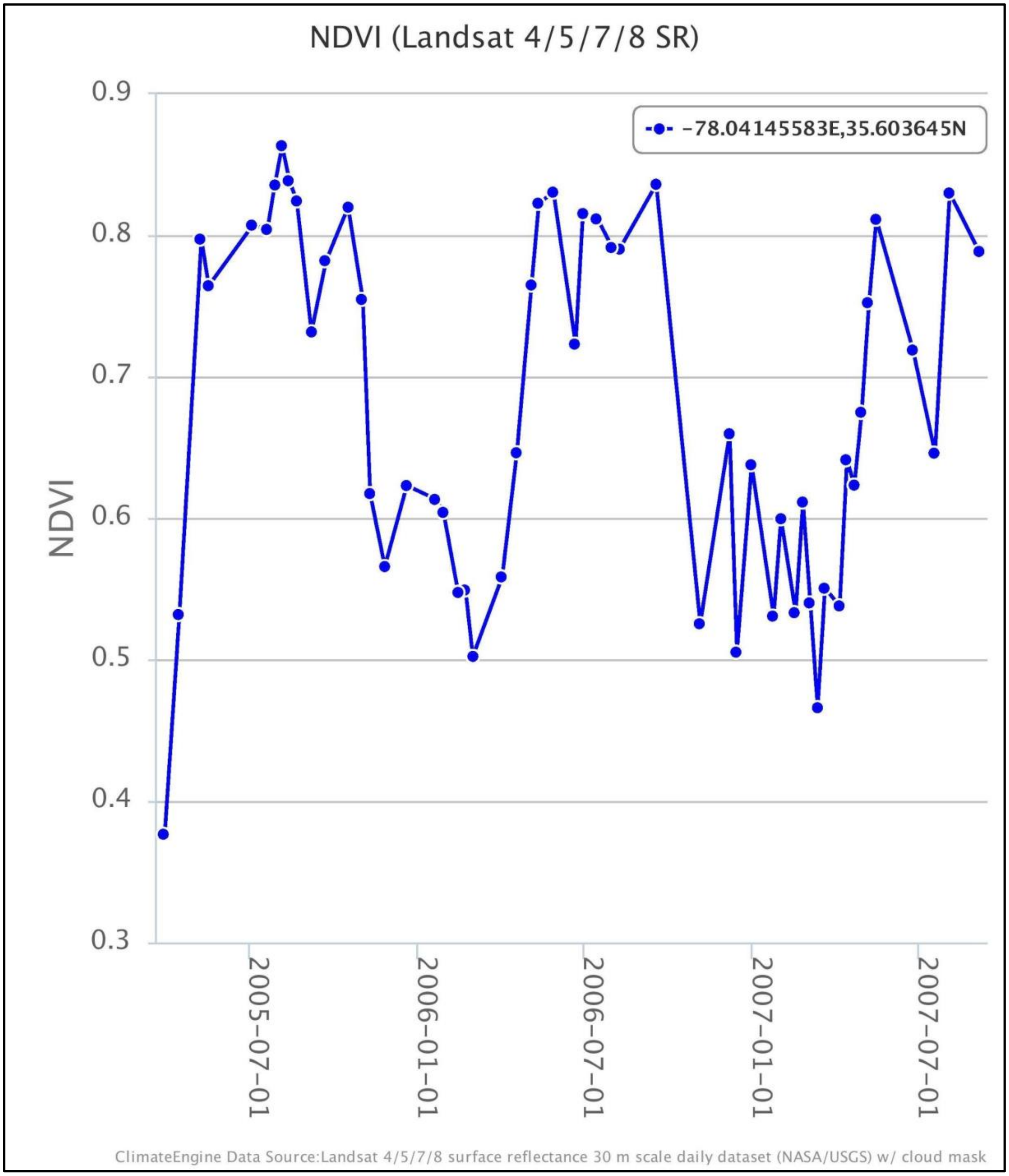


Figure 2. Site 2's NDVI Graph.

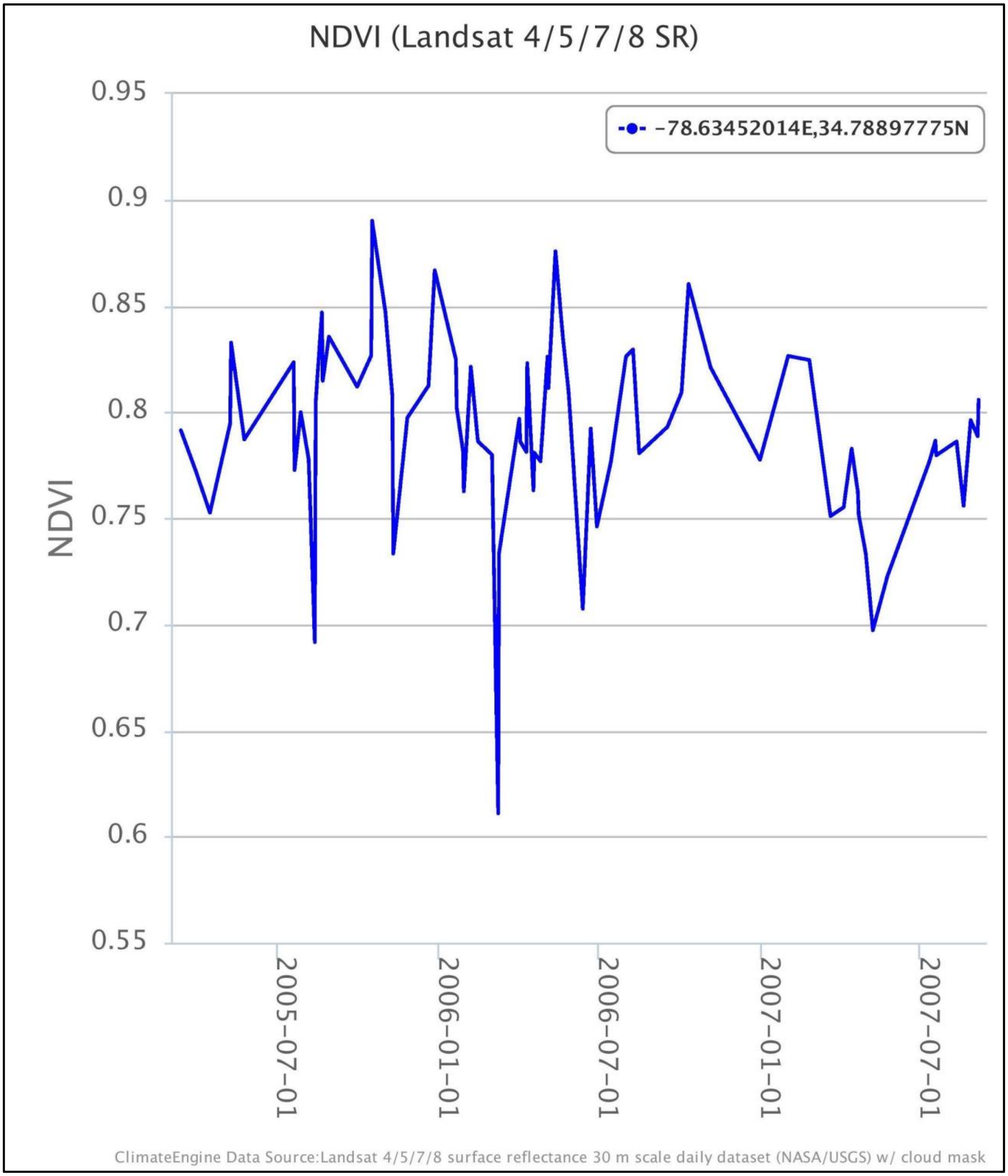


Figure 3. Site 3's NDVI Graph.

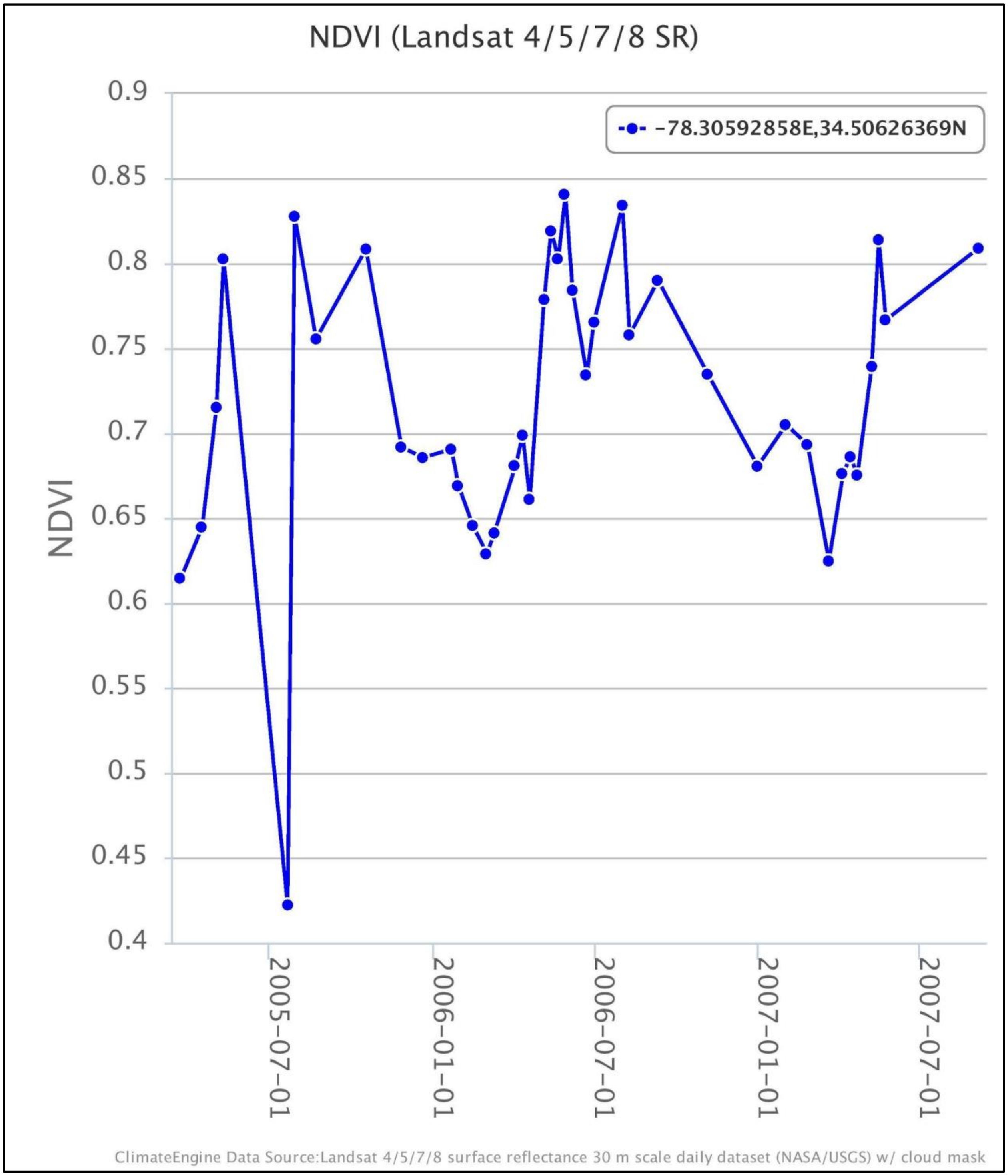


Figure 4: Site 4's NDVI Graph.

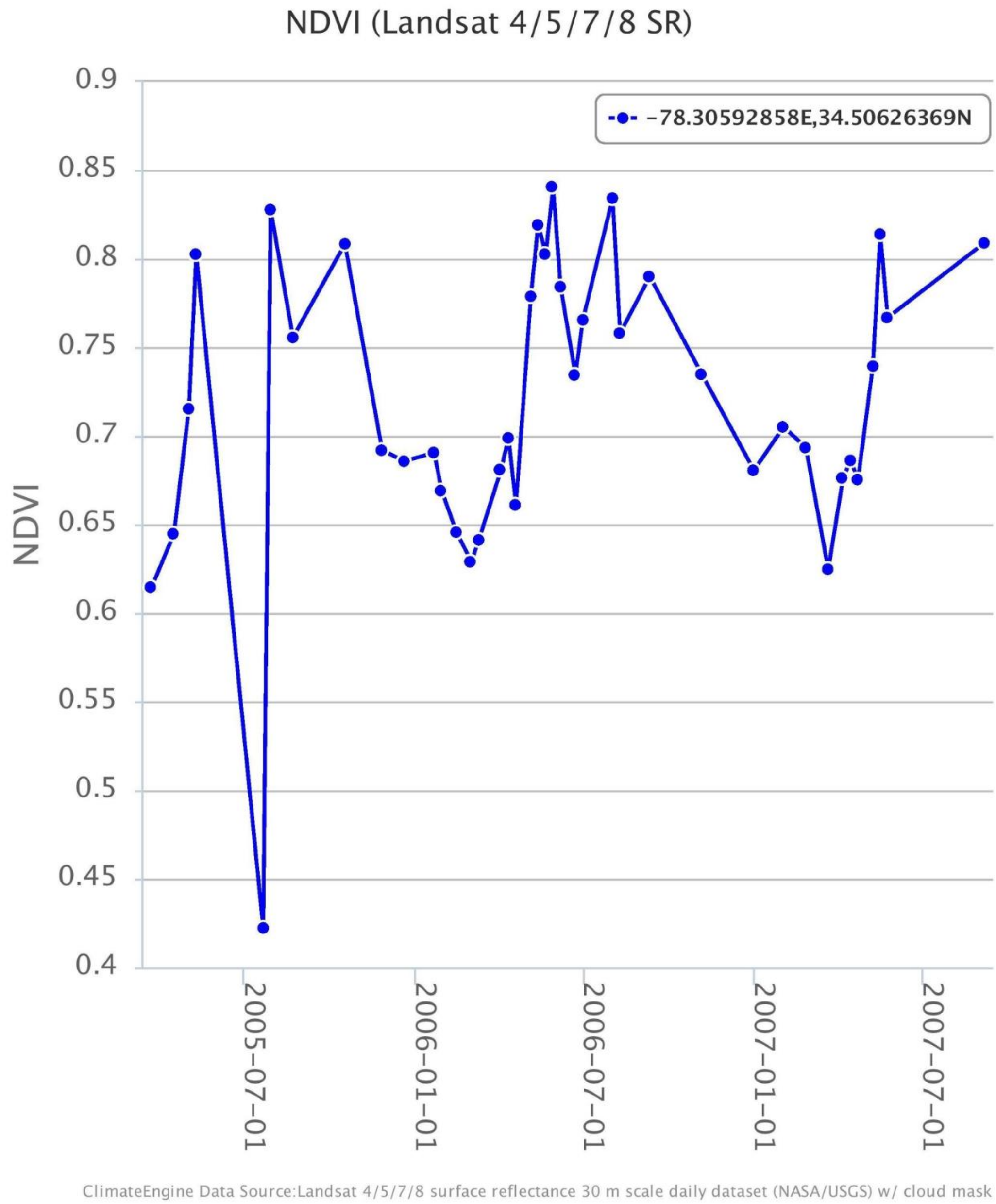


Figure 5: Site 5's NDVI graph.

