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ORIGINAL ARTICLE

Quantifying Patterns of Lightning-Caused Canopy Disturbances via Integration of Drone Imagery and Field Surveys

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Received: 12 February 2025 | **Revised:** 15 July 2025 | **Accepted:** 16 July 2025

Associate Editor: Francis Q. Brearley | **Handling Editor:** Jess Zimmerman

Funding: This work was supported by Smithsonian Tropical Research Institute fellowship program, National Science Foundation (DEB-1354060, DEB-1655346, DEB-2213246, DEB-2213245), Smithsonian Scholarly Studies, and National Geographic Society (9703-15).

Keywords: Barro Colorado Island | forest dynamics | forest gaps | lightning-strikes | Panama | trees

ABSTRACT

Lightning is an important agent of tree mortality and gap formation. Here we quantified spatial and temporal patterns of lightning-caused canopy disturbance in a 50-ha plot in Panama using monthly drone imagery, and compared these patterns with field measurements of disturbance severity and spatial extent. Of 22 lightning strikes that we tracked, the impacts of 18 were monitored for at least 12 months (range of 17–50 months), and 67% of these 18 strikes led to canopy disturbances. The mean time for the first and last canopy disturbance to appear post-strike was 8.2 months (range: 0.8–14 months) and 14.6 months (range: 0.8–23.9 months), respectively. Canopy disturbances were generally highly irregular in shape (i.e., not circular), and clustered around the rooting point of the directly struck tree. A mean of 43% (±19%) of the total lightning-associated canopy disturbance area was within 10 m of the rooting point, whereas only 3% (±5%) occurred 30–40 m from this point. Drone-based measurements of canopy disturbance area and volume were good predictors of variation in ground-estimated dead biomass ($r^2 = 0.48$ and 0.46, respectively), reflecting their strong association with overstory dead biomass ($r^2 = 0.42$ and 0.41, respectively). The total drone-estimated canopy disturbance area was 49% of the ground-estimated canopy disturbance area. Thus, lightning typically causes canopy disturbances that are detectable with drone imagery despite their irregular shape, and drone-detected gap formation lags 8–15 months poststrike, potentially disconnecting drone-detected disturbances from their ultimate cause.

1 | Introduction

The dynamics of gaps in tropical forests contribute to the maintenance of diversity and forest carbon cycling (N. Brokaw 2024; Chambers et al. 2013; Marra et al. 2014; Marra et al. 2018). Canopy gaps promote habitat heterogeneity, and the processes that create gaps cause biomass loss and, ultimately, carbon emissions (Chambers et al. 2013). Climate change is altering the frequencies and intensities of various types of disturbances (storms, droughts, lightning, etc.) and thereby patterns of gap formation (Harel and Price 2020; Lavigne et al. 2019; McDowell et al. 2018), but we lack information about how gaps differ among disturbance types (Gora et al. 2021). Lightning is the least studied among major drivers of tropical forest turnover; in particular, the temporal dynamics of canopy gaps created by lightning are poorly understood (Gora et al. 2021).

Lightning strikes are a major agent of tree mortality and gap formation (Anderson 1964; Gora et al. 2021; Sherman et al. 2000; Yanoviak et al. 2020). Individual lightning strikes typically damage and kill groups of trees in tropical forests without igniting fires or causing explosive damage (Anderson 1964; Gora et al. 2020; Yanoviak et al. 2017). In some types of tropical forests (e.g., swamps and mangroves), circular gaps are conspicuous in aerial images and believed to be caused by lightning (Amir 2012; Amir and Duke 2019; Sherman et al. 2000); however, we lack field verification of the causes of these gaps and quantification of their impact. The only study to quantify disturbance area from verified lightning strikes in a tropical forest relied on ground-based observations with limited follow-up observations (Gora et al. 2021). Consequently, we do not know if lightning gaps are detectable via remote sensing in terrestrial tropical forests, and we have no validated data regarding the characteristics of lightning-caused gaps in any forest.

