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RESEARCH ARTICLE

Taller Trees Experienced Less Crown Damage During a Severe Hurricane in a Tropical Forest

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ABSTRACT

Hurricanes strongly regulate vegetation structure and dynamics in coastal tropical forests by causing tree mortality and damaging the crowns of surviving trees. Despite the importance of this damage for long-term forest demography and carbon dynamics, the patterns and drivers of variation in hurricane-induced damage across heterogeneous landscapes remain poorly quantified. Here, we integrate field inventory data with repeated airborne LiDAR measurements to quantify tree crown damage following Hurricane María (Category 4) in the Luquillo Experimental Forest, Puerto Rico. We applied two approaches: manually delineated crowns and an automatic 3D crown delineation algorithm (AMS3D) to quantify individual crown damage from Hurricane Maria over the 16-ha Luquillo Forest Dynamics Plot (LFDP). Both methods consistently revealed that taller canopies experienced less damage compared with shorter canopy trees, contradicting previous pixel-based remote sensing assessments reporting greater damage in taller trees and forests. Analysis of crown-level responses to hurricanes showed that tall canopy trees (≥ 25 m) suffered approximately 30% less crown area damage than shorter canopy trees (~15 m), while other tree-level factors had negligible effects. At the stand level, canopy height was also negatively associated with damage. Quadrats dominated by *Prestoea acuminata var montana* and *Dacryodes excelsa* experienced less damage. The effect of stand canopy rugosity and topography was limited. Across the landscape, canopies at low elevations experienced higher damage, possibly due to shifts in species composition along the elevation gradient. As climate change is expected to increase hurricane frequency and intensity in the North Atlantic, our findings highlight the need for incorporating organismal attributes (tree size and species identity) into process-based ecosystem models to accurately predict hurricane-induced damage. Furthermore, moving from pixel-based to crown-based remote sensing approaches is essential to correctly capture forest responses and reduce prediction biases in tropical forest vulnerability and resilience under intensifying storm regimes.

Tao Han and António Ferraz contributed equally to this work.

1 | Introduction

Hurricanes and other tropical cyclones are among the largest and most damaging disturbances affecting inland and coastal forests (Ibanez et al. 2024; Uriarte et al. 2019). The degree of damage hurricanes inflict on forests depends on the severity and frequency of storms (Asner and Goldstein 1997; Wehner and Kossin 2024). Category 4–5 hurricanes (Simpson 1974) alter forest structure, drive changes in species composition and diversity, and regulate forest functions (Lugo 2008). Models suggest that the frequency and intensity of severe hurricanes will significantly increase in the North Atlantic due to climate warming, as hurricanes derive their energy from ocean heat (Balaguru et al. 2018; Knutson et al. 2019, 2020). The expected shifts in the frequency and intensity of hurricanes can reduce the long-term resilience of tropical forests, potentially shifting these ecosystems from carbon sink to sources (Hall et al. 2020; Uriarte et al. 2023). Evaluating how these ecosystems respond to severe hurricanes would enable us to more accurately predict their future in a warming world and guide the development of effective strategies to protect them from hurricane damage.

Hurricanes can lead to stem breakage, uprooting, partial crown loss, and standing death, with significant variability among species (Canham et al. 2010; Zimmerman et al. 1994). Among these categories, stem breakage and uprooting represent the most severe forms of damage, with nearly 100% crown loss, and are the most commonly quantified metrics (Ibanez et al. 2024; Walker 1991) and longer lasting legacies of hurricanes. In contrast, nonlethal crown damage, defined as partial loss of branches and defoliation, reduces trees' capacity for photosynthesis and carbon production while also weakening their resilience to drought, pests, and diseases (Anderegg et al. 2015; McDowell et al. 2008; Needham et al. 2022). This type of damage is typically quantified in the field by visually estimating the percentage of remaining crown (Arellano et al. 2021; Zuleta et al. 2022). However, this method is often not accurate because assessments are subjective, and pre-hurricane crown data is lacking. Furthermore, field inventories are labor-intensive and time-consuming, and perhaps more importantly, cannot be scaled to larger areas.

Remote sensing methods offer a powerful approach to detect hurricane-induced structural changes in forest canopies at broad scales. Compared to satellite-based pixel-level analyses (Feng et al. 2020; Hall et al. 2020), airborne LiDAR provides detailed three-dimensional structure information, enabling assessments of structural damage at large scales (Leitold et al. 2021; Uriarte et al. 2023). Such LiDAR-based analyses often use predefined absolute or relative height thresholds to infer canopy loss (Brokaw 1982). For instance, Leitold et al. (2018, 2021) used fixed 1 and 3 m absolute height differences between multi-temporal LiDAR acquisitions to infer canopy change and canopy turnover events, respectively. Recent work suggests that relative height loss thresholds outperform fixed ones in capturing crown dynamics and aligning with observed mortality patterns in the Amazon (Dalagnol et al. 2021). However, the effectiveness and accuracy of this relative threshold for capturing individual-level hurricane-induced crown damage remains unknown. In addition, estimation and analysis of individual crown-level damage from LiDAR data is lacking due to challenges in crown segmentation. Alternatively, automatic crown delineation algorithms such as the Adaptive Mean Shift in 3D (AMS3D) algorithm (Ferraz et al. 2012, 2016) do not require predefined height thresholds to estimate crown damage. Using 3D LiDAR point clouds instead of the canopy height model (CHM), AMS3D can segment individual crowns and estimate both multi-dimensional damage metrics from pre- and post-hurricane LiDAR point clouds, enabling calculation of three-dimensional crown damage. This approach has been applied to extract individual crowns in various tropical forests, including those in Panama, Costa Rica, and French Guiana (Aubry-Kientz et al. 2019; Ferraz et al. 2016, 2020). Nevertheless, AMS3D and other similar algorithms can be sensitive to parameters related to crown allometry and suffer from segmentation errors.

Lack of robust estimates of crown damage further limits our understanding of the biotic and abiotic factors shaping crown damage from individual tree level to landscape scales (Hall et al. 2020; Leitold et al. 2021; Uriarte et al. 2019; Wagner et al. 2018; Yun et al. 2021), which is critical to modeling forest responses and resilience to hurricanes (Needham et al. 2022). Tree-level characteristics such as tree size (diameter, height, and crown dimensions), species identity, and wood density are considered the most important biotic traits influencing hurricane resistance (Arellano et al. 2019; Ibanez et al. 2024). Although trees with larger diameters generally exhibit greater mechanical stability, the relationship between size and hurricane-induced damage remains inconsistent across studies, showing positive, negative, or nonsignificant correlations (Asner and Goldstein 1997; Franklin et al. 2004; Ostertag et al. 2005; Uriarte et al. 2019). The relationship between tree height and hurricane-induced damage also remains uncertain. One hypothesis is that taller trees should experience greater damage because increased wind exposure and longer lever arms amplify mechanical stress (Gardiner 2021). Conversely, taller individuals can also exhibit greater mechanical stability, for example, lower height-to-diameter (H/D), and stronger rooting (Ankori-Karlinsky et al. 2024; Cushman et al. 2021). Besides biomechanical processes, tree height effect can emerge from the interaction between plant life history trait coordination, land use history, and long-term environmental filtering. Taller trees frequently occur in less disturbed, late-successional stands where species show higher structural resistance (Thompson et al. 2002), possibly because late-successional species with high wood density tend to be more resistant to stem damage, while pioneers suffer severe damage during storms (Canham et al. 2010; Rifai et al. 2016; Uriarte et al. 2019; Zimmerman et al. 1994). These species are also generally longer-lived and taller, creating an association between tree height and wind resistance that reflects the history of land use (Thompson et al. 2002; Uriarte et al. 2009). Therefore, height–damage associations can be negative if higher wind resistance of taller canopy trees outweighs higher wind exposure. However, due to the limited availability of reliable height measurements in forest inventories, the height effect on hurricane damage remains underexplored (Ibanez et al. 2024). Species-level traits also influence the extent of hurricane damage. High wood density confers increased resistance to hurricane damage (Zimmerman et al. 1994), although this protection may depend on storm intensity (Uriarte et al. 2019). In general, late-successional species with high wood density are more resistant to hurricane damage than early-successional ones with low wood densities (Canham et al. 2010). Other species traits, such as canopy and root architecture can also confer tree resistance.

For example, flexible stems and leaves and their unique canopy architecture protect palms from wind damage (Uriarte et al. 2019), while root grafting can confer increased stability during storms (Basnet et al. 1993; Zimmerman et al. 1994).

Stand-level characteristics, such as canopy rugosity (variation in surface height) and topography (aspect and elevation), might also influence hurricane damage (Ankori-Karlinsky et al. 2025). However, the relationships between these variables and crown damage remain poorly understood. For example, trees at higher elevations (e.g., peaks and ridges) generally suffer more damage due to increased wind exposure (Boose et al. 1994), but the opposite pattern was also reported, with trees at lower elevations experiencing more severe damage than those at higher elevations (Leitold et al. 2021). These differences may arise from variation in forest composition along elevation gradients and soil moisture, especially during storm events. Addressing these knowledge gaps requires an integrative approach that combines individual crown delineation, species identification, and LiDAR-derived damage metrics with field-based observations.

Hurricane María (Category 4) struck the Luquillo Experimental Forest in Puerto Rico in October 2017, causing widespread damage (Figure 1), offering a unique opportunity to study forest responses to severe hurricanes from individual trees to landscape level. In this study, we leveraged pre-and post-storm high-resolution aerial imagery and LiDAR data collected over 779.04 ha of forest, along with damage inventory data from the 16-ha Luquillo Forest Dynamics Plot (LFDP), to address three key questions: (1) What is the magnitude and spatial variation of hurricane-induced crown damage for canopy trees? (2) What is the relationship between canopy height and crown damage? Did taller canopy trees experience more or less crown damage? (3) Do factors other than canopy height affect crown damage from individual and landscape scales?

