Determining the Physical and Environmental Impacts of Hurricanes on Mid-Atlantic Barrier Islands using Remote Sensing

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An independent study completed to fulfill the requirements for the University of Vermont Geographic Information Systems and Data Communication Professional Certificate Program

Abstract

Due to their location as the first line of defense for the mainland, barrier islands are a huge economic asset for minimizing hurricane damage to coastal communities, but the islands' ecosystems and land composition are also extremely vulnerable to hurricanes. Targeting this vulnerability, this project aimed to quantify and display how these barrier islands are affected by hurricanes physically and environmentally. Using Google's cloud-based geospatial analysis platform Google Earth Engine and ESRI's mapping software ArcGIS Pro, Landsat satellite imagery from four barrier island locations on the east coast of the United States was analyzed to monitor island movement, vegetative changes (NDVI), and island land cover change. With these remote sensing tools, we found that hurricanes are a contributing factor to the natural ebb and flow of barrier island positioning. On average, the barrier islands moved 26.99 meters per year However, during Hurricane Sandy, Holgate Beach moved 37.78 meters per year and Sandy Hook 34.56 meters per year in comparison to 12.96 and 9.72 meters per year respectively, when no large hurricanes were present. During years when large hurricanes contact barrier islands, there is a relationship between hurricanes and estuary vegetation mitigation, sand relocation, i.e. erosion and deposition, and large land mass migrations both in distance and velocity. The data also suggests that the changes in sand, vegetation, and developed landcover throughout the islands help to explain the NDVI trends. These findings can help environmental managers and scientists create models to determine how hurricanes will affect barrier islands in the future and where on the islands it is the most beneficial to locate human developments with minimal risk of hurricane damage. These findings will become important to inform restoration as hurricane intensity increases with climate change.

1. Introduction to Study

Climate change has caused hurricane intensity to dramatically increase in the past two decades, with further intensification predicted in the future (Banholzer et al., 2014). As reported by the Intergovernmental Panel on Climate Change, the frequency of Category 4 and 5 hurricanes has nearly doubled, reaching an increase of likelihood by 25-30% per global °C of global warming (Holland and Bruyère, 2014). The intensification of hurricanes is concerning for coastal ecosystems that bear the brunt of hurricane's impacts.

Barrier islands are ever changing sand deposits that form parallel to the shoreline due to the constant deposit and erosion from waves (NOAA, 2021) and are a main characteristic of the mid-Atlantic coastline of the United States. As the first line of defense for the mainland from storms (National Park Service, 2019), barrier islands' dunes and grasses absorb the wave energy from storm surges before hitting the coastal mainland (NOAA, 2021). Barrier islands therefore have important economic value for the protection they provide from storms (Halls et al., 2018). Aside from protection, barrier islands have immense ecological importance as they possess high biodiversity and innumerable ecosystem services (Valasquez-Montoya et al., 2021), and host their own unique ecosystems of plants and animals that are critical to the upkeep of the coastal marine food chains (National Park Service, 2020). For these reasons, barrier islands are important for focused conservation effort, legislative decision making on land use, and citizen recreational and entertainment usage.

Despite the important link between hurricanes and barrier islands, we lack a full understanding of the physical and environmental changes of barrier islands in response to hurricanes. Satellite imagery and the use of Google Earth Engine allows us to map the changes in barrier islands over time and in response to hurricanes. While satellite imagery has been used to study barrier island movement in other regions of the world (Lin et al., 2020 and Yoon et al., 2007), analyzing the coastal morphological changes of barrier islands in the eastern United States is a relatively under-investigated area of research. This research is also crucial because the impact of hurricanes on barrier islands will likely increase in future decades as hurricanes continue to intensify.

In this study, we researched the impacts of Hurricane Sandy (October 2012) on four barrier islands on the mid-Atlantic coast of the United States. We chose specific barrier islands in order to compare the effects of islands close to and far from Hurricane Sandy's path: Sandy Hook and Holgate Beach (New Jersey) were near the impact of Hurricane Sandy, while Assateague Island (Virginia) and Pea Island (North Carolina) were hundreds of miles from the hurricane path. Using satellite imagery from 2010 to 2024, we test if Hurricane Sandy altered the geographic positioning and land cover composition of barrier islands.

1.1 Background

This study aims to build on previous research on the movement of barrier islands and other sea features.

A similar study conducted by the U.S. Geological Survey and U.S. Department of Interiors focused also on the impact of Hurricane Sandy and modeled the physical and environmental changes to barrier islands up the eastern United States (Plant et al., 2018). Using Landsat imagery, they created true color images and detailed classification imagery of the various island features. They also determined changes to barrier islands and estuary in size and position before and after Hurricane Sandy (Plant et al., 2018). They concluded that the physical effects seen to the barrier islands from Hurricane Sandy are attributed to multiple storm events creating deposition and erosion to the islands. From this study, we borrowed the true color image and classification methodology as well as using the idea to model positional effects. Our study differs from Plant et al. (2018) because we extended their timeline from 2017 to 2024, did not model future effects of hurricanes, or use field collected data to help determine land cover.

A study conducted by the University of North Carolina compared morphological changes to the northern Outer Banks of North Carolina in response to hurricane events from 1998 to 2014 (Halls et al., 2018). They created detailed geomorphological classifications of the ROIs and compared land cover changes, as well as calculated area changes to the ROIs (Halls et al., 2018). The primary findings from this study were that hurricanes and tropical storms have the most influence on barrier island movement yet have less of an effect on developed land. From this study, we borrowed the methodology to create classifications, and quantify land cover and island area changes.