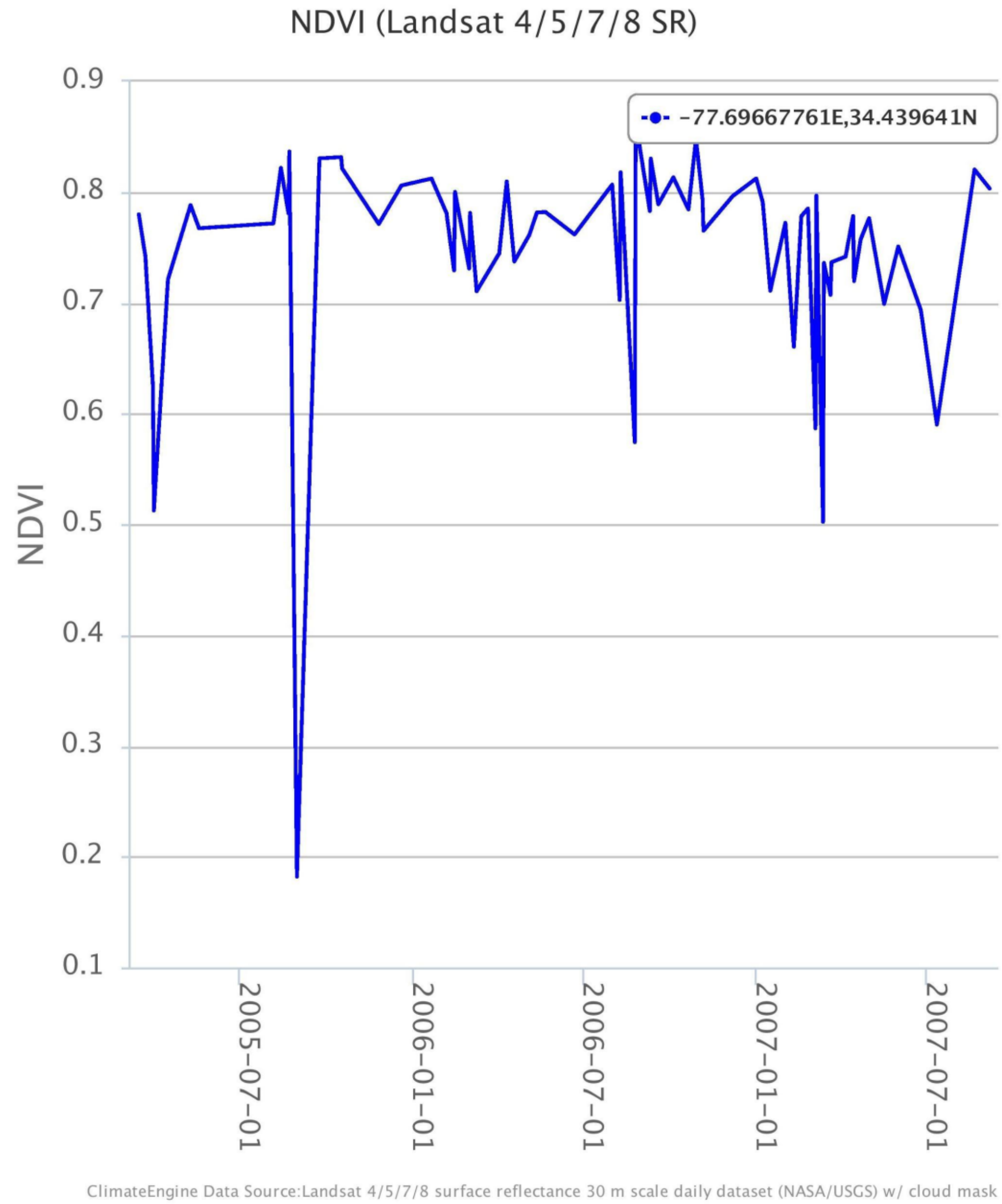


Figure 6: Site 6's NDVI Graph.

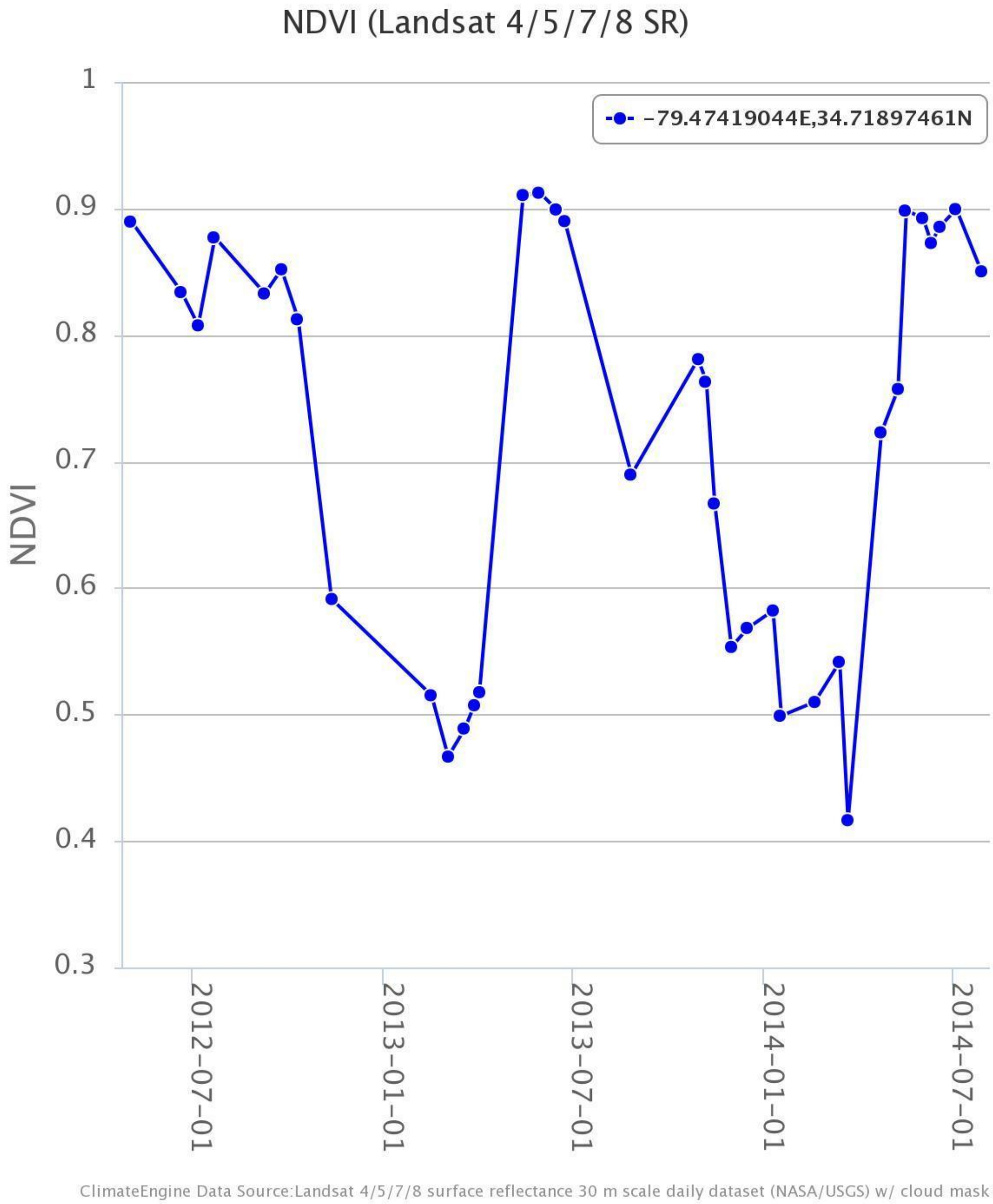


Figure 7: Site 7's NDVI Graph.

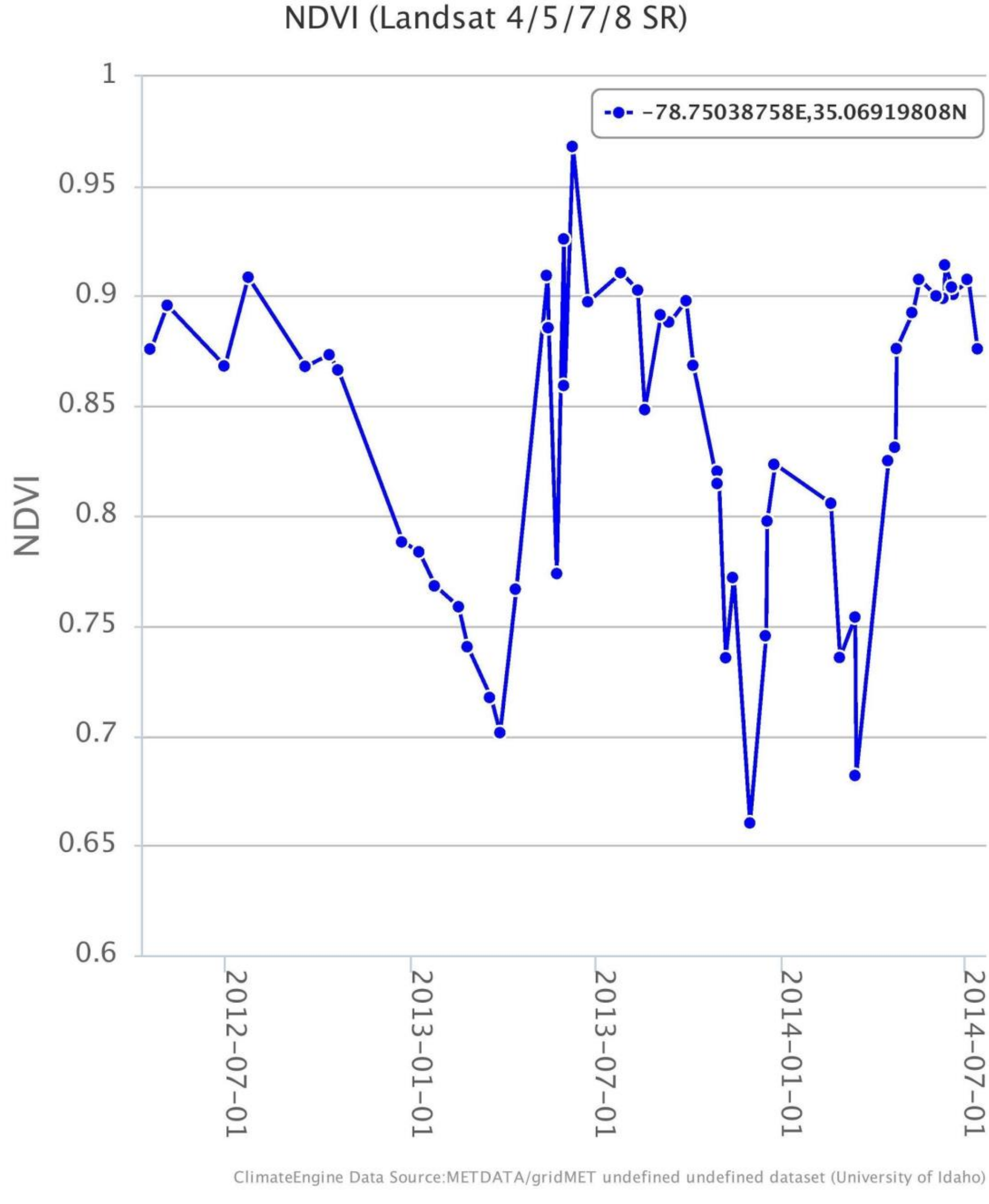


Figure 8: Site 8's NDVI Graph.

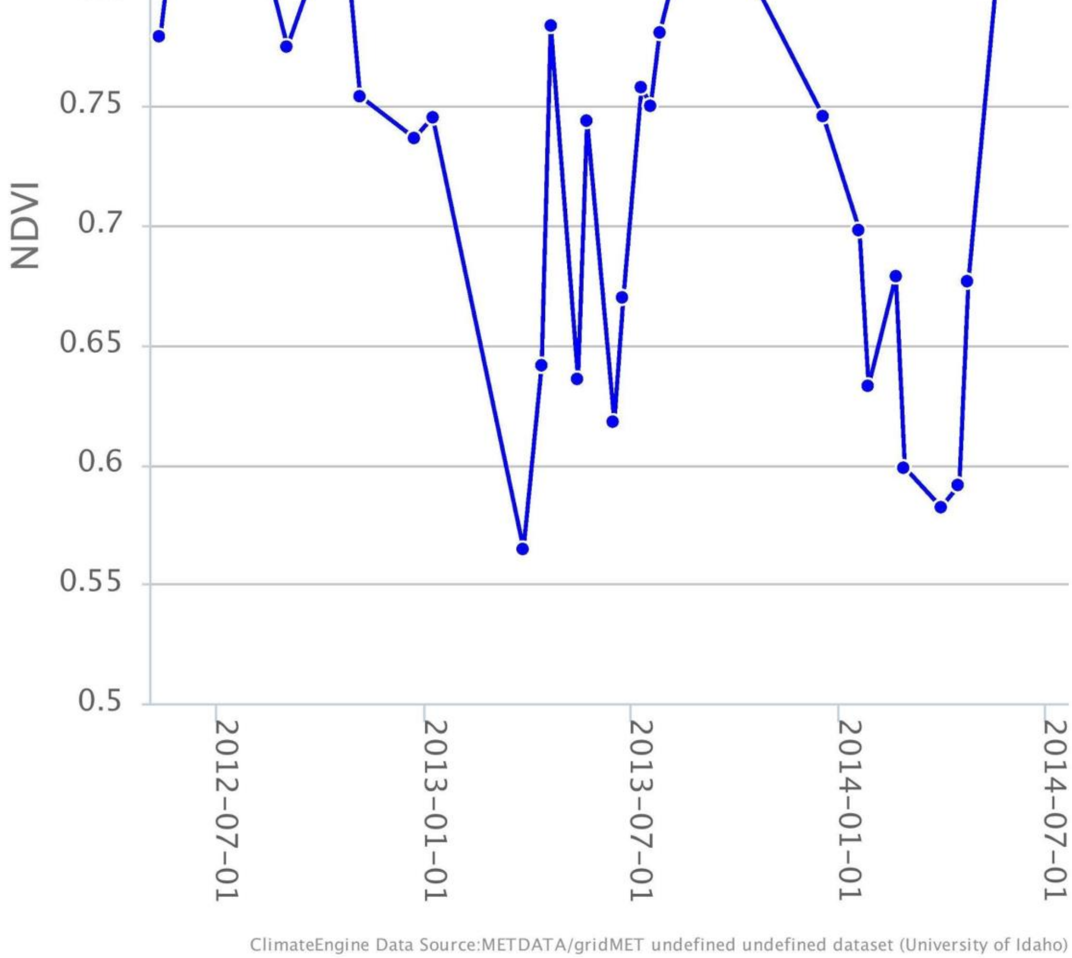


Figure 9: Site 9’s NDVI Graph.