To answer the first question, we used two independent methods to segment individual crowns and estimate crown damage. For the second question, we evaluated the height effect on various crown damage metrics estimated using both methods. To address the third question, we tested three hypotheses at both crown and plot scales: (1) Fast-growing and early-successional species like *Cecropia schreberiana* will suffer more crown damage than late successional ones, and wind-resistant species such as palms and tabonuco will suffer low crown damage; (2) Greater canopy complexity, measured as local neighborhood height variability at the individual neighborhood scale and plot-level canopy rugosity at the plot scale, will result in higher hurricane damage; (3) Trees on windward slopes and at higher elevations will suffer more severe damage due to greater wind exposure. We focus on those three primary factors of species identity (palms and Cecropia), canopy complexity, and topography because these attributes can be consistently derived from LiDAR data from individual to plot scales.

2 | Materials and Methods

2.1 | Study Area

The Luquillo Experiment Forest (LEF) spans an elevation range of 100–1000 m. Rainfall ranges between 2000 mm/year at lower elevations to 5000 mm/year at high elevations. The LEF contains four main vegetation zones based on elevation: (1)

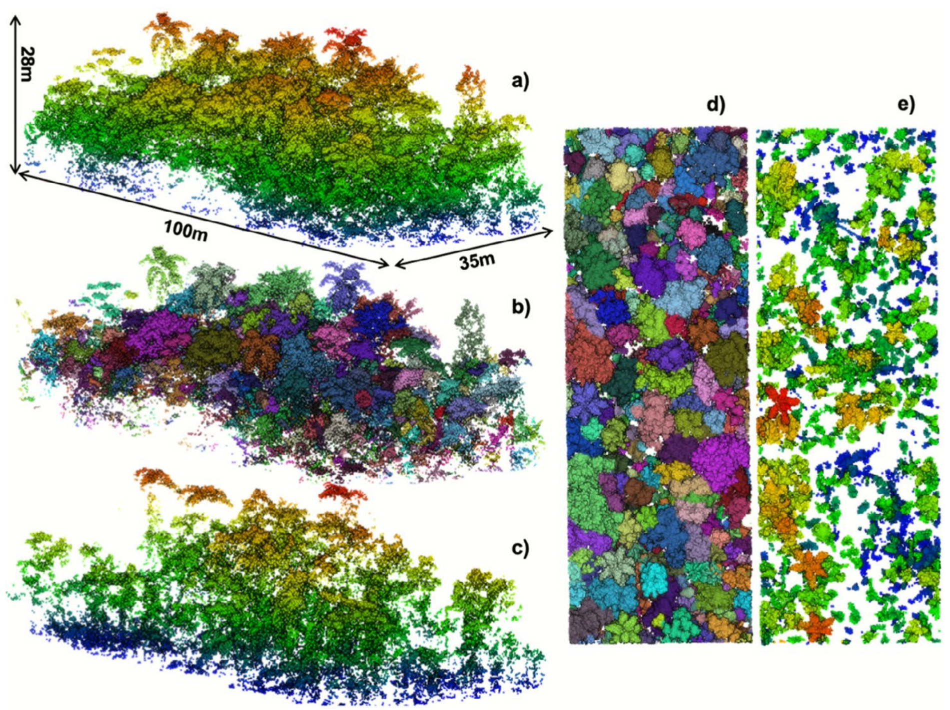


FIGURE 1 | The Impact of Hurricane María shown through a lidar point cloud transect (100 m × 35 m) in (a, b, d) pre- and (c, e) post-hurricane conditions over LFDP (320 m × 500 m). In (a) and (c) the points are colored by height, whereas in (b) and (d) the random colors represent different individual crowns segmented by AMS3D (Ferraz et al. 2012, 2016). We show the points cloud from (a–c) a profile and (d and e) nadir perspective. Lidar points lower than 2 m have been removed for visual purposes.

tabonuco forest, found up to approximately 600 m, is dominated by *Dacryodes excelsa* Vahl; (2) Palo Colorado forest, located between 600 and 900 m, is dominated by *Cyrilla racemiflora* L.; (3) Sierra palm forest, dominated by *Prestoea acuminata var. montana* (Graham) A. Henderson & Galeano, occurs above 500 m; (4) Elfin woodland, found above 900 m, is characterized by stunted vegetation adapted to harsh conditions (Leitold et al. 2021; Weaver 1983). Palms dominate at higher elevations and in riparian areas, although palms are also present in lower elevation stands (Uriarte et al. 2023).

This study area included in the LFDP, a 16-ha (320 m × 500 m) long-term monitoring plot in the Luquillo Experimental Forest (18°20′ N, 65°49′ W). The LFDP is classified as a subtropical wet forest within the Holdridge life zone system (Lugo et al. 1999). Mean annual precipitation is 3500 mm, mean annual temperature 25.2°C, and elevation ranges from 320 to 450 m. The LFDP is laid out on a grid of 400 20 × 20 meter subplots. Soil in the LFDP is derived from volcaniclastic rock. The vegetation in the LFDP is characterized as a Sierra palm forest zone, dominated by the palm *Prestoea acuminata var. montana* and several late-successional tree species such as *Dacryodes excelsa*, *Sloanea berteroana* Choisy ex DC. and *Manilkara bidentata* (A. DC.) A. Chev.

These forests have a well-documented history of natural and human disturbances over the past century. Prior to 1932, parts of the LFDP were subjected to light logging and agriculture, but the forest structure and canopy cover had substantially recovered by 1989. After a 57-year period without major storms, two severe hurricanes impacted the forest: Hurricane Hugo in 1989, a Category 3 storm with wind speeds of 166 km/h, and Hurricane Georges in 1998, also a Category 3 storm with wind speeds of 144 km/h. Following an 18-year recovery period after Hurricane Georges, a Category 4 storm, Hurricane María, with wind speeds of 250 km/h, struck the island in 2017 (Uriarte et al. 2019).

2.2 | Data

2.2.1 | Ground Census Data

Pre-hurricane ground observation data for the LFDP was collected during the 2016 census, providing detailed information on pre-storm tree characteristics, including stem locations, species identification, and stem diameters. The census documented a total of 140 species, for which wood density data are available for 121 tree species.

Tree damage data for the LFDP was collected in 2018 following Hurricane María. The surveys recorded several qualitative and quantitative observations on tree damage for all trees with a diameter at breast height (DBH) of ≥ 10 cm resulting from the hurricane, such as stem break or uprooting and type of damage to stems, tree crowns, and branches. Immediate mortality from the storm was also recorded (see Uriarte et al. [2019] for details).

2.2.2 | Airborne Lidar Data

Airborne lidar data covering a portion of the LEFs (779.04 ha) were collected using NASA Goddard's Lidar, Hyperspectral, and Thermal (G-LiHT) Airborne Imager (Cook et al. 2013) in two separate campaigns. Data were acquired in March 2017 (pre-hurricane) and April 2018 (7 months post-hurricane). Both surveys employed the same G-LiHT v2 instrumentation, which included two VQ-480i scanning lidar (Riegl, Horn, Austria) and an additional high-resolution camera to provide 3-cm resolution RGB imagery (Phase One, Copenhagen, Denmark). Specifically, we used digital terrain models (DTMs), digital surface models (DSMs), and CHMs produced for each survey at a 1-m spatial resolution available from G-LiHT data archive. The DTM represents the elevation of the ground and the DSM captures the elevation of canopy surface. The CHM is calculated as the difference between the DSM and DTM, representing canopy height. We also used pre- and post-hurricane 3D point clouds for the LFDP.