More generally, connections between aerial imagery and ground-validated measurements of forest disturbance (e.g., tree death, biomass mortality) for specific types of disturbance are rare in tropical forests (Simonetti et al. 2023). This knowledge gap is not unique to lightning, but lightning-caused disturbances could be especially challenging to measure with remote sensing because (1) lightning-caused mortality typically occurs many months poststrike (Yanoviak et al. 2020), and (2) directly struck trees can survive lightning strikes that cause substantial death and damage in the understory (Richards et al. 2022). Thus, the successful application of remote sensing as a tool for quantifying the effects of lightning in tropical forests requires validation of aerial imagery with ground-based data from known lightning strikes.

The principal goals of this study were to quantify spatiotemporal patterns of lightning-caused canopy disturbance using drone imagery and to link those patterns to ground-validated tree damage. Our first objective was to quantify spatiotemporal patterns of lightning-caused canopy disturbances, specifically their timing after the strike date, their spatial distribution in relation to the strike site, their typical shape, and how they were previously classified (i.e., treefalls, branchfalls, and standing dead trees). Our second objective was to evaluate the utility of high-resolution drone imagery in quantifying lightning-caused disturbances by comparing drone-detected patterns of lightning-associated canopy disturbances with ground-assessed patterns of tree damage, tree mortality, and biomass mortality.

2 | Methods

2.1 | Study Site

Field work for this study was conducted in a moist tropical forest on Barro Colorado Island, Panama (BCI; 9.15° N, 79.83° W), and specifically focused on the 50-ha forest dynamics plot (1000 × 500 m) in the center of the island (Leigh Jr. 1999; Muller-Landau and Wright 2024). The plot is located in an old-growth forest, with the exception of a small area of 1.92 ha of old secondary forest (~100 years old) in the northern central part of the plot (Harms et al. 2001). The average canopy height is 24 m (Marthews et al. 2008), with the largest emergent tree reaching 57 m (Martínez Cano et al. 2019). The plot was established in the early 1980s and has been re-censused approximately every 5 years (Condit 1998; Hubbell et al. 2024).

2.2 | Field and Drone Data Collection and Processing

We quantified patterns of canopy disturbance associated with known lightning strikes (Gora et al. 2021) using a dataset of canopy disturbances within the BCI 50-ha plot with near-monthly resolution (Araujo et al. 2021b, 2021a). We operationally defined a canopy disturbance as an area in which a contiguous patch of canopy decreases in height due to a treefall, branchfall, or the decomposition of standing dead trees (Araujo et al. 2021a). Many (but not all) canopy disturbances create canopy gaps, defined as areas of low canopy height (e.g., maximum canopy heights of 2, 5, and 10 m were used to define canopy gaps in Lobo and Dalling (2014)). Canopy disturbances were identified from visual examination of high-resolution (3–7 cm) orthomosaics for successive months, together with observations of decreases in canopy surface elevation over the affected area (Araujo et al. 2021a). Orthomosaics (3–7 cm resolution) and canopy surface elevation models (1 m horizontal and 0.1 m vertical resolution) were obtained from photogrammetry processing of drone RGB imagery collected ~180–200 m above the canopy (Araujo et al. 2021a). When possible, canopy disturbances were classified as treefalls (i.e., a tree with a green crown fell, creating a clearly visible gap on the forest floor, or the whole crown disappeared), branchfalls (i.e., a portion of a tree crown fell), or standing dead trees (i.e., a tree was conspicuously dead with the crown entirely leafless) based on visual examination of before and after imagery (Araujo et al. 2021a). We categorized branchfalls as either green or dry branchfalls based on whether they had green leaves in the last image prior to the disturbance.

Lightning strikes were located using a combination of cameras and electric field change meters (Gora et al. 2021; Yanoviak et al. 2020). The lightning location system changed over time to provide greater coverage, increasing from ca. 15% in 2014 to 100% of BCI in 2019. This system included three to five video cameras mounted on towers extending above the forest canopy or at nearby mainland sites, and then incorporated 3–4 electric field change meters measuring electromagnetic waves emitted by lightning strikes. Within the study area, we were able to locate lightning strikes recorded on at least two cameras and/or three field change meters (Yanoviak et al. 2020). Lightning strike data used for this analysis spanned from September 21, 2015 to October 5, 2019, and canopy disturbance data spanned from October 2, 2014 to November 28, 2019.