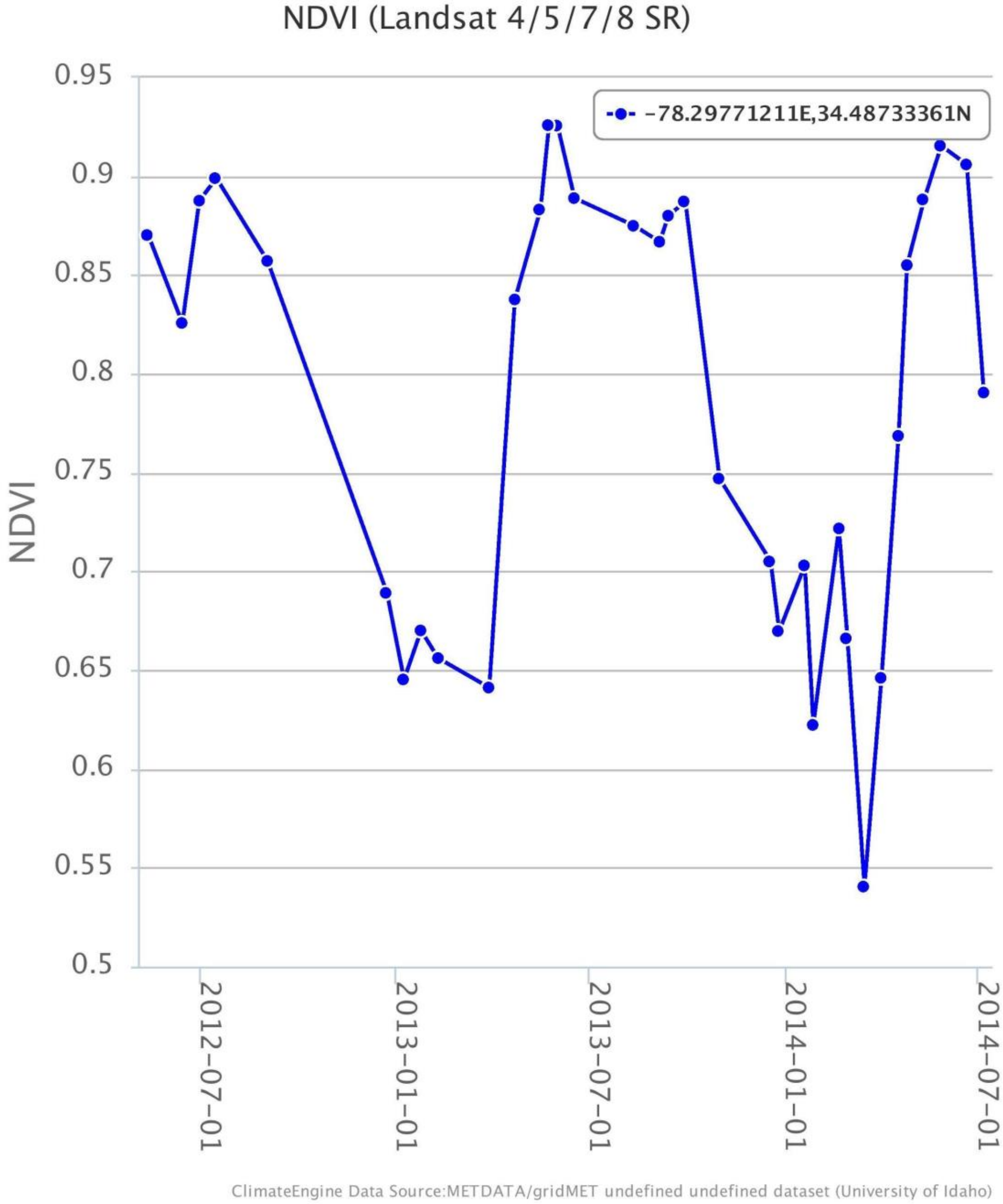


Figure 10: Site 10's NDVI Graph.

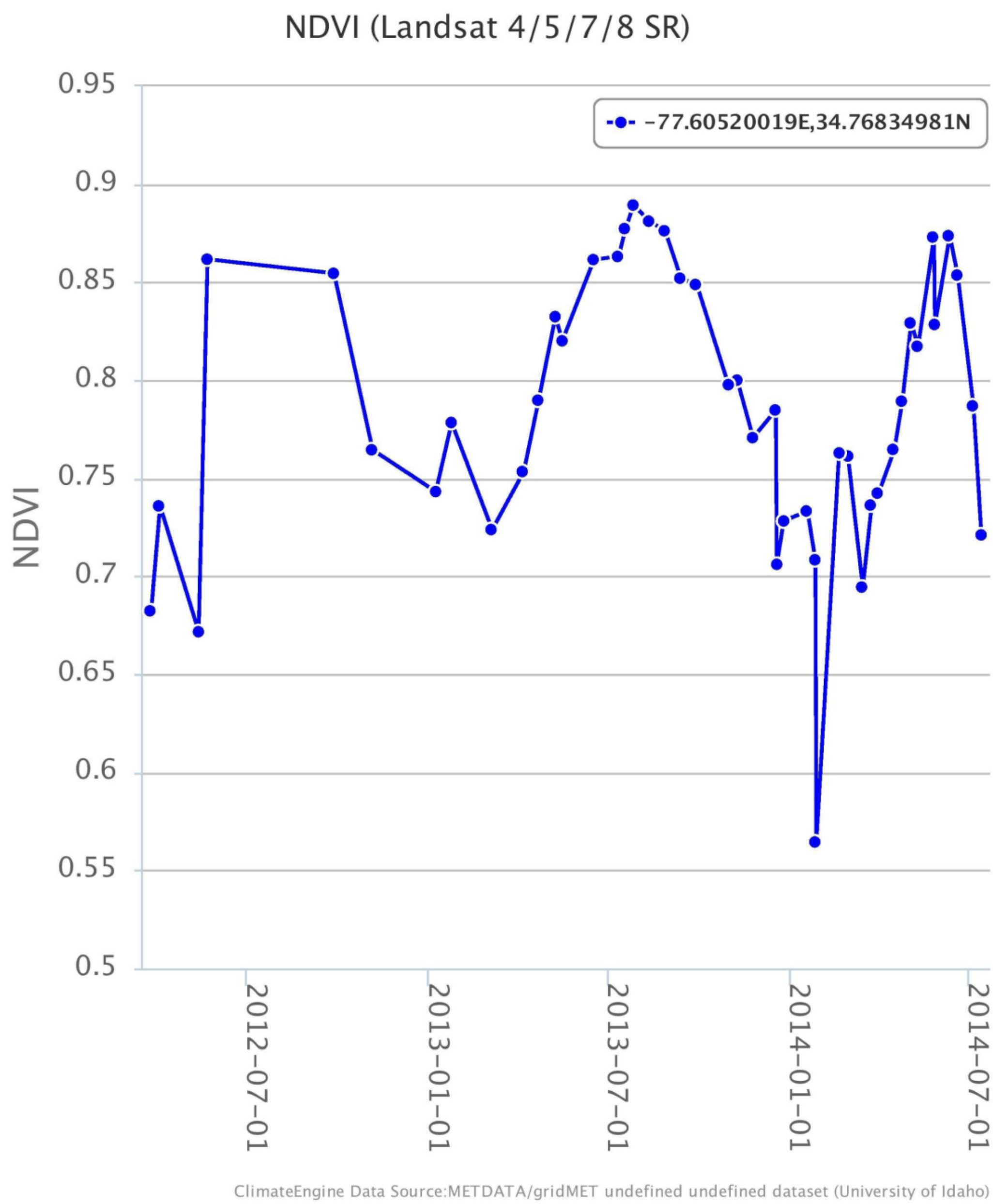


Figure 11: Site 11's NDVI Graph.

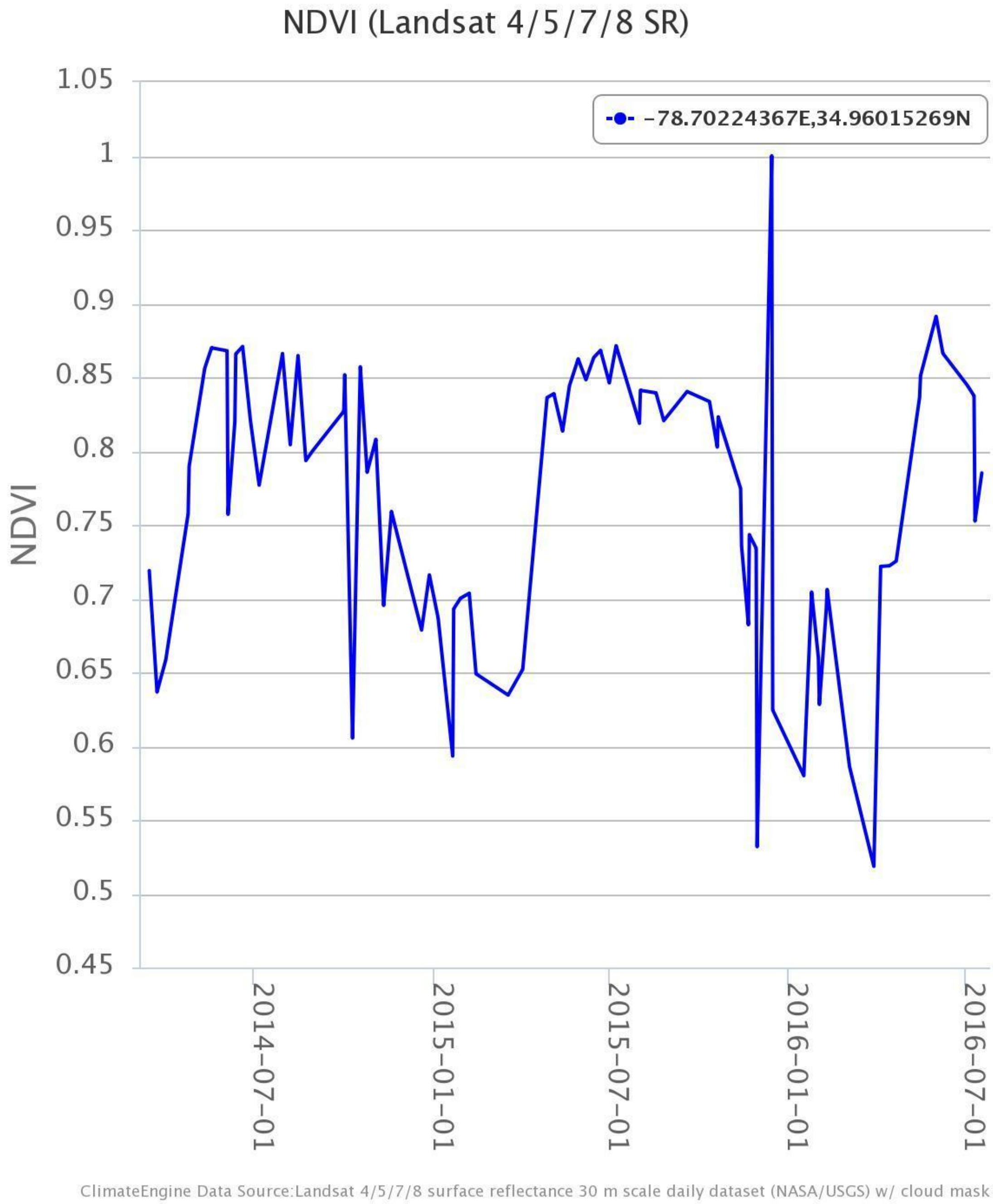


Figure 12: Site 12's NDVI Graph.

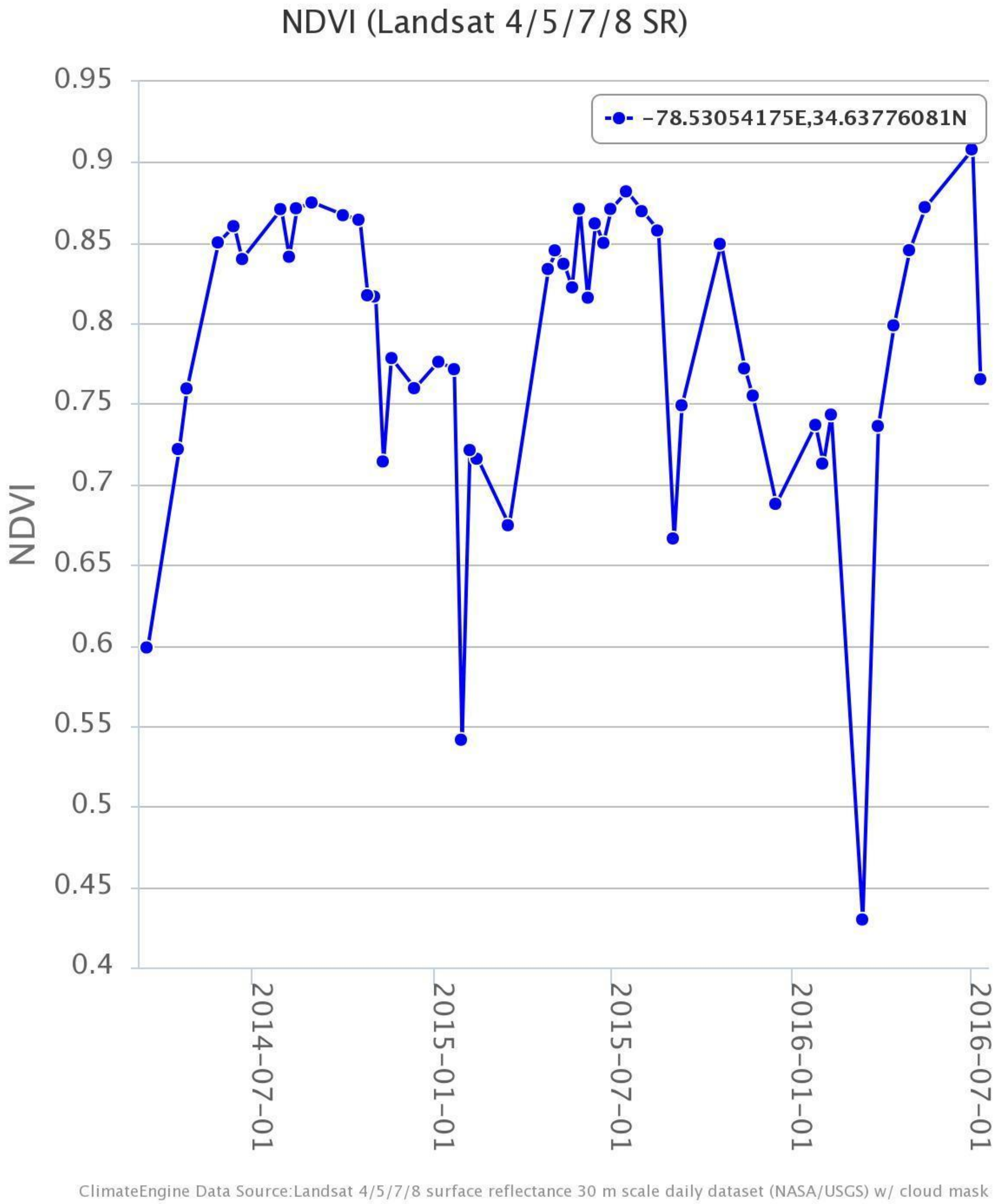


Figure 13: Site 13’s NDVI Graph.

