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Data-Driven Assessment of the Impact of Hurricanes Ian and Nicole: Natural and Armored Dunes in the Aftermath of Hurricanes on Florida's Central East Coast

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Abstract: Hurricanes Ian and Nicole caused devastating destruction across Florida in September and November 2022, leaving widespread damage in their wakes. This study focuses on the assessment of barrier islands' shorelines, encompassing natural sand dunes and dune vegetation as well as armored dunes with man-made infrastructure such as seawalls. High-resolution satellite imagery from Planet was used to assess the impacts of these hurricanes on the beach shorelines of Volusia, Flagler, and St. Johns Counties on the Florida Central East Coast. Shorefront vegetation was classified into two classes. Normalized Difference Vegetation Index (NDVI) values were calculated before the hurricanes, one month after Hurricane Ian, one month after Hurricane Nicole, and one-year post landfall. LiDAR (Light Detection and Ranging) was incorporated to calculate vertical changes in the shorelines before and after the hurricanes. The results suggest that natural sand dunes were more resilient as they experienced less impact to vegetation and elevation and more substantial recovery than armored dunes. Moreover, the close timeframe of the storm events suggests a compound effect on the weakened dune systems. This study highlights the importance of understanding natural dune resilience to facilitate future adaptive management efforts because armored dunes may have long-term detrimental effects on hurricane-prone barrier islands.

Keywords: Hurricane Ian; Hurricane Nicole; sand dunes; seawalls; planet; Florida Central East Coast; dune vegetation; NDVI; LiDAR

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1. Introduction

Coastal regions are frequently exposed to the destructive forces of storms, posing significant challenges for maintaining natural and man-made coastal defenses. Two prominent examples of defense infrastructure along beachfront shorelines, sand dunes and seawalls, serve as barriers against the erosive forces of storm surges and high winds [1].

Sand dunes are natural formations comprising loose sand that accumulates through wind and wave action. They act as a dynamic buffer zone between the sea and inland areas, absorbing and dissipating the energy of storm surges and overwash, and lessening the effects of sea-level rise [2,3]. Dune ecosystems harbor an array of plant species adapted to thrive in harsh oceanfront conditions. Deep-rooted plants such as sea oats (*Uniola* *paniculata*) and panic grass (*Panicum amarum*) are known for their ability to anchor sand and stabilize dunes with their stems and leaves, gradually building up dune profiles [4]. The sand accumulation acts as a buffer against storm surges and tidal forces. The extensive network of plant roots reinforces the stability of the substrate, reducing the risk of erosion; the vegetated dunes not only are more resilient to wave-induced erosion, but increase environmental and aesthetic value [5,6]. Dune plants also regulate sand movement, creating microenvironments that facilitate the deposition of sand, which enhances dune growth and stability over time [7].

Seawalls are man-made structures designed to provide a rigid defense against wave action and storm surges. Typically constructed from concrete or other durable materials, seawalls aim to prevent erosion and protect coastal infrastructure. Seawalls are recognized for their ability to provide immediate protection against wave action. These armored structures have been widely employed for several hundred years to protect infrastructure and communities from storm surges and rising sea levels [8]. However, their effectiveness may diminish over time due to factors such as erosion, subsidence, and changing wave dynamics [8,9]. Regardless of a barrier island's first line of defense (natural dune or seawall), a storm surge represents an overwhelming destructive force that can only be mitigated, not prevented.

Coastal dunes face varying impacts from storm events, bringing in large deposits of sand while also causing a range of dune destruction events through inundation, overwash, and scarping [10]. Tropical cyclones exert various pressures on sand dunes, including wind erosion, saltwater inundation, and sediment redistribution. Morton and Barras (2011) documented how the vulnerability of sand dunes to overwash and breach led to inland flooding and ecosystem disruption after the 2005 Hurricane Katrina [11]. Hurricane Irma in 2017 caused both vertical and horizontal erosion of the beach–dunes system of the Virgin Islands [12]. The highly active 2004 and 2005 hurricane seasons on Santa Rosa Island in northwest Florida resulted in large-scale dune erosion, first by Hurricane Ivan and then Hurricane Dennis, allowing little dune recovery time between hurricane events [10]. Seawalls also are susceptible to structural failure under extreme conditions, often induced by uplifting wave action, high winds, the scouring of exposed ground, and even ground failure [13]. Hurricane Sandy in 2012 showcased the potential for seawall damage, leading to breaches and inundation in certain areas [14]. Furthermore, seawalls can have unintended consequences, altering coastal dynamics such as erosion and accretion patterns, impacting sediment transport, and disrupting further dune development [15,16].

With rising global temperatures and subsequent sea-level rise, coastal regions are facing challenges that necessitate adaptive and resilient defense measures to protect and stabilize vulnerable coastlines [17]. Previous studies have found that the intensity of tropical cyclones is likely to increase under a future warming climate [18,19]. Sea-level rise, accompanying the warming, is likely to lead to higher storm inundation levels [20].

When two tropical cyclones make landfall in close succession, the impact might be amplified as the structures weakened by the first storm become more vulnerable to the following storm. Xi et al. [21] found that the chance of sequential tropical cyclone hazards has been increasing over the past few decades at many US locations. Special attention should be given to the increased frequency and intensity of extreme weather events, such as successive hurricanes, and their compounding effects on coastal vulnerabilities, as the diminishing time of recovery and intensifying storm hazards increase associated risk assessments [22].

From late September to November 2022, two hurricanes, Hurricane Ian and Hurricane Nicole, impacted the state of Florida (Figure 1). On 28 September 2022, Hurricane Ian made landfall in southwestern Florida, with an estimated intensity of 125 kt. As Ian moved northeastward across the Florida peninsula late that day and overnight, the cyclone steadily weakened, becoming a tropical storm with maximum sustained winds of 60 kt by 1200 UTC on 29 September, just as it moved back over the Atlantic waters near Cape Canaveral, Florida. Hurricane Ian caused maximum inundation levels of 1 to 1.2 m above ground-level to occur along the northeast coast of Florida, from Volusia County to the Florida–Georgia border [23].