Any canopy disturbance identified within 45 m of a known lightning strike was systematically evaluated to determine its possible relationship to that strike (Figure 1 and Figures S1–S5; Araujo et al. 2025). We used a 45 m radius for this determination based on the maximum distance observed between the rooting point of a directly struck tree and the rooting point of damaged neighboring trees in ground-based surveys of 22 lightning strikes at this site (Yanoviak et al. 2020). We inspected images prior to the strike event to evaluate the condition of the focal tree (i.e., canopy disturbances created by trees with crown damage

FIGURE 1 | Time series of the forest canopy before and after a lightning strike that occurred on June 30, 2016 centered at local coordinates X = 936 m, Y = 291 m within the 50-ha plot at Barro Colorado Island, Panama. Each panel shows a 60 × 60 m area centered on the rooting point of the directly struck tree, which is represented as a red dot. The first panel is the last prestrike image, and the subsequent 11 panels show changes in the forest canopy over 16 months poststrike. Inset numbers are months poststrike for each image. The small leafless region on the crown of the focal tree 0.4 months poststrike is presumably the spot where lightning struck the tree (b). The focal tree was completely leafless 3.7 months after the strike (d). New associated canopy disturbances (red polygons) continued to form up to 14 months after this strike (e, f, j).

present before the lightning strike were not attributed to the lightning strike) and images after the strike occurrence until the end of the study period (November 2019) to evaluate and describe the dynamics of canopy disturbances creation (Figure 1, and Figures S1–S5). We compared changes in canopy disturbance creation with ground-based confirmations of lightning-caused tree damage at each site (Gora et al. 2021; Yanoviak et al. 2020).

We visually inspected the time series of high-resolution imagery for all lightning strike sites to omit false negatives resulting from the slow fragmentation of standing dead trees (i.e., the loss of branches from a tree that was conspicuously dead with the crown entirely leafless) and false positives from nonassociated canopy disturbance. To avoid false negatives, we also analyzed canopy elevation models at annual time scales. This approach led to a single correction, expanding the area of a polygon associated with a standing dead tree. We used a similar approach to eliminate false positives (in particular, we removed one branchfall of a green, previously-undamaged branch that was separated in space and time from nearby lightning-damaged trees). We confirmed that all other canopy disturbances in the drone images were unambiguously associated with lightning damage.

2.3 | Quantifying Patterns in Lightning-Associated Canopy Disturbances

We characterized the temporal trajectory of canopy disturbance after lightning strikes by calculating the cumulative area and cumulative volume of canopy disturbances for each strike site as a function of time poststrike. For each canopy disturbance, we calculated its volume by multiplying the area of the disturbance by the mean height reduction during the time interval. Note that canopy disturbances across long time intervals may overlap the same areas and volumes, so the cumulative area and volume over all disturbances may be greater than the total area and volume affected (Figure S4b,c). We report canopy area results in the main text because canopy area is more commonly reported in the literature, and therefore directly comparable to g studies; canopy volume results were qualitatively the same and are given in Supporting Material. We also calculated the time to first and last observed canopy disturbances for each strike site. The length of poststrike monitoring periods varied among strike sites from 1.8 to 50.2 months; descriptive statistics were calculated for subsets of the data, including strikes monitored for specified minimum numbers of months (12, 24, and 36 months). We quantified the contributions of canopy disturbances classified as treefalls, branchfalls, and standing dead trees to the total disturbance trends.

We calculated canopy disturbance circularity using a unitless circularity metric (Equation 1) for the canopy disturbance created by each strike (Noelke et al. 2015). The circularity metric equals 1 for a perfect circle and approaches zero for increasingly irregular shapes:

$$Circularity = \frac{4\pi \, . \, Area}{(Perimeter)^2} \quad (1)$$

We evaluated the spatial distribution of canopy disturbance area relative to distance from the rooting point of the directly struck tree. Specifically, we examined cumulative percentages of canopy disturbance area at 1 m intervals, and calculated the percentage of the total canopy area disturbed by a strike in different 10-m bins extending from the rooting point to 40 m (0–10, 10–20, 20–30, and 30–40 m). We then calculated the weighted average for each 10-m bin by dividing the sum of the damage areas in each bin by the total area damaged by all strikes.