A study from the University of China aimed to measure sand barrier morphology over time. They calculated the sand barrier centroid for each year of study and isolated the island morphology. They then plotted the directional movement of the island based on centroid movement and mapped the isolated feature morphologies on a map to easily display the feature movement with time (Lin et al., 2020). They concluded that each side of the barrier island had different levels of erosion and deposition depending on its location relative to the ocean, which in turn effected directional movement of the island over time. From this study, we borrowed the centroid movement and isolated terrestrial land features plot methodology.

2. Approaches/Methods

2.1 Regions of Interest

Four regions of interest (ROIs) were chosen for this analysis, all of which are located within nationally protected wilderness areas to minimize major human developmental impacts (see ROI description in Table 1). Holgate Beach, within the Edwin B. Forsythe National Wildlife Refuge of New Jersey, was chosen due to its location within the area of landfall of Hurricane Sandy in 2012. Sandy Hook, within the Gateway National Recreation Area of New Jersey, is located north of the area of impact of Hurricane Sandy and sustained measurable damage from the hurricane. Assateague Island Hook, of the Chincoteague National Wildlife Refuge of Virginia, and Pea Island National Wildlife Refuge of North Carolina were chosen as control locations as they did not sustain a direct hit by Hurricane Sandy. Using the polygon-geometry tool of Google Earth Engine, GEE, polygons were drawn around each ROI, including desired terrestrial land area and surrounding water ranging from 0.5 to 0.75 miles offshore.

Table 1: Regions of Interest Details

ROI	State	Preserved Land Type	Hurricane Impact Direct Landfall
Sandy Hook	New Jersey	Gateway National Recreation Area	2012: Hurricane Sandy (60 miles north of landfall)
Holgate Beach	New Jersey	Edwin B. Forsythe National Wildlife Refuge	2012: Hurricane Sandy
Assateague Island Hook	Virginia	Chincoteague National Wildlife Refuge	2012: None; control
Pea Island	North Carolina	Pea Island National Wildlife Refuge	2012: None; control

2.2 Satellite imagery collection and pre-processing

Satellite imagery from the USGS Landsat 5 and Landsat 8 Level 2, Collection 2, Tier 1 was acquired from the GEE cloud-based database and filtered based on date, cloud cover, and median pixel value across the entire image collection. For Sandy Hook and Holgate Beach, the years 2010, 2013, 2016, 2018, 2021, and 2023 were selected and for Assateague Island and Pea Island the years 2010, 2013, 2016, 2018, 2020, and 2024 were selected. These specific years were selected to highlight a time point before and after Hurricane Sandy, as well as consecutive years moving forward to today based on data availability. The slight discrepancy in years from location is due to the availability of cloud-free imagery during the selected time-period. For each ROI, the Landsat imagery was further filtered by date to only include March 1 to April 30. This was selected as March 1, 2013 was the earliest date available for Landsat 8 to be able to get as close to Hurricane Sandy's date of impact as possible. This date range was continued throughout for accuracy. Cloud cover was filtered ranging from 5-20% depending on the conditions of the imagery. The fully filtered imagery was then clipped by the ROIs polygon and the red, green, and blue bands were selected to create a true color image (Figure 1A).

2.3 Vegetation Health Changes (NDVI)

The Normalized Difference Vegetation Index (NDVI) was calculated for each ROI and year using the cloud-free satellite imagery (Eq. 1). NDVI represents the health and density of vegetation growing on these islands. An example of the NDVI maps for Assateague Island in 2010 and 2018 are shown in Figure 1 C and D.

$$\textit{Equation 1:} \quad \mathbf{NDVI} = \frac{(\boldsymbol{Near\ Infrared\ Band - Red\ Band})}{(\boldsymbol{Near\ Infrared\ Band + Red\ Band}}$$

The mean NDVI was the calculated for each year and ROI. To ensure the calculation only represented NDVI over terrestrial land, the mean NDVI was specifically calculated within the isolated terrestrial feature described in *Section 2.5*. The mean NDVI for each ROI and year were then graphed in line charts to display change in vegetation health and density over time (Figure 2).

2.4 Land Cover Changes (Pixel-Based Supervised Classification)
Each year was grouped based off land similarity to ease training data acquisition. 2010 and 2013 were grouped and labeled “2013”, 2016 and 2018 as “2018”, and 2020/21 and 2023/24 as “2024. Thirty to fifty training points, depending on image detail, were placed on the true color images. The pixel locations were compared between time periods to assure accuracy. The Landsat bands from Coastal Blue to Short Wave Infrared and Surface Temperature were selected for analysis. A Supervised Random Forest Classification was conducted and a palette of yellow for sand, green for estuary, blue for water, and purple for developed regions (only used if represented on map) was assigned. In this study, the term estuary is a catch all term to describe both terrestrial and aquatic “marsh” vegetation. This data was then mapped (Figure 1B) and an accuracy assessment was conducted to ensure the classification was conducted correctly (Table 2).

From the categories created from the classification, the pixel area was calculated for each ROI during each time-period. This value was then multiplied by 900 to get to land cover area in meters squared. The sum was then calculated, and a reducer was used to get the final weighted area for each classification variable (Figure 3).

2.5 Barrier Island Movement (Centroid Analysis)
Using the classification categories from *Section 2.4*, the terrestrial land pixels were isolated from the water into a new feature, which represented total land mass of each ROI. The centroid was calculated for each year and ROI to determine if island movement had occurred. The centroid coordinates were mapped (Figure 5) and the isolated terrestrial ROIs were exported to ArcGIS Pro where they were overlayed, a color outline was assigned per year, and data was mapped (Figure 4).

The distance of consecutive yearly centroid movements was calculated, representing total yearly drift of the barrier islands. The velocity, distance divided by years between time points, was also calculated (Figure 6) to represent the rate at which these changes had occurred and highlight other external forces, e.g., large storms.

