Received: 20 September 2024 | Revised: 4 February 2025 | Accepted: 20 February 2025

DOI: 10.1002/ecs2.70226

ECOSPHERE
AN ESA OPEN ACCESS JOURNAL

ARTICLE

Coastal and Marine Ecology

Assessing mangrove canopy height and health changes in Puerto Rico post-Hurricane Maria using remote-sensing techniques

Jahnelle Howe[1] | **Shakila Merchant**[1,2] | **William J. Hernández**[3] | **Jeffery Pessutti**[4] | **Peter Groffman**[1,5]

[1]Department of Earth and Environmental Sciences, CUNY Graduate Center, New York, New York, USA

[2]CUNY Remote Sensing Earth System (CREST) Institute, New York, New York, USA

[3]Research and Development Center, University of Puerto Rico, Mayagüez, Puerto Rico, USA

[4]NOAA NMFS, Fisheries Ecology Branch, James J Howard Marine Laboratory, Highlands, New Jersey, USA

[5]Advanced Science Research Center at The Graduate Center, CUNY Graduate Center, New York, New York, USA

Correspondence
Jahnelle Howe
Email: jhowe1@gradcenter.cuny.edu

Funding information
Office of Education; The National Oceanic and Atmospheric Administration (NOAA) – Cooperative Science Center (CSC) for Earth System Sciences and Remote Sensing Technologies (CESSRST-II), Grant/Award Number: NA22SEC4810016

Handling Editor: Sean P. Powers

Abstract

Mangroves are critically important ecosystems that are highly vulnerable to hurricanes. This study assessed the impact of Hurricane Maria on mangrove canopy heights and vegetation at two sites in Puerto Rico—La Parguera (southwest) and the Northeast Ecological Corridor (northeast)—and examined factors influencing recovery. Using remote sensing techniques, including light detection and ranging (LiDAR) and normalized difference vegetation index (NDVI) analysis, we quantified canopy height loss and vegetation health changes over time. Results show a significant reduction in canopy height immediately after the hurricane, with greater damage in the Northeast Corridor site than in the La Parguera site. NDVI analysis revealed site-specific variation in post-hurricane recovery, with some areas exceeding pre-hurricane vegetation health despite initial losses. Recovery patterns appeared to be linked to pre-storm canopy height and potential human disturbances, such as land-use change and hydrologic alteration. The integration of LiDAR and NDVI provided complementary insights, with LiDAR capturing structural damage and NDVI reflecting vegetation health dynamics. This study highlights the value of remote sensing in evaluating mangrove resilience and identifying factors influencing recovery after extreme weather events.

KEYWORDS

blue carbon, canopy height, coastal ecosystems, ecosystem resilience, Hurricane Maria, LiDAR, mangrove, mangrove ecosystem recovery, NDVI, remote sensing, satellite imagery, vegetation health

INTRODUCTION

Mangroves are trees and shrubs that live in coastal intertidal zones in tropical and subtropical latitudes. They provide critical habitats for diverse species, serve as significant carbon sinks, and act as natural barriers against wave action and tropical storms (Kumar et al., 2014; Nagelkerken et al., 2000). Mangroves also enhance water quality by filtering nutrients and pollutants, reducing coastal erosion, and supporting fisheries and other ecosystem services (Kumar et al., 2014). Collectively, these functions make mangroves ecologically, socially, and economically invaluable, contributing an estimated $800 billion annually to global economies through ecosystem services, including tourism, fisheries, and storm protection (Acharya, 2002; Cabrera et al., 1998). As key "blue (ocean and coastal) carbon" ecosystems, mangroves remove and sequester significant amounts of atmospheric carbon dioxide (CO_2). They are the store the largest global blue carbon stocks, with storage persisting for centuries (IPCC, 2013; Murray et al., 2011) Protection of mangroves is thus important for mitigating climate change impacts at both local and global scales (Mcleod et al., 2011).

Despite their importance, mangroves face severe threats from anthropogenic activities, including deforestation, urbanization, pollution, and climate change. Extreme weather events such as hurricanes further exacerbate these threats, damaging mangrove canopies, uprooting trees, and obstructing drainage pathways (Gilman et al., 2008; Patel, 2020). Puerto Rico, located in the Greater Antilles, experiences frequent tropical storms and hurricanes, with increased frequency and intensity posing a risk to its ecological and social resilience (Puerto Rico Climate Change Council, 2013). These vulnerabilities are compounded by habitat loss, pollution, and food security challenges, as the islands import approximately 85% of their food (Gould et al., 2017). Approximately 28% of Puerto Rico's shorelines are vegetated by mangroves. However, historical losses in mangrove cover are significant, with a 35% decline between the 1980s and 2009, surpassing deforestation rates of tropical rainforests and coral reefs (Martinuzzi et al., 2009). On September 20, 2017, Hurricane Maria, a Category 4 storm, severely affected Puerto Rico with winds up to 249 km/h and record rainfall, causing widespread flooding and vegetation damage (Hu & Smith, 2018; Pasch et al., 2018). Severe hurricanes like Maria significantly impact mangrove structure and vegetation health, requiring years of recovery under stable conditions (Lagomasino et al., 2021; Patel, 2020). Understanding the factors influencing mangrove damage and recovery is crucial for assessing their resilience to extreme weather events.

Remote sensing techniques provide valuable tools for monitoring mangrove ecosystems, offering spatiotemporal data on vegetation distribution, health, and structure changes (Kuenzer et al., 2011). Light detection and ranging (LiDAR), which uses pulsed laser light to create high-resolution 3D Earth models, is particularly effective for quantifying canopy height and structural damage (NOAA, 2017; NOAA NWS, 2017; Pham et al., 2019). Normalized difference vegetation index (NDVI) analysis provides information on vegetation "greenness" and health. Together, these methods allow for detailed assessments of mangrove damage and recovery following hurricanes.