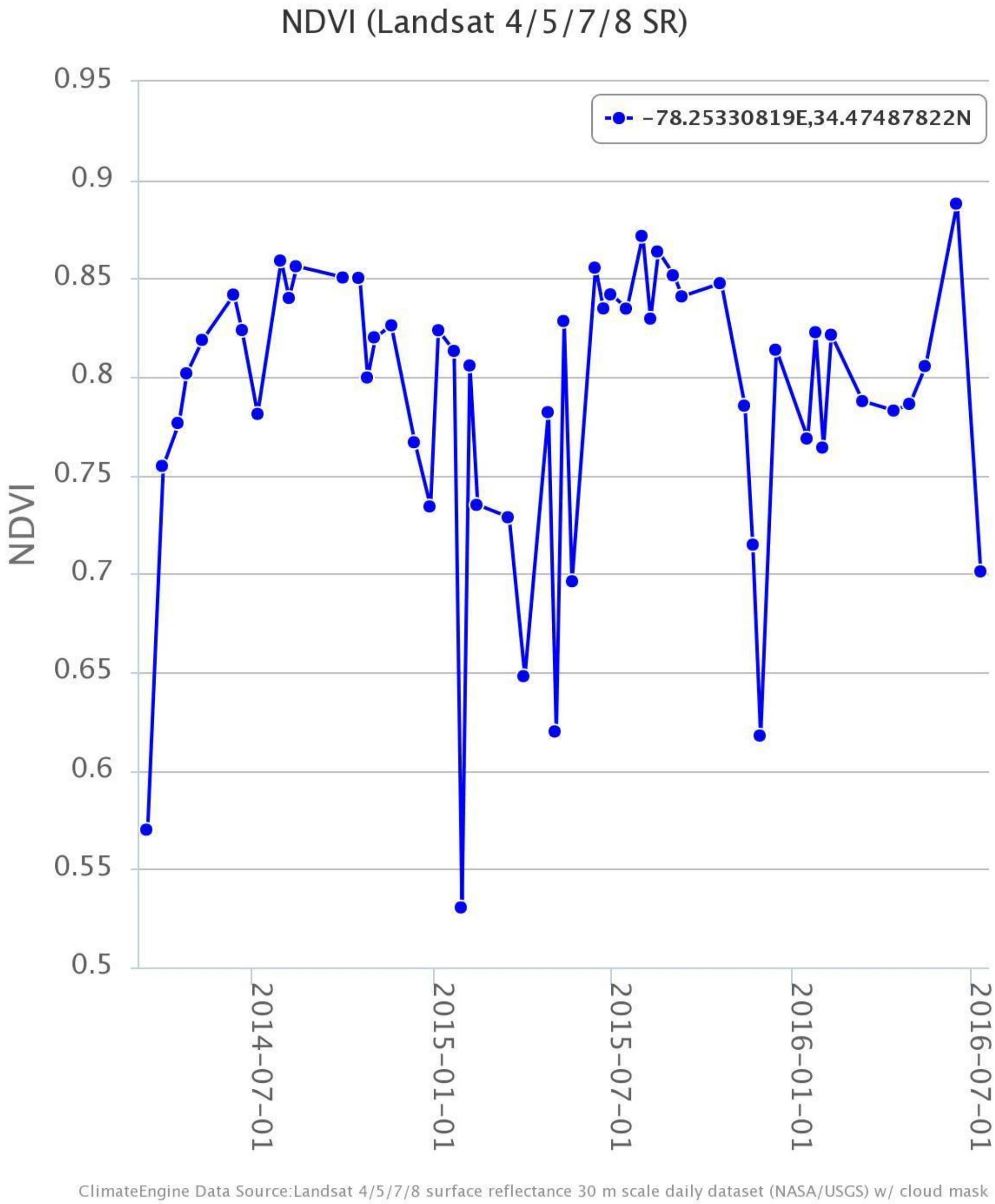


Figure 14: Site 14's NDVI Graph.

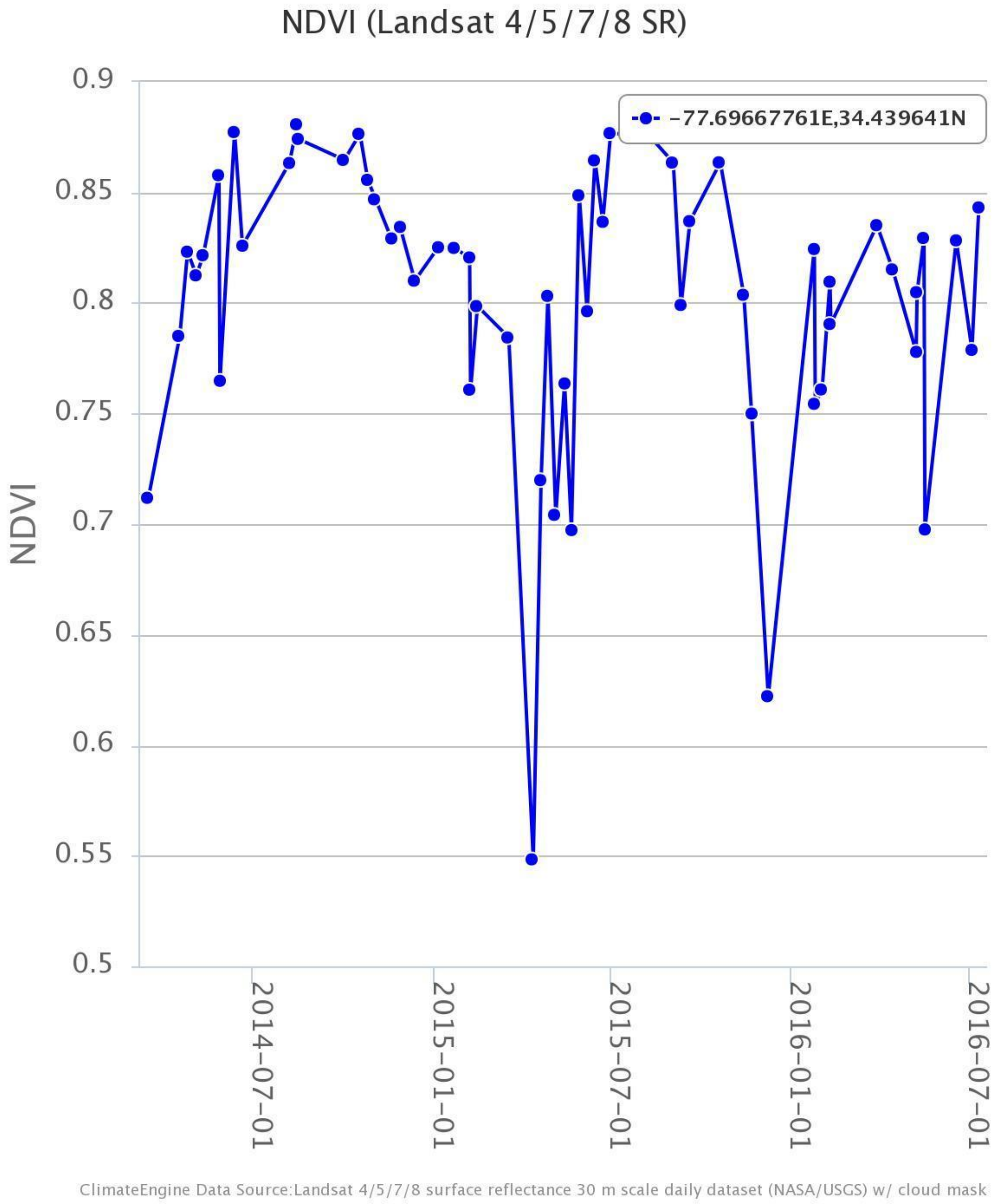


Figure 15: Site 15's NDVI Graph.

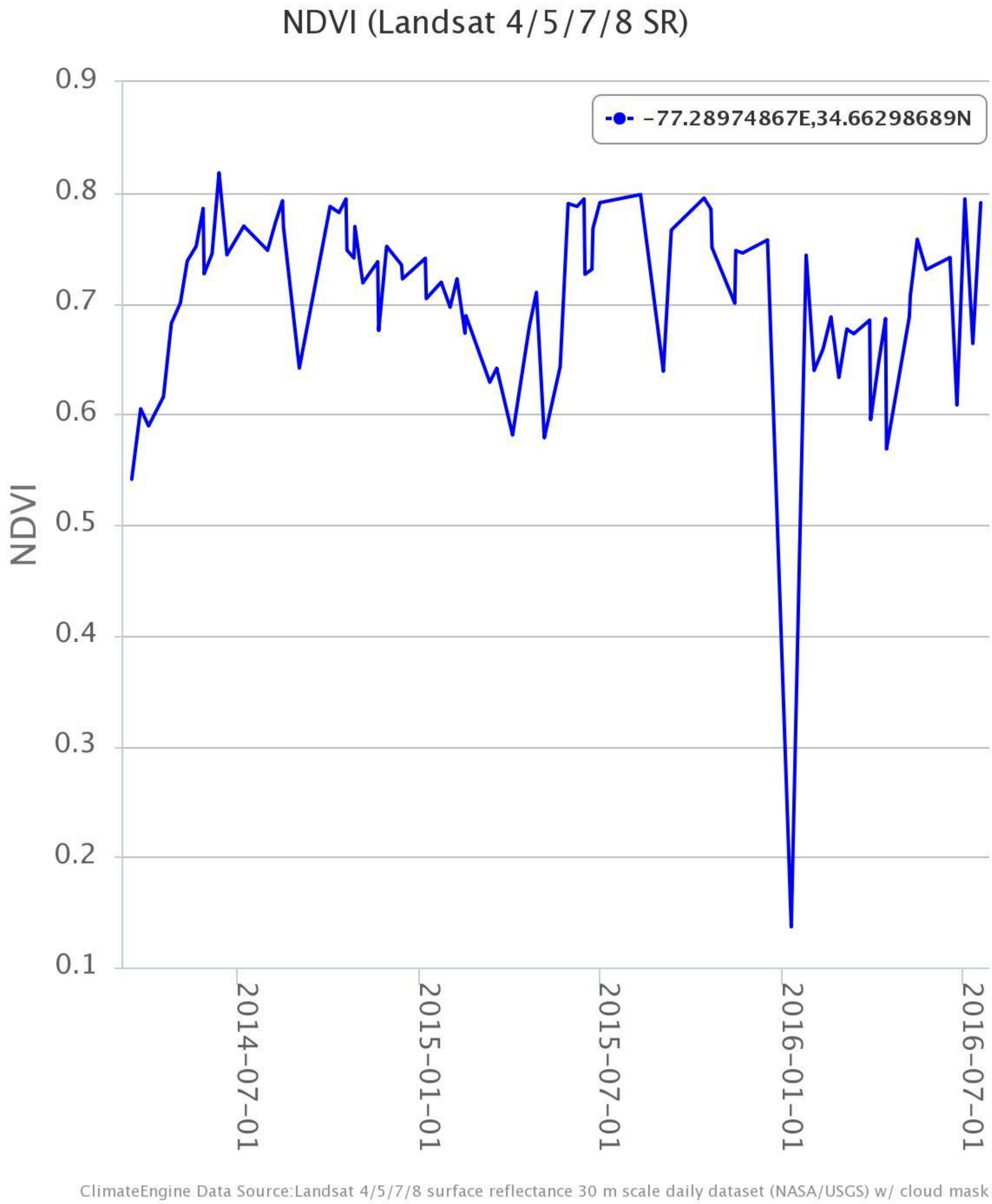


Figure 16: Site 16's NDVI Graph.

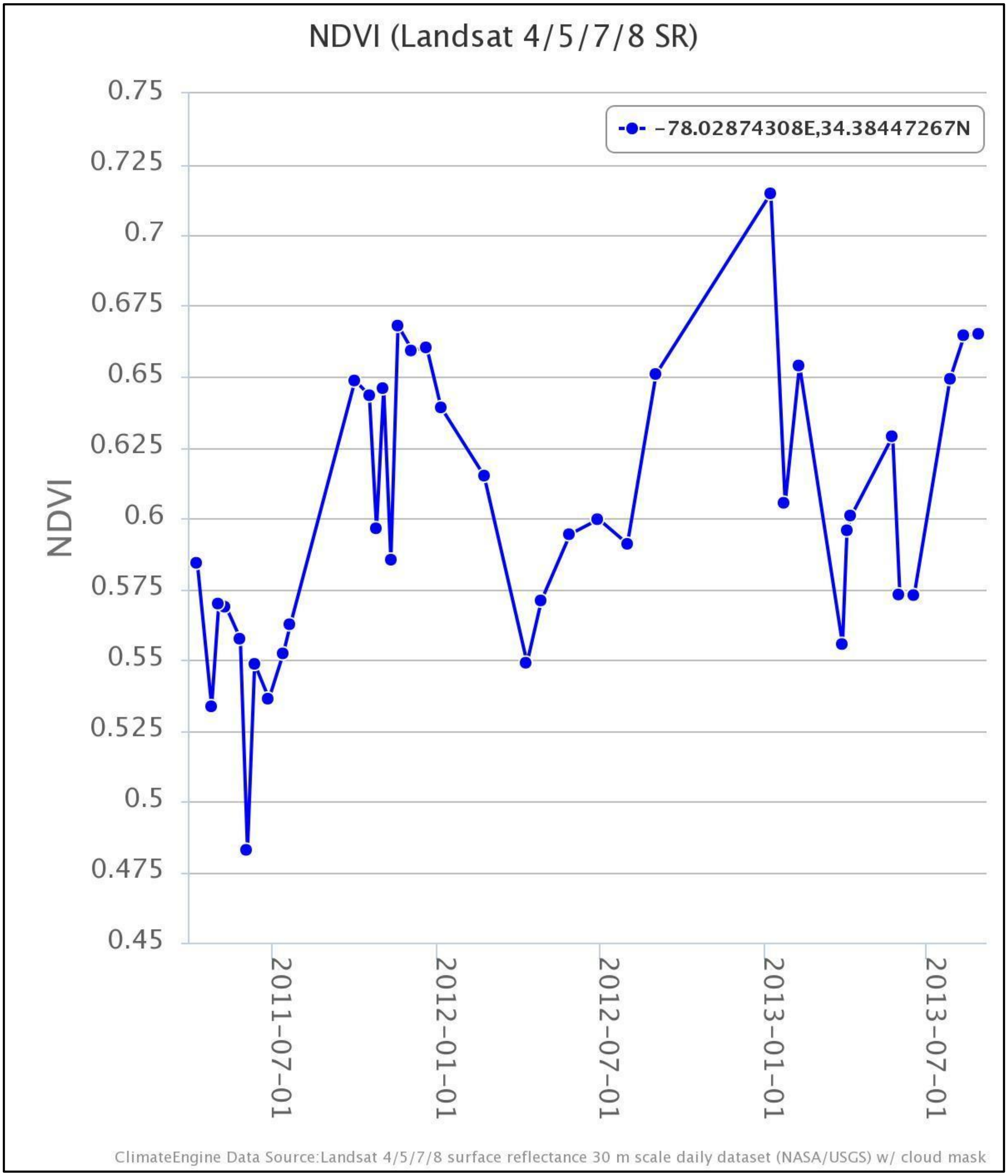


Figure 17: Site 17's NDVI Graph.