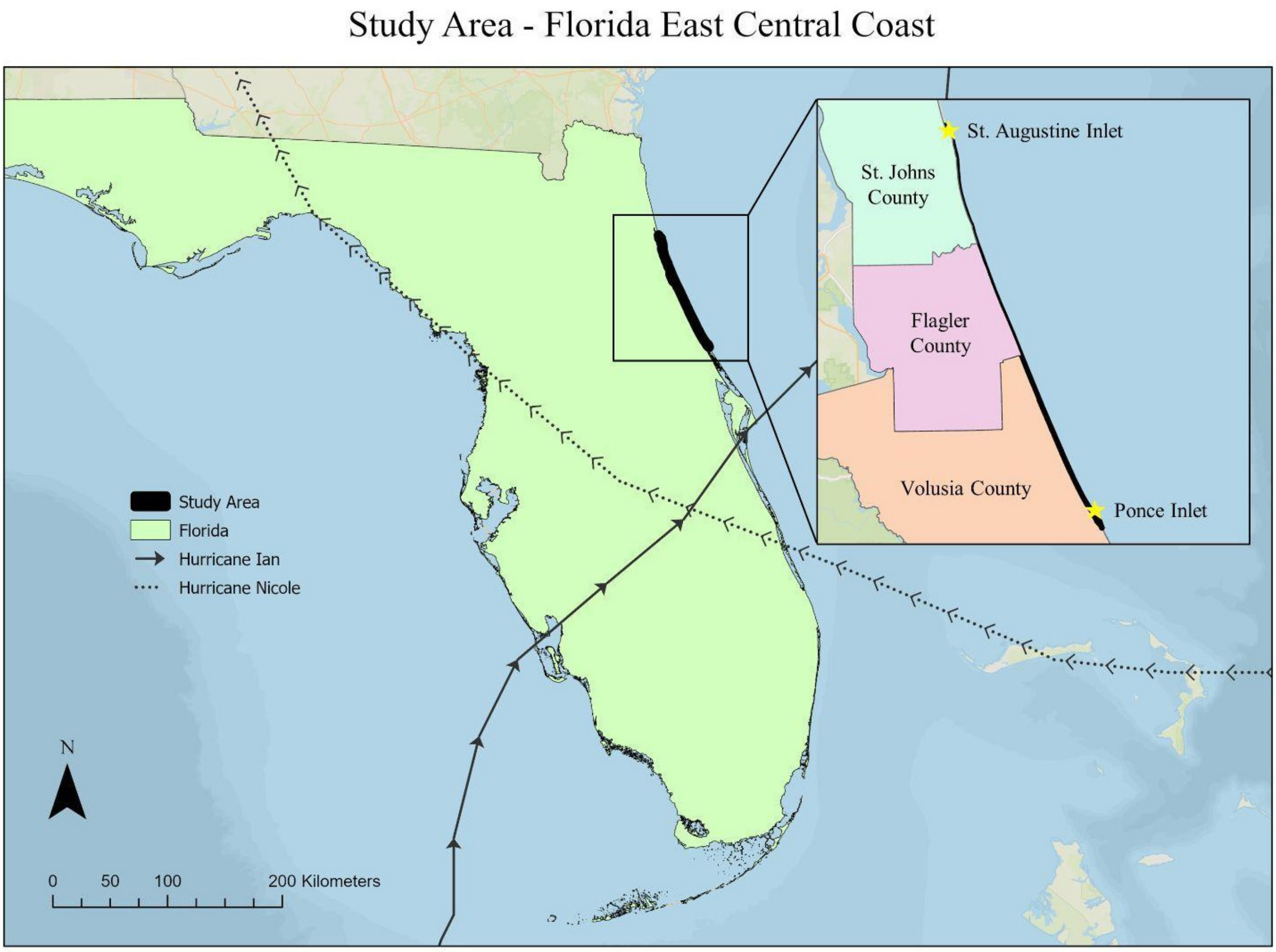

Figure 1. Map of the study area along the Florida East Central Coast with paths from Hurricanes Ian and Nicole. The inset map displays the extent of the region of interest (ROI) used in this study, a narrow and long stretch of the oceanfront coastlines between Ponce Inlet Beach from Ponce Inlet in Volusia County and St. Augustine Inlet in St. Johns County (inlets designated by yellow stars).

Hurricane Nicole originated as a subtropical storm east of the Bahamas, gradually intensifying into a tropical storm and making landfall on Florida's east coast with an estimated intensity of 65 kt at Vero Beach on 10 November 2022 [24]. Despite reaching Category 1 hurricane intensity and subsequent reduction back to a tropical storm after landfall in Vero Beach, Nicole's large size and slow development led to a substantial wind field across the Atlantic coast. This resulted in offshore wave heights exceeding 9 m and localized inundation levels of up to 2 m, causing severe beach and dune erosion [24,25]. The beach erosion along the east coast, caused by Ian in late September, likely left the area more vulnerable to storm surge from Nicole.

In particular, Volusia County faced severe erosion following the back-to-back strikes of Hurricanes Ian and Nicole, occurring six weeks apart. A damage assessment conducted by the Volusia County Property Appraiser's Office estimated the total to be approximately USD 500 million. Dozens of beachfront condominiums, hotels, and single-family homes were declared unsafe after Hurricane Nicole, with many already damaged by Hurricane Ian [25]. The changing coastal dynamics, particularly the scarping observed at higher elevations, reflect the significant alterations in the landscape due to the consecutive hurricanes (Figure 2).

Figure 2. Photos of some of the severe instances of dune erosion and property destruction in the study area. The photos were taken shortly after Hurricane Nicole on 11 November 2022, in the Wilbur-by-the-Sea area (near Ponce Inlet) at approximately 29.126N, 80.954W (courtesy of Daniel Burow).

This study describes the impact of Hurricanes Ian and Nicole in 2022 on coastal defense structures, specifically natural sand dunes, dune vegetation, and armored dunes (i.e., dunes in front of seawalls) along Florida's Central East Coast using high-resolution optical satellite data, LiDAR (Light Detection and Ranging), and aerial imagery. The study location encompasses the barrier island's oceanfront shores of the Florida Central East Coast, including dunes, vegetation, and man-made seawalls situated between Ponce Inlet and St. Augustine Inlet (Figure 1).

This study was conducted to gain insight into the overall resilience of coastal infrastructure, considering both natural and engineered components. Taking this hybridized approach for natural and built infrastructure into account will likely improve protective measures against extreme weather events and coastal flooding while ameliorating environmental drawbacks that arise from using solely engineered components [26]. The findings from this study have the potential to inform local strategies for coastal resilience and preparedness in the face of increasingly intense hurricane events.

2. Materials and Methods

2.1. Study Area and Vegetation Identification

The study location was a narrow stretch of the oceanfront coastlines east of Florida State Road A1A between the St. Augustine Inlet, St. Augustine Beach (29.9102; −81.2895) and Ponce de Leon Inlet, Ponce Inlet Beach (29.0964; 80.9370) (Figure 1).

Google Earth (10.45.0.3 @2023 Google LLC) images were used to collect and digitize the point data within the ROI (region of interest) extent for dune types (natural vs. armored) and vegetation categories (sparse forbs on sandy beach, primary vegetation on foredunes, and secondary vegetation on the top and behind foredunes). The Google Earth imagery was from November 2014 to February 2023. Only woody hammocks, coastal scrubs, and herbs/forbs were the prominent vegetation because the study area predominantly covered the oceanfront dunes and properties. At least 100 points were collected for each class.

2.2. Planet Data

PlanetScope imagery with <5% cloud cover was downloaded from the Planet imagery hub (https://www.planet.com/, accessed on 16 January 2024). These scenes were orthorectified and atmospherically corrected by Planet and represented surface reflectance during five different time periods to detail conditions before and after Hurricanes Ian and Nicole (Table 1). This imagery had eight bands, ranging from coastal blue to near-infrared (NIR).

Table 1. Dates of Planet imagery used for each time period.

Date(s)	Description
3 December 2021	Dry season; 9–11 months before hurricanes
28 March 2022	6–8 months before hurricanes
2, 6, and 7 October 2022	After Ian and before Nicole
1, 4, and 6 December 2022	Dry season; shortly after hurricanes
1 December 2023	Dry season; 13–15 months after hurricanes

The early December 2022 Planet data represent immediate impact and conditions shortly after hurricanes. December 2021 and 2023 were included to represent one year prior and post hurricane events, respectively. This study also incorporated images from March and October 2022 to depict the conditions six months before Hurricane Ian and in between the two hurricanes. Cloud-free imagery encompassing the entire study region on a single date was not available for October 2022 and December 2022; thus, composite images were created by combining imagery from no more than five days apart. Reflectance values from overlapping pixels in these composites were averaged. Normalized Difference Vegetation Index (NDVI) values were calculated using the red and the NIR bands for each of the five study periods. NDVI difference images were then created from four pairs of dates: NDVI Diff (December 22–December 21), NDVI Diff (December 23–December 22), NDVI Diff (October 22–March 22), and NDVI Diff (December 22–October 22) (Table 2).

Table 2. Descriptions of NDVI difference images.