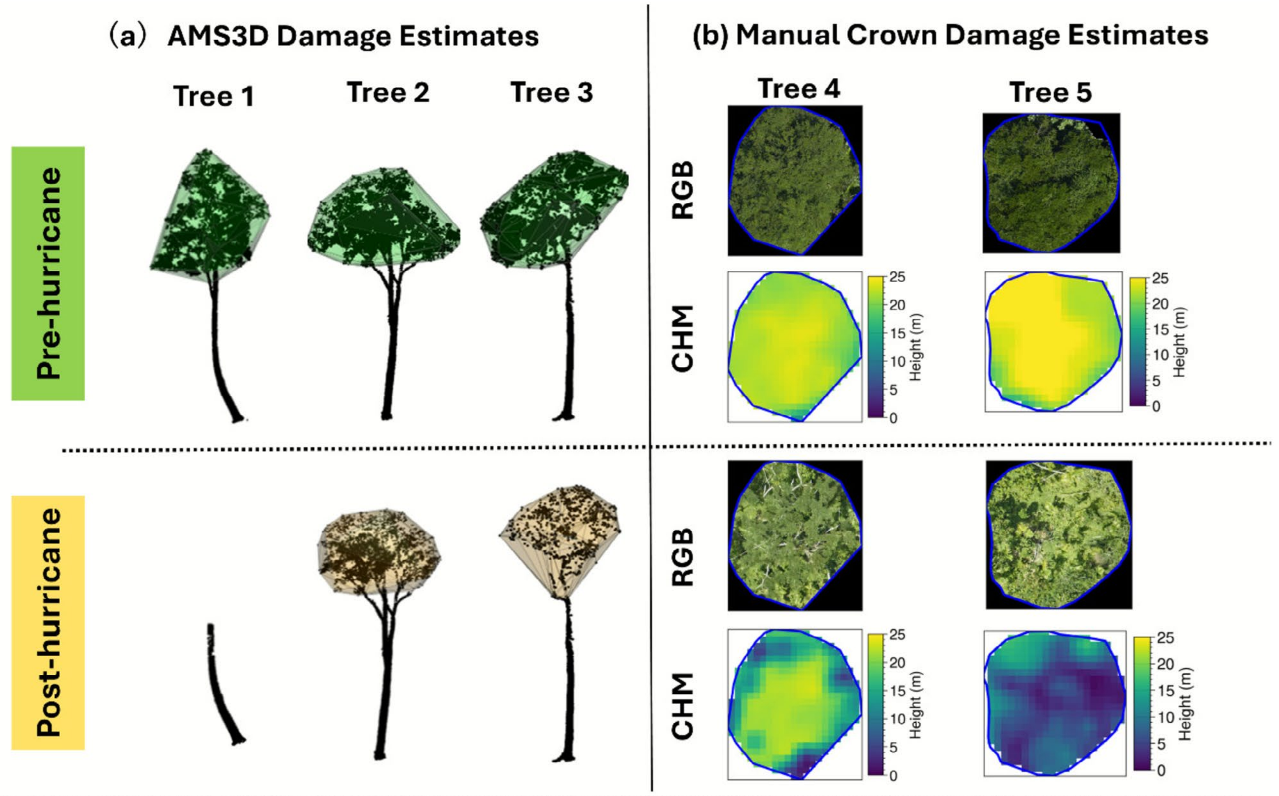
2.2.3 | Manually Delineated Crowns

High-resolution (3 cm × 3 cm) G-LiHT georeferenced aerial RGB images of the LFDP were used to manually segment individual tree crowns (Gan 2022). To enhance the crown delineation process, we conducted visual inspection of color, shape, and texture in the RGB images, supplemented by auxiliary datasets such as the LiDAR-derived CHM and field inventory data. Due to slight spatial misalignments between the RGB imagery and CHM, the crown boundaries initially delineated in the RGB data were adjusted to align with their corresponding positions in the CHM.

The manual delineations were performed in QGIS using the toggle editing tool. A total of 3840 overstory tree crowns visible in the aerial imagery from the LFDP area were delineated. This number closely aligns with the total number of stems with a diameter at breast height (DBH) greater than 20 cm recorded in the census data. Those canopy trees are more visible to LiDAR owing to their height and canopy exposure. To ensure data quality, all preliminary crown delineations were carefully reviewed by a team of forest ecologists with expertise in the study area. The finalized manual crown dataset is publicly available to support further research and analysis (Gan 2022).

2.3 | Crown Damage Detection

We used two independent methods for crown damage detection (Figure 2): (1) a state-of-the-art automated crown segmentation algorithm AMS3D (Ferraz et al. 2016) and (2) an approach based on CHM changes within manually delineated crowns constrained by ground mortality survey (CHM method hereafter). AMS3D has the advantage of detecting full 3D canopy changes while the manual crown delineation provides additional species information for further analysis. The AMS3D algorithm was parameterized using a locally derived height–crown radius allometry based on a number of manually delineated crowns in the Luquillo Experimental Forest. Both methods are subject to uncertainties caused by under or over-segmentation of canopy tree crowns. To qualitatively evaluate crown damage detected by the two methods, we also conducted 3D change detection using raw lidar point clouds between 2017 (pre-hurricane) and



Broken/uprooted stems	yes	no	no	—	—
Crown height loss	—	10%	4%	3%	37%
Crown length loss	—	6%	7%	—	—
Crown area loss	—	60%	53%	44%	100%
Crown volume loss	—	68%	76%	—	—
Plant material loss	—	79%	83%	—	—

FIGURE 2 | Illustration of individual crown damage estimation using two different approaches: (a) AMS3D algorithm and (b) relative height loss threshold of 19% based on manual delineation (see Supporting Information for details); Plant material loss from AMS3D is calculated as the relative reduction of number of lidar points associated with each crown between pre- and post-hurricane point clouds. Plant material loss, crown length loss, and volume loss are not available for CHM method.

2018 (post-hurricane) and examined whether estimated full crown loss (crown area loss > 90%) corresponded to significant 3D distance changes.

2.3.1 | AMS3D

We employed the AMS3D algorithm to extract individual tree crowns (ITCs) from the LiDAR point cloud (Ferraz et al. 2012, 2016). The AMS3D algorithm was parameterized using local allometric relationships between tree height and crown width, as well as between tree height and crown depth (Ferraz et al. 2016). This method has previously demonstrated strong performance in estimating forest attributes such as stem density, crown area, and height distributions, tree-level basal area, and biomass across several tropical forest sites (Ferraz et al. 2020). In this study, a total of 4218 overstory tree crowns were segmented from the pre-hurricane LiDAR point clouds. Crown damage, expressed in terms of height, area, and volume loss, was then calculated as the difference in crown attributes (height, area, and volume) derived from the pre- and post-hurricane AMS3D segmentations (Figure 2).

2.3.2 | CHM Changes Within Manual Crowns

We also used CHM changes within each manually delineated crown to quantify crown damage. Due to the absence of a standardized protocol for detecting crown loss using CHM changes, we calibrated relative height loss thresholds ($RHLT_{CHM}$) against ground-based damage observations (see Figures S1 and S2). Specifically, we evaluated a series of relative height loss thresholds ($RHLT_{CHM}$ of 10%–50%, Figure S1) and determined which value resulted in full crown loss ratio values ($FCLR_{CHM}$) that best matched the observed 44.66% ground stem loss ratio (see Table S1 for definitions) across the entire LFDP (Uriarte et al. 2019) because both metrics should approximate the fraction of full crown loss for canopy trees. Based on this analysis, we selected a $RHLT_{CHM}$ of 19%, which resulted in a $FCLR_{CHM}$ closely aligned with the observed stem loss ratio in the LFDP (see Supporting Information). The key metrics and their definitions used in benchmarking and subsequent analysis process are also summarized in Table S1. Individual crown damage (ICD_{CHM}) was assessed by comparing pre- and post-hurricane CHMs at 1-m resolution, derived from airborne LiDAR data (Figure 2). Crowns with an area smaller than $4\,m^2$, which accounted for 1.51% of all crowns, were excluded from the analysis (Leitold et al. 2018).

Furthermore, we evaluated the spatial consistency and correlations between damage estimates derived from manually delineated crowns (ICD_{CHM}) and those generated using the AMS3D algorithm (ICD_{AMS3D}). To enable this comparison, we calculated the centroid of each AMS3D-delineated crown and applied a nearest neighbor algorithm to match them with their corresponding manually delineated crowns. Because the AMS3D dataset contains 378 more crowns than the manual dataset, some manual crowns were matched to two or more AMS3D crowns. However, this overlap should not affect the comparison of crown damage between the two methods since these instances represent fewer than 10% of all manual crowns.

We also computed the cloud-to-cloud (C2C) distance between the 2017 (pre-hurricane) and 2018 (post-hurricane) 3D point clouds in CloudCompare v2.13.2. This metric represents the distance for each lidar return in the 2017 point cloud to the closest return in the 2018 point cloud. Larger distances between 2017 and 2018 returns indicate a likely loss of plant materials. We overlaid polygons corresponding to estimated full crown loss (defined as area loss > 90%) from both methods with the 3D distance to qualitatively assess individual crown segmentation and crown damage detection from both methods.

2.4 | Analysis

2.4.1 | Height Effect on Crown Damage Metrics

To evaluate the relationship between tree height and crown damage, we applied a moving window approach across the height gradient to assess how crown damage metrics varied with height. We incorporated four damage metrics in the height effect analysis: (1) proportion of full crown loss (area damage > 90%), (2) change in 2D crown area, (3) change in crown maximum height, and (4) change in 3D crown volume. For the CHM-based method, the analysis was limited to the first three metrics since crown volume cannot be calculated with this method.

2.4.2 | Crown Damage Drivers at Individual Level, Quadrat Level, and Landscape Scale

To evaluate our hypotheses on drivers of crown damage other than height, we employed an XGBoost regression tree model in combination with SHAP (SHapley Additive exPlanations) values (Lundberg and Lee 2017). SHAP values reflect the partial contribution from each variable to each model prediction. We used the CHM-based damage in this analysis because individual-crown-level species information is only available for manually delineated crowns, and it is straightforward to apply the same relative height change threshold from individual to quadrat and landscape scales.

At the individual tree level, we modeled individual crown damage as the response variable and extracted structural and topographic attributes, including maximum crown height, crown area, elevation, land-use history and aspect from the pre-hurricane LiDAR for each delineated crown. The land-use history variable includes two categories: *disturbed* and *undisturbed*. Disturbed areas are defined as regions with less than 80% forest cover in 1936, whereas undisturbed areas correspond to regions with greater than 80% forest cover in 1936. Individual-level diameter and wood density data were not available, due to the challenges of accurately matching individual crowns with the GPS locations of censused trees, particularly in dense tropical forests. We also calculated the height difference between each focal crown and its neighboring crowns within a 20-m radius to assess local canopy structure. To test effects of height and species, we manually labeled 208 *Prestoea acuminata* var. *montana* and 194 *Cecropia schreberiana* crowns using high-resolution G-LiHT RGB imagery, which are easily identified by visual inspection. The spatial distributions of all seven variables used in the individual crown damage analysis across the LFDP are presented in Figure S3. The correlation matrix among these seven variables is shown in Figure S4. Additionally, we provide distributions of aspect, elevation, crown height, and crown area across different species (Figure S5).