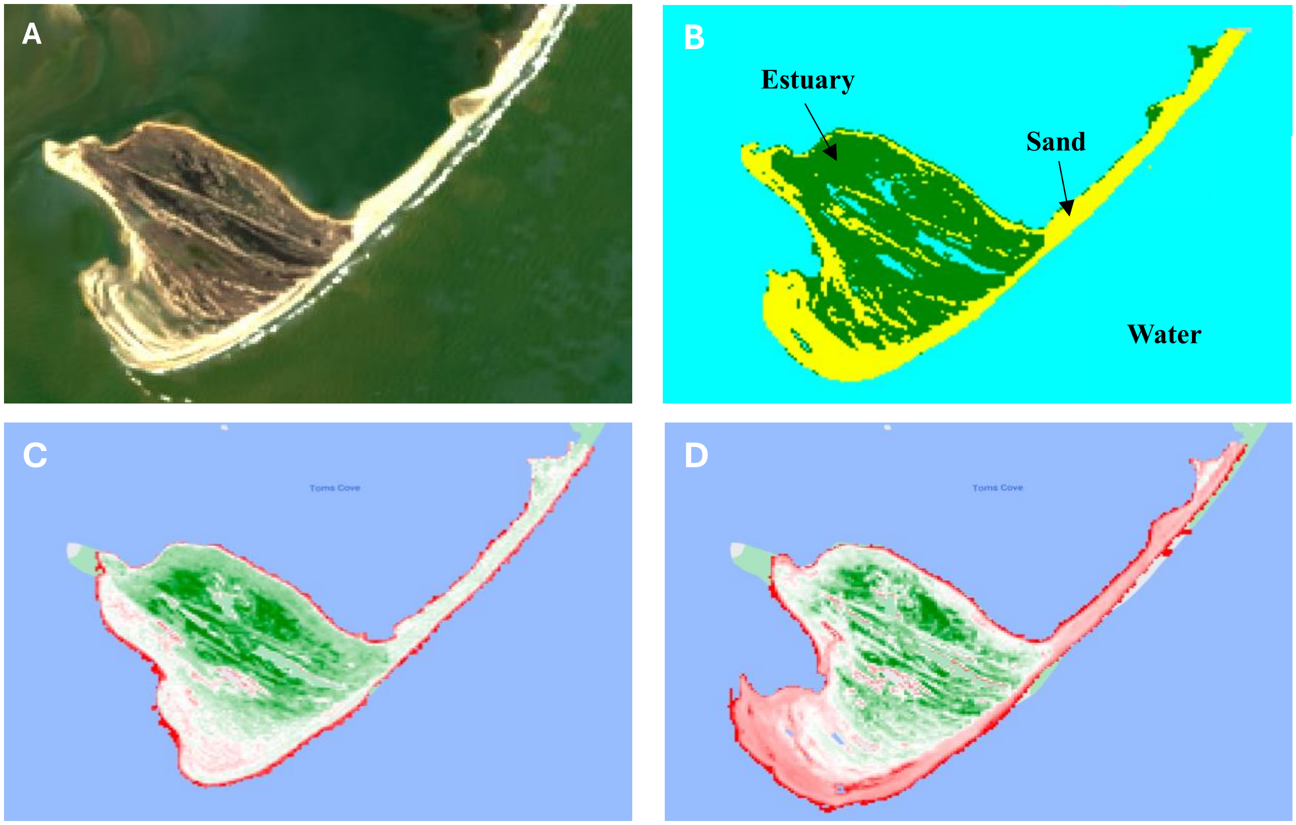

Figure 1: *This figure includes examples of the steps utilized to acquire the results figures. Panel **A** shows a true color image created for Assateague Island, VA for March 1, 2016 to April 30, 2016. Panel **B** represents a Random Forest Pixel-Based Classification map of the same ROI for March 1, 2018 to April 30, 2018. The yellow pixels represent sand, green represent estuary, and blue represents water (labeled). Panel **C** and **D** show a complete NDVI map from 2010 (left) to 2013 (right) calculated based on the isolated terrestrial land feature. The values are displayed on a gradient from -1 to 1, and with a red-white-green palette, red representing -1 and green representing 1.*

3. Results

Focusing on the environmental changes occurring over each ROI, the major changes seen are shifts in vegetation cover and sand cover. In Sandy Hook (Figure 2A), mean NDVI values remained stable over time, staying between 0.10 and 0.12, with the largest decline occurring between 2010 and 2013. In Sandy Hook, we also saw an increase in built up land cover between 2010 and 2013 (purple, Figure 3A) and a slight increase in estuary cover towards the end of the time-period (green, Figure 3A). A similar pattern was seen at Pea Island where NDVI decreases (Figure 2D), developed land area from 2010 to 2013 increases, and followed by a decrease in estuary vegetation (Figure 3D). A large spike in estuary land cover was seen from 2016 to 2020 and plateaus at 2024 (Figure 3D), which was also seen in the NDVI values (Figure 2D). Next looking at the mean NDVI for Holgate Beach, the increase in NDVI from 2010 to 2013 (Figure 2B) represents an increase in vegetation other than estuary vegetation as the landcover in Figure 3B shows a large decrease. From 2016 to 2024 there was a steady increase in NDVI and estuary land cover increased as well. Moving south to Assateague Island, there was opposition in NDVI and landcover for 2010 and 2013 as NDVI increased and estuary landcover decreased, but for

2016 to 2024 both plots displayed a gradual increase in vegetation from 2013 to 2018, then a slight decrease in the last few years (Figure 2C and 3C).