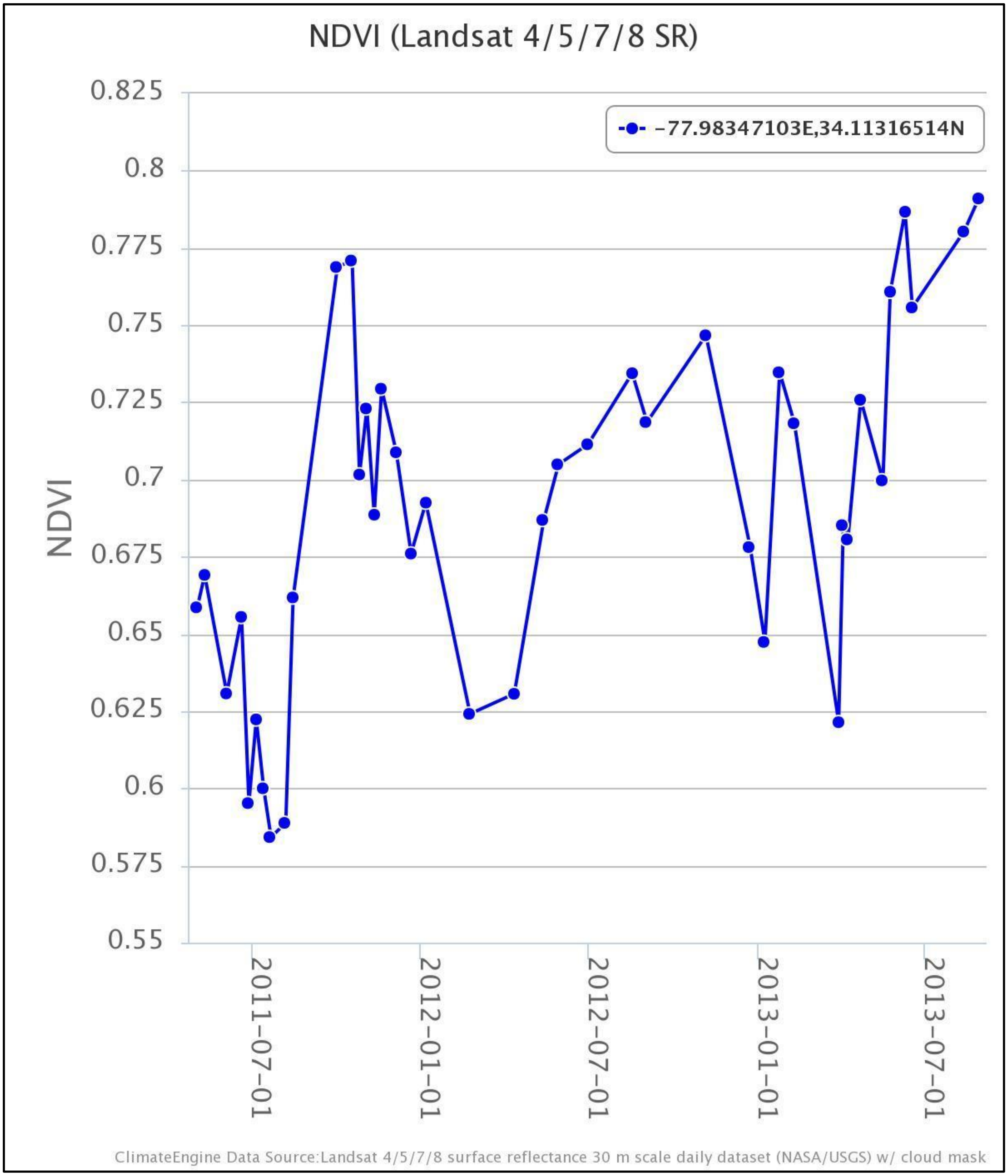


Figure 18: Site 18's NDVI Graph.

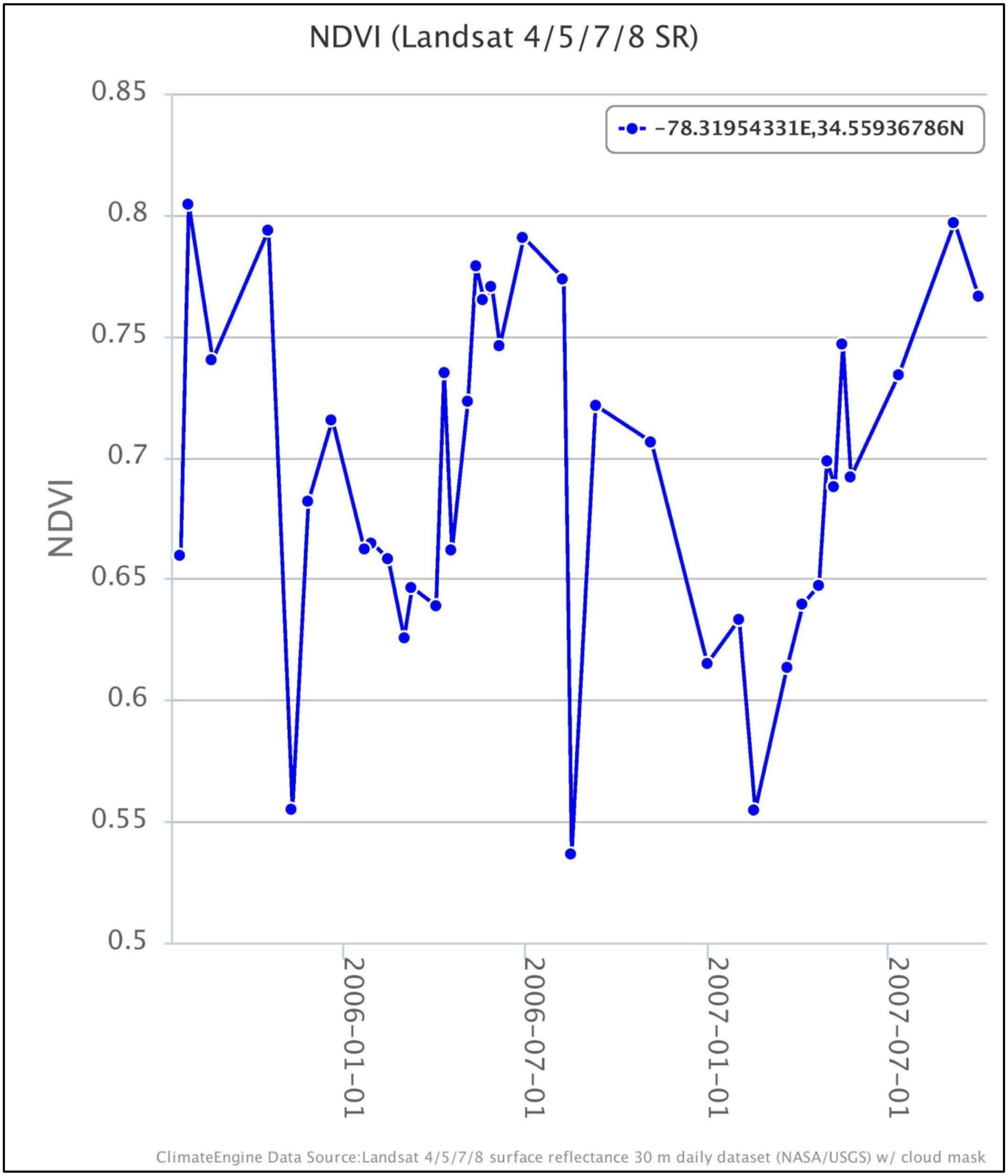


Figure 19: Site 19's NDVI Graph.

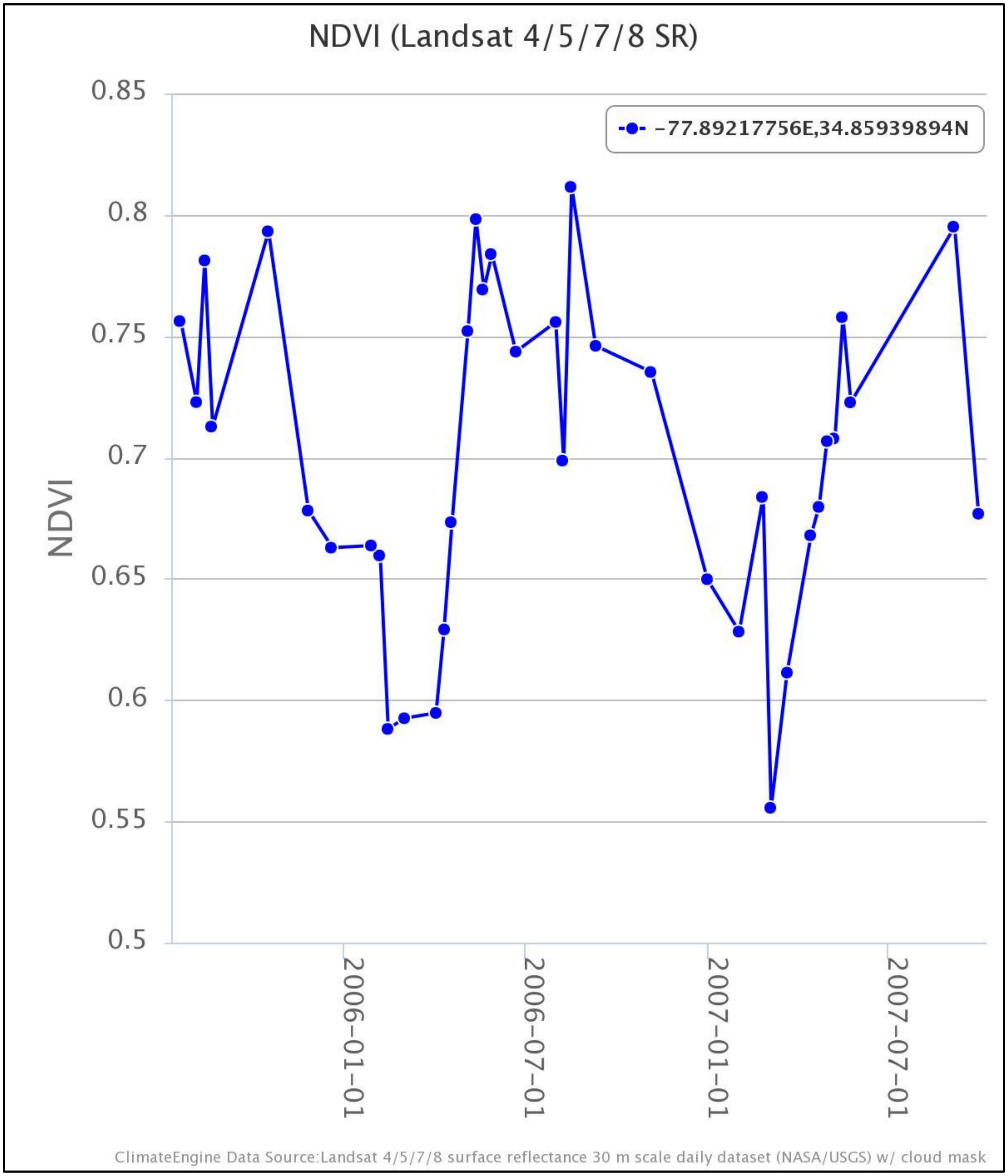


Figure 20: Site 20's NDVI Graph.

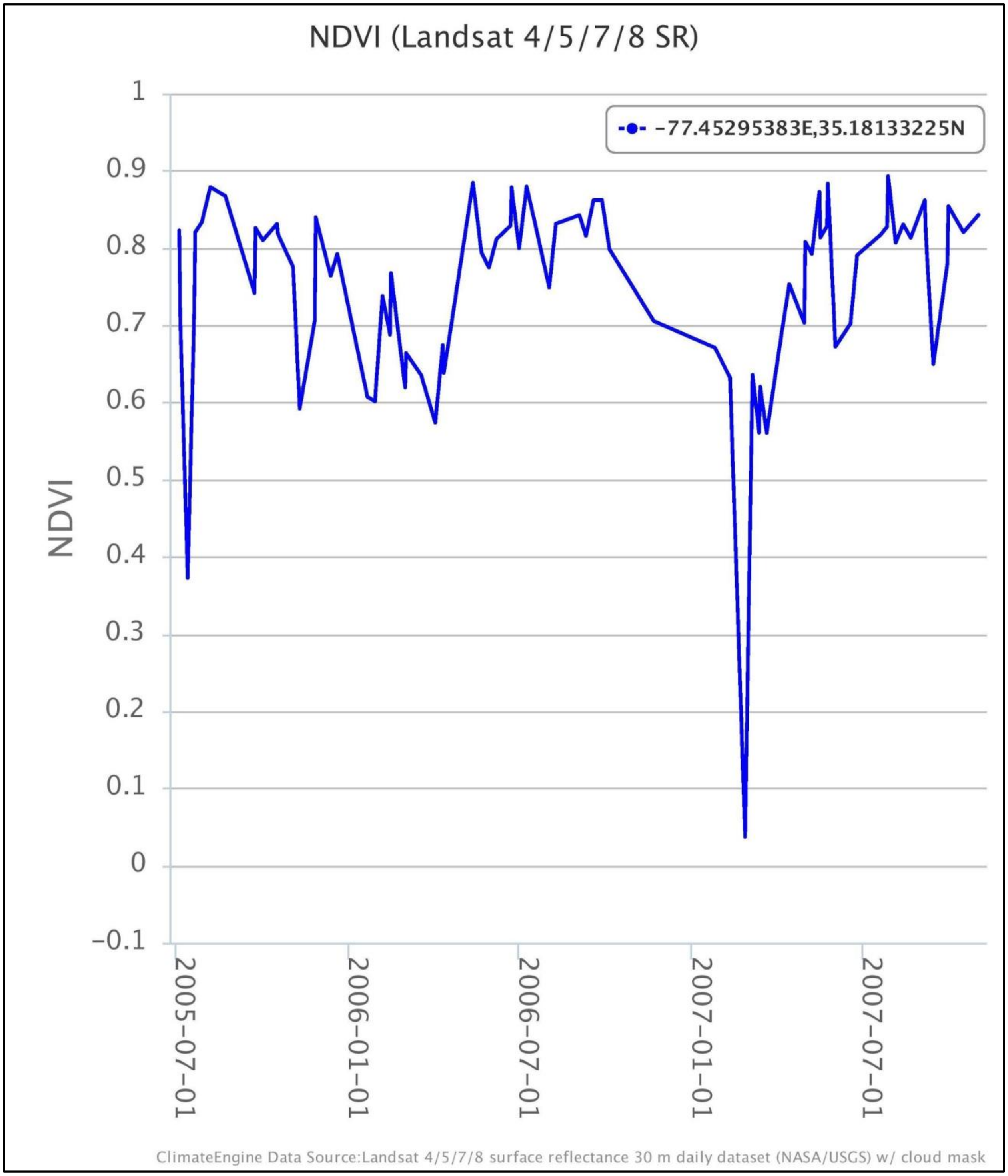


Figure 21: Site 21's NDVI Graph.