2.4 | Comparison Between Drone and Ground-Based Disturbance Metrics

We tested for relationships between drone photogrammetry measurements of canopy disturbances and previously published ground-based measurements of lightning-caused disturbance severity and spatial extent (Gora et al. 2021). We evaluated relationships for the maximum values of each disturbance metric rather than for metrics at fixed times poststrike, because we expect disturbance-related changes in canopy structure to be delayed relative to the timing of lightning-caused tree damage and death (Yanoviak et al. 2020). The duration of poststrike surveys differed between ground and drone data collection: ground surveys extended between 0.97 and 2.05 years poststrike, depending on the strike site; drone surveys extended between 0.15 and 4.1 years poststrike (Figure S6). We used linear regression to quantify how drone-estimated canopy gap area related to the time elapsed from the first drone survey.

We performed two parallel sets of univariate regression analyses to determine whether or to what degree canopy disturbance area or canopy disturbance volume as estimated from drone imagery explained among-strike variation in six ground-based measurements of disturbance severity and spatial extent: (1) total dead biomass, (2) dead biomass from overstory trees (i.e., canopy or emergent trees), (3) dead biomass from understory trees (all trees below the canopy), (4) count of damaged trees, (5) count of dead trees, and (6) total disturbed area (calculated as the total area within a convex hull bounded by the rooting points of all lightning-damaged trees). In all cases, dead biomass was estimated as the summed total estimated biomass of dead trees plus estimated crown biomass loss associated with crown dieback for surviving trees. We estimated total tree biomass using a generalized tropical forest allometric equation (equation 7 in Chave et al. 2014), and we estimated crown biomass loss as total tree biomass multiplied by the product of crown dieback and the fraction of tree biomass in an average tropical tree of a given diameter (see Gora et al. 2021), for details of the crown fraction allometry based on data from Falster et al. (2015). Variables were log-transformed to meet regression assumptions regarding the distribution of residuals. In the cases of the five metrics with one or more zero values, we first added one in the case of the count metric (total dead trees) and half the minimum observed value to the other four metrics.

We also contrasted photogrammetry measurements of canopy disturbances with ground-based estimates of "idealized canopy gap area." Specifically, idealized canopy gap area was calculated as a convex hull encompassing the idealized circular crowns of canopy and emergent trees with > 75% crown dieback centered on their rooting points and with radii equal to community-wide allometric crown area weighted by crown dieback (following the methods of Gora et al. 2021). Both methods estimated zero disturbance area for eight strikes; they agreed about the zero area for five strikes, but only one metric or the other estimated zero disturbance area for an additional three lightning-caused disturbances. We compared drone-based versus ground-based estimates of canopy gap area using a simple regression without transformations.

3 | Results

3.1 | Temporal and Spatial Patterns of Canopy Disturbance by Lightning Strikes

Among 22 lightning strikes that occurred between Sept 21, 2015 and Oct 5, 2019, 14 (64%) had associated canopy disturbances (Table S1, Figure S7), with canopy disturbance defined as areas in which a contiguous patch of canopy decreases in height due to a treefall, branchfall, or the decomposition of standing dead trees (Araujo et al. 2021b). Among 18 strikes with at least 12 months of poststrike imagery, 12 (67%) had associated canopy disturbances. Those disturbances averaged 236.5 m^2 (range: 18.9–691.4 m^2) in canopy disturbance area and 2540 m^3 (range: 66.4–10,810 m^3) in canopy disturbance volume (Figures 2 and S8, Table S2). The average times for the first and last canopy disturbance to appear for the 12 lightning strikes monitored for at least 12 months were 8.2 months (SD = 4.5 months; range: 0.8–14 months) and 14.6 months (SD = 6.8 months, range: 0.8–23.9 months, Figure 2), respectively. The timing of canopy disturbance formation was generally similar for all strikes with > 12 months of sampling (comparison with strikes with 24 and 36 months of monitoring in Table S2), but total disturbance area was greater for strikes with longer monitoring periods ($F_{1,20} = 4.10$, $p = 0.056$, $R^2 = 0.13$; Figure S13).