At the stand scale, we tested the influence of canopy height, canopy rugosity, species composition, land-use history and topographic factors on canopy damage using a 40×40 m quadrat aligned with the LFDP plot. We defined the quadrat-level damage as the fraction of 1 m grid cells experiencing relative height change greater than 19%. Although there are no exactly matching ground-based metrics for this damage metric, we assessed the correlation between this quadrat-level canopy damage proxy and ground-based basal area loss ratio (Figure S6). For each quadrat, we calculated canopy rugosity as the within-quadrat variation in canopy height and derived median aspect and elevation from LiDAR-based aspect and DTM layers. Additional covariates included median canopy height, total basal area, basal area-weighted wood density, maximum diameter (mean diameter of five largest trees), and pre-hurricane species composition. For species composition, we calculated the basal area fractions of all species in each quadrat and focused on the nine most dominant species, which account for approximately 59% of all inventoried trees (Table S2). The spatial distributions of all 17 variables used in canopy damage analysis across the LFDP are presented in Figure S7. We also provide a correlation matrix of all covariates to show potential collinearity among predictors (Figure S8).

To extend our analysis to the landscape scale, we applied the same 40×40 m quadrat approach across the full 779.04 ha LEF area where repeated LiDAR data was available. Since species composition data and land-use history were not available outside of the LFDP, we only included canopy rugosity, elevation, aspect, and median height as predictors. Quadrats with pre-hurricane canopy heights below 9 m were excluded from the analysis, as this threshold corresponds to the minimum crown height considered in the individual crown damage assessment. In addition, we quantified the exposure of each quadrat using the EXPOS model, a simplified framework that integrates hurricane track, wind speed, and topography to estimate spatial heterogeneity in wind impact (Boose et al. 2004). Exposure was not included at the individual crown level, as over 90% of crowns within the LFDP were classified as protected. The spatial distributions of all five variables used in the canopy damage analysis across the landscape are presented in Figure S9. The correlation matrix among these five variables is shown in Figure S10. For all XGBoost models, we applied tenfold cross-validation to optimize hyperparameters and assess model performance.

3 | Results

3.1 | Crown Damage Detection and Comparison

The distribution of crown area (Figure 3a) shows that the median crown area derived from the CHM-based method is smaller than that obtained from the AMS3D delineation ($20.0\,m^2$ vs. $31.2\,m^2$) because AMS3D tends to over-segment larger crowns, especially in the southern part of LFDP, compared with the manual segmentation (Figure 3d,e). In contrast, both methods exhibit comparable height distributions, with median values of 20.2 m for CHM and 19.4 m for AMS3D (Figure 3b). The CHM method identifies a greater number of crowns with both low and high levels of damage relative to AMS3D. The median crown damage estimated by the CHM approach is approximately 10% higher than that derived from AMS3D (Figure 3c). Overall, only 5% of manual delineated crowns showed no damage based on LiDAR analysis and approximately 50% of crowns lost more than 84% of their area during Hurricane María (Figure S11). In contrast, around 20% of AMS3D-delineated crowns exhibited no damage, with a median ICD_{AMS3D} of 74%. Additionally, 20% of AMS3D crowns showed no volume loss, and the median crown volume damage was 86% (see Figure S11).

Despite differences in average damage estimation, patterns in spatial variation of individual crown damage (ICD) within the LFDP are highly consistent between the two methods. Both

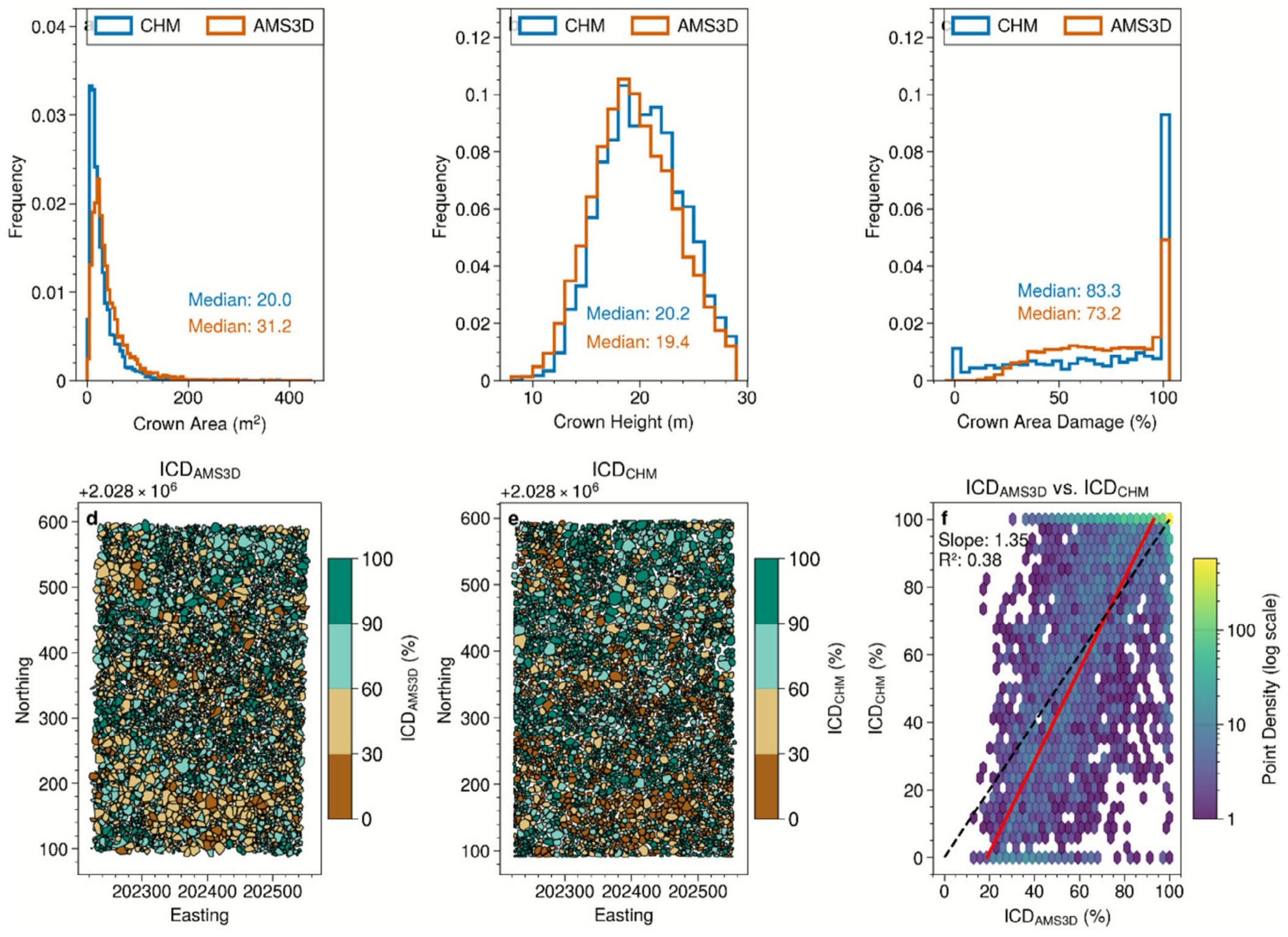


FIGURE 3 | Comparison of crown metrics and crown damage between AMS3D and CHM methods, and spatial pattern of individual crown damage at LFDP. (a) Frequency distribution of crown area for AMS3D and CHM; (b) Frequency distribution of crown height for AMS3D and CHM; (c) Frequency distribution of crown area damage for AMS3D and CHM; (d) Individual crown damage for AMS3D (ICD_{AMS3D}); (e) Individual crown damage for manual delineated crowns (ICD_{CHM}); (f) Hexbin plot showing the relationship between damage estimates from automatic and manual crown delineations (ICD_{AMS3D} vs. ICD_{CHM}). Each bin represents point density. The red line between ICD_{AMS3D} and ICD_{CHM} is fitted by reduced major axis (RMA) regression as both metrics have errors.

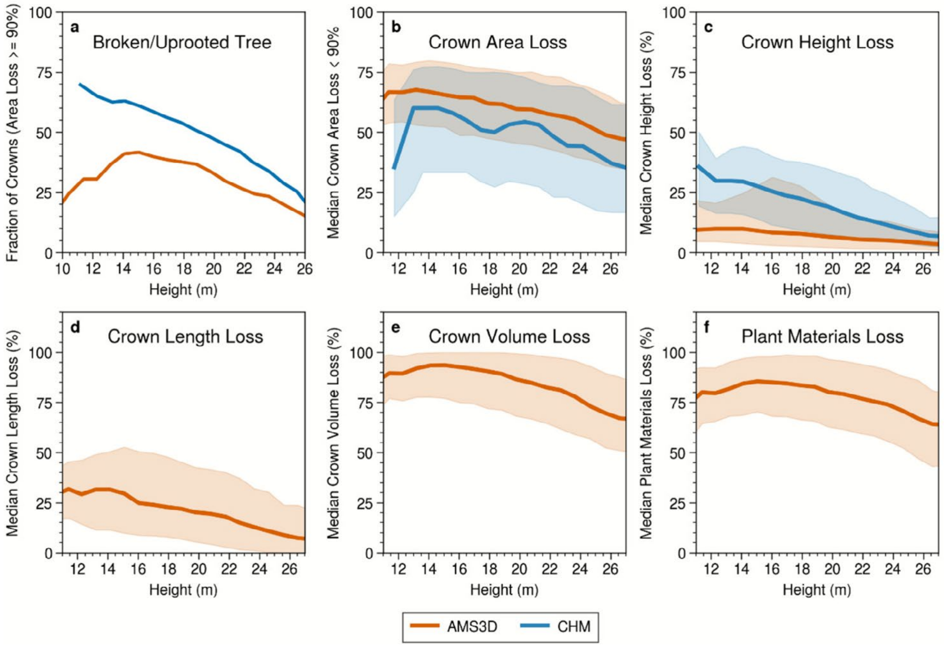


FIGURE 4 | Influence of tree height on crown damage metrics using moving windows in canopy height. (a) Fraction of crown with area damage higher than 90% across height; (b) Median crown area damage for crowns with area loss less than 90% across height; (c) Median crown height loss across height; (d) Median crown length loss across height; (e) Median crown volume loss across height; (f) Median plant materials loss across height. The shading indicates 95% confidence intervals.

methods revealed that the most severely damaged crowns were in the northern region of the LFDP, whereas those crowns in the southern areas experienced lower crown damage (Figure 3d,e). Moreover, the slope between corresponding ICD_{AMS3D} and ICD_{CHM} is 1.35 (Figure 3f), and both metrics show strong agreement in identifying severely damaged crowns, particularly those with ~100% loss (yellow bins). Three-dimensional change detection analysis (Figure S12) further confirmed that both the AMS3D and CHM methods successfully captured significant canopy point cloud changes.