NDVI Difference Images	Vegetation Change Description
December 2022–December 2021	Before and after the hurricanes with seasonality-held constant
December 2023–December 2022	Year after hurricanes with seasonality-held constant
October 2022–March 2022	After Hurricane Ian
December 2022–October 2022	After Hurricane Ian and from Hurricane Nicole

The Planet imagery had a spatial resolution of 3 m and the study area was 32.7 km^2. As a result, each time period contained approximately 3.63×10^6 pixels across the study area. Each pixel contained nine attributes: NDVI values from the five different time periods are presented in Table 1, and NDVI difference values are listed in Table 2. To examine common trends in NDVI across the study region, an Iso Cluster and maximum likelihood unsupervised classification [27,28] was performed in ArcGIS Pro, using the five NDVI and four NDVI difference values of each pixel as inputs. Eight clusters were initially defined to represent eight temporal trends in vegetation from December 2021 to December 2023 within the study area. Of these eight clusters, two pairs exhibited similar NDVI values before and after the hurricanes—one pair with NDVI values between 0.10 and 0.25, indicating minimal vegetation, and another pair with NDVI values above 0.6, indicating dense vegetation. These pairs were combined with each other, leaving six remaining clusters.

Finally, the most common land cover type in each of these clusters was estimated using data from the National Land Cover Database (NLCD) 2021 classification (https://www.mrlc.gov, accessed on 16 January 2024). It is important to consider that NLCD land cover has a spatial resolution of 30 m, which is 100 times coarser than the 3 m resolution of the Planet imagery. This can cause mixed pixel problems where the true land cover is not perfectly represented in any given pixel.

2.3. LiDAR Data

Airborne LiDAR digital elevation models (DEMs) were used to assess natural dune and armored dune (seawall behind dune) damages. LiDAR data from 2018 (pre-storm) and November 2022 (after hurricanes) were obtained. The pre-storm LiDAR DEM was the FL Peninsular 2018 LiDAR Project—Volusia County, conducted by Dewberry for the U.S. Geological Survey, collected between December 4, 2018, and March 22, 2019 [29]. The post-storm LiDAR DEM was the 2022 U.S. Army Corps of Engineers (USACE) Federal Emergency Management Agency (FEMA) Post Nicole Topobathy LiDAR DEM: Florida [30], and was retrieved from NOAA Digital Coast (https://coast.noaa.gov/dataviewer/#/, accessed on 1 March 2024). Both DEMs had a 1 m horizontal ground resolution and referenced the NAVD88 vertical datum. The 2018 data represent dune/seawall elevation pre-hurricane events; the 2022 data show the immediate impact on the dunes. The DEMs were clipped to this study's ROI and contained sufficient deformation information across the study area (Figure 3).

A noticeable instance of elevation change is evident along the coastline in all three areas shown in Figure 3. The starker contrast (light to dark) of the beach in the DEM shown in the bottom row (blue) compared to the top row (green) indicates erosion resulting in steep topographic relief, commonly referred to as scarping.

2.4. LiDAR Data with NDVI

The NDVI images were coupled with the change in topographic height derived from LiDAR data to monitor the condition of dunes and man-made structures. To compare natural dunes (Figure 4) and armored dunes (i.e., dunes behind seawalls; Figure 5) for their changes in vegetation and elevation during the study period, eighty sample points were selected within the ROI for each of the following three categories: secondary vegetation (dominated by woody vegetation on the tops and backside of foredune), edges of primary vegetation (forbs and herbs on the lower parts of foredune), and sand in front of the foredune (Figures 4 and 5). Figures 4 and 5 show examples of each category for natural and armored dunes. Natural dunes are composed of sand and vegetation and lack man-made structures such as concrete, rocks, or wood, which are found on armored dunes. The categories and classes of the sample points were labeled using satellite ArcGIS Pro 3.0 World Imagery from February 2024.

The five Planet NDVI and two LiDAR datasets were then extracted to these points and analyzed using the means of each category. T-tests were performed to analyze changes in NDVI and elevation over time for the two types of dunes (natural and armored dunes) and three corresponding sample categories. A diagram flowchart summarizing these methods is shown in Figure 6.

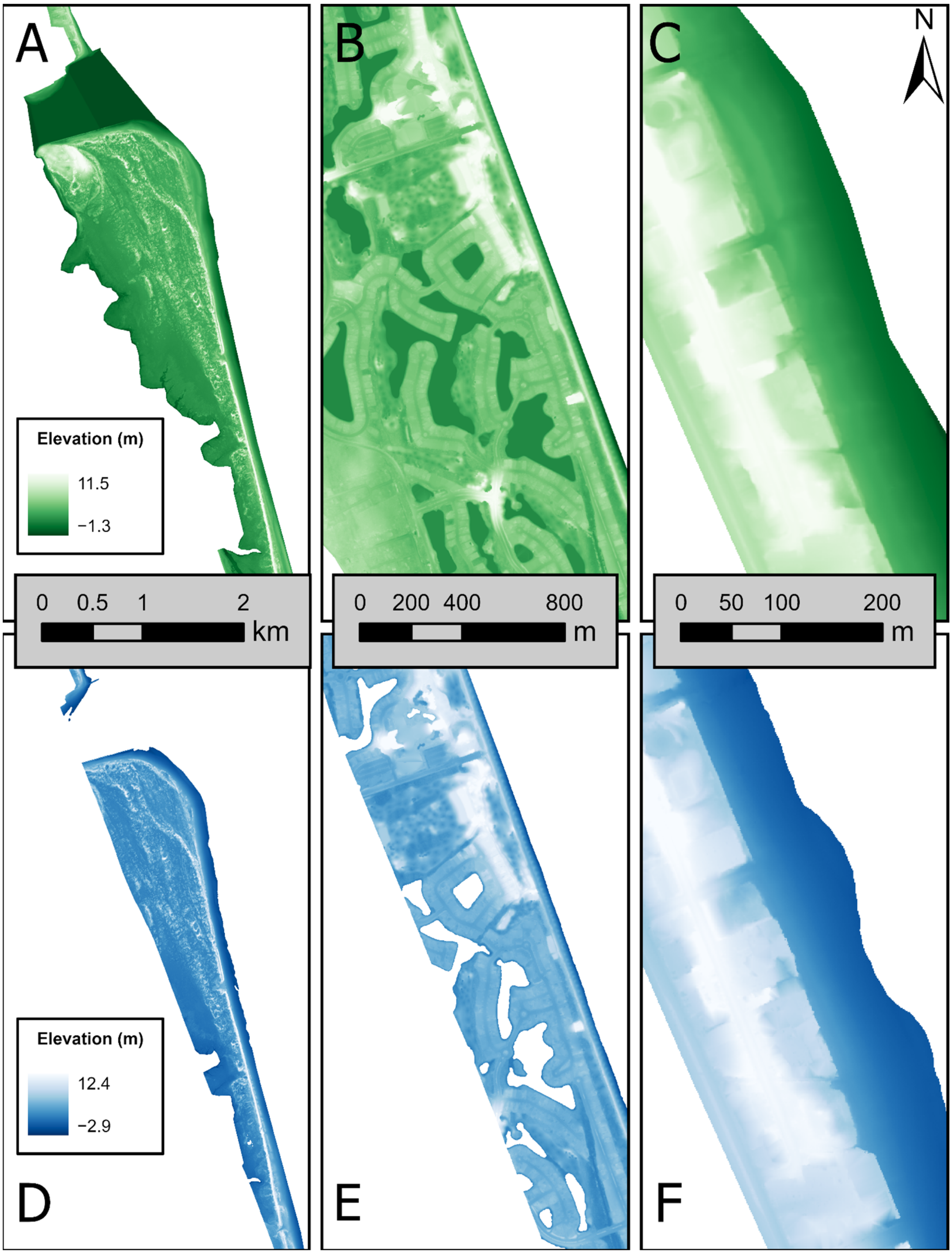

Figure 3. Pre (**top**) and Post (**bottom**) lidar digital elevation models for select locations in the region of interest. (**A**,**D**) St. Augustine Inlet (undeveloped); (**B**,**E**) Ocean Hammock Golf Course (developed with open space); and (**C**,**F**) south of Daytona Beach Main Street Pier (high-intensity development).