The shapes of canopy disturbances created by lightning strikes were highly variable and not circular (mean circularity: 0.36; 95% CI: 0.23–0.50, min = 0.15, max = 0.89, see Figures S7 and S9 for detailed canopy disturbance delineations). Among the modes of canopy disturbances caused by the lightning strikes, 68% were formed by the fragmentation of standing dead trees (i.e., the loss of branches from a tree that was conspicuously dead with the crown entirely leafless), 26% were green or dry branchfalls, and 6% were treefalls. Regarding the total lightning-caused canopy disturbance area, the decomposition of standing dead trees accounted for 80.6%; green and dry branchfalls accounted for 11.4%; and treefalls accounted for 7.9%.

Canopy disturbances were concentrated close to the rooting point of the directly struck tree (Figures 3 and S9). Specifically, the largest fraction (average ± SD = 43% ± 19%) of the total lightning-associated canopy disturbance area was within 10 m of this rooting point, and only 3% ± 5% of the canopy disturbance area occurred 30–40 m from this rooting point. Only one strike caused a canopy disturbance extending beyond 40 m from the strike point (Figure S9n). The distribution of canopy disturbance area within 30 m of the directly struck tree was highly variable among strikes (Figure 3).

3.2 | Drone Imagery Versus Field Metrics of Disturbance

Across 22 lightning strikes, drone-estimated canopy disturbance area was a good predictor of variation in field-estimated biomass mortality (log–log regressions, $F_{1,20} = 20.4$, $p < 0.001$, $R^2 = 0.48$, Figures 4 and S10). Drone-detected canopy

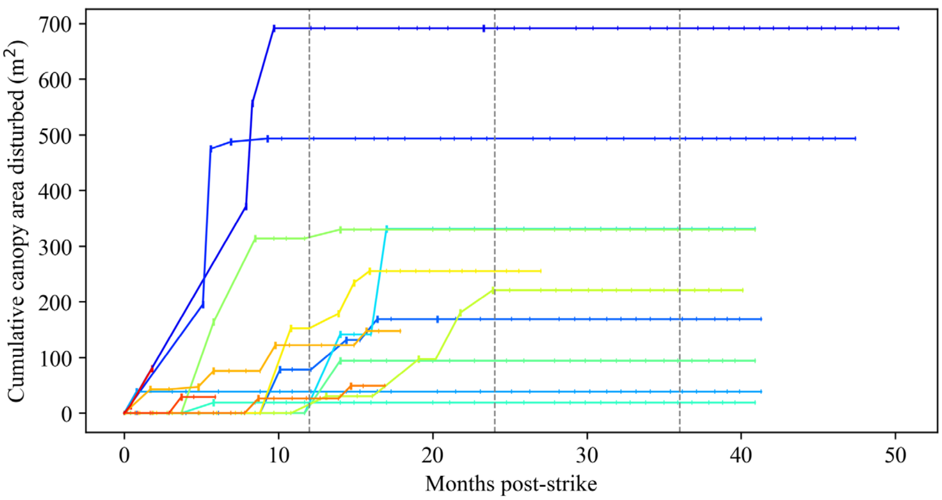

FIGURE 2 | Trajectories of cumulative disturbed canopy area for 14 individual lightning strikes observed for 1.8–50.2 months (i.e., the length of poststrike monitoring period for all 22 strikes analyzed; 8 strikes had no observed disturbed canopy area in the 4.5–49.7 months they were observed) on Barro Colorado Island, Panama. Thin vertical ticks indicate the dates of inspected images, and the thicker vertical ticks indicate detection dates of new canopy disturbance events. Dashed vertical gray lines indicate 1, 2, and 3 years after strike occurrence. Strikes are colored by the date of occurrence according to the spectrum of the rainbow, from dark blue for the earliest to red for the latest strikes.