3.2 | Height Effect on Crown Damage

The proportion of crowns exhibiting full crown loss (area damage > 90%) decreased with tree height for both methods, indicating that taller trees were generally less damaged by Hurricane Maria (Figure 4a). In addition, both methods reveal a negative relationship between crown height and crown damage for surviving trees (area damage < 90%) (Figure 4b). Moreover, for crown height damage, both methods show a decreasing trend with tree height; however, the CHM estimates declined from approximately 35% to 10%, whereas AMS3D estimates decreased from around 10% to 5% (Figure 4c). The difference implies AMS3D estimated smaller height loss compared with the CHM method, particularly for shorter canopy trees, likely arising from differences in crown segmentation and height estimation between the two methods. Crown volume damage from the AMS3D is generally very high (mostly > 75%) while also demonstrating a declining trend with increasing tree height. This declining trend across height was also consistent to crown length loss and plant material loss.

3.3 | Crown Damage Driver Analysis

3.3.1 | Drivers of Individual Crown Damage at the LFDP

The XGBoost model, which incorporated crown area, tree height, elevations, aspect, neighbor height, and species as predictors, explained 20.13% of the variance in crown damage for manually delineated crowns, with a cross-validation root mean square error (CV-RMSE) of 31.70%. Among all predictors, tree height was the most influential, with taller crowns exhibiting lower crown damage (Figure 5a). Canopy crowns taller than 25 m experienced 20% less individual crown damage compared with the average while canopy crowns shorter than 15 m suffered 10% more damage than the average. The variables including elevation, neighboring height, aspect, and crown area had smaller effects on crown damage. We also observed that trees in undisturbed areas exhibited approximately 2% less crown damage compared to those in disturbed areas (Figure 5f). Moreover, we found *Cecropia schreberiana*, a species particularly vulnerable to wind damage, experienced higher crown damage compared with average, although the magnitude of this species effect was relatively low, at approximately 3.0% (Figure 5g). In contrast, palms experienced similar individual crown damage compared with the average.

3.3.2 | Drivers of Quadrat-Level Canopy Damage at the LFDP

The XGBoost model, which incorporated elevation, aspect, canopy rugosity, height, basal area, maximum diameter, mean wood density and nine dominant species at the LFDP explained 93.94% of

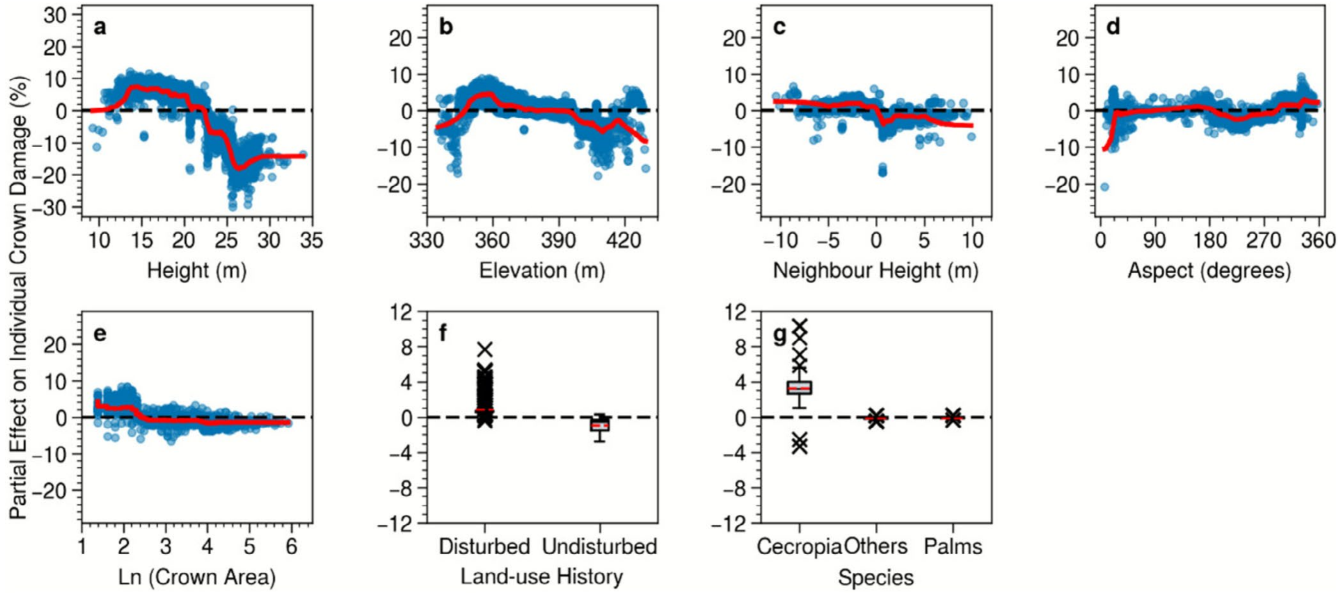


FIGURE 5 | The spatial pattern of individual crown damage at LFDP from CHM estimates (a) and the partial effects of tree-level factors on individual crown damage based on SHAP values of XGBoost regression modeling: (a) Height; (b) Elevation; (c) Neighbor Height; (d) Aspect; (e) Crown Area; (f) Land-use History; (g) Species. Each dot represents SHAP value of one crown and red line represents moving average.

the variance in canopy damage, with a CV-RMSE of 11.88%. At the quadrat scale, taller canopies were associated with lower canopy damage, consistent with our tree-level analysis (Figure 6a). A quadrat with an average canopy height of 25 m experienced about 10% less canopy damage compared with a quadrat with an average canopy height of 15 m. Lower canopy rugosity, indicative of more uniform canopy structure, also reduced canopy damage by up to 5% (Figure 6b). In addition, quadrats with lower basal area were generally more vulnerable to damage (Figure 6c). Elevation, aspect, quadrat-level wood density and tree maximum diameter showed less clear influence on canopy damage.

The increased abundance of *Dacryodes excelsa* and *Prestoea montana* was linked to lower canopy damage, but this effect became evident only when their relative abundances exceeded approximately 25% and 40%, respectively (Figure 6h,i). In contrast, the abundance of the remaining seven species showed no detectable effects on canopy damage. Land-use history showed no impact on canopy damage, possibly because its effect had been captured by the variation in species compositions (Figure 6q).

3.3.3 | Drivers of Quadrat-Level Canopy Damage at the LFF

In addition to applying 40 × 40 m quadrats within the LFDP, we extended this approach to the broader Luquillo Experimental Forest (LEF) to investigate how elevation, canopy height, wind exposure, aspect, and canopy rugosity influence hurricane-induced canopy damage. At the landscape level, the XGBoost model, which incorporated elevation, aspect, canopy rugosity, and height, explained 42.41% of the spatial variance in 40 × 40 m quadrat canopy damage, with a CV-RMSE of 15.27%. Across the entire 779.04 ha lidar transect, we observed a clear spatial gradient, with canopy damage consistently decreasing from west to east (Figure 7a), or in the upslope direction (Figure 7b). Overall, at least the median canopy damage of the 40 × 40 m quadrats was 54%. SHAP values suggest canopies at lower elevations experienced greater damage (Figure 7b), and those in more wind-exposed locations also exhibited higher canopy damage (Figure 7c). Increasing canopy height reduced canopy damage for canopies taller than 15 m, the same as results at LFDP. Meanwhile, canopy height showed a small positive effect on canopy damage for canopies shorter than 15 m (Figure 7d). In contrast, the topographic aspect had a relatively smaller impact on damage compared to elevation and height (Figure 7e). Forests with east-facing aspects tended to have higher damage (less than 10%) than those facing west. Additionally, canopy rugosity has limited impact on canopy damage (Figure 7f).