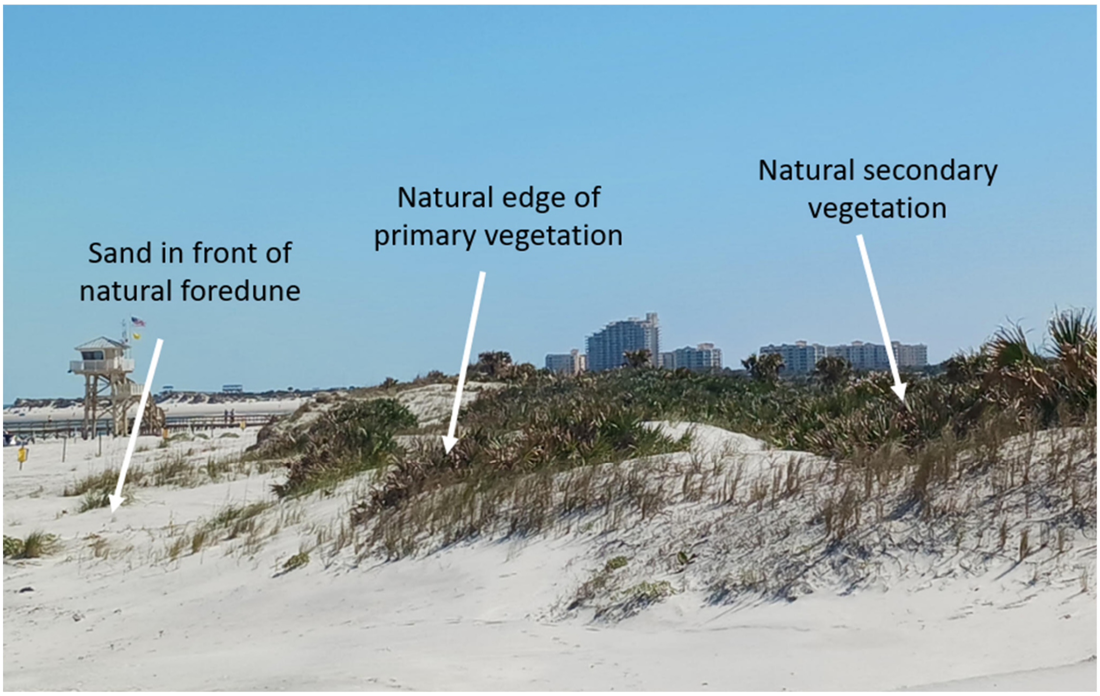

Figure 4. Example of a natural dune with three categories (secondary vegetation, edge of primary vegetation, and sand in front of natural foredune). The photo was taken on 26 February 2024, on Ponce Inlet Beach (courtesy of Kelly San Antonio).

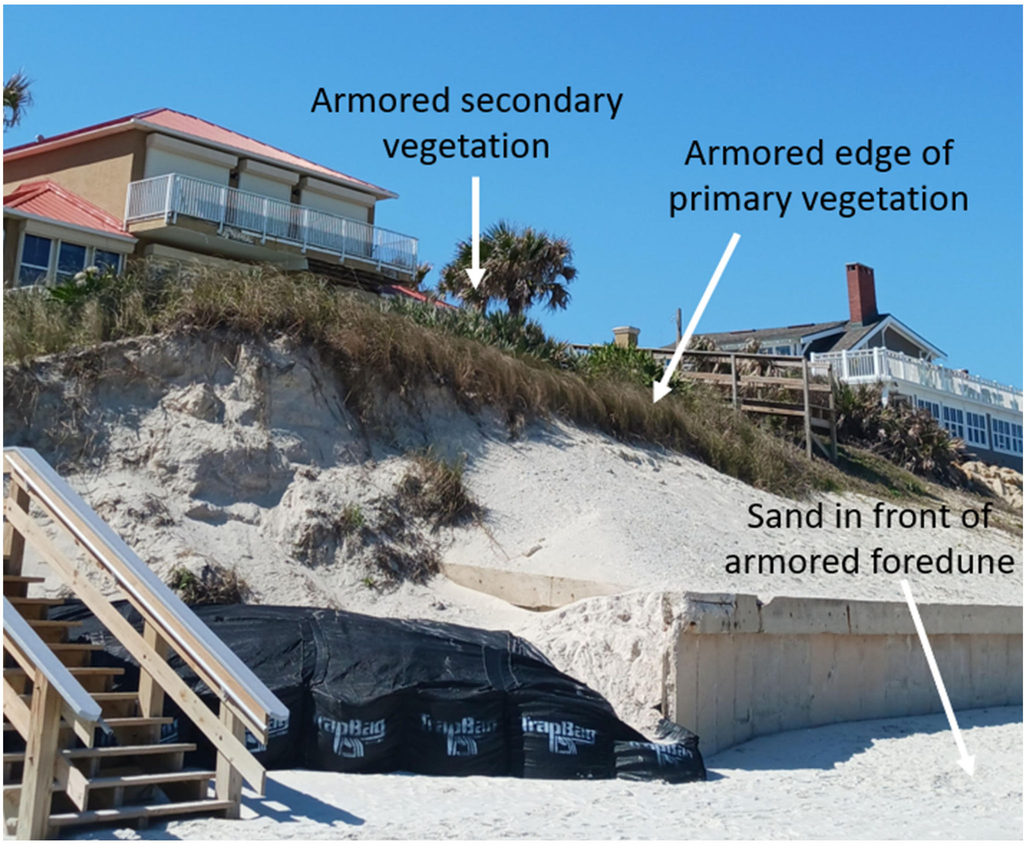

Figure 5. Example of an armored dune with three categories (secondary vegetation, edge of primary vegetation, and sand in front of armored foredune). The photo was taken on 26 February 2024, near Toronita Avenue Beach Park (courtesy of Kelly San Antonio).