This study aims to quantify changes in mangrove canopy height caused by Hurricane Maria and evaluate subsequent recovery using remote sensing techniques. Focusing on two areas with variation in mangrove condition, mangroves in La Parguera (southwest Puerto Rico) and the Northeast Ecological Corridor (northeast Puerto Rico), our objective was to characterize damage and recovery patterns to better understand the mechanisms of damage and recovery that underlie mangrove ecosystem resilience to extreme weather events.

STUDY AREA

The La Parguera mangrove ecosystem (Figure 1) is located in southwest Puerto Rico and is the drier of the two sites due to higher temperatures and lower precipitation (Osbourn, 2023 Warne et al., 2005). The study area includes the Boquerón State Forest and La Parguera Natural Reserve, both managed by the Puerto Rico Department of Natural and Environmental Resources (DNER) (Hernández et al., 2022). Historically, La Parguera was impacted by Hurricane Edith (1963) (Glynn et al., 1964). The drier conditions and lower freshwater input in this region may influence mangrove recovery rates by limiting freshwater availability, potentially slowing regeneration following extreme storm events.

The Northeast mangrove site near San Juan (Figure 1) includes the Northeast Ecological Corridor Reserve, also managed by the DNER. This site experiences higher precipitation and humidity than La Parguera, which may increase vegetation regrowth after disturbances. However, this site is subjected to greater human impacts than La Parguera due to its proximity to San Juan. Notable human impacts include coastal development, which has reduced mangrove buffer zones; water pollution from urban runoff and wastewater discharge; and dredging, which has altered hydrologic connectivity and sediment dynamics (Wigand et al., 2021). These anthropogenic pressures may exacerbate mangrove vulnerability to hurricanes by disrupting natural recovery processes. The Northeast site was affected by Hurricane Hugo (1989).

The sites were selected to allow for the evaluation of how differences in climate, human disturbances, and canopy structure influence mangrove damage and recovery following Hurricane Maria. Additionally, understanding how these factors affect carbon sequestration potential in each site provides insight into broader ecosystem resilience. While both sites fall under DNER

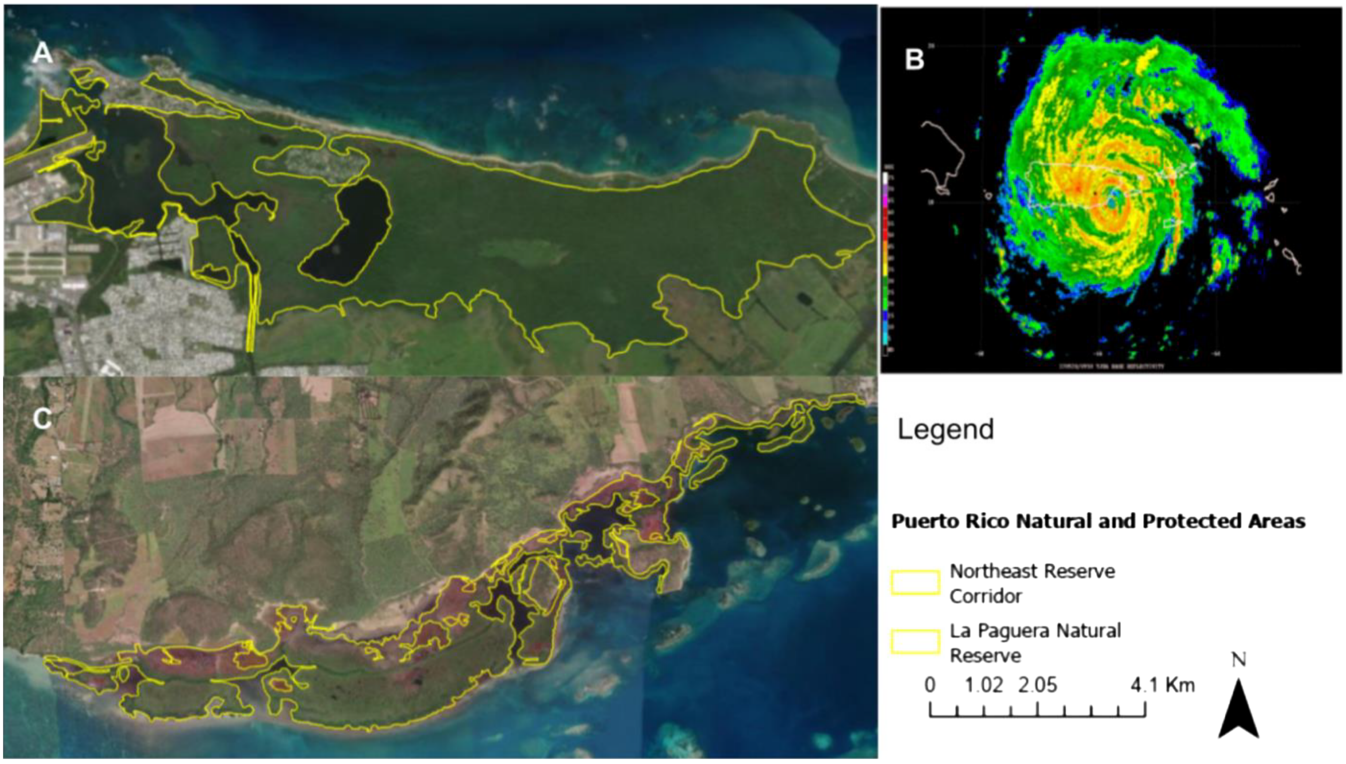

FIGURE 1 Map of study site mangroves in Puerto Rico. (A) The Northeast Reserve Corridor. (B) A NOAA NWS San Juan WSR-88D radar image of Hurricane Maria at 0950 UTC on 20 September, just before landfall in Puerto Rico, showing the more dominant outer eyewall. This was the last image from the radar before it was destroyed. (C) The La Parguera Mangroves.

management, potential differences in conservation strategies, land-use policies, or enforcement levels may also play a role in shaping mangrove health and recovery outcomes.