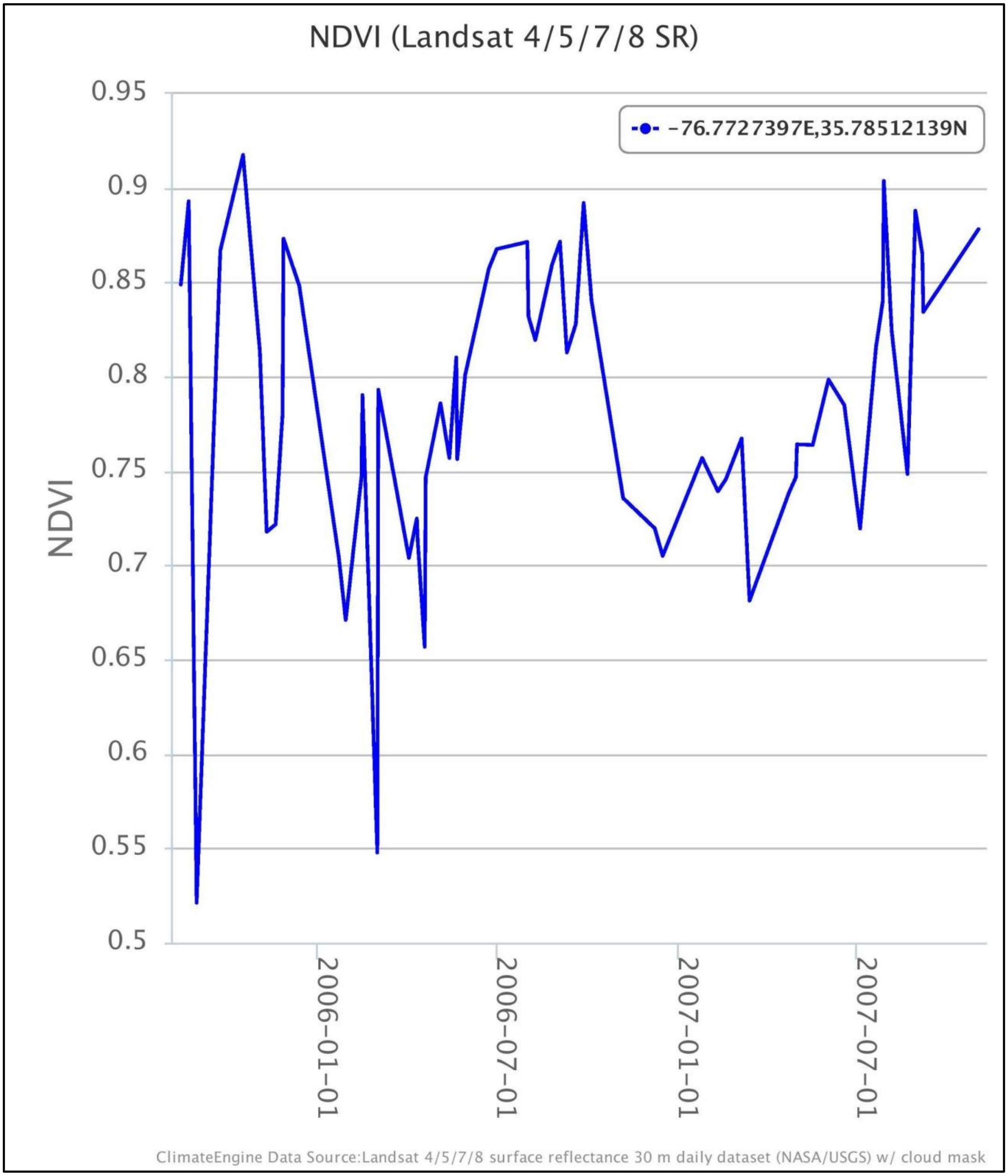


Figure 22: Site 22's NDVI Graph.

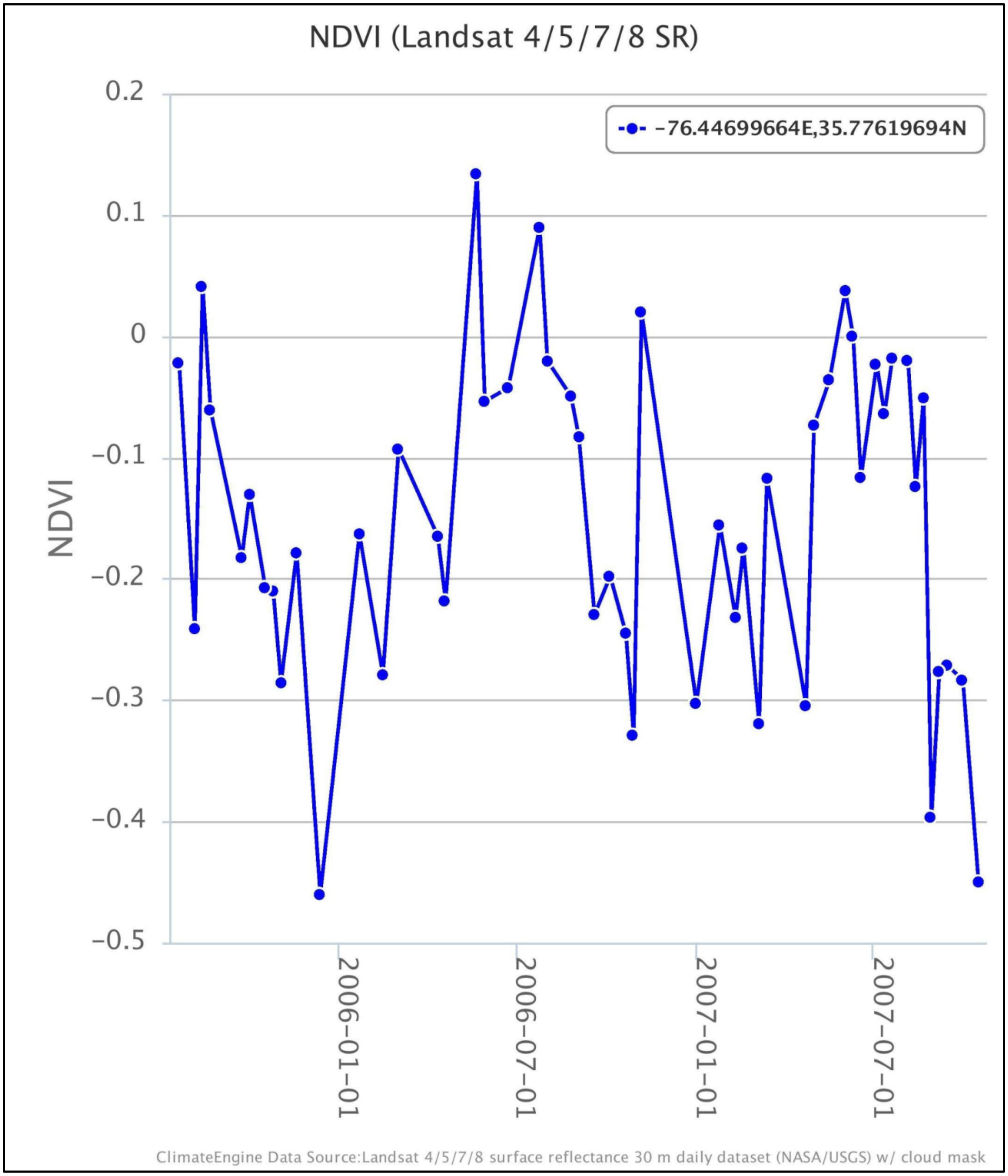


Figure 23: Site 23's NDVI Graph.

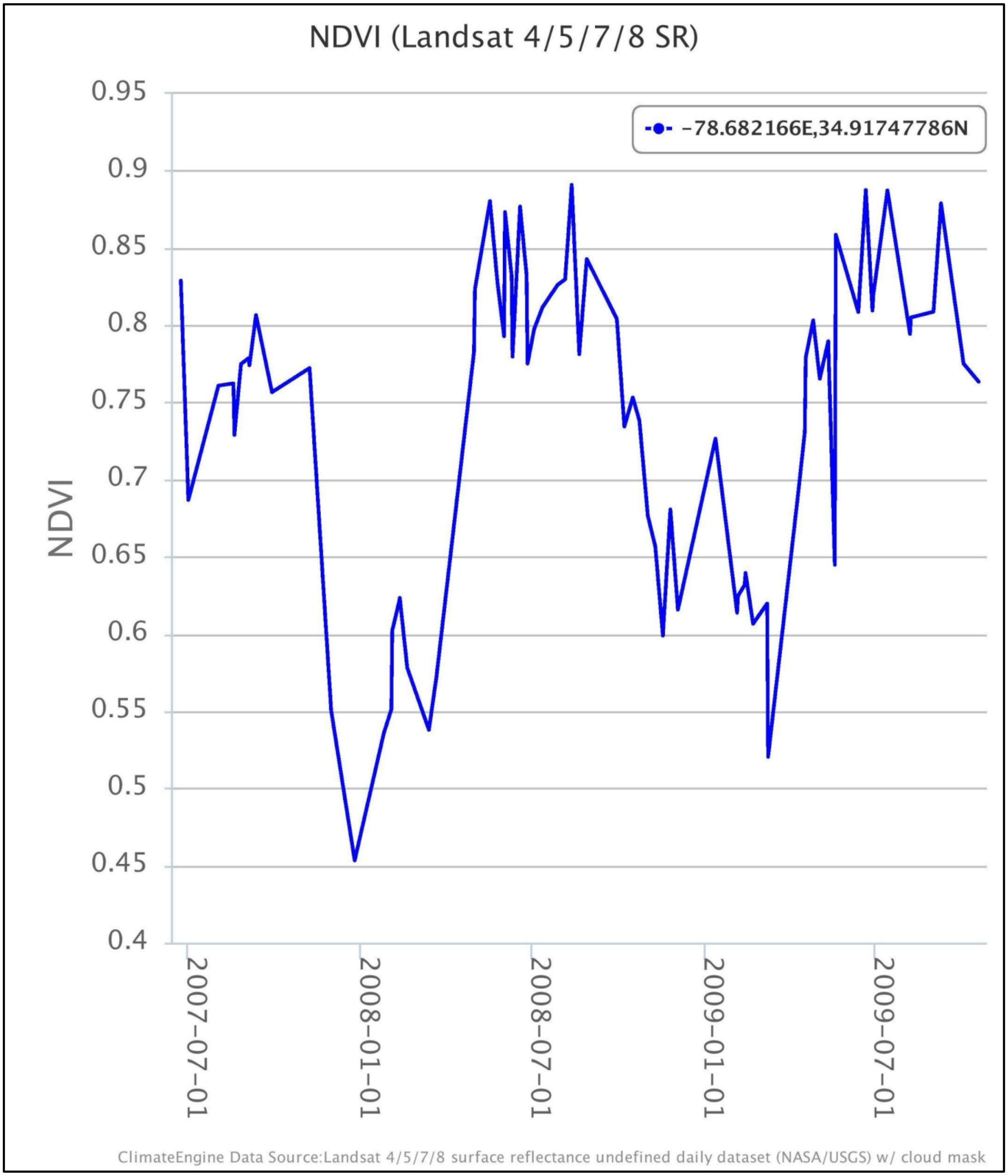


Figure 24: Site 24's NDVI Graph.

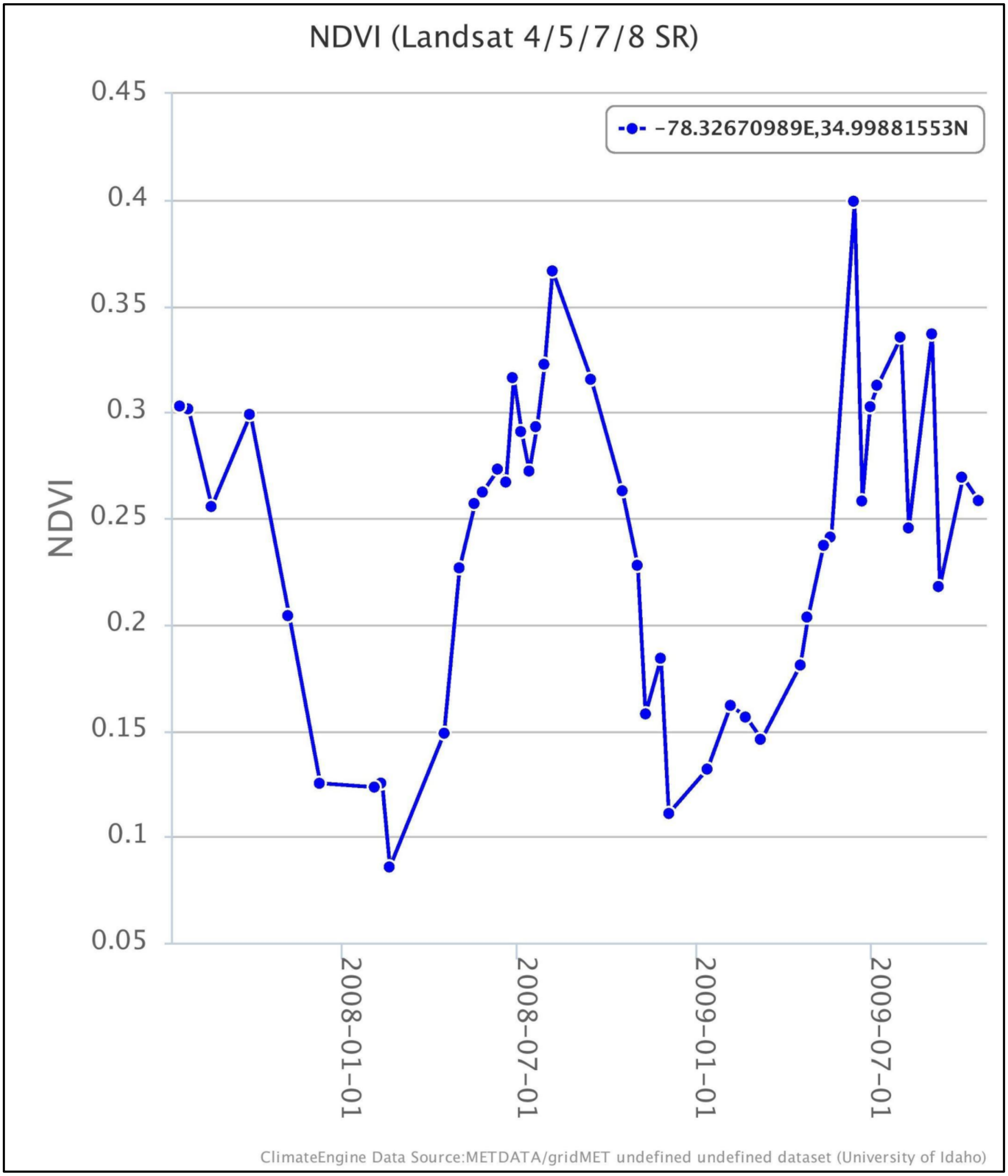


Figure 25: Site 25's NDVI Graph.

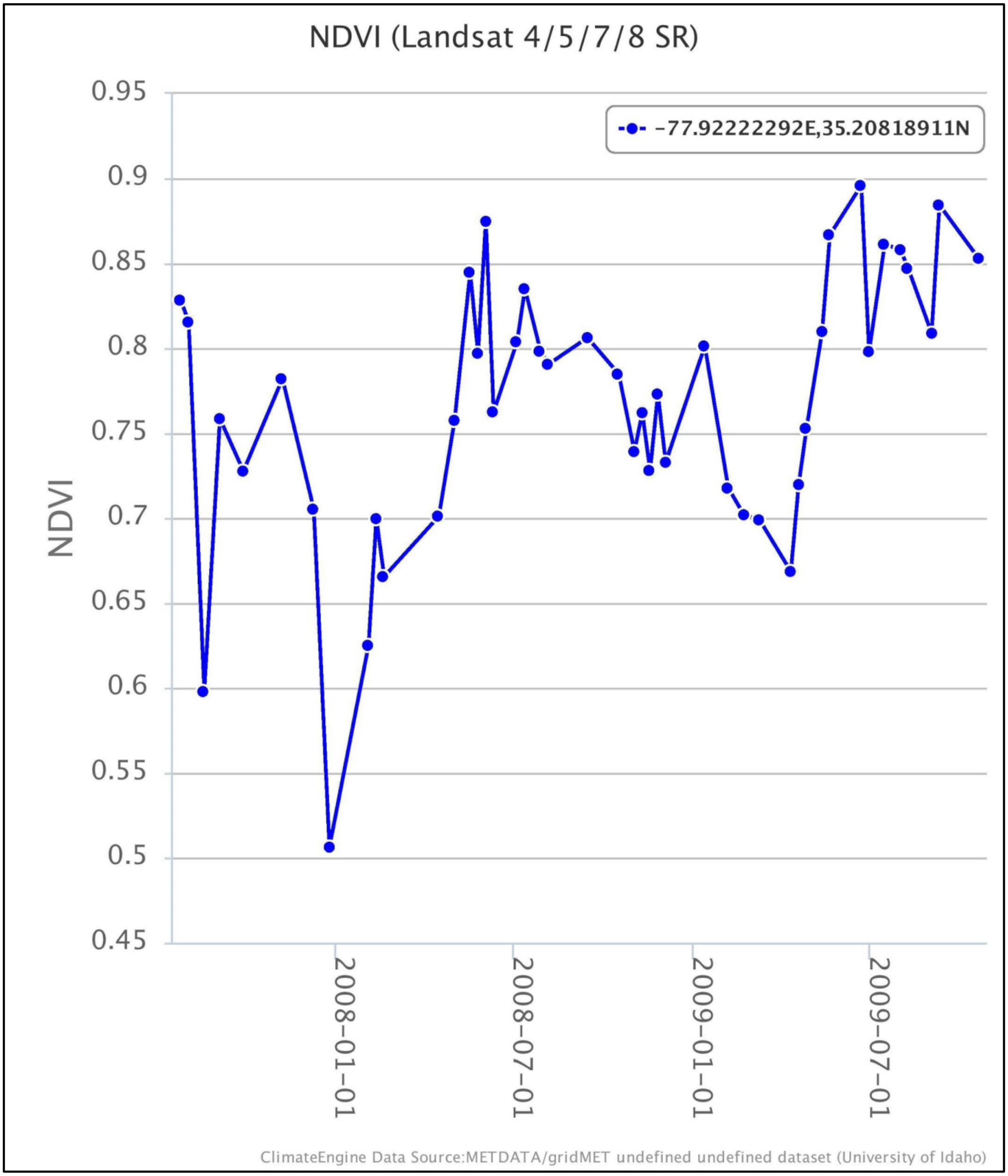


Figure 26: Site 26’s NDVI Graph.