4 | Discussion

4.1 | Detecting Crown-Level Damage With LiDAR Data

Detecting individual tree crown damage in tropical forests is a challenging remote sensing task yet critical to parameterizing and benchmarking vegetation demography model predictions (Fisher et al. 2018; Needham et al. 2022). The high spatial consistency between AMS3D crown damage, CHM-based damage with manual crown delineation, and 3D point change (Figure 3 and Figure S12) demonstrates that our methodologies could robustly estimate spatial patterns of canopy damage at least in our study region. Nevertheless, estimated AMS3D crown damages were, on average, lower than those from the CHM-based approach using manual crown delineation, and AMS3D also systematically underestimated full crown loss relative to both the CHM-based method and canopy tree mortality from ground surveys (Figure S2). While all approaches have uncertainties and linking forest damage measured by ground survey

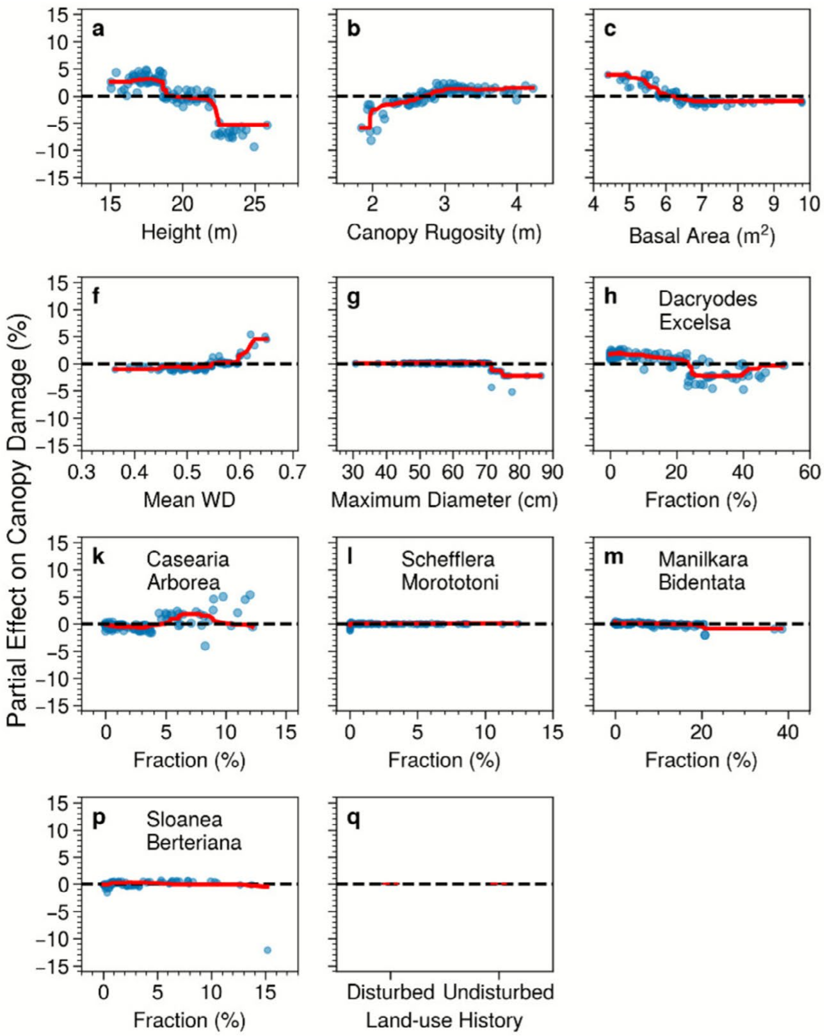


FIGURE 6 | The partial effects of stand-level factors on canopy damage across 40 m quadrats in LFDP based on SHAP values of XGBoost regression modeling: (a) Median quadrat canopy height; (b) Canopy Rugosity; (c) Basal Area (m^2); (d) Elevation; (e) Aspect; (f) Mean WD; (g) Maximum Diameter (cm); (h) *Dacryodes Excelsa* Fraction; (i) *Prestoea Montana* Fraction; (j) *Cecropia Schreberiana* Fraction; (k) *Casearia Arborea* Fraction; (l) *Schefflera Morototoni* Fraction; (m) *Manilkara Bidentata* Fraction.; (n) *Ocotea Leucoxylon* Fraction; (o) *Inga Laurina* Fraction; (p) *Sloanea Berteriana* Fraction; (q) Land-use history. The red solid line represents moving average smoothing.

to remotely sensed measurements was difficult in tropical forests, these differences likely arise from under-segmentation and over-segmentation of large trees in the AMS3D algorithm when applied to complex tropical forest canopies (Figure S13). On the other hand, manual delineation based solely on 2D RGB data could fail to separate close-by crowns with similar colors and textures. Meanwhile, it should be noted that the automatic workflow of AMS3D without defining an empirical relative height loss threshold can lead to high potential of scalability across space and time. Future research integrating both high-resolution RGB data and 3D lidar point cloud can advance crown delineation and species identification methods to improve accuracy and scalability of forest damage analysis.

Our study also enhances our understanding of relative height loss thresholds in CHM-based analysis, which has been used to account for heterogeneity in canopy heights (Dalagnol et al. 2021). Leveraging timely collection of ground survey data after Hurricane María in Puerto Rico (Uriarte et al. 2019), our results support the use of 19% as height loss threshold to quantify individual and quadrat-level crown damage. Higher height loss thresholds may be too conservative, leading to an underestimate of crown damage, while a threshold lower than 19% could result in overestimation (Figure S1). This relative threshold translates into ~2 m absolute height loss for a 10 m tall crown and a ~6 m absolute height loss for a 30 m tall crown. These absolute height losses are about half of reported crown depth for canopy trees in neotropics (5–15 m, Loubota Panzou et al. 2021), providing mechanistic support of our statistically estimated threshold. The consistency between our results and reported tropical crown allometry implies that the relative height threshold might be generalizable to estimate crown damage across other tropical forests although additional ground data validation would be necessary. It is also encouraging that quadrat-level canopy damage is a good proxy for basal area loss (Figure S6), suggesting that the relative height threshold inferred from individual crown level data can be used to robustly infer stand-level forest damage. It is

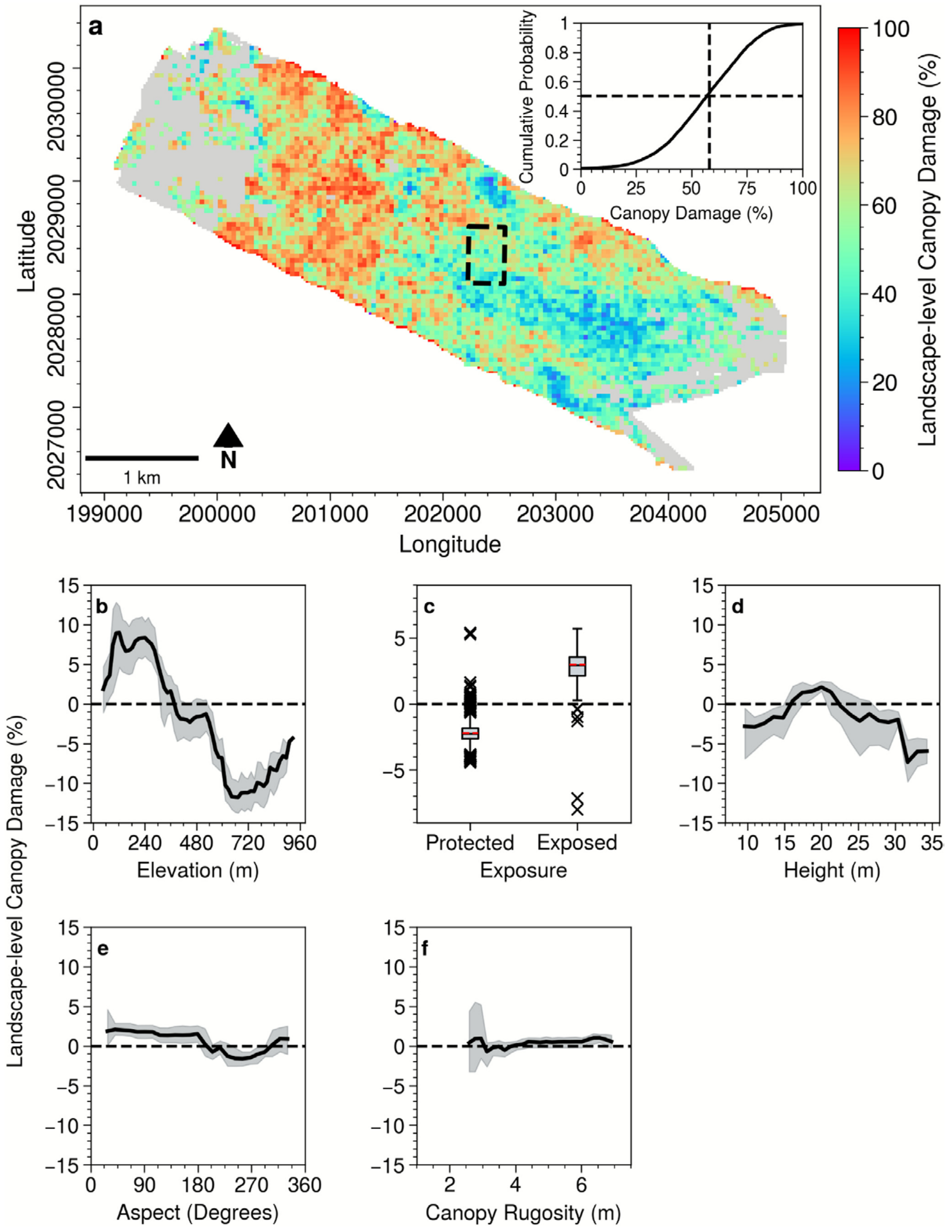


FIGURE 7 | The spatial pattern of canopy damage at Luquillo Experiment Forest (a) and the partial effects of landscape-level factors on canopy damage across 40 m quadrats based on SHAP values of XGBoost regression modeling: (b) Elevation; (c) Topographical Exposure; (d) Canopy Height; (e) Aspect; (f) Canopy Rugosity; The gray color in panel (a) indicates the region with canopy height lower than 9 m that was not included in the analysis; The shading indicate 5th to 95th percentile of partial effect on canopy damage; The black solid line represents moving average smoothing.

not surprising that CHM-based canopy damage is systematically higher than ground-based basal area loss because severe canopy damage does not necessarily indicate tree death, particularly for wind-resistant species such as palms.