MATERIALS AND METHODS

LiDAR

The LiDAR datasets used were the 2015–2017 USGS LiDAR: Puerto Rico and 2018 USGS LiDAR: Post Hurricane Maria downloaded from the NOAA Digital Coast Data Access Viewer (https://coast.noaa.gov/dataviewer/#/). The 2018 USGS LiDAR: Post Hurricane Maria dataset was collected approximately one year after Hurricane Maria affected Puerto Rico (https://www.fisheries.noaa.gov/inport/item/60085). LiDAR point clouds, previously ground classified, were input into Global Mapper, and points were classified to differentiate between vegetation and other land covers. Before classifying, a significant amount of time was used to clean the dataset of noise points. The classified point cloud was then used to create a digital elevation model (DEM) and a digital surface model (DSM). A DEM represents the ground elevation above sea level, and a DSM describes the elevations of the highest surface at a given location. Raster math was used to develop a mangrove canopy height model (CHM). The equation was as follows:

$$\mathrm{CHM} = \mathrm{DSM} - \mathrm{DEM}. \tag{1}$$

After calculating the CHM, change was identified by subtracting the CHM for one date from another. Using raster algebra in a pixel-by-pixel process, the pre-hurricane CHM was subtracted from the post-hurricane CHM. The difference in CHM (ΔCHM) is regarded as forest damage caused by Hurricane Maria. The following equation calculates the difference in CHM:

$$\Delta\mathrm{CHM} = \mathrm{CHMpre} - \mathrm{CHMpost}. \tag{2}$$

CHMpre represents the CHM before hurricane landfall, and CHMpost represents the CHM for the year after Hurricane Maria (2018). After calculating CHM models, the maps were exported from Global Mapper and imported into ArcGIS Pro for height difference calculations and final visualization.

Satellite imagery

Satellite imagery from 2010, 2017 to 2018, and 2021 to 2023 was obtained to assess mangrove vegetation health before and after Hurricane Maria (Table 1). The 2009–2010 imagery was used to establish pre-hurricane baseline conditions, the 2017–2018 imagery captured the immediate post-hurricane impact, and the 2021–2023 imagery was used to evaluate mangrove recovery. Imagery from 2009 to 2010 (USACE NCMP 4-Band 8 Bit Imagery): was downloaded from the NOAA Digital Coast Data Access Viewer (https://coast.noaa.gov/dataviewer/#/). To manage the large dataset, Puerto Rico was divided into tiles, and only those containing the mangrove ecosystems under study were downloaded. For the 2017–2018 period, Planetscope Scene imagery was used for the Northeast Ecological Corridor site, and very high-resolution (VHR) satellite imagery was used for the La Parguera site. Data selection prioritized cloud-free images, high spatial resolution, and spectral coverage necessary for mangrove monitoring (Hernández et al., 2022).

To ensure comparability across datasets, all imagery underwent preprocessing steps. Raw satellite images underwent atmospheric correction using the dark object subtraction (DOS) method to standardize reflectance values across time periods and sensors. All datasets were aligned to a consistent coordinate system (WGS84) and resampled to match the spatial resolution of the highest-resolution dataset (Planetscope: 3 m). A consistent water masking process was applied across datasets using the Modified Normalized Difference Water Index (MNDWI) to exclude non-mangrove areas, ensuring an accurate analysis of mangrove vegetation changes.

Given the difference in spatial and spectral resolution between the datasets, particular care was taken to address potential inconsistencies. The spectral bands used for NDVI calculations (red and near-infrared) were matched as closely as possible across sensors. Higher resolution data (e.g., NAIP imagery) were aggregated to match the coarser resolution of older datasets when conducting temporal comparisons to avoid bias.

The selection of Planetscope imagery for 2017 and NAIP imagery for 2021–2023 was guided by their suitability for the study objectives. Planetscope offers high temporal resolution and sufficient spatial detail for capturing post-hurricane impacts in the Northeast Ecological Corridor site. NAIP imagery, widely used for vegetation monitoring, provided cloud-free, high-resolution data for assessing long-term recovery in both study sites. This approach allowed for a detailed, reliable analysis of mangrove vegetation health across varying spatial and temporal scales.

Change detection for vegetation

NDVI is used to quantify changes in vegetation density and plant health in mangrove ecosystems. The NDVI assesses the condition of live green vegetation and indicates photosynthetic activity (Hernández et al., 2022; Rouse et al., 1973). The NDVI equation is

$$\mathrm{NDVI} = \frac{\mathrm{NIR} - \mathrm{RED}}{\mathrm{NIR} + \mathrm{RED}}. \tag{3}$$

RED and NIR refer to the spectral reflectance value in the visible (RED) and invisible (near infrared: NIR) regions, respectively. NDVI values range from −1.0 to +1.0, where negative values can represent clouds and water, positive values close to zero can indicate bare soil, rock, sand, or snow, and higher values from 0.1 to 0.5 indicate low vegetation. Anything 0.6 and above indicates dense green vegetation (Ya'acob et al., 2014). Mangroves are considered "rainforests of the sea" and are defined as a type of tropical and subtropical forest (Lüttge, 2008). Satellite imagery was acquired without clouds; however, since mangroves are a coastal ecosystem, a mask was applied to reduce water effects when calculating NDVI for the sites.

All image datasets were standardized regarding resolution, bounding boxes, and projection before any NDVI calculation change. After calculating NDVI, the change area was identified by subtracting the NDVI image for one date from another (Cakir et al., 2006). The

TABLE 1 Imagery specifications.