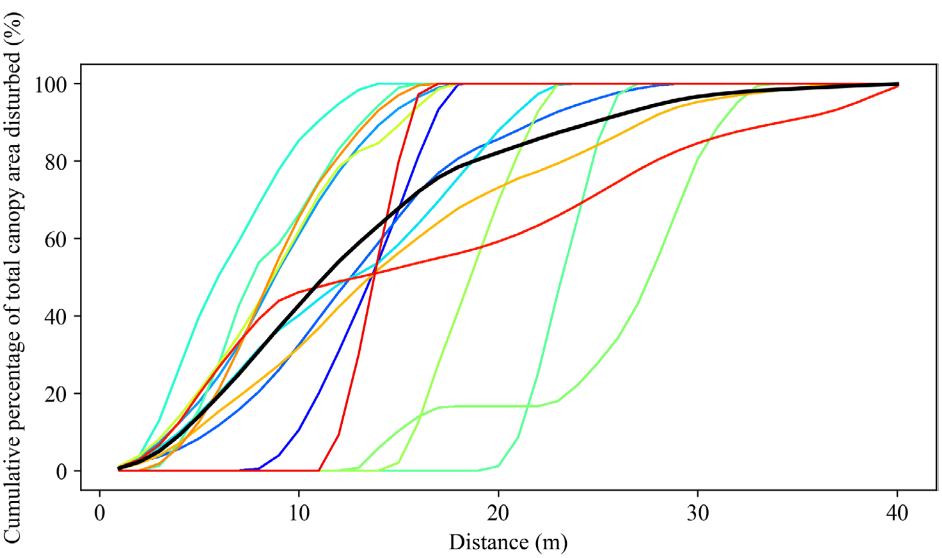

FIGURE 3 | Comparison of cumulative percentages of the total area of canopy disturbances for each 1-m bin of distance from the rooting point of a directly lightning-struck tree on Barro Colorado Island, Panama. Colored lines represent each individual strike. The black line represents the weighted average for each 1-m distance bin.

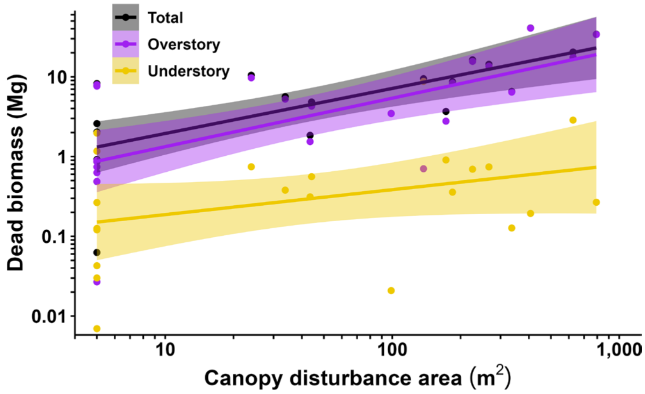

FIGURE 4 | Cumulative canopy disturbance area estimated from repeat drone photogrammetry was a good predictor of variation in total field-estimated woody biomass mortality among 22 lightning strike sites on Barro Colorado Island, Panama. This association was driven by dead biomass among overstory trees (purple) because understory biomass mortality (yellow) was both minimal (note log scale axis) and not significantly related to disturbance area. Points represent individual lightning strikes, lines represent linear model fit, and shaded regions represent the 95% confidence intervals for these relationships. Note that an offset of half the minimum nonzero value was added to the canopy disturbance area to enable inclusion of 8 points with zero observed disturbance in the regressions of log-transformed variables.