4.2 | Taller Trees and Canopies Experienced Less Crown Damage During Hurricane María

Forests exposed to frequent cyclones tend to develop lower canopy heights (Ibanez et al. 2019; Uriarte et al. 2023). Therefore, it is generally expected that taller trees, which are more exposed to wind, would experience greater damage. Previous ground-based studies have indeed reported that trees with larger diameters suffer more severe damage than smaller ones during hurricanes (Franklin et al. 2004; Ostertag et al. 2005), although the diameter effect could vary substantially across species (Uriarte et al. 2019). On the other hand, taller trees generally have larger stem and canopy branch diameters that could provide more biomechanical support. However, direct assessments of the relationship between tree height and hurricane damage remain rare, largely due to the lack of reliable tree height data (Ibanez et al. 2024). To our knowledge, only two previous studies reported that taller trees showed lower sensitivity to forest fragmentation and smaller canopy height reductions following a tropical blowdown (Cushman et al. 2021; Fagan et al. 2024). Using LiDAR-derived height data, our results show taller crowns and canopies received less damage from individual crown to landscape scales (Figures 4–7) for the first time, suggesting the higher resistance likely outweighs higher wind exposure for taller trees at least for Luquillo forests during Hurricane María. Sensitivity analysis showed this pattern held when we used relative height loss thresholds ranging from 10% to 50% (Figure S14), confirming the robustness of the strong negative height effect.

We attribute the negative height effect to several potential reasons. First, the mechanical stability of taller trees in the LEF may outweigh the high wind exposure they experienced during Hurricane Maria. The height-to-diameter (H/D) ratio, an important indicator of mechanical stability, has been shown to positively correlate with damage risk (Ankori-Karlinsky et al. 2025; Putz et al. 1983). This ratio tends to decrease with increasing tree height because the scaling exponent in the power-law relationship between height and diameter is typically less than 1 (West et al. 1999). As a result, taller trees tend to have lower H/D ratios, which enhances their mechanical stability and makes them more resistant to hurricane damage. Second, those tall trees in LEF are partially sheltered from the strong wind exposure, therefore resulting in reduced crown damage by hurricanes. However, testing this hypothesis will need explicit wind speed and direction data, which is not available yet. Finally, at a longer time scale, repeated hurricane disturbances result in strong selective pressure for canopy-reaching trees in this ecosystem toward plant structural adaptations to mitigate physical stress from hurricanes.

It is important to note that our findings are not in conflict with observations of shorter canopies in more storm-affected forests (Lin et al. 2020; Uriarte et al. 2023). Although height has a negative effect on canopy crown damage and mortality, taller trees still experienced much higher mortality under hurricane than background mortality in normal conditions (Uriarte et al. 2019). Moreover, partially damaged crowns of taller trees could suffer enhanced mortality in the subsequent years (Arellano et al. 2019; Needham et al. 2022; Zuleta et al. 2022). In regions with higher hurricane frequency, the interval between successive storms may be too short to allow damaged trees sufficient time to recover their pre-hurricane height, thereby contributing to long-term canopy shortening (Simard et al. 2019).

4.3 | Species Effects on Crown Damage

Our individual-level analysis indicates that *Cecropia schreberiana* trees suffer higher crown damage, and this may also indicate fast-growing, early successional species might be more vulnerable to hurricanes. In addition, palms are often regarded as wind-resistant species since the greater wind resistance of palms likely arises from their flexible fronds and crown/leaf morphology, which help dissipate wind energy (Uriarte et al. 2023; Zimmerman et al. 1994). Meanwhile, tabonuco is a late-successional species often occurring in less disturbed areas. This species can benefit from high wood density and strong root anchorage due to root grafting, enhancing its stability during hurricanes (Basnet et al. 1993; Canham et al. 2010). Consistent with those expectations, at the LFDP, our analysis confirms quadrats with a higher abundance of palms (*Prestoea acuminata var. montana*) and tabonuco (*Dacryodes excelsa*) exhibit reduced canopy loss (Figure 6).

Interestingly, high wood density has long been associated with hurricane resistance, with previous studies linking this trait to reduced stem breakage and lower mortality (Asner and Goldstein 1997; Canham et al. 2010; Ibanez et al. 2024). However, our findings show that quadrats with high wood density likely do not exhibit greater resistance to severe hurricane damage (Figure 6). Under extreme wind and rainfall conditions like Hurricane Maria, the mechanical thresholds of dense-wood species may be exceeded, weakening the effect of wood density (Uriarte et al. 2019).

4.4 | Neighborhood and Topographic Effects on Crown Damage

Our results indicate that neighboring canopy structure has limited influence on crown damage across both individual and landscape scales. At the individual tree level, we did not detect any clear trends associated with variation in neighboring height (Figure 5). At the LFDP scale, we found quadrats with higher canopy rugosity experienced slightly more damage (Ankori-Karlinsky et al. 2024; Gao and Yu 2021), the explanatory power of this variable remained low, accounting for less than 5% of the observed variation (Figure 6). This suggests that under the extreme wind conditions of a Category 4 Hurricane, even structurally homogeneous stands may suffer high crown damage. The extreme intensity of the hurricane may also explain why high stand basal area, typically associated with greater structural buffering (Foster 1988; Xi et al. 2008), had a limited effect on reducing crown damage (Figure 6).

Our results show crown damage patterns are different between east- and west-facing areas at the landscape scale, and this may relate to the storm's path. Since tropical cyclones spin counterclockwise in the Northern Hemisphere, hurricanes moving east to west, such as Hurricane María, typically produce stronger winds on the north of the eye due to the additive effect of the storm's forward motion and rotational force. In addition, we found that quadrats with higher wind exposure experienced greater canopy damage compared to more protected quadrats. This pattern is consistent with findings from previous studies (Ibanez et al. 2024; Uriarte et al. 2023).

We also found that trees at lower elevations suffered greater crown damage, regardless of tree height, especially at the landscape level (above 20% effect, Figure 7). A likely explanation is that species composition in the Luquillo mountains is closely tied to elevations. Sierra palm forests (*Prestoea acuminata var. montana*) dominate above 500 m, while elfin woodlands, characterized by shorter statures and extensive root systems, dominate elevations above 900 m. These species effects along elevation gradients may explain the observed effects of elevation on crown damage. However, this assumption requires further validation through detailed species mapping across the entire Luquillo mountains.

4.5 | Limitations and Outlook

Despite consistent height effects, our statistical modeling of spatial variations showed better performance at quadrat scale (93.94%) compared with individual crown scale (20.13%). The difference in variance explained between the crown-level and quadrat-level analyses is primarily due to the higher stochasticity of crown damage at the individual level. The standard deviation of crown damage is much higher for ~4000 individual crowns (32.99%) than for 96 quadrats (12.46%). In addition, other important variables such as wind speed and rainfall interception are not available at the individual level. Previous studies suggest that wind speed and rainfall are important predictors of hurricane-induced damage (Hall et al. 2020; Ibanez et al. 2024). Heavy rainfall can reduce tree resistance by saturating the soil, thereby decreasing soil strength and increasing the likelihood of damage (Gardiner 2021). Additionally, the canopy intercepts rainfall, with the volume depending on the distributions of crown structure (e.g., the numbers of vertical layers), which increases mechanical stress on trees (Herwitz 1985). Similarly, wind can also increase mechanical stress by interacting with multiple crown layers (Ibanez et al. 2024). These vertical crown layers may also explain why species with simpler architecture, such as palms, are more resistant to hurricane damage. Palms have flexible stems and fewer vertical layers and thus experience less mechanical stress from wind and rainfall.

Recent advances in terrestrial laser scanning (TLS) can capture detailed 3D information about tree architecture (Calders et al. 2015), offering a promising opportunity for quantifying vertical forest structure. By using TLS to measure tree architecture, we can better understand how structural traits influence crown damage, potentially making tree architecture a more important predictor of hurricane damage. This is because tree architecture directly influences how trees interact with wind and rainfall. Furthermore, combining tree architecture from TLS with crown features derived from RGB imagery may offer a more robust method to improve species identification. Integrating species identification and tree architecture into our analysis would provide a more comprehensive understanding of how species-specific traits and forest structure influence hurricane damage, ultimately enhancing our ability to predict and mitigate the impacts of severe hurricanes on tropical forests.