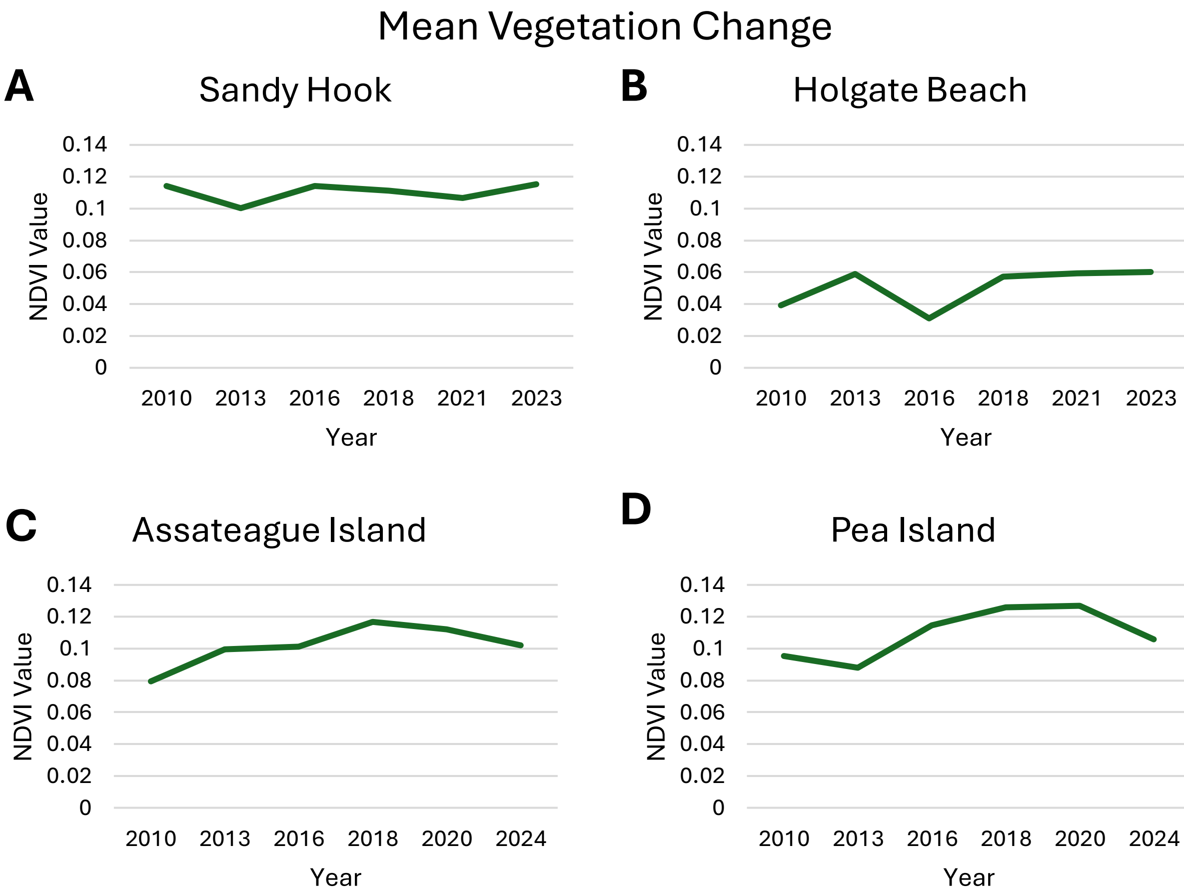

Figure 2*: This figure represents the mean NDVI (normalized difference vegetation index) values taken from the entire terrestrial ROI geometry. NDVI indicates vegetation density and health with more positive values denoting increased vegetation or vegetation health, and values near zero denoting low vegetation cover.*