Sensor	Image date	Location	Spatial resolution (m)
Dove Classic "PS2"	16 December 2017	Northeast Reserve Corridor	3.7
NAIP	2021–2023	La Parguera, Northeast Mangrove	0.60
ADS40 8bit	2009–2010	La Parguera, Northeast Mangrove	0.30
Pleiades-1A	6 January 2018	La Parguera Natural Reserve	PC (0.55), MS (2.4)

Abbreviations: MS, multispectral; NAIP, National Agriculture Imagery Program; Northeast RC, Northeast Corridor Reserve; PC, panchromatic.

pre-hurricane NDVI image was subtracted from the post-hurricane image using map algebra in a cell-by-cell process. The difference in NDVI (ΔNDVI) is regarded as forest damage caused by Hurricane Maria. The following equation calculates the difference in NDVI:

$$\Delta\text{NDVI} = \text{NDVIpre} - \text{NDVIpost}. \quad (4)$$

NDVIpre represents the NDVI image before hurricane landfall, and NDVIpost represents the NDVI after hurricane landfall. Satellite imagery was downloaded before Hurricane Maria, the year of Hurricane Maria, and several years after to calculate ΔNDVI. Specifically, satellite imagery was obtained from 2010, 2017 to 2018, and 2021 to 2023 (Table 1). 2009–2010 USACE NCMP 4-Band 8 Bit Imagery: Puerto Rico and 2021–2023 USDA NAIP 4-Band 8 Bit Imagery: Puerto Rico and USVI were obtained from NOAA Digital Coast Data Access Viewer (https://coast.noaa.gov/dataviewer/#/). Satellite imagery for the effects of Hurricane Maria (years 2017–2018) was obtained from different sources (Table 1).

RESULTS

CHMs (LiDAR)

The pre-Hurricane Maria CHM for the Northeast Corridor Reserve mangroves (Figure 2A) showed a maximum height of 15 m, with an average canopy height of 6.8 m

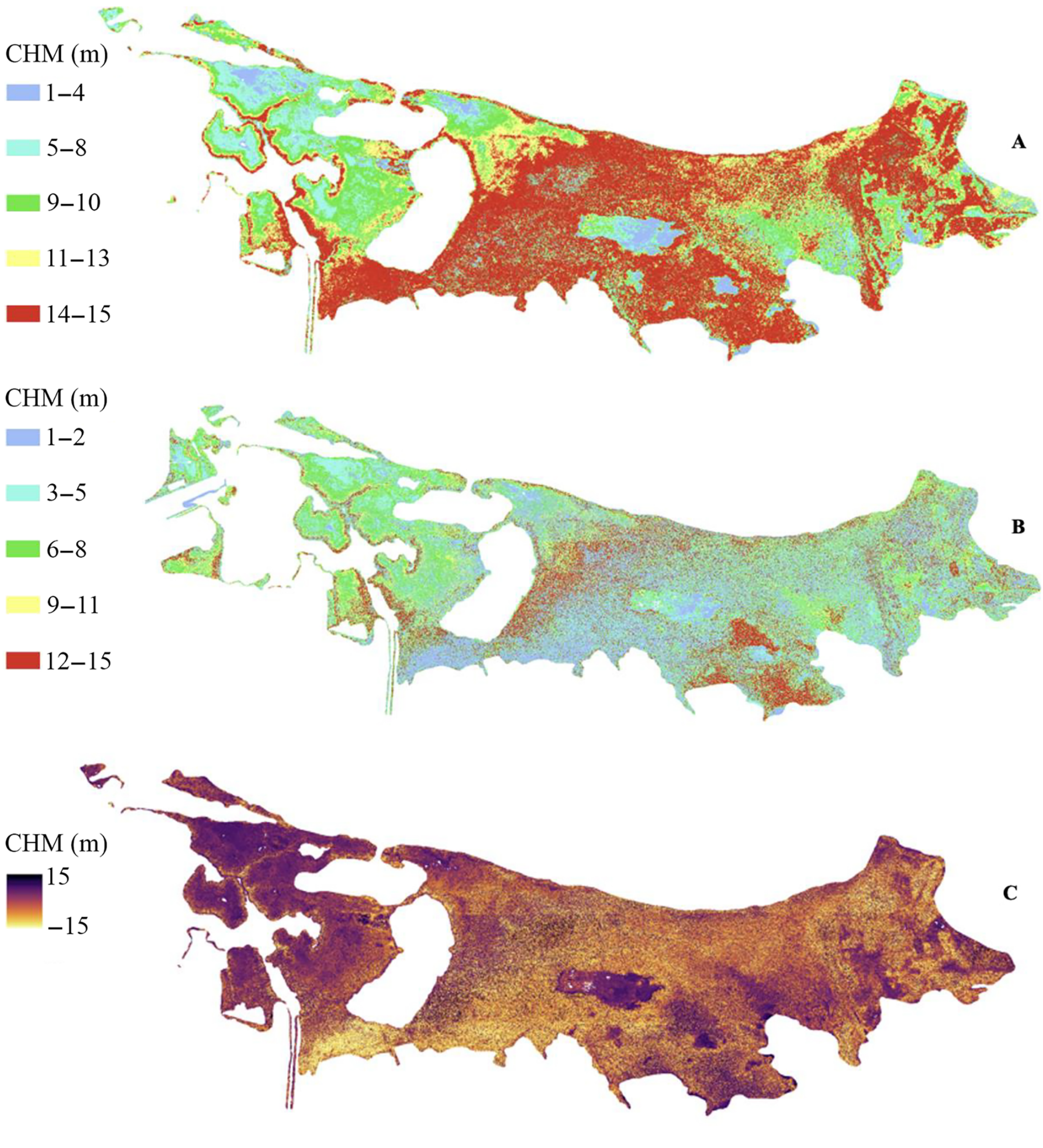

FIGURE 2 Canopy height models (CHMs) for the northeast mangrove ecosystem (A) before (2015) and (B) after (2018) Hurricane Maria, and (C) the height difference between the two CHMs. The canopy heights are shown in meters (m).

± 5.5 m (σ) (Appendix S2: Figure S1). Taller mangroves (10–16 m) comprised 38.7%, while low-canopy mangroves (0–4 m) made up 40.7% of the total area (Table 2).