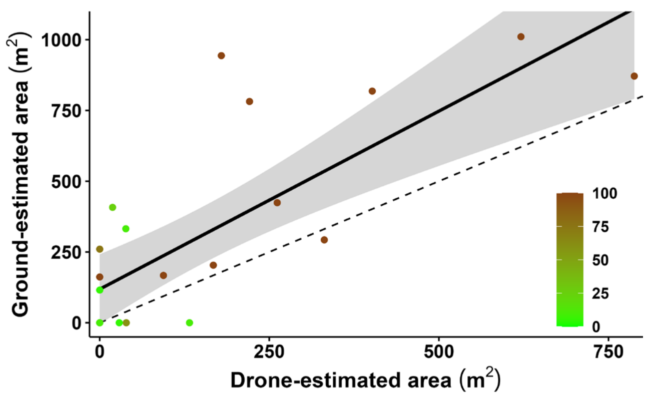

FIGURE 5 | Canopy disturbance area estimated using drone imagery and ground-based surveys of tree damage on Barro Colorado Island, Panama. Points represent individual strikes colored by the percent of crown dieback (i.e., progressive partial crown damage) exhibited by the directly struck tree. The solid black line depicts a significant linear relationship between the estimated types ($F_{1,20}=30.5$, $p<0.001$, $R^2=0.58$), and the shaded region is the 95% confidence interval for this relationship. The dashed line represents the 1:1 line.

disturbance volume was a similarly good predictor of total biomass mortality ($F_{1,20}=19.2$, $p<0.001$, $R^2=0.46$, Figure S11). Drone imagery metrics performed well overall because canopy disturbance area and canopy disturbance volume were strongly associated with overstory biomass mortality (overstory defined as canopy or emergent trees; area: $F_{1,20}=16.2$, $p<0.001$, $R^2=0.42$; volume: $F_{1,20}=15.4$, $p<0.001$, $R^2=0.41$; Figures 4, S10 and S11) and overstory trees contributed 90% of total biomass mortality. Drone imagery did not predict variation in understory biomass mortality (area: $F_{1,20}=2.82$, $p=0.109$, $R^2=0.08$; volume: $F_{1,20}=2.02$, $p=0.171$, $R^2=0.05$; Figures 4 and S11). The ground-based data for the eight lightning strikes that had zero canopy disturbance comprised, on average (±SD), 2.8±3.3 Mg of dead biomass, 3.3±5.5 killed trees, and 17.1±10.1 total damaged trees. We confirmed that these trends did not change when the four lightning strikes with <12 months of data were excluded.

Drone-estimated canopy disturbance area was closely associated with variation in ground-estimated canopy disturbance area ($F_{1,20}=30.58$, $p<0.001$, $R^2=0.58$, Figure 5). Total drone-estimated canopy disturbance area averaged 49% of ground-estimated canopy disturbance area, with large variation in percentages among strikes (Figure 5). The differences between these estimates ranged up to 764 m². When only considering strikes with >12 months of drone monitoring, drone-estimated canopy disturbance area averaged 48% of the ground-based estimate, and their predictive relationship remained essentially the same ($F_{1,16}=24.08$, $p<0.001$, $R^2=0.58$).

Drone-based metrics did not perform as well in predicting other ground-based disturbance metrics of lightning disturbance. Drone-estimated canopy area and volume were weak predictors of the number of trees killed (area: $F_{1,20}=6.62$, $p=0.018$, $R^2=0.21$; volume: $F_{1,20}=4.88$, $p=0.039$, $R^2=0.16$; Figure S12) and total disturbed area (i.e., the total area bounded within the trunks of each damaged tree; area: $F_{1,20}=4.43$, $p=0.048$, $R^2=0.14$; volume: $F_{1,20}=3.52$, $p=0.75$, $R^2=0.10$; Figure S12). Neither canopy disturbance area nor canopy disturbance volume was associated with the number of trees damaged ($F_{1,20}<2.02$, $p>0.171$, $R^2<0.05$; Figure S12). None of these relationships was significant when excluding the four lightning strikes with <12 months of data.

4 | Discussion

Here, we present the first explicit, field-validated quantification of canopy disturbances by lightning strikes using remote sensing in tropical forests. The results confirm that lightning strikes often cause substantial canopy disturbances with implications for patterns of forest recovery and the maintenance of forest diversity. They also show that drone imagery can be useful for mapping and measuring lightning-caused disturbance to canopy trees, but does not detect all understory lightning damage, and that many challenges remain.

This study adds a new dimension to our understanding of how storms influence tropical forest dynamics. Storms are typically associated with windthrow events that cause instantaneous canopy disturbance (Araujo et al. 2017; Negrón-Juárez et al. 2018). However, here we show that lightning strikes from storms can continue to create canopy disturbances for 2 years. Their delayed formation presents a challenge for associating lightning-caused disturbances with individual storms. In