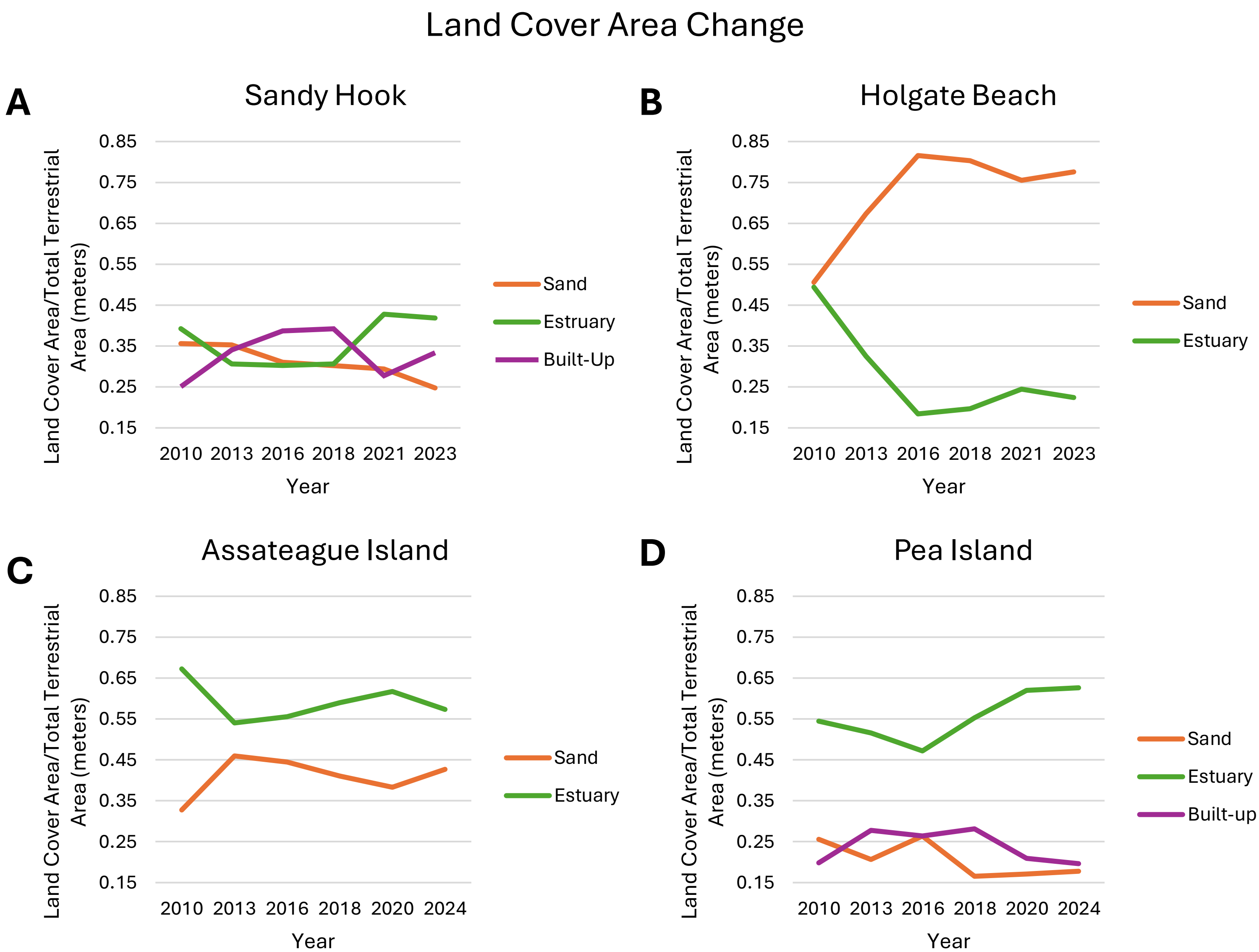

Figure 3: *This figure represents the terrestrial land cover composition in each barrier island, acquired from a pixel-based random forest classification. The orange lines represent pixels identified as sand. The green lines represent pixels represented as estuary or vegetation. The purple lines represent pixels identified as human development, where applicable. The y-axis value is a ratio derived from the land cover area measured in meters divided by the total terrestrial area of the ROI geometry.*

Table 2: *This table displays accuracy measures from the supervised classification results shown in Figure 3. The accuracy values represent total accuracy of the classified map in ROI and year.*

	2010	**2013**	**2016**	**2018**	**2020/21**	**2023/24**
Sandy Hook	0.983	0.980	0.984	0.984	0.981	0.986
Holgate Beach	0.994	1	1	1	0.994	1
Assateague Beach	1	1	0.991	0.991	1	1
Pea Island	0.979	0.978	0.987	1	1	0.993

All barrier islands displayed movement over time, through the direction of movement was not consistent among barrier islands and years. Figure 4 shows the outlines of each barrier island and their movement through time, and Figure 5 displays the movements of the islands' centroids. Sandy Hook (Figure 4A, 5A) showed progressively westward movement, i.e., towards the mainland, and returned to slightly west of the starting point in 2023. 2010 to 2013 displayed a northwest drift, 2013 to 2016 a northeast drift, 2016 to 2018 a westward drift, 2018 to 2021 a southwest drift and 2021 to 2023 a southeast drift. Holgate Beach (Figure 4B, 5B) showed a progressive northward drift. 2010 to 2013 displayed a southwest drift, 2013 to 2016 a southeast drift, 2016 to 2018 a northward drift, 2018 to 2021 a southwest drift and 2021 to 2023 a northward drift. Assateague Island (Figure 4C, 5C) showed a progressively southwestward movement. Each time point from 2010 to 2024 slowly drift in the southwest direction. Finally, Pea Island (Figure 4D, 5D) showed a progressively northward movement. 2010 to 2013 displayed a northwest drift, 2013 to 2018 displayed a southeast drift, and 2018 to 2024 showed a northwest drift.