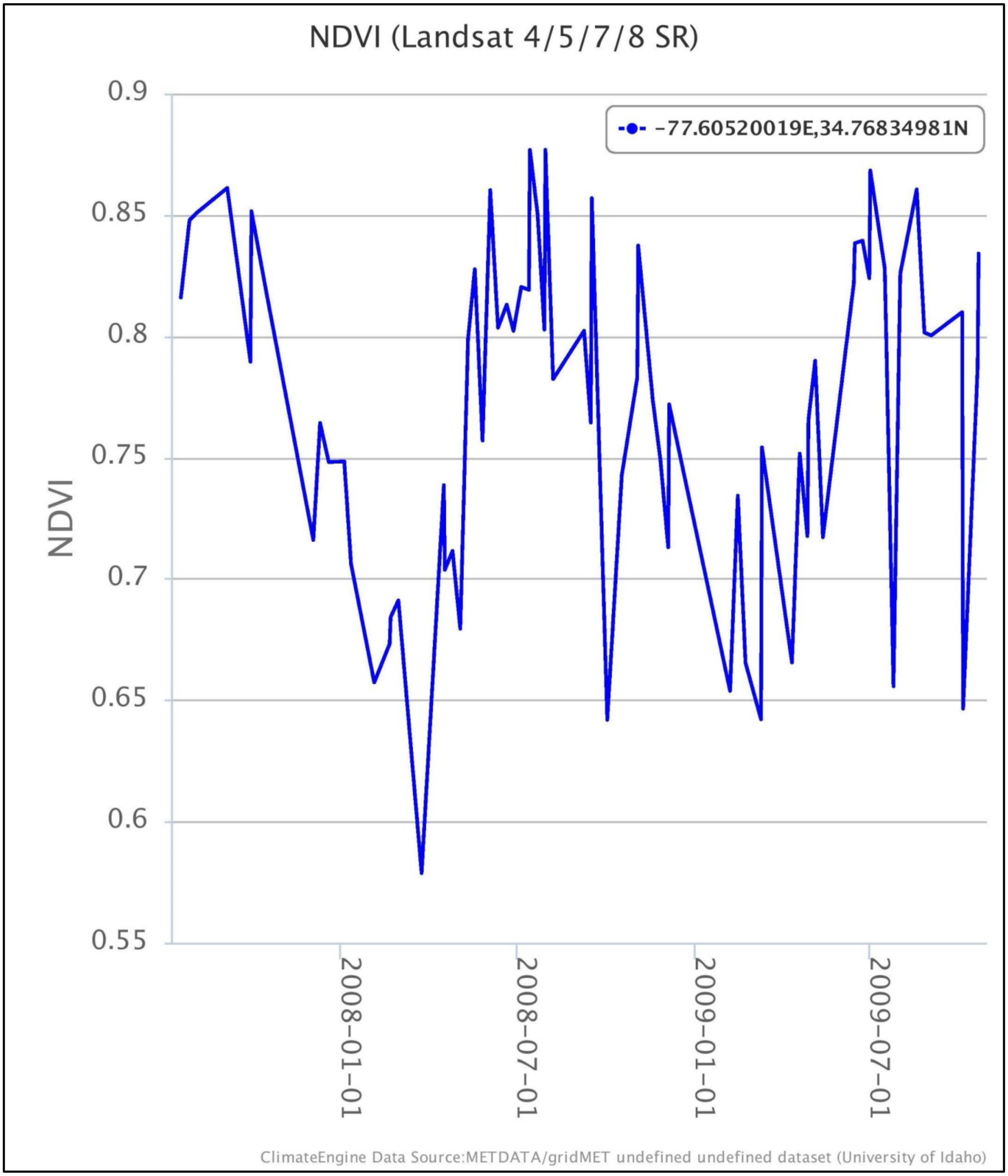


Figure 27: Site 27's NDVI Graph.

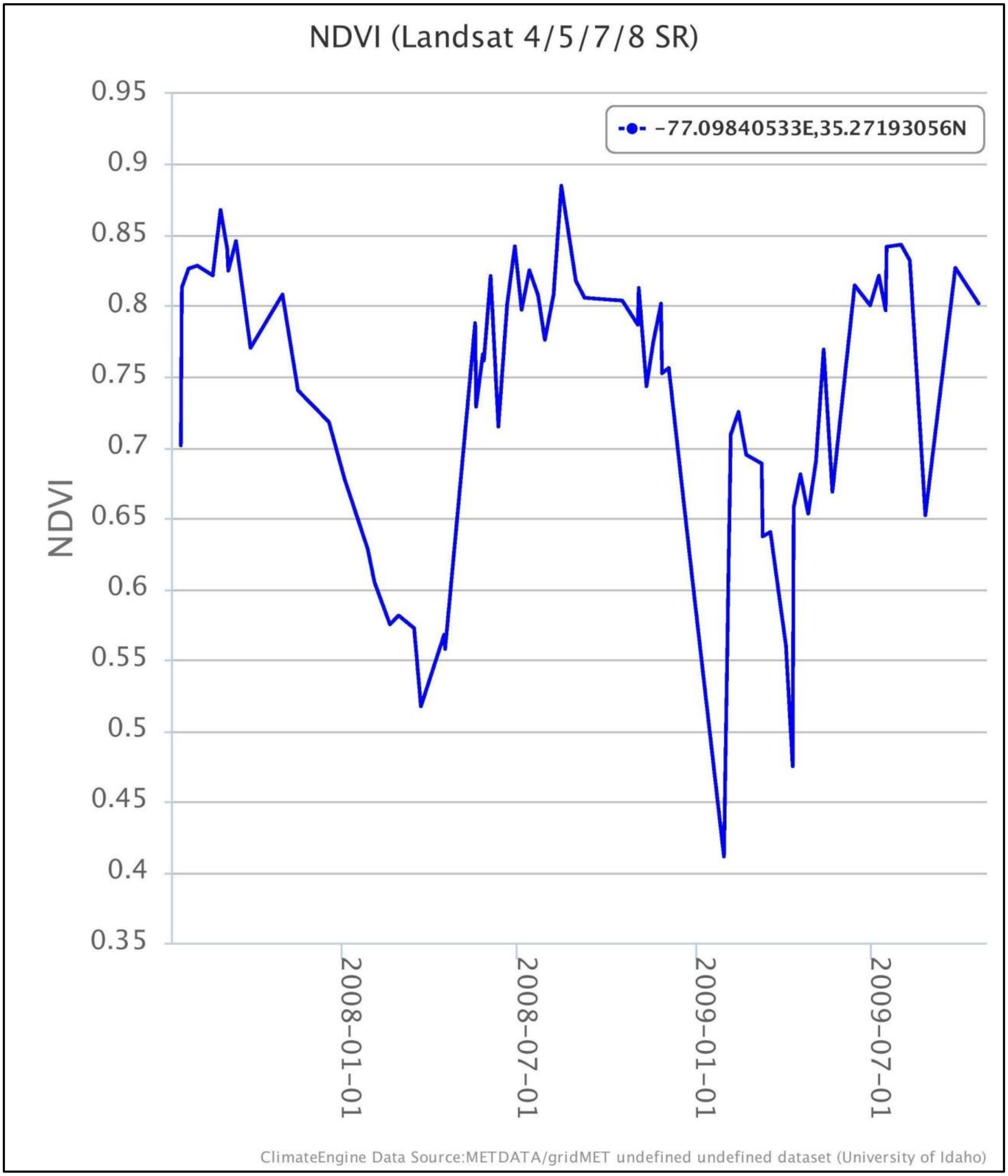


Figure 28: Site 28’s NDVI Graph.

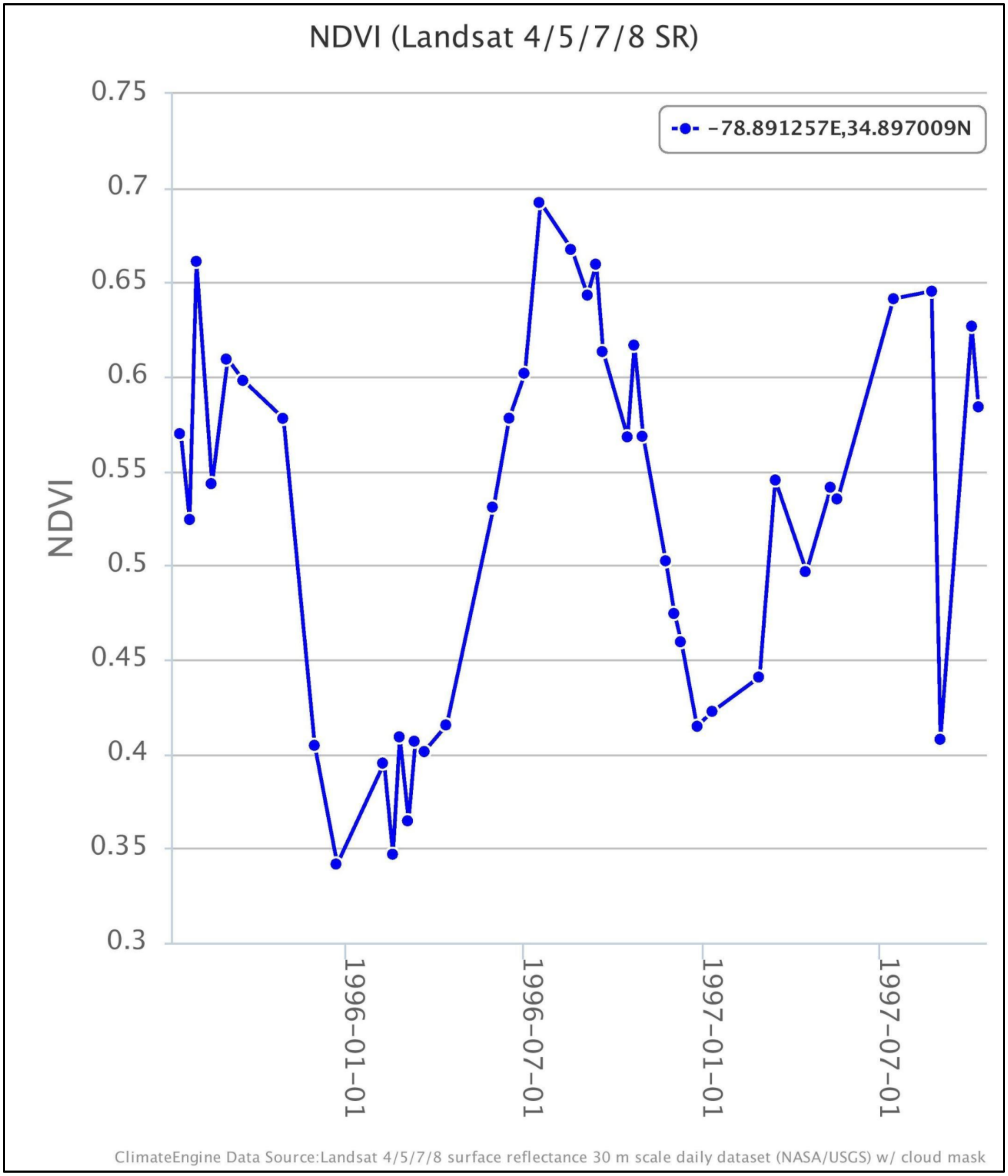


Figure 29: Site 29's NDVI Graph.

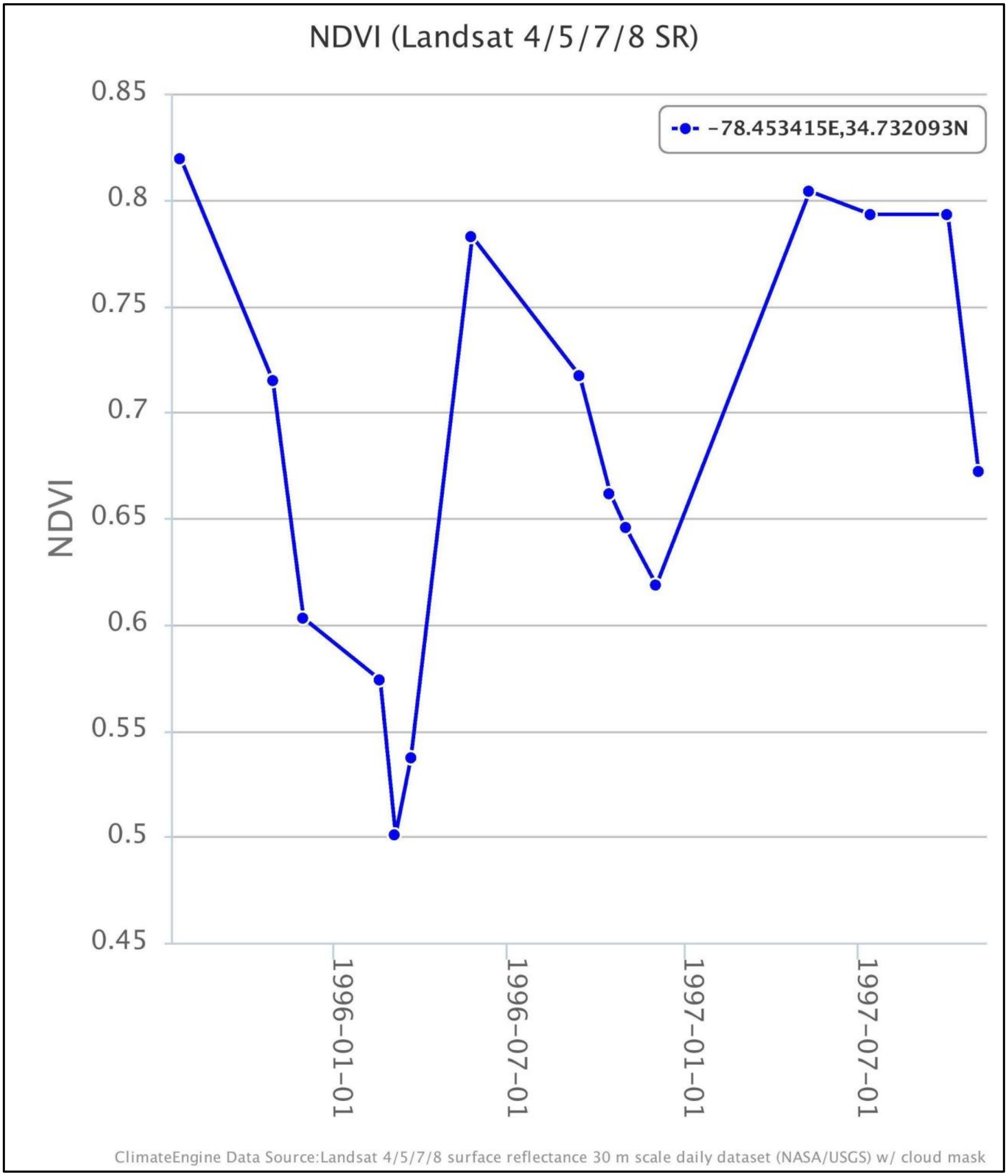


Figure 30: Site 30's NDVI Graph.