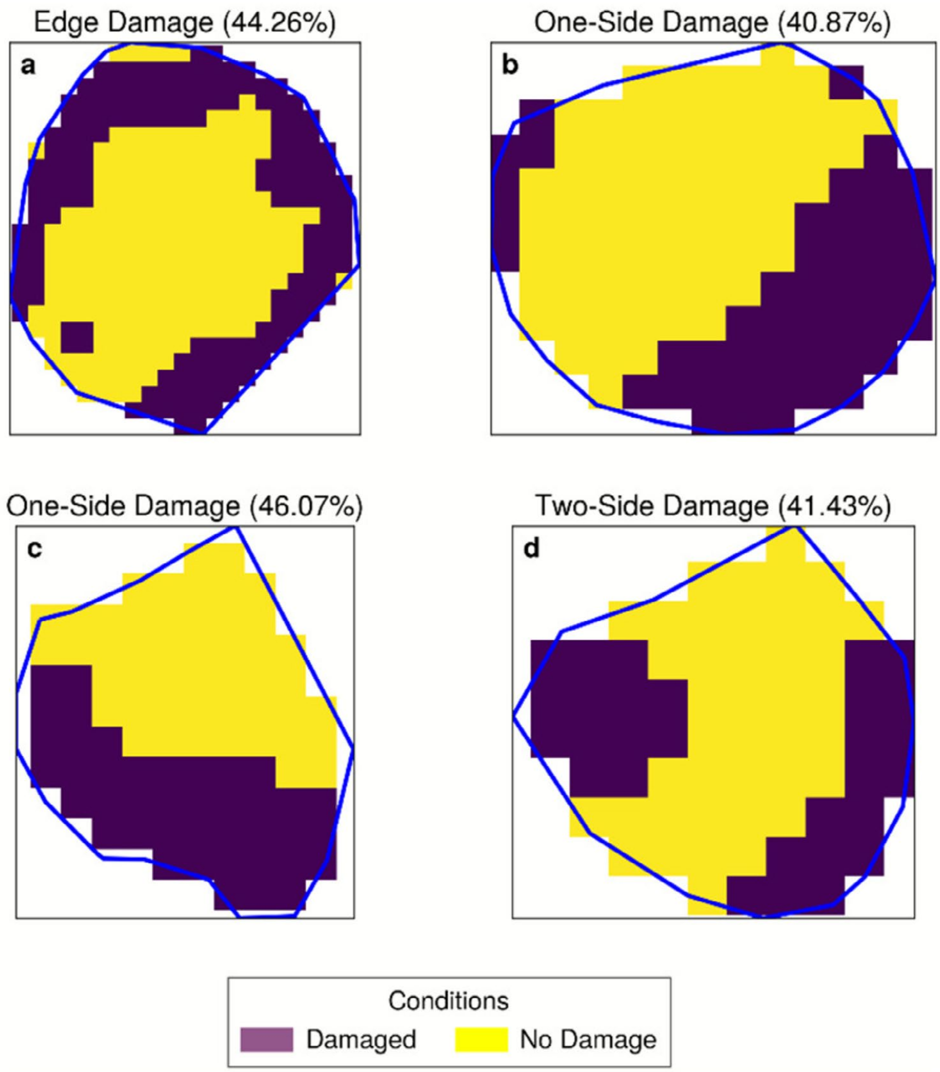


FIGURE 8 | The crown damage patterns for different crowns. (a) Edge damage; (b) one-side damage; (c) one-side damage but different direction; (d) two-side damage.

It is also noteworthy that we only analyzed average crown area loss in this study and did not consider the variations in geometric patterns of crown damage. As illustrated in Figure 8, trees with similar levels of individual crown damage can exhibit distinct geometric patterns. These patterns reflect more details in hurricane-induced damage that are relevant to predict post-disturbance recovery. For example, edge damage may have relatively minor impacts on tree function and allow for faster recovery (Figure 8a). In contrast, crowns with damage on both sides (Figure 8d) may indicate loss of major branches and experience prolonged recovery periods or even delayed mortality due to a more substantial loss of photosynthetic capacity.

Airborne LiDAR, as used in this study, has proven to be a transformative technology for forest inventories, offering the spatial detail and accuracy required to characterize canopy structure across diverse forest types and large spatial extents (Coops et al. 2023). The LiDAR data enables detailed characterization of tree architecture, and with automatic crown delineation algorithms, different types of crown damage can be explicitly extracted to capture multiple dimensions of structural disturbance (e.g., crown length, volume, and vegetation material loss) (Ferraz et al. 2016). Such categorization not only complements traditional classifications such as "broken" and "uprooted" trees but also provides a quantitative basis for assessing post-disturbance carbon loss and reductions in photosynthetic capacity (Leitold et al. 2018).

Moreover, LiDAR-derived structural metrics could also be used with high-resolution optical or radar data for tree species classification and carbon dynamics quantification (Dalponte et al. 2014; Mitchell et al. 2017), enabling broader spatial and temporal extrapolation where LiDAR coverage is limited. Establishing long-term LiDAR monitoring networks, particularly across tropical forests, would greatly enhance our capacity to detect, quantify, and model forest disturbance and recovery under changing climatic and land-use conditions (Duncanson and Dubayah 2018). Such networks would reduce reliance on costly field inventories by providing consistent, high-accuracy structural data that can complement or even substitute field-based measurements in data-scarce regions (Dalagnol et al. 2021).

5 | Conclusions

Our study provided a novel individual crown level assessment of hurricane-induced damage and identified drivers of the spatial variation of canopy damage from crown to stand scales in a tropical wet forest, leveraging a rare combination of airborne remote sensing and ground survey before and after a Category 4 hurricane. We estimated an average of 74%–84% of crown area damage across canopy trees at the LFDP. Furthermore, we showed that height and species composition are the dominant factors regulating crown damage. Our results show strong evidence that taller trees experience less damage across scales, contradicting earlier remote sensing assessments based on pixel-level analyses that failed to resolve individual crown level damage and mortality. By explicitly quantifying crown-level responses, our study advances our understanding of forest resistance and resilience to severe hurricanes and provides novel data for parameterizing and benchmarking hurricane impacts in ecosystem models (Leitold et al. 2018, 2021; Needham et al. 2022). Particularly, our findings highlight the need to incorporate tree size, particularly tree height, and species diversity to accurately predict hurricane-induced damage in process-based models, echoing the increasing representation of vegetation demography in ecosystem models (Fisher et al. 2018).

Author Contributions

T.H., A.F., M.K., D.M., M.U. and X.X. conceived and designed the research. R.A.-K., G.A., M.U., J.K.Z. contributed to field data collection. R.A.-K., D.F., T.Z. and T.H. carried out the manual crown delineation. A.F. and M.K. carried out AMS3D analysis. T.H. and X.X. carried out CHM analysis. T.H., A.F. and X.X. drafted the manuscript. All authors contributed to the analysis and writing of the manuscript.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The canopy height models (CHMs), digital terrain models (DTMs), digital surface models (DSMs), and image mosaics are openly accessible through the G-LiHT data portal (https://gliht.gsfc.nasa.gov). The 3840 manually delineated crowns are publicly available on Mendeley Data (https://doi.org/10.17632/gfpwnpw4jk.1). The codes and data for this study can be accessed through Zenodo (https://doi.org/10.5281/zenodo.15097967).

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Figure S1:** Determination of the relative height loss threshold at the individual tree level. The red horizontal line indicates the stem loss ratio based on ground observations (44.66%); the black vertical line indicates the best threshold used (19%) in subsequent analyses. **Figure S2:** Comparison of lidar-derived and ground-based full crown loss; (a) Relationship between full crown loss ratio and stem loss ratio across all quadrats for manual ($FCLR_{CHM}$) and AMS3D ($FCLR_{AMS3D}$) delineated crown; (b) Spatial distribution of stem loss ratio for each quadrat at LFDP; (c) Spatial distribution of full crown loss ratio of manual crowns ($FCLR_{CHM}$) for each quadrat at LFDP; (d) Spatial distribution of full crown loss ratio of AMS3D crowns ($FCLR_{AMS3D}$) for each quadrat at LFDP. **Figure S3:** The spatial distribution of different variables used for individual crown damage analysis at the LFDP. (a) Height; (b) Elevation; (c) Crown Area; (d) Aspect; (e) Neighboring Height; (f) Species; (g) Land-use History. **Figure S4:** The correlation matrix for seven variables used for individual crown damage analysis. **Figure S5:** Distribution of different variables; Frequency distribution of aspect (a), elevation (b), crown heights (c) and crown area (d) across species. **Figure S6:** Spatial variation in (a) LiDAR-derived canopy damage and (b) ground-based basal area loss ratio is compared. (c) The relationship between canopy damage and basal area loss for all quadrats. **Figure S7:** The spatial distribution of different variables used for canopy damage analysis at the LFDP. (a) Height; (b) Canopy Rugosity; (c) Elevation; (d) Aspect; (e) Basal Area; (f) Mean Wood Density; (g) Maximum Diameter; (h) *Dacrydoes excelsa* fraction; (i) *Prestoea montana* fraction; (j) *Cecropia schreberiana* fraction; (k) *Casearia arborea* fraction; (l) *Schefflera morototoni* fraction; (m) *Manilkara bidentata* fraction; (n) *Ocotea leucoxylon* fraction; (o) *Inga laurina* fraction; (p) *Sloanea berteriana* fraction; (q) Land-use History. **Figure S8:** The correlation matrix for 17 variables used for canopy damage analysis at LFDP. **Figure S9:** The spatial distribution of different variables used for canopy damage analysis at the landscape level. (a) Canopy Height; (b) Elevation; (c) Aspect; (d) Canopy Rugosity; (e) Exposure. **Figure S10:** The correlation matrix for five variables used for canopy damage analysis at the landscape level. **Figure S11:** The cumulative distribution of relative crown area and volume damage. (a) ICD_{CHM}; (b) ICD_{AMS3D}; (c) AMS3D-based crown volume damage. **Figure S12:** 3D change detection based on 2017 and 2018 lidar point clouds, and the comparison between AMS3D and CHM crowns for estimated full crown loss (crown damage $>90\%$). (a) Overlay of raw point clouds from 2017 (blue) and 2018 (red); (b) Cloud-to-cloud (C2C) distance map quantifying structural changes between 2017 and 2018. A high contrast colorbar is chosen so that red and white colors indicate no post-hurricane points can be found within $\geq \sim 5$ m of pre-hurricane points. These points likely represent plant material lost during the hurricane. Top-down view of the 3D distance change is overlaid with estimated full crown loss by (c) AMS3D and by (d) manual delineation and CHM changes. For visualization purposes, we focus on a 150 m-by-150 m subplot in the northwestern corner of the whole 16-ha plot. **Figure S13:** The likely under-segmentation and over-segmentation of crowns using AMS3D algorithms; (a) Likely under-segmentation, multiple adjacent crowns are incorrectly merged into a single segment; (b) Likely over-segmentation, a single tree crown is incorrectly divided into multiple smaller segments. **Figure S14:** The partial effect of tree height on crown damage (ICD_{CHM}) under relative height loss threshold of (a) 10%; (b) 20%; (c) 30%; (d) 40%; (e) 50%. **Table S1:** Definitions of key metrics used to analyze crown damage patterns. **Table S2:** The 10 dominant species at the LFDP site.