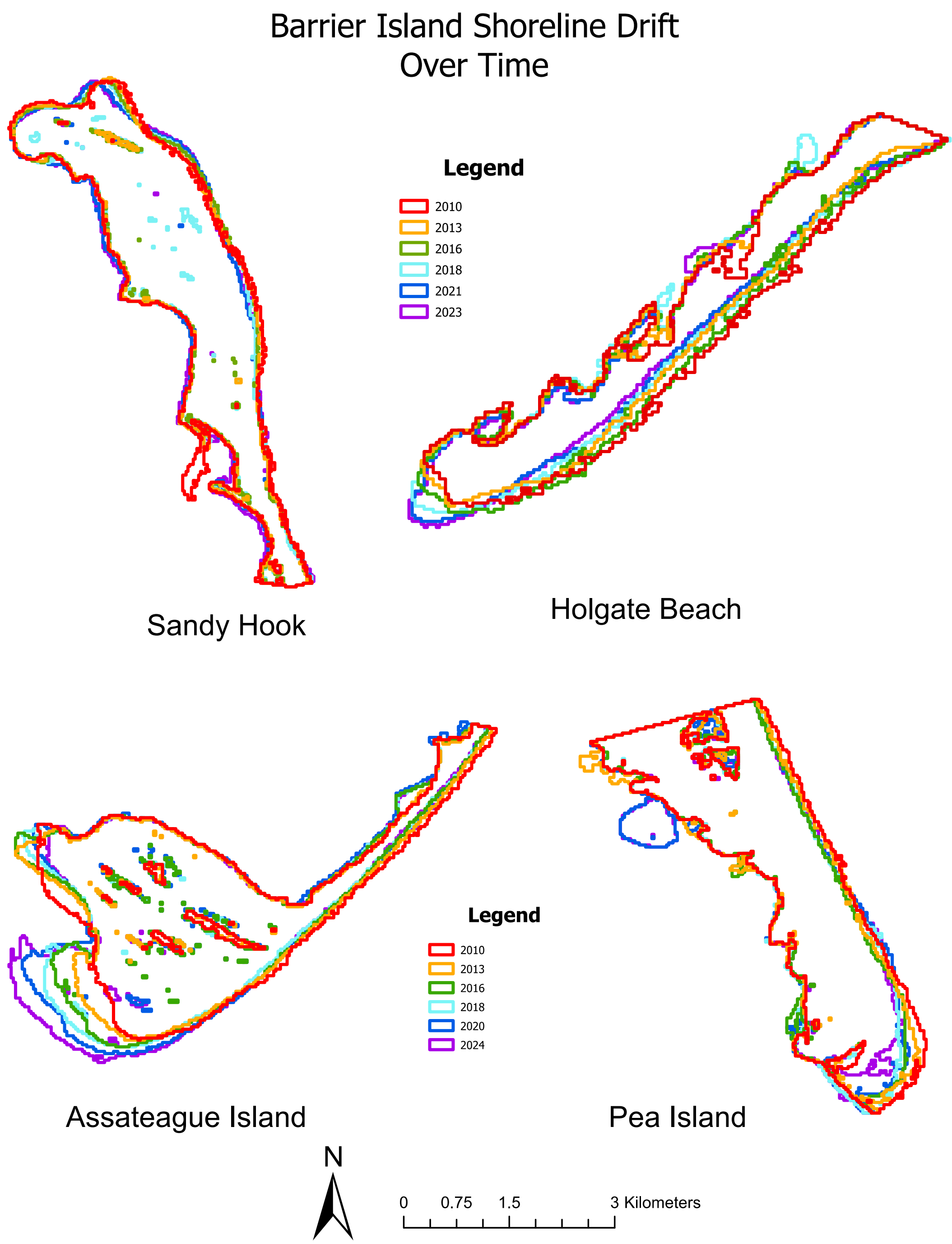

Figure 4*: This figure represents the total barrier island movement observed and feature position from 2010 to 2023/24. The red outline shows the island position during 2010, orange position during 2013, green position during 2016, cyan position during 2018, blue position during 2020 or 2021, and purple position during 2023 or 2024.*

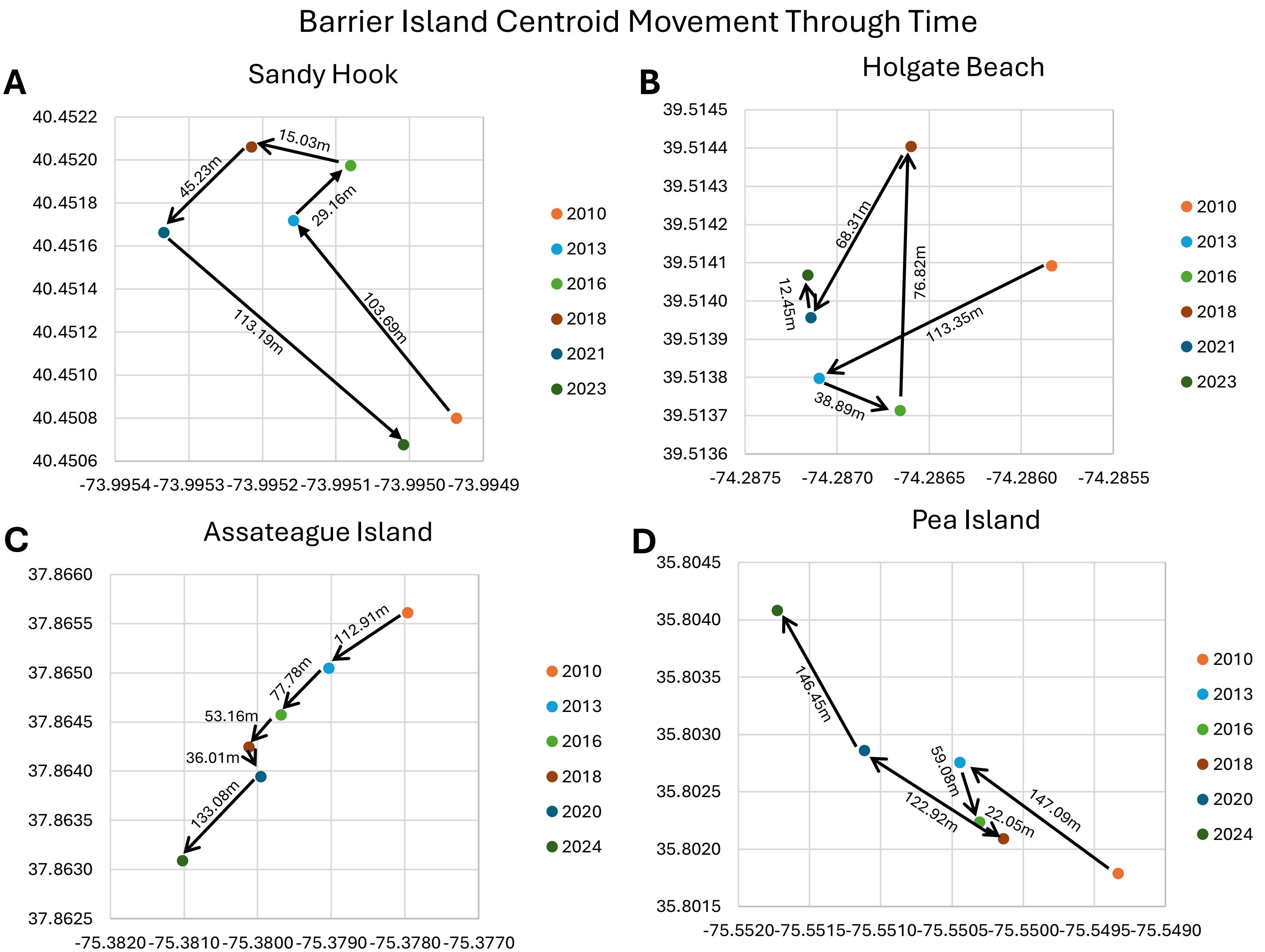

Figure 5: *This figure represents how the centroid (center most point) of each barrier island moves through space and time. The points represent the individual time points and the arrows connecting them show the movement distance and direction by which they drifted.*