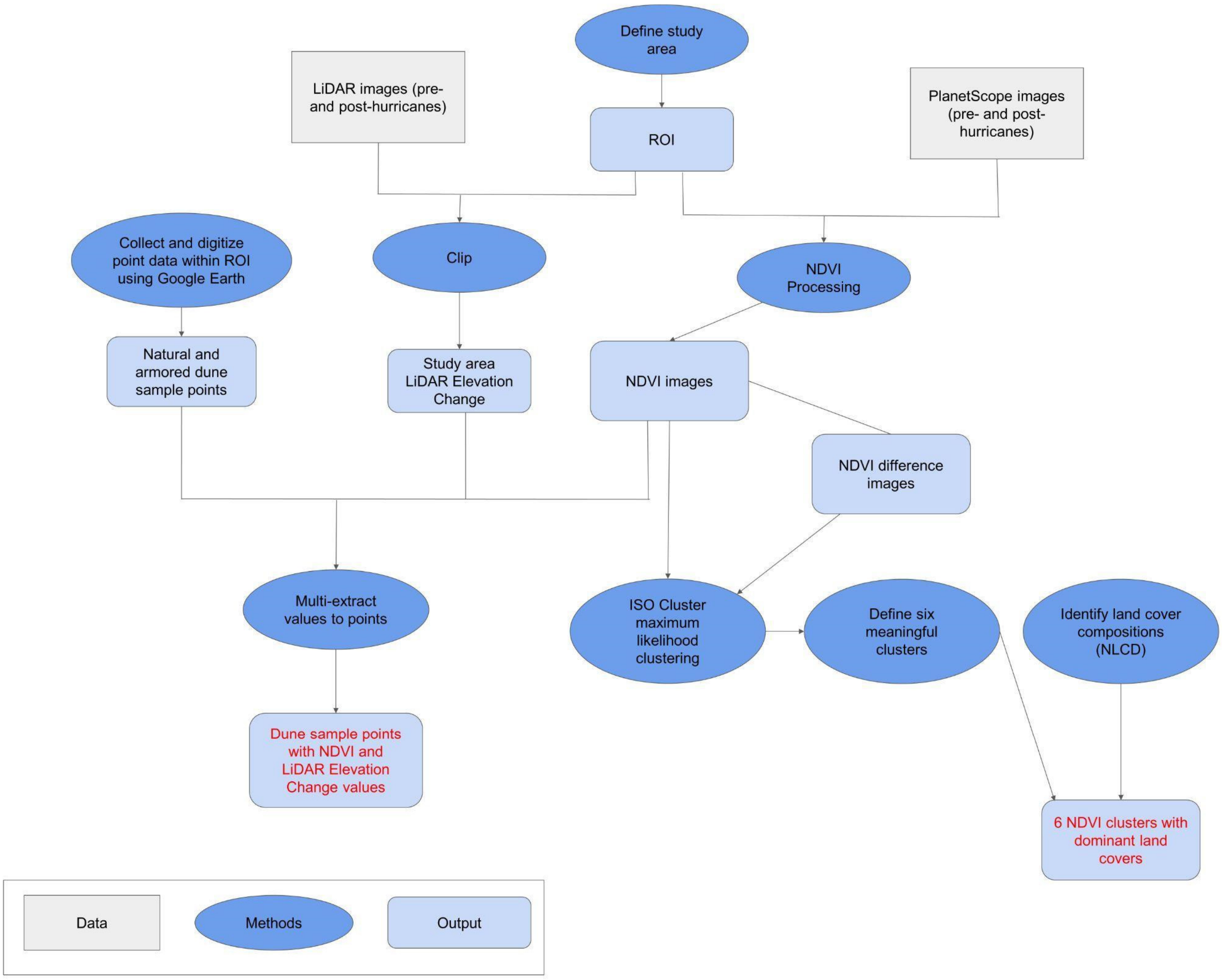

Figure 6. Workflow diagram of data and methods.

3. Results

3.1. NDVI Analysis

The six clusters derived from temporal patterns in NDVIs from December 2021 to December 2023 are shown in Table 3 and Figures 7 and 8. Clusters are ordered numerically from unvegetated (Cluster 1) to heavily vegetated (Cluster 6). Table 3 also shows the land cover composition from NLCD 2021.

Table 3. Geographic characteristics of the six clusters derived from temporal patterns in NDVIs from December 2021 to December 2023.

Cluster	Mean Pre-Storm NDVI December 21 and March 22	Mean ΔNDVI October 22 to December 22	% of Study Area	Most Common NLCD Class	Vegetation
1	−0.03	−0.01	6.12	Water	None
2	0.16	−0.03	33.29	Barren (sand)	Barren
3	0.34	−0.03	14.78	Developed, Medium	Sparse
4	0.45	−0.14	5.31	Developed, Medium	Damaged, possibly from hurricanes
5	0.48	−0.04	11.56	Developed, Medium	Moderate
6	0.68	−0.05	28.93	Evergreen forest	Dense

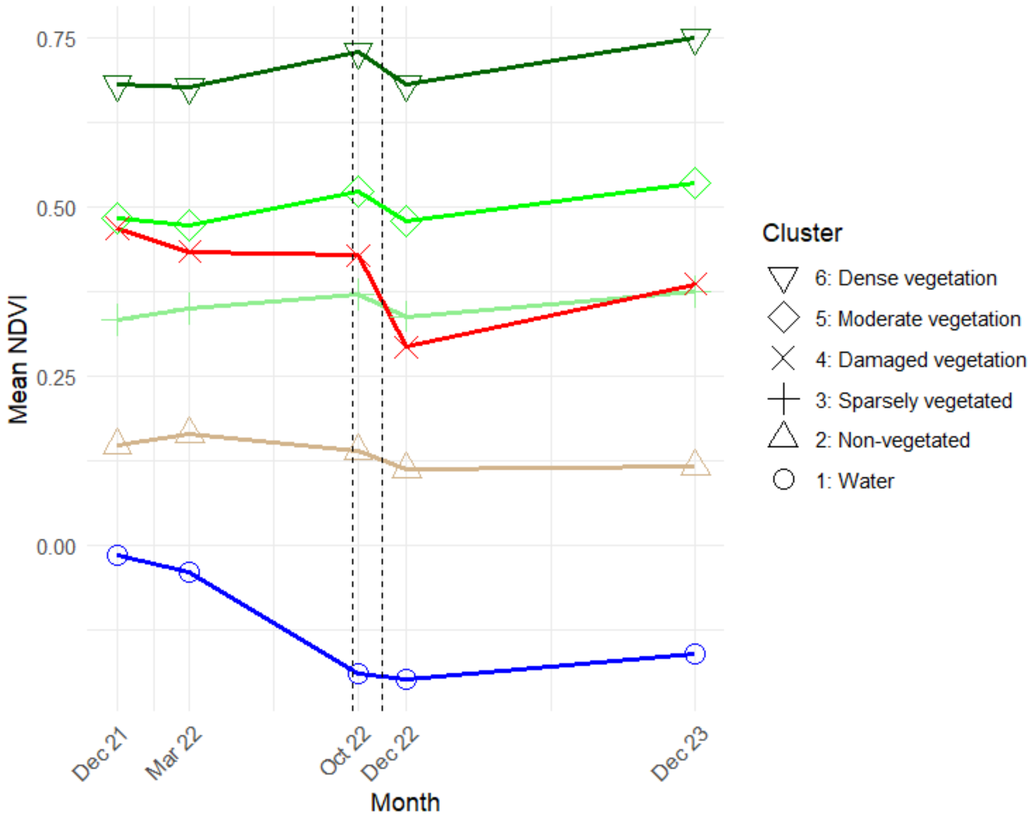

Figure 7. NDVI trends for each of the six clusters. The timing of the hurricanes is indicated by the vertical dashed lines.

These six clusters can be interpreted based on their NDVI values throughout the study period (Figure 7). Cluster 1, which is mostly water, exhibits negative NDVI values across the study period. Cluster 2 exhibits positive but low NDVI values, with little trend during the study period, suggesting non-vegetated land covers such as sand and impervious surfaces. Cluster 3 exhibits mean NDVI values near or slightly above 0.3, with little trend during the hurricanes, indicating sparse vegetation. Cluster 4 (red Xs in Figure 7), has mean NDVI values above 0.4 before the hurricane, but exhibits a substantial decrease in mean NDVI of about 0.13 between October and December 2022, unlike the rest of the clusters. These NDVI values recover somewhat by December 2023, although not quite to their pre-hurricane values. Clusters 5 and 6 are more heavily vegetated and show the highest NDVI values during every step of the study period. They show slight drops in NDVI of about 0.04 between October and December 2022 (Figure 7), but rebound completely during 2023. The relative locations of points assigned to each cluster can be seen in Figure 8, which shows three regions of interest within our larger study area. Cluster 2 pixels (tan triangles in Figure 8), which are largely non-vegetated, are located along the beachfront and in developed areas. Pixels in Cluster 3 (light green crosses in Figure 8) tend to be located near the beach as well. Pixels in Cluster 4 (red Xs), which exhibited the greatest decreases in NDVI coincident with the 2022 hurricanes, are largely along the beachfront, suggesting dune-top vegetation that was eroded away. However, some Cluster 4 pixels are located farther inland, particularly around Washington Oaks State Park. This could be indicative of non-surge damage (i.e., wind), or vegetation loss could be from non-meteorological factors altogether, such as building construction. Clusters 5 and 6 (medium and dark green, respectively) exhibit denser vegetation and are largely on the inland side of the study area.