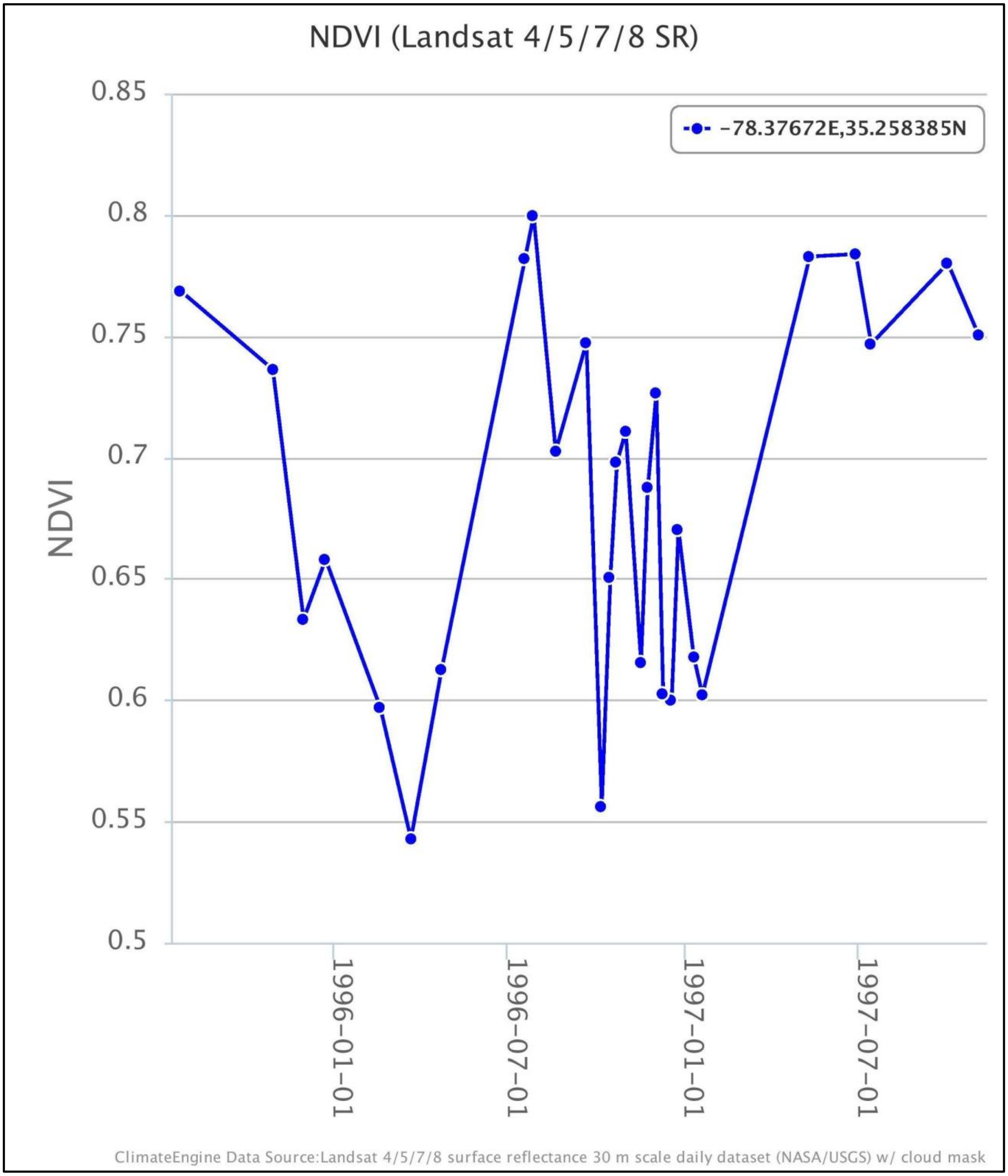


Figure 31: Site 31's NDVI Graph.

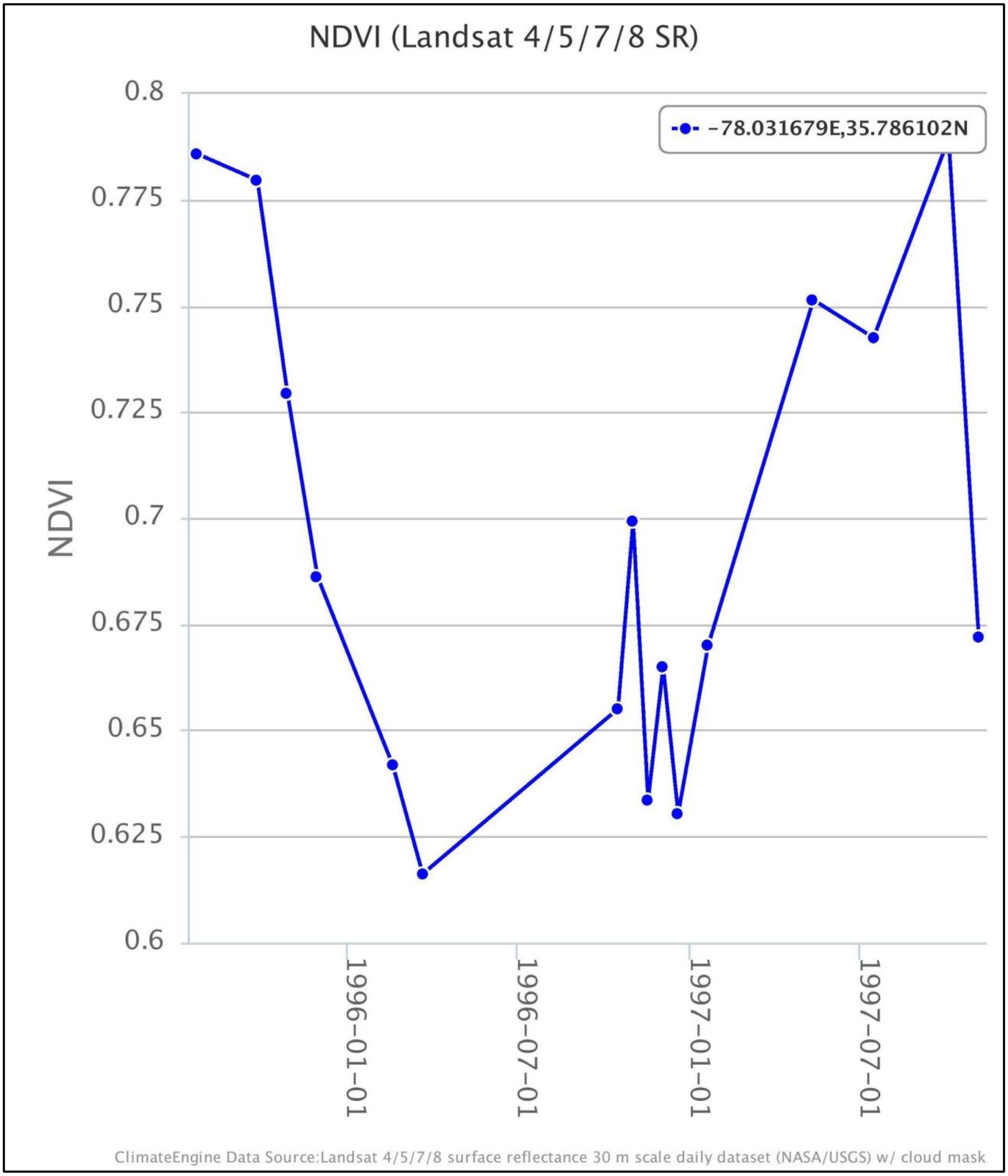
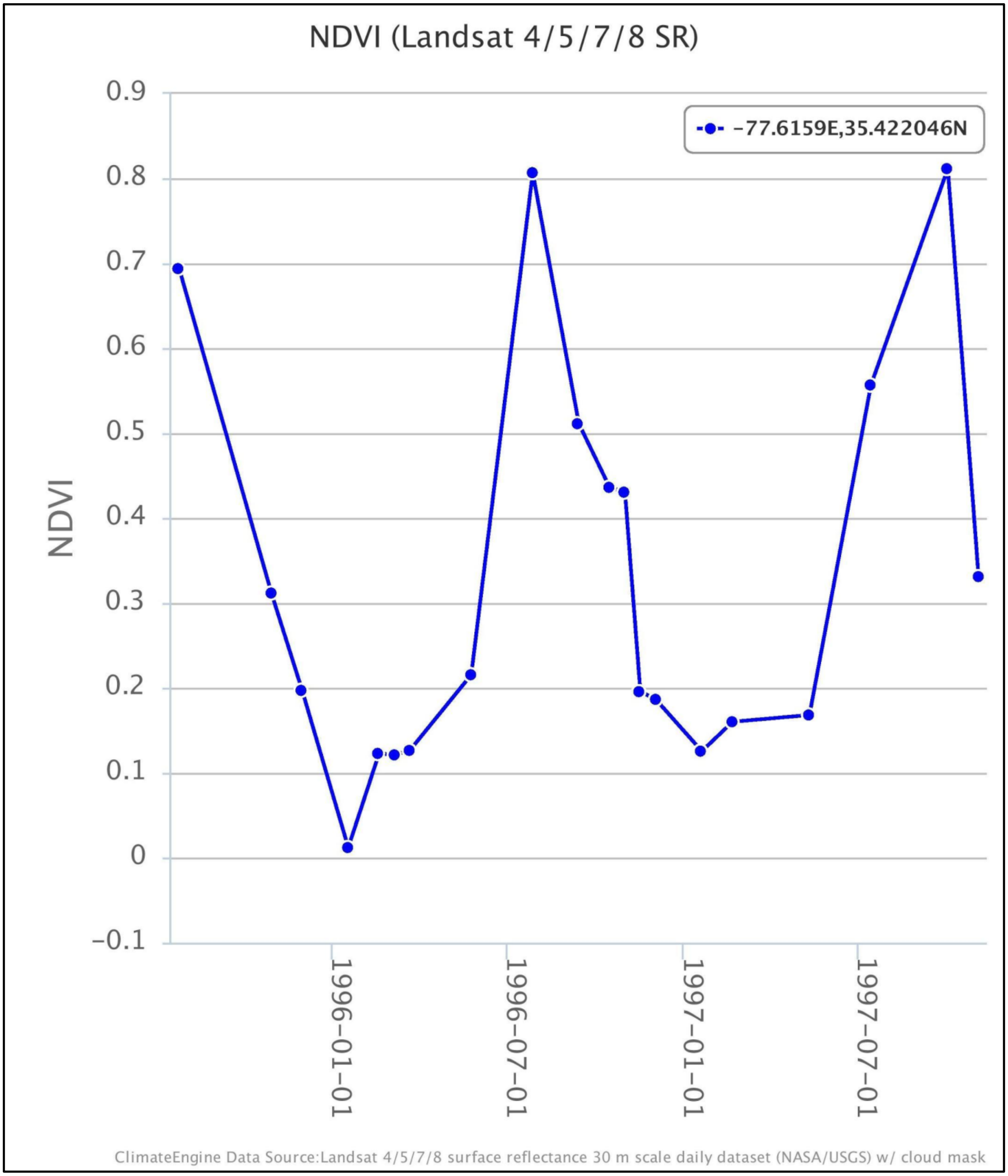


Figure 32: Site 32's NDVI Graph.



Appendix D. Study site tables for each hurricane

Table 19. Hurricane Alberto study site's Information.

Study Site Number	Location Relative to the Hurricane Path	Latitude	Longitude
1	Left, 30 km	78.04145583	35.603645
2	Hurricane Path	78.72466328	35.05632414
3	Right, 30 km	78.63452014	34.78897775
4	Right, 70 km	78.30592858	34.50626369
5	Right 100 km	77.69667761	34.439641

Table 20. Hurricane Andrea (NOAA Storm Number 2013157N25273) Information

Study Site Number	Location Relative to the Hurricane Path	Latitude	Longitude
6	Left, 30 km	79.47419044	34.71897461
7	Hurricane Path	78.75038758	35.06919808
8	Right, 30 km	78.47419044	34.88518086
9	Right, 70 km	78.29771211	34.48733361
10	Right 100 km	77.60520019	34.76834981

Table 21. Hurricane Ana (NOAA Storm Number 2015126N27281) Information

Study Site Number	Location Relative to the Hurricane Path	Latitude	Longitude
11	Left, 30 km	78.70224367	34.96015269
12	Hurricane Path	78.53054175	34.63776081
13	Right, 30 km	78.25330819	34.47487822
14	Right, 70 km	77.69667761	34.439641
15	Right, 100 km	77.28974867	34.66298689

Table 22. Hurricane Beryl (NOAA Storm Number 2012147N30284) Information

Study Site Number	Location Relative to the Hurricane Path	Latitude	Longitude
16	Left, 30 km	78.03874308	34.38447267
17	Hurricane Path	77.98347103	34.11316514

Table 23. Hurricane Ernesto (NOAA Storm Number 2006237N13298) Information

Study Site Number	Location Relative to the Hurricane Path	Latitude	Longitude
18	Left, 30 km	78.31954331	34.55936786
19	Hurricane Path	77.89217756	34.85939894
20	Right, 30 km	77.45295383	35.18133225
21	Right, 70 km	76.77272397	35.78512139
22	Right 100 km	76.44699664	35.77619694

Table 24. Hurricane Hanna (NOAA Storm Number 2008241N19303) Information

Study Site Number	Location Relative to the Hurricane Path	Latitude	Longitude
23	Left, 30 km	78.682166	34.91747786
24	Hurricane Path	78.32670989	34.99881553
25	Right, 30 km	77.92222292	35.20818911
26	Right, 70 km	77.60520019	34.76834981
27	Right, 100 km	77.09840533	35.27193056

Table 25. Hurricane Fran (NOAA Storm Number 1996237N14339) Information

Study Site Number	Location Relative to the Hurricane Path	Latitude	Longitude
28	Left, 30 km	78.891257	34.897009
29	Hurricane Path	78.453415	34.732093
30	Right, 30 km	78.37672	35.258385
31	Right, 70 km	78.031679	35.786102
32	Right, 100 km	77.6159	35.422046