Aside from directional movements, the speed at which these barrier islands drifted also varied in time and space (Figure 6). 2010 to 2013 saw a steady increase in drift velocity. Sandy Hook had a velocity of 34.5 m/year; Holgate Beach a velocity of 37.8 m/year; Assateague Island a velocity of 37.6 m/year; Pea Island a velocity of 49.0 m/year. 2013 to 2016 saw the slowest collective movement. Sandy Hook had a velocity of 9.7 m/year; Holgate Beach a velocity of 12.9 m/year; Assateague Island a velocity of 25.9 m/year; Pea Island a velocity of 19.7 m/year. In 2016 to 2018, Sandy Hook and Pea Island slowed, 7.5 m/year and 11.0 m/year respectively, Holgate Beach sped up to 38.4 m/year, and Assateague remained constant at 25.6 m/year. In 2018 to

2020/21, Sandy Hook and Pea Island sped up, 15.1 m/year and 61.5 m/year respectively, and Holgate Beach and Assateague Island slowed down, 22.8 m/year and 18.0 m/year respectively. From 2020/21 to 2023/24, the velocity of Sandy Hook and Assateague Island increased to 37.7 m/year and 33.3 m/year respectively, and Holgate Beach and Pea Island slowed to 4.1 m/year 36.6 m/year respectively.

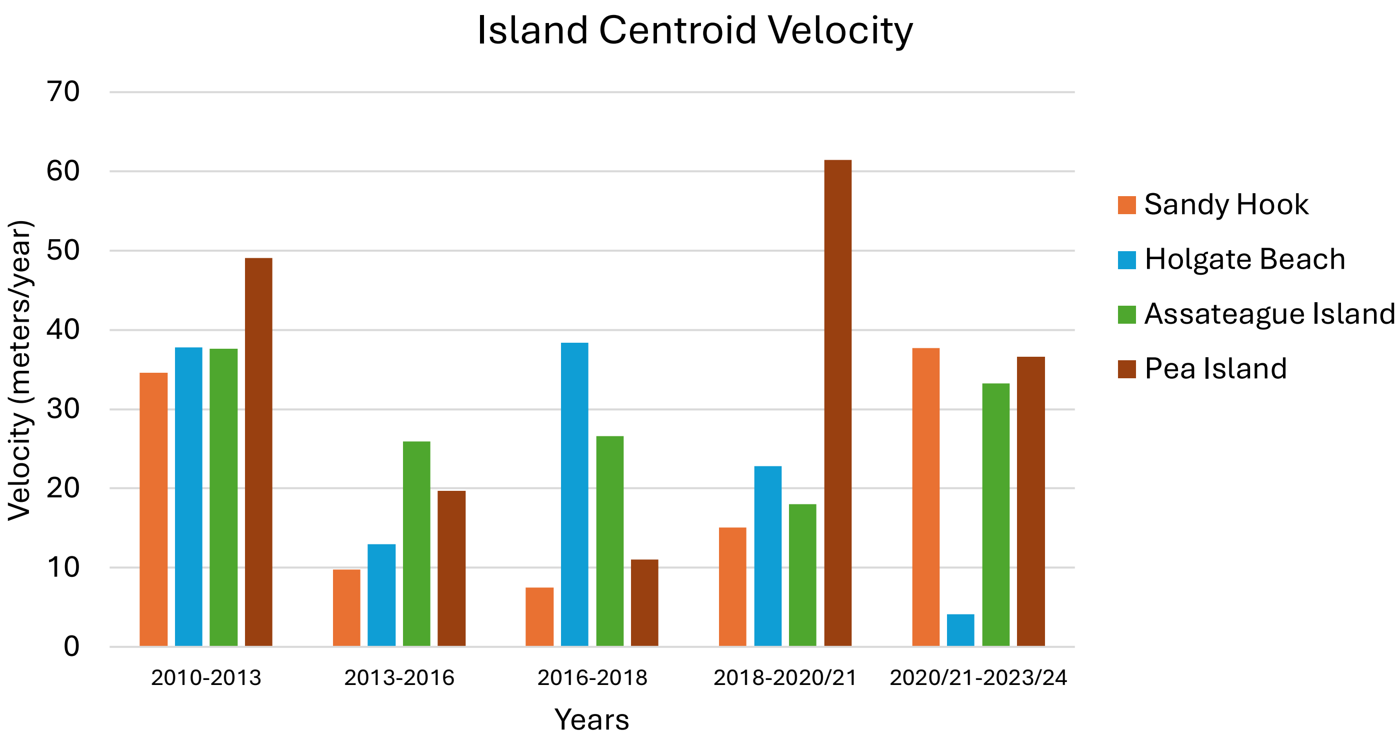

***Figure 6**: This figure represents the measured velocity of the centroid that was determined for each ROI during each time-period. The centroid acts as a proxy for movements made by the entire barrier island ROI. The velocity is calculated by dividing the centroid distance traveled between consecutive time points and the number of years between time points. The orange bars show Sandy Hook, blue Holgate Beach, green Assateague Island, and red bars Pea Island.*

4. Discussion

Using Landsat satellite imagery and the geospatial coding software Google Earth Engine, we were successful in monitoring and analyzing the morphological and vegetation changes occurring to four barrier islands on the eastern coast of the United States in response to Hurricane Sandy. Close analysis of the physical and environmental changes occurring to the barrier island ROIs reveals strong evidence of hurricane impacts to the ROIs closest to the point of landfall as there was much movement, land cover shifts, and vegetation shifts with time. However, it is likely that there are several other factors influencing island movement and land cover change, including other large hurricanes (discussed below).