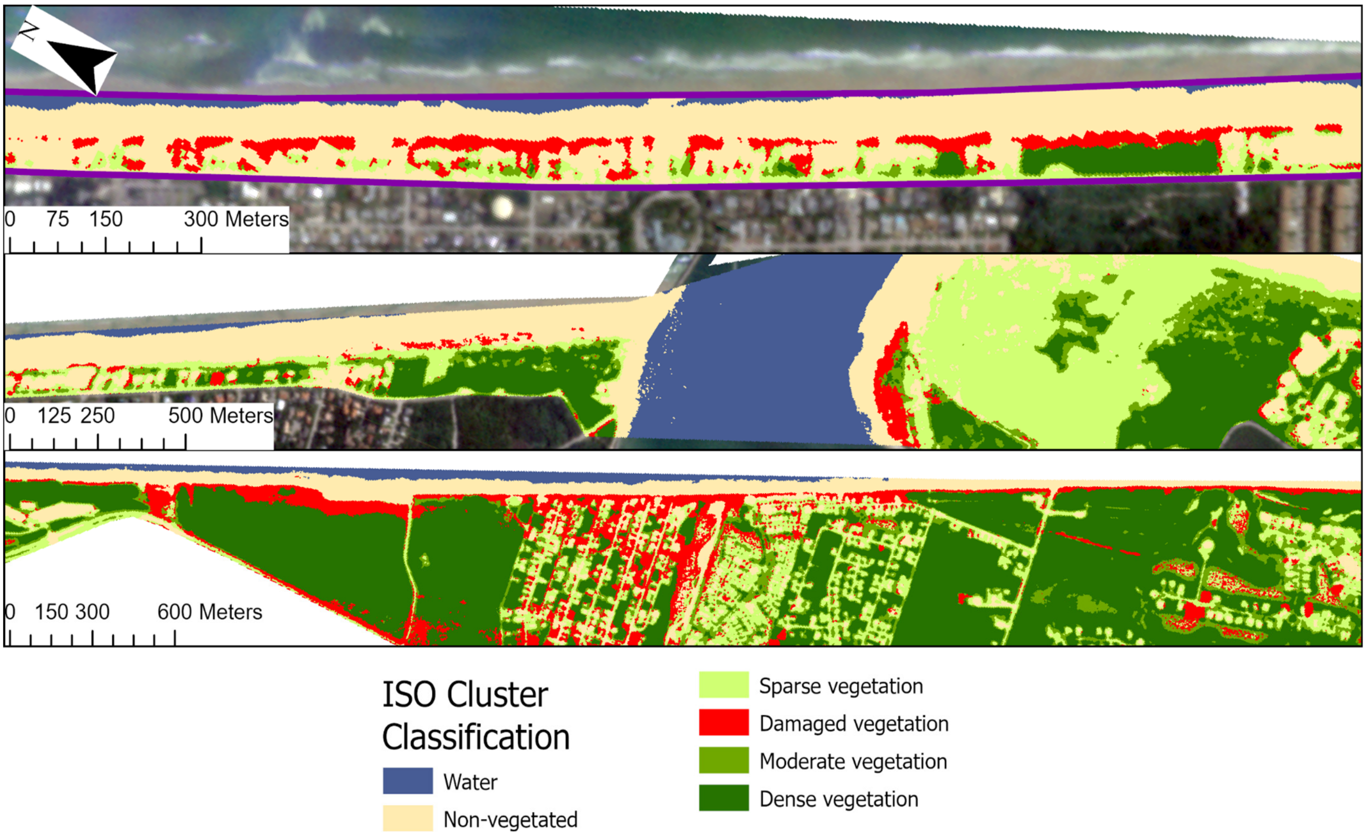

Figure 8. Cluster classifications of pixels in three regions of interest in the study area: Wilbur Beach (**top**), Ponce Inlet (**middle**), and the Washington Oaks State Park region near Palm Coast (**bottom**). Background Planet imagery obtained in December 2021.

3.2. Impact on Natural vs. Armored Dunes Using LiDAR and NDVI

Table 4 and Figures 9 and 10 show temporal trends for NDVI and LiDAR along dune gradients (from the dune's secondary vegetation to the edge of the primary vegetation to the sand in front of the foredunes). Dunes and dune vegetation appeared not to be reduced after Hurricane Ian, except for the armored edges (forbs on the lower front of foredunes), evidenced by the NDVI values from March to October 2022 (Figure 9). All dune vegetation was significantly (p < 0.05) reduced after Hurricane Nicole, as seen in the NDVI values of December 2022 in Figure 9. The vegetation reduction in December 2022 from December 2021 was substantially higher at armored dunes compared to the natural dunes (Table 4 and Figure 9). Secondary vegetation (woody vegetation on tops and back of foredunes) on natural dunes largely recovered a year later (to 95% of the mean 2021 NDVI), while the counterpart in the armored dunes only regained vegetation up to less than 60% of the mean 2021 NDVI (Table 4 and Figure 9). The edges of primary vegetation exhibited similar changes in NDVI values over time between natural and armored dunes. The edges of both dunes were almost identical in the initial December 2021 NDVI (Figure 9). However, armored edges experienced decreases in NDVI by October 2022 (after Hurricane Ian) and again after Hurricane Nicole in December 2022, and less recovery by December 2023 than the natural dunes. With more intense loss and less recovery, vegetated edges of armored dunes experienced double the reduction in NDVI compared with vegetated edges of natural dunes between December 2021 and December 2023 (Table 4). Sand in front of armored and natural foredunes had similar patterns with NDVI over time, but there was a further loss of vegetation in 2023 on armored sand.

Table 4. Percent change in mean NDVI and elevation over time at selected points of three categories (secondary vegetation, edge of primary vegetation, and sand) along natural and armored shorelines (* denotes a statistical significance of $p < 0.05$ from t-tests). Eighty sample points were selected for each of the following categories.