After Hurricane Maria, the CHM (Figure 2B) shows a dramatic reduction in canopy heights, shifting toward shorter canopy classes. The tallest mangroves (14–16 m) declined from 8.6% to just 1.4%, while the 0–2m category increased from 35% to 46.5% of the total area. The most common canopy height post-Maria was 3–5 m, with an average of 3.7 m ± 3.9 m (σ) (Appendix S2: Figure S2). This widespread canopy loss is visually evident in Figure 2, where the disappearance of red areas signifies the loss of taller mangroves.

In La Parguera, pre-hurricane canopy heights (Figure 3A) were generally shorter, with a maximum height of 15 m, but most mangroves (28.8%) were between 6 and 10 m (Table 2). Post-hurricane CHM (Figure 3B) indicates a substantial loss of mid-range canopy heights, with the 0–2-m category increasing by 29.7%, reflecting widespread defoliation and structural damage. The average canopy height dropped from 5.0 m ± 2.8 m (σ) to 2.8 m ± 2.7 m (σ), indicating more severe height reductions compared with the Northeast Corridor site.

Changes in coastal vegetation (NDVI)

Pre-Hurricane Maria NDVI values in the Northeast Corridor Reserve (Figure 4A) ranged from 0.2 to 1.0, with 56.2% of values between 0.25 and 0.5, indicating low to moderate vegetation density and vigor (Table 3). Immediately after the hurricane (2017), NDVI unexpectedly increased, with most values clustering around 0.5–0.6, a shift explained by foliage loss exposing underlying branches and increasing the near-infrared reflectance (NASA, 2010). By 2021–2023, NDVI values returned to pre-hurricane levels, with an increase in 0.25–0.5 NDVI values from 56.2% to 76.6%, reflecting significant vegetation recovery. However, a 1.7% increase in negative values suggests some areas of persistent mangrove loss.

In La Parguera (Figure 5A), pre-hurricane NDVI ranged from −1.0 to 1.0, with 38.4% of the values being between 0.25 and 0.5, indicating low vegetation density (Table 3). Post-hurricane (2018) NDVI (Figure 5C) showed a similar temporary increase as at the Northeast Corridor Reserve site, peaking around 0.6 due to canopy thinning effects (NASA, 2010). However, by 2021–2023, La Parguera saw a notable 13.2% increase in negative NDVI values, indicating expanded bare ground and greater mangrove loss than in the Northeast Corridor site. The mean change of −1.0 ± 1.9 (σ) suggests that while some areas recovered, others suffered permanent loss, possibly due to lower initial canopy heights and drier conditions limiting regeneration.

Both sites exhibited substantial canopy height reductions and initial NDVI increases, followed by gradual recovery. However, La Parguera experienced more persistent loss, with a greater increase in bare ground and lower post-hurricane NDVI recovery. This difference was associated with differences in pre-storm canopy height, hydrological conditions, and human impacts. The Northeast Corridor had a greater proportion of tall mangroves, which, while heavily damaged, retained some structural integrity, aiding in recovery. The wetter climate in the northeast may have facilitated faster regrowth, while drier conditions in La Parguera may have slowed recovery despite its proximity to San Juan. The Northeast Corridor benefits from conservation efforts that may have aided regrowth. In contrast, La Parguera mangroves face ongoing stressors such as coastal development and altered hydrology, potentially hindering full recovery. This analysis highlights the importance of site-specific factors in mangrove resilience and recovery following extreme weather events.

DISCUSSION

Hurricane Maria had significantly different impacts on the Northeast Corridor and La Parguera mangroves, offering key insights into patterns of mangrove

TABLE 2 The percentage distribution of mangrove canopy height classes before and after Hurricane Maria in the Northeast Corridor (NE) and La Parguera (SW).

Region and timing	Height (m)							
	0–<2	2–<4	4–<6	6–<8	8–<10	10–<12	12–<14	14–<16
NE pre-Maria	35	5.7	4.9	6.8	8.9	11.7	18.4	8.6
NE post-Maria	46.5	17.1	10.5	8.4	6.8	5.4	3.9	1.4
Percent change	11.5	11.4	5.6	1.6	−2.1	−6.3	−14.5	−7.2
SW pre-Maria	16.7	21.9	27.8	19.9	8.9	3.8	0.9	0.1
SW post-Maria	46.5	21	18.8	9.3	3.2	1	0.2	0
Percent change	29.7	−0.8	−9	−10.6	−5.7	−2.8	−0.7	−0.1