Focusing on the two ROIs closest to Hurricane Sandy's landfall, Sandy Hook and Holgate Beach have concurrent data suggesting a substantial impact of Hurricane Sandy on these barrier islands during the 2010 to 2013 time-period. The physical changes that can be observed are a large increase in island movement velocity (Fig. 6), and an approximately 100 meter directional shift inland (Fig. 5). On the other hand, the environmental changes are a decrease in estuary land cover for both ROIs and slight shifts in NDVI, but a large increase in sand land cover in Holgate Beach, where the hurricane made landfall, and little change in sand cover in Sandy Hook (Fig. 2 and 3). Then, looking at the time period after Hurricane Sandy, 2013 to 2016, there is opposite physical changes and what appears to be a stabilization in environmental changes. The velocity immensely decreased (Fig. 6) and the islands only had a small approximately 30 meter seaward shift (Fig. 5). Sand cover in Holgate Beach continued to increase but balanced out to the current sand cover level seen in 2024, while Sandy Hook decreased to the level seen in 2024 (Fig. 3). The inverse pattern for estuary cover was seen as Holgate Beach continued to decrease but level out and Sandy Hook stayed constant (Fig. 3), which is also reflected in the NDVI (Fig. 2).

In comparison, the control ROIs far from the point of landfall of Hurricane Sandy, Assateague Island and Pea Island had results more counterintuitive. During the 2010 to 2013 time-period, the control islands exhibited similar changes to those of the ROIs near the impact zone. There was an observed large increase in velocity (Fig. 6), an approximately 100 meter directional shift inland (Fig. 5), a decrease in estuary land cover for both ROIs, a slight shifts in NDVI (Fig. 2 and 3), and an increase in sand cover in Assateague Island (Fig. 3). Even though the landcover changes were smaller than that of Sandy Hook and Holgate Beach, the trends still resembled one another. From these results, it is clear that Hurricane Sandy was not the sole influence of these changes. Some other influences on barrier island changes and movement include tides, wind, rising sea level (Malmquist, 2022), and other storm systems.

While this study focused on Hurricane Sandy, there was also other hurricanes between 2010 and 2024 that might had affected the barrier islands. For example, Hurricane Dorian (Cat. 5) made landfall around Peas Island in 2019 (NOAA National Hurricane Center, 2019), which might explain the peak of movement in that time-period. As well, Hurricane Isais (Cat. 1) made landfall in southern North Carolina and continued up the coastline in 2020 (NOAA National Hurricane Center, 2020). This may explain why we see a sharp increase in movement, loss of vegetation health, and an increase in sand land cover in Sandy Hook, Assateague Island, and Pea Island between 2020/21 and 2023/24. Interestingly, we did not see an impact of this Hurricane on Holgate Beach.

Our findings suggest that hurricanes play a considerable role in the natural ebb and flow of barrier island positioning. During years when large hurricanes made landfall near a barrier island, we generally saw increased movement, increase in sand relocation, i.e., erosion and deposition, and a loss of vegetation. However, even though these variables were very clear within the bounds of this study, there are limitations. Since Landsat imagery has 30 meter resolution, this study would benefit from using a higher resolution imagery. A huge aspect of a determining physical changes, as done here, is having data collected in the field to accurately confirm the remote sensed findings (Plant et al., 2018). This is particularly important for determining the environmental changes with hurricane activity. Due to its lower resolution, it is hard for the GEE algorithm to accurately assess the vegetative changes with much detail, so having supporting data from field vegetative analyses, photo evidence, or on the ground data logging devices would help immensely. It would have also been helpful to have field GPS coordinate acquisition taken around the border of each ROI to make sure the satellite coordinates were correct in case the Landsat data had calibration issues or outside interferences hindering its accuracy (Plant, et al., 2018). It may also be helpful to use another remote sensing data method, like LIDAR, to get higher-resolution data (Priestas and Fagherazzi, 2009 and Halls et al., 2018).

It is also important to note the tidal effects on barrier island movement and data collection. The fluctuations seen during daily tide cycles will significantly influence the "outer border" or island feature outline with time. If the imagery collected during the 2010 time-period was at low tide and the imagery from 2013 was at high tide, then the data collected for island movement and velocity may become skewed. For future studies, it would be important to include a tidal correction into the code to account for some of this misrepresentation as well as longer selected time-period to have multiple tidal events included in the data (Lin et al., 2020 and Yoon et al, 2009).

5. Conclusion

Due time constraints, this study has left many questions still unanswered on the complete explanation for hurricane induced barrier island movement. In order to obtain a more well-rounded conclusion, this study will need more work moving forward. Some potential future directions for this study would be to examine more hurricane events in more detail and include more locations to get a more robust conclusion. Including multiple ROIs in the same state or looking at multiple points of interest within the previously chosen ROIs would allow one to analyze hurricane impacts through a very detailed lens. Other potential directions include measuring inter-year differences, including field work and tide data, and adding in statistical test to validate the findings. Even though there is still more to uncover, it is clear that hurricanes play an immense role in how barrier islands evolve on the landscape with time.

6. Self-Reflection

I found the independent study process to be very beneficial for my future career success. The more experience that I have with seeing a research project from idea to completed manuscript, the more I will be prepared to complete unsupervised projects later in my career. I came into the independent study course looking to gain confidence using Google Earth Engine and ArcGIS Pro, which I felt like having the freedom given in this course I was able to explore on my own and gain the skills I was seeking. I also really enjoyed having the assistance of my advisor to give me guidance for small issues and how to execute my plans for the project. If I was to get more out of this course, I would have liked more time to work on it. I feel like it has so much more potential and I would have loved to see how what other directions I could have taken it in.

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