Dune Type		**% Change Over Time**			
		NDVI			**Elevation**
		December 2021–December 2022	**December 2022–December 2023**	**December 2021–December 2023**	**October 2018–December 2022**
Secondary Vegetation	Natural Dune	−14.29 *	10.42 *	−5.36 *	−3.65
	Armored Dune	−46.34 *	9.09 *	−41.46 *	−23.67 *
Edge of Primary Vegetation	Natural Dune	−38.71 *	21.05 *	−25.81 *	−10.71 *
	Armored Dune	−56.25 *	14.29 *	−50 *	−31.56 *
Sand	Natural Dune	−26.67 *	9.09 *	−20 *	−9.40 *
	Armored Dune	−33.33 *	−10 *	−40 *	−40.85 *

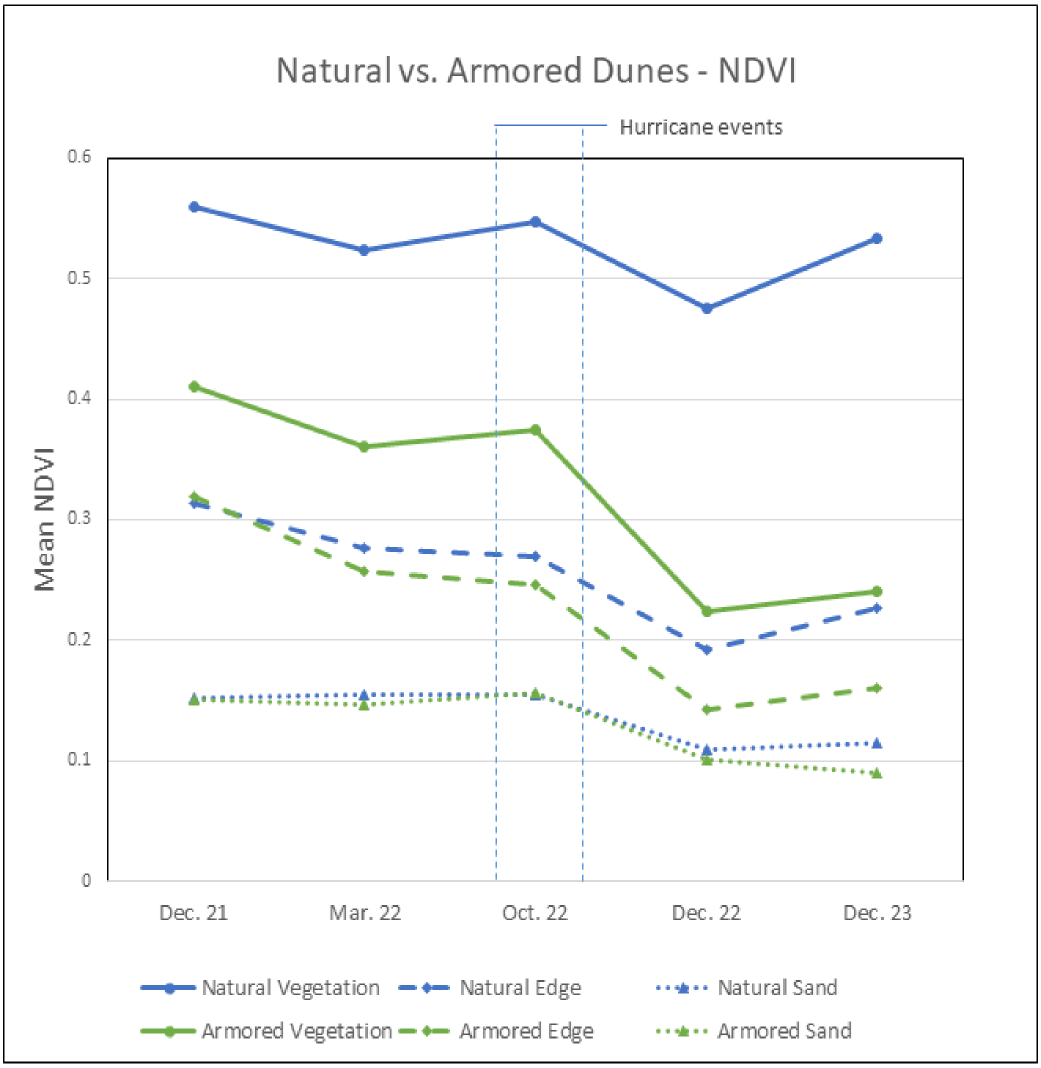

Figure 9. Mean NDVI from selected points of secondary vegetation (vegetation), edge of primary vegetation (edge), and sand, comparing natural vs. armored dunes. Eighty sample points were selected for each of the categories.

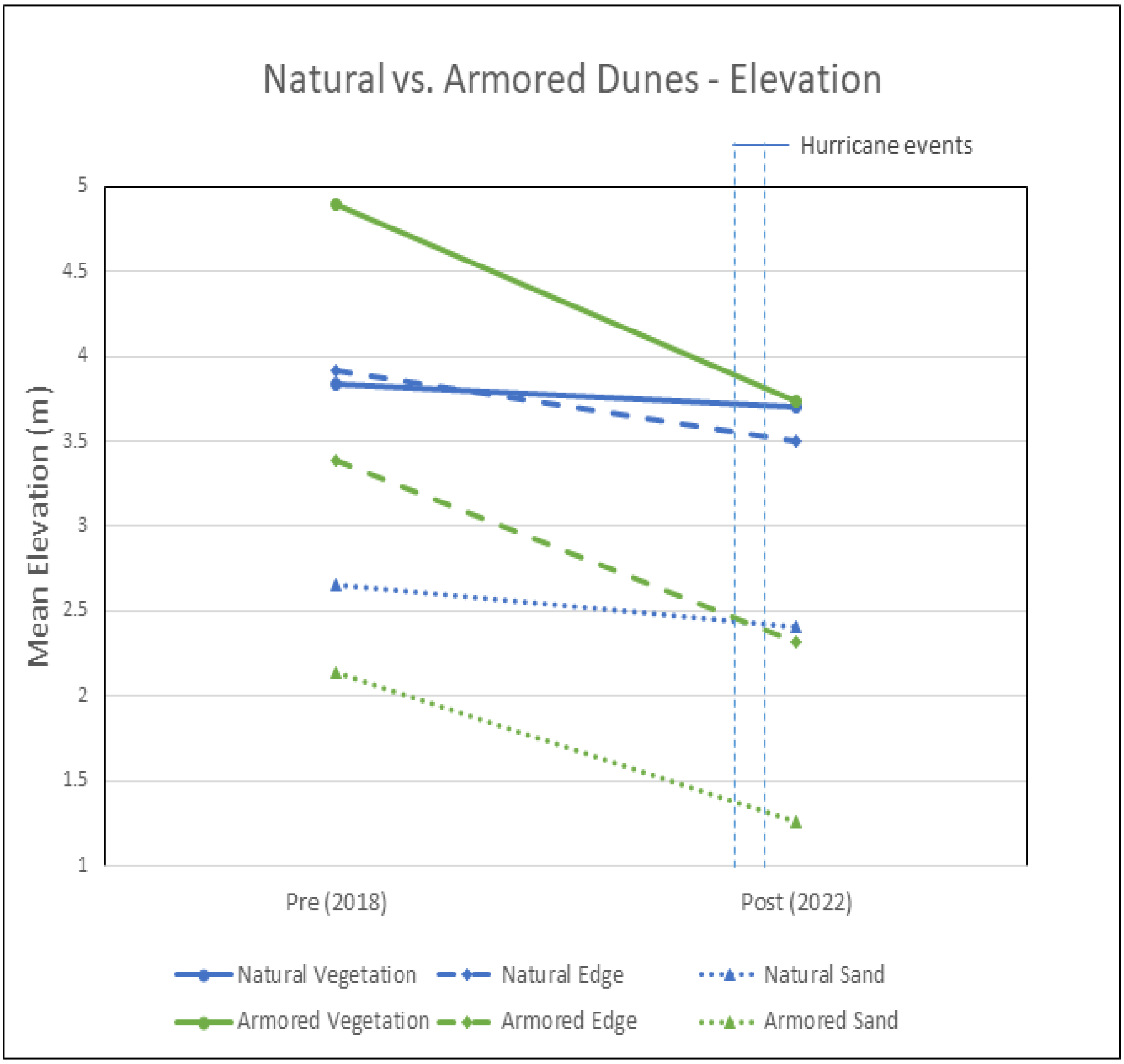

Figure 10. Mean elevation (m) from selected points of secondary vegetation (vegetation), edge of primary vegetation (edge), and sand, comparing natural vs. armored dunes. Eighty sample points were selected for each of the categories.