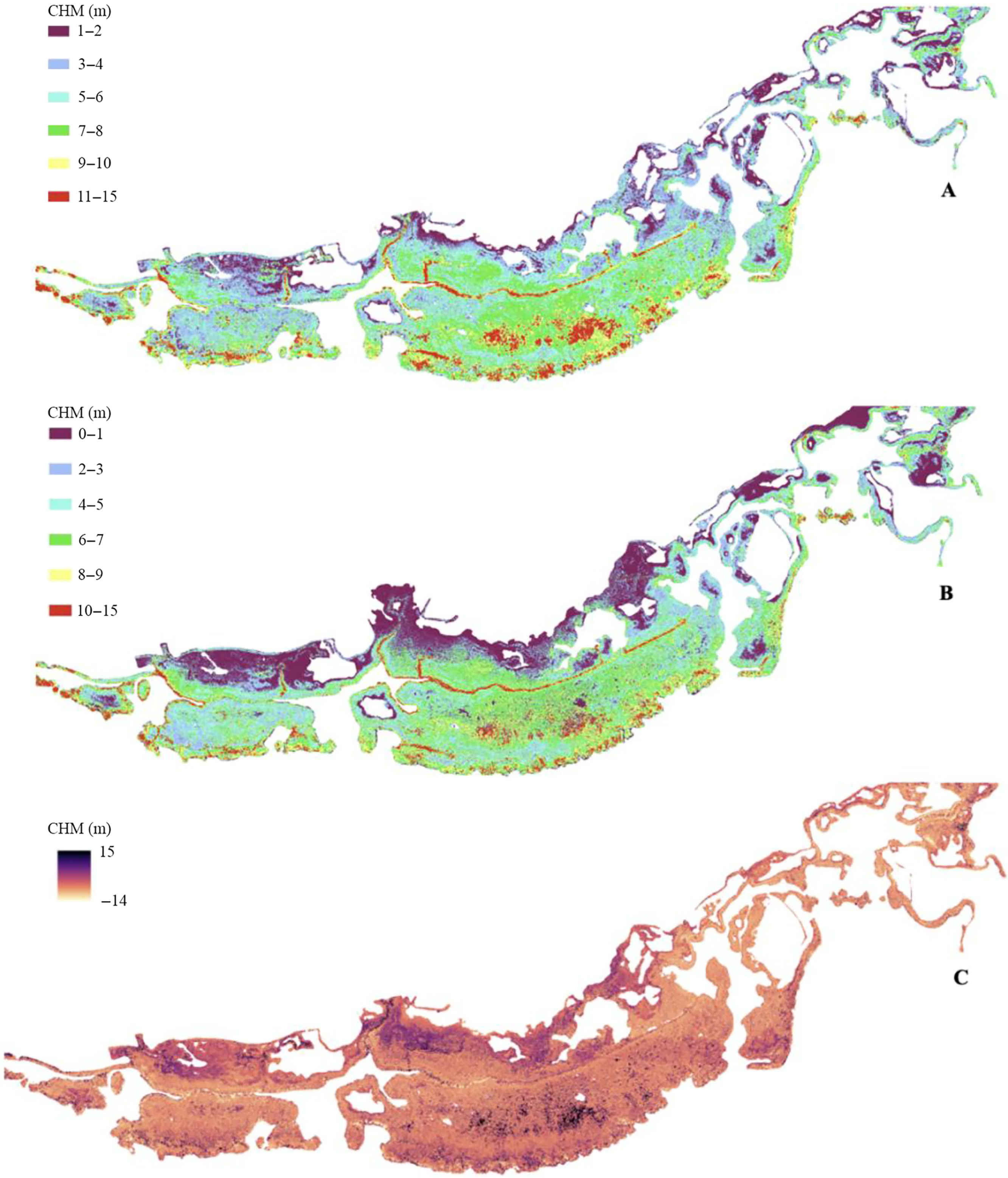

FIGURE 3 Canopy height models (CHMs) for the southwest mangrove ecosystem (A) before (2015) and (B) after (2018) Hurricane Maria, and (C) the height difference between the two CHMs. The canopy heights are shown in meters (m).

vulnerability and resilience. The Northeast Corridor experienced more severe damage, with a 30.1% reduction in canopy height, while La Parguera saw only a 9.3% reduction. This disparity is likely due to a combination of storm intensity, pre-hurricane canopy structure, and local environmental conditions. Given the hurricane's

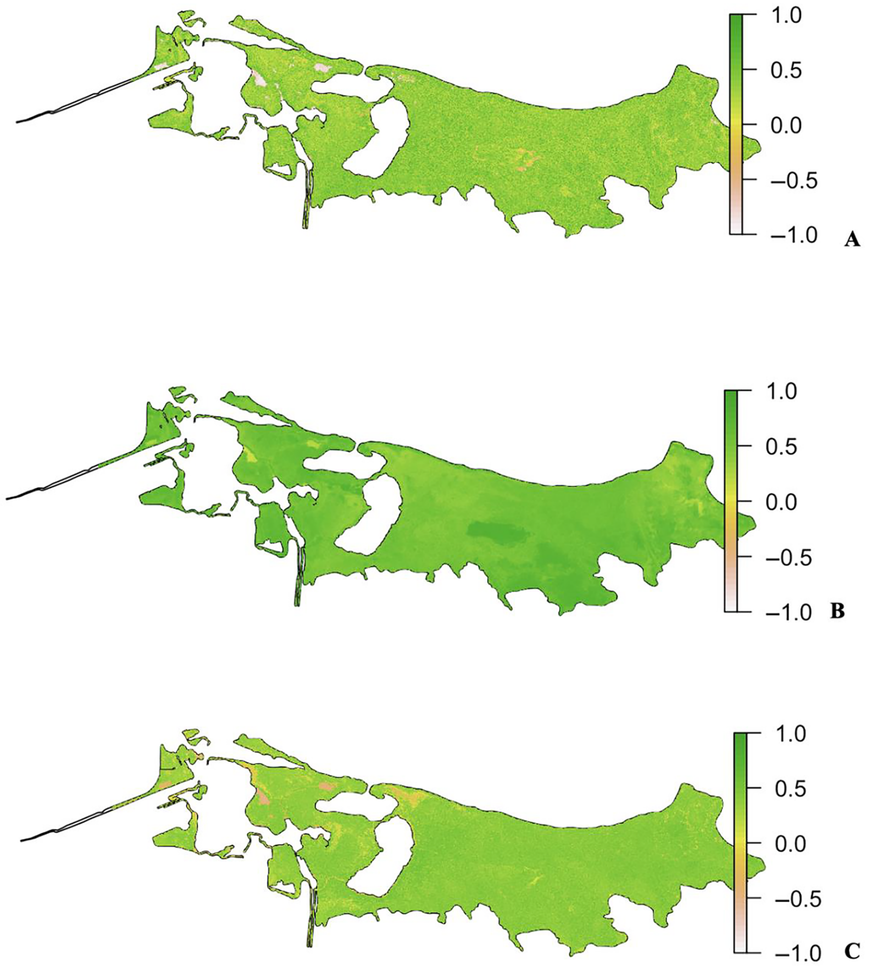

FIGURE 4 Normalized difference vegetation index (NDVI) maps for the northeast Mangrove ecosystem, (A) before Hurricane Maria before (2015), (B) year of Hurricane Maria (2017), and (C) post Hurricane Maria (2023).

TABLE 3 The percentage distribution of mangrove normalized difference vegetation index (NDVI) values before (2010) and after (2021–2023) Hurricane Maria in the Northeast Corridor (NE) and La Parguera (SW).

	NDVI categories							
Region and timing	**−1.0 to <−0.75**	**−0.75 to <−0.5**	**−0.5 to <−0.25**	**−0.25 to 0**	**0 to <0.25**	**0.25 to <0.5**	**0.5 to <0.75**	**0.75 to 1**
NE pre-Maria	0.9	0.4	0.4	0.8	19	56.2	20.3	2.1
NE post-Maria	0	0.1	1	1.8	5.7	76.6	14.8	0
Percent change	−0.9	0.3	0.6	1.1	−13.3	20.4	−5.5	−2.1
SW pre-Maria	1.2	7	4.6	7.6	33.9	38.4	7	0.3
SW post-Maria	0.7	11.7	12.8	8.3	7.3	26.7	32.3	0.3
Percent change	−0.5	4.7	8.3	0.7	−26.7	−11.7	25.2	0

trajectory—moving from southeast to northwest—winds were stronger in the Northeast Corridor, while La Parguera, located in the southwest, was exposed to less-intense wind.

The higher pre-hurricane canopy structure in the Northeast Corridor site e likely contributed to its greater susceptibility to wind damage. Before the storm, 8.6% of the Northeast Corridor mangrove area had canopy heights of 14–16 m, compared to only 0.1% in La Parguera. Taller, denser mangroves, while beneficial for carbon sequestration and ecosystem productivity, can have increased vulnerability due to their higher

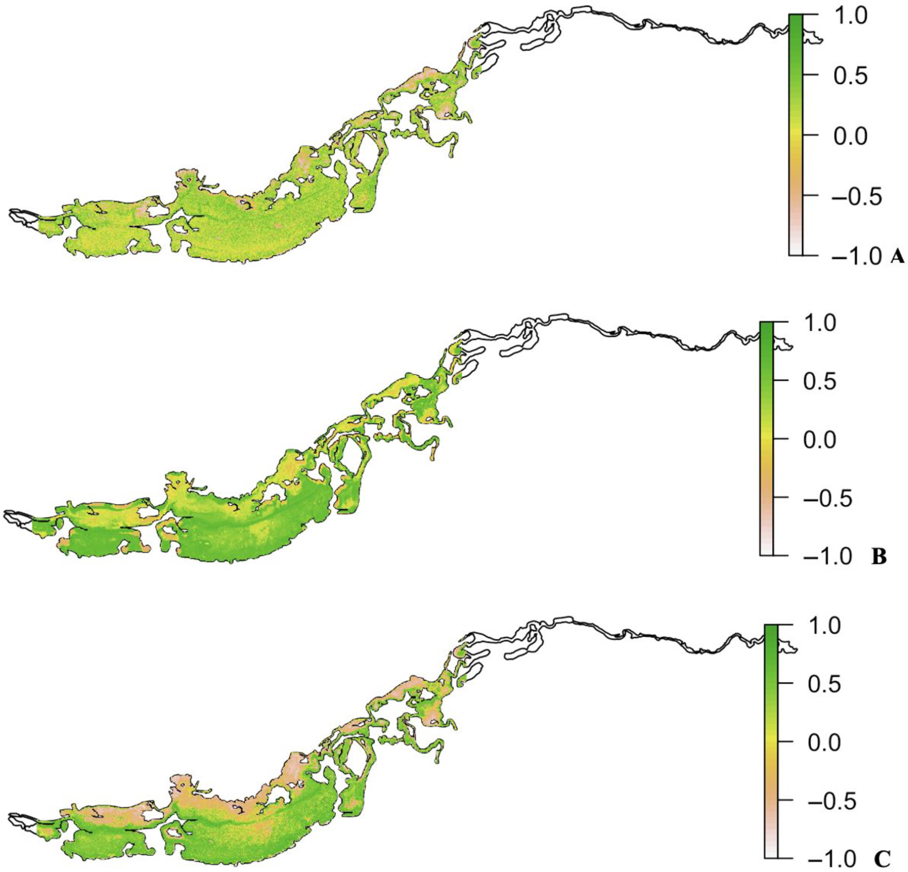

FIGURE 5 Normalized difference vegetation index (NDVI) maps for the southwest mangrove ecosystem (A) before Hurricane Maria (2015), (B) year of Hurricane Maria (2018), and (C) post Hurricane Maria (2023).

exposure to sustained hurricane-force winds (Gao & Yu, 2022). This finding aligns with global patterns, where taller, less frequently disturbed mangroves in high-rainfall regions tend to be more susceptible to extreme storm damage (Simard et al., 2019). Importantly, these results highlight a trade-off between carbon sequestration potential and storm resilience, which should be considered in blue carbon conservation and management strategies.

Beyond canopy loss, Hurricane Maria also triggered widespread mangrove die-off events, particularly in areas where tidal flow was disrupted. Evidence of die-off events, particularly in zones where canopy height declines exceeded 15 m in the Northeast Corridor site and 6–7 m in the La Parguera site, suggests the loss of entire trees rather than just defoliation. One key driver of these events is tidal attenuation, which occurs when storm debris and sediment deposition blocks tidal channels, reducing water exchange (Reed et al., 2018). This process leads to water stagnation, increased salinity, and oxygen depletion, creating conditions that impair mangrove recovery and cause large-scale mortality (Montgomery et al., 2019).

The impact of tidal attenuation on recovery is particularly concerning because it not only kills existing trees but also slows regeneration by limiting seed dispersal, sediment deposition, and nutrient cycling (Furukawa et al., 1997; Krauss et al., 2003). This suggests that hydrological restoration—such as clearing blocked tidal channels—could be a crucial intervention to support mangrove recovery in areas affected by hurricane-induced die-off events.

While changes in canopy height provide strong evidence of hurricane effects, vegetation health assessed through NDVI analysis reveals further differences in recovery trajectories between the two sites. Pre-hurricane NDVI values between 0.5 and 0.75 (moderate to high vegetation vigor) were 14.8% of the area in the Northeast Corridor, but this decreased post-hurricane, with an increase in lower NDVI values (0.25–0.5) of 20.4%. This suggests that vegetation health declined substantially post-hurricane and that while some regrowth has occurred, full recovery has not yet been achieved. In contrast to the Northeast Corridor site, La Parguera NDVI values in the 0.5–0.75 range increased by 25.2% post-hurricane, indicating a stronger recovery trajectory.

Importantly, high NDVI values (0.75–1) remained stable in La Parguera, whereas they declined in the Northeast Corridor. These trends suggest that La Parguera mangroves have recovered more rapidly, likely because they suffered less initial damage. The lower initial canopy heights may have contributed to greater structural resilience, reducing exposure to high wind forces and enabling faster post-hurricane regrowth.

One key factor contributing to slower recovery in the Northeast Corridor is its proximity to urban development near San Juan. Anthropogenic influences such as pollution, altered hydrology, urban development pressures, and sedimentation have been shown to weaken mangrove resilience by reducing water quality, increasing nutrient imbalances, and distributing natural recovery processes (Akram et al., 2023; Bhagarathi & DaSilva, 2024). Pollution from urban runoff and wastewater discharge can increase nutrient loads, leading to hypoxic conditions and algal blooms, which may hinder mangrove seeding establishment. Infrastructural development and coastal modifications alter natural tidal flows, exacerbating tidal attenuation and reducing the ability of mangroves to recover post-disturbance. Increased sedimentation from urban construction can bury mangrove roots, reducing oxygen availability and further delaying regeneration. In contrast to the Northeast Corridor site, the La Parguera site, though not free from human impacts, is a less urbanized site with a more intact hydrological system, which may have facilitated faster mangrove regrowth following Hurricane Maria. The study area in La Parguera is also part of a State Forest and Natural Reserve that limits urban development pressures, contrary to the Northeast, which is exposed more due to its proximity to the San Juan urban center.

The findings from this study highlight several key considerations for mangrove conservation and restoration efforts in hurricane-prone regions. While taller, productive mangroves store more carbon, they are also more vulnerable to extreme storm events. Blue carbon management strategies should thus consider diversifying mangrove age and height structures to enhance ecosystem stability. Since tidal attenuation is a major factor in mangrove die-off and slow recovery, restoration projects should prioritize clearing blocked tidal channels and maintaining natural water flow. Urban-adjacent mangroves, such as those in the Northeast Corridor, may require targeted management strategies to mitigate the effects of pollution, sedimentation, and hydrological changes. Programs such as BoriCorps and other NOAA-funded restoration projects are already being implemented to rehabilitate mangroves damaged by hurricanes. Expanding these initiatives and incorporating local community involvement can enhance long-term ecosystem resilience.

Historical case studies reinforce the potential for mangrove recovery following extreme storm events. For example, Hurricane Katrina (2005) severely impacted U. S. Gulf Coast mangroves, but long-term monitoring showed that natural regrowth and hydrological restoration projects facilitated significant recovery (Alongi, 2008). In 2008, cyclone Nargis caused catastrophic damage to mangroves in Myanmar, but community-led reforestation programs successfully restored 13,000 ha of mangrove forest, highlighting the importance of integrating socio-economic factors into restoration planning (Zöckler & Aung, 2019). Applying lessons from these past events to Puerto Rico's post-Maria recovery efforts can enhance restoration success and improve the long-term resilience of its coastal mangrove ecosystems.

CONCLUSIONS

Hurricane Maria's impact on Puerto Rico's mangroves highlights the vulnerability of these ecosystems to extreme weather events, particularly the increased susceptibility of taller, more productive mangroves to storm damage. The greater canopy loss and die-off events in the Northeast Corridor, compared to La Parguera's more moderate decline and faster recovery, underscore the influence of pre-hurricane canopy height and human disturbances on mangrove resilience. While taller mangroves enhance blue carbon sequestration, their structure makes them more prone to wind damage, emphasizing a trade-off between carbon storage and storm resilience. The slower recovery at the Northeast Corridor site is further linked to urban pressures, such as pollution, hydrological alterations, and sedimentation, which can impede natural regrowth. In contrast, La Parguera's less urbanized setting and lower initial canopy height contributed to faster post-hurricane recovery. These differences highlight the need for targeted restoration strategies, particularly in urban-adjacent mangroves, where human impacts may hinder recovery. Looking ahead, active restoration efforts and socio-economic integration will be critical for ensuring the long-term sustainability of Puerto Rico's mangroves. Lessons from past recovery efforts, such as those following Hurricane Katrina and Cyclone Nargis, reinforce the importance of community engagement, hydrological restoration, and conservation policies in supporting mangrove resilience. As climate change intensifies the frequency and severity of hurricanes, a proactive approach combining natural resilience with targeted management will be essential to safeguarding these vital coastal ecosystems.

ACKNOWLEDGMENTS

The authors thank Dr. Kirk Waters, Rebecca Mataosky, Nate Herold, and Erik Hund from the NOAA Office of Coastal Management (OCM) in North Charleston, SC, for all their help and guidance. This study is supported by The National Oceanic and Atmospheric Administration (NOAA)—Cooperative Science Center (CSC) for Earth System Sciences and Remote Sensing Technologies (CESSRST-II) under the Cooperative Agreement Award #NA22SEC4810016. The author would like to thank the NOAA Office of Education, The Educational Partnership Program with Minority Serving Institutions (NOAA-EPP/MSI), and the NOAA-CESSRST-II for full fellowship support for the corresponding author, Jahnelle Howe. The statements, findings, conclusions, and recommendations are those of the author(s).

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data (Howe et al., 2024) available from Dryad: https://doi.org/10.5061/dryad.2ngf1vhzd.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Howe, Jahnelle, Shakila Merchant, William J. Hernández, Jeffery Pessutti, and Peter Groffman. 2025. "Assessing Mangrove Canopy Height and Health Changes in Puerto Rico Post-Hurricane Maria Using Remote-Sensing Techniques." *Ecosphere* 16(3): e70226. https://doi.org/10.1002/ecs2.70226