Compared to the levels in 2018, the post-hurricane elevation was significantly reduced at all dune types except for the secondary vegetation (Table 4). Overall, armored dunes experienced larger reductions in elevation in all categories than natural dunes, which underwent subtler changes (Figure 10 and Table 4). While secondary vegetation of armored dunes had higher initial elevation than the natural dune counterpart, elevation immediately post storm events was fairly identical. The edges of primary vegetation for natural and armored dunes exhibited parallel responses, yet the decrease in elevation by 2022 for this category of armored dunes was three times larger than the vegetated edges of natural dunes (Table 4). Similarly, the elevation of sand in front of armored foredunes diminished four times more than sand in front of natural foredunes after the hurricane events (Figure 10 and Table 4).

4. Discussion

Barrier islands serve as primary buffers against wind and wave action; as a result, dune morphology and vegetation on the barrier islands are repeatedly and dynamically modified by winds and waves [3,31]. Moreover, hurricane events have the capacity to dramatically alter dune composition through three major processes: inundation, overwash, and scarping [10]. The results of this study demonstrate that the dune elevations at both natural and armored shorelines were significantly reduced after the consecutive 2022 hurricanes when compared to the 2018 elevations (Table 4; Figure 10). There was no notable storm-driven dune erosion or shoreline destruction in this area between 2018 and prior to the hurricanes in 2022; however, this latency and lack of LiDAR data immediately before the storm is a limitation of this study, and one that is common in coastal research. The barrier island vegetation, particularly the foredune vegetation, was also significantly reduced after the hurricanes (Table 4; Figures 7 and 9). Changes in NDVI during the study period were not likely impacted by extreme conditions such as drought or excessive rain, as yearly precipitation values for Volusia and Flagler counties between 2021 and 2023 were fairly similar (1.8–2.1 m, https://data.statesmanjournal.com/weather-data/flagler-county-florida/12035/1948-02-01/table accessed on 24 February 2024).

The temporal changes in NDVI and LiDAR-derived elevations from before, in between, and after the two hurricanes suggested that the natural dunes had a higher resilience to storm events compared to the armored dunes (Table 4; Figures 7–9). Vegetation loss on the edges of foredunes was more prominent along the armored dunes than the natural dunes; likewise, this vegetation recovery was also smaller along the armored dunes (Table 4; Figure 9). While the armored dunes had a higher mean elevation than the natural dunes prior to the hurricanes, erosion was substantially greater at the armored dunes (Figure 10). Dune erosion, evidenced by the elevation changes after the hurricanes (Figure 10), with complete loss of dunes at many armored locations (Figure 2), made these dunes less suitable or unsuitable for the natural recovery of vegetation and sand accumulation.

Coastal dune habitats, in natural conditions, extend from the foredune to interdune and backdune zones, with each zone exhibiting distinct vegetation patterns shaped by plant succession, exposure, disturbance, and resource availability [32]. Major storms also result in a loss of species richness across these habitats, as dune habitat diversity is reduced by erosion [32]; foredune height is related to the foredune plant diversity [33]. Dune species diversity is crucial in strengthening resilience against high-energy storm events and ongoing sea-level rise [34]. This study's results, with the loss of dune elevation and vegetation and the slow vegetation recovery along armored shorelines, indicate compromised long-term resilience of barrier island systems.

The sample location for NDVI in Figure 7 extended from the coastline to the backdunes and residential areas behind the foredunes. On the other hand, the sample points for NDVI and elevation shown in Table 4 were collected primarily from vegetated foredunes. The coastal vegetation growing season in central Florida lasts until late fall (personal communication, Hyun Jung Cho), which explains the resilience and relatively high NDVI values for secondary vegetation on the foredunes and backdunes (Clusters 5 and 6, dominated by woody hammock) after Hurricane Ian (October 2022; Figures 7 and 9). However, primary vegetation on the shoreface of foredunes appears to have been impacted by Hurricane Ian (Cluster 4 in Figures 7 and 8). While the use of remote sensing data enables this type of research across an ROI of this scale, the lack of immediate (or even proximate) pre-storm ground truth vegetation data is a limitation of this study. However, NDVI is a mature and well understood application of multispectral remote sensing; therefore, the findings presented here are useful for applications such as future adaptive management planning.

The impacts of the consecutive hurricanes on the dunes are evident both from the reduced NDVI values and elevation, particularly at the lower front of the foredunes (Figures 7 and 9; Table 4). Many of these results were likely compounded from the back-to-back storm events, since vegetation immediately following Hurricane Ian did not see significant change until after Hurricane Nicole. Even the sturdy secondary vegetation was significantly affected by Hurricane Nicole (Table 4; Figure 9). The hardwood coastal hammock in the study area does not have winter senescence or prominent seasonality [35]. The close timing of these hurricanes exacerbated an already de-stabilized system and did not allow a period of recovery for dune vegetation or elevation [31,36].

Natural recovery of vegetation was observed one year after the hurricanes (Table 4; Figure 9). The recovery, evidenced by increases in NDVI from December 2022 to December

2023, was higher at the natural dunes than at armored dunes (Table 4; Figure 9). For woody vegetation further from the coastlines, in particular, the recovery was close to or even higher than the pre-hurricane year's NDVIs (Figure 7); similar recovery was also seen on the secondary vegetation of natural foredunes (Table 4; Figure 9). Houser et al. [37] observed varying rates and patterns of dune recovery after storms, depending on the sand availability and rate of vegetation recovery.

Sandy beach ecosystems maintain their structure and function over various spatial and temporal scales by land retreat [38]; as such, shorelines can retreat substantially after strong hurricanes. For example, the coastal shoreline near Pensacola Beach, Florida, retreated by an average of 64 m during the 2004–2005 hurricane season, which included Hurricanes Ivan, Dennis, and Katrina [36]. Shoreface recovery in the subsequent years was observed in areas where remaining vegetation on low-profile dunes promoted backshore accretion [36]. The ability of a barrier island to recover and withstand subsequent storms depends on factors such as storm frequency and duration, as well as available space for sand retreat, which allow for vegetation and dune recovery [37].

The implementation of engineered barriers such as seawalls and other armored shorelines impedes shoreline retreat and diminishes adaptive capacity and ecological resilience against sea-level rise [38] and storms. This reduction in adaptive capacity places barrier islands at risk, threatening species richness and diversity as they become constricted between fortified structures and rising sea levels. A model to predict the response of dune communities to increases in storm frequency has predicted that fore- and interdune communities will converge towards dominance by storm-resilient species [31].

Local dynamics between hurricanes, sea-level rise, and dune ecosystems should be integrated into developing effective management strategies to ensure the resilience of coastal communities and ecosystems in the face of climate-change-induced challenges. The findings in this study suggest that shoreline armoring and development may have long-term adverse impacts on the fate of barrier islands prone to sea-level rise and hurricane storm surges.

5. Conclusions

The pressures facing coastal dunes on barrier island systems are increasing with global climate change. This highlights the importance of understanding dune behavior in response to coastal storms. Using NDVI and LiDAR, our study shows the temporal differences in resilience and recovery in natural and armored dunes after back-to-back hurricanes. Overall, natural dunes not only exhibited more adaptability and recovery in dune vegetation than armored dunes, but also showed lower impacts in terms of elevation change. We recommend further research into the resilience of various dune types to coastal storms, particularly in comparison to nature-based solutions such as living shorelines, as well as hybrid strategies. This research on dune responses to coastal storms amplified by climate change can inform adaptive management efforts and increase coastal resilience in these vulnerable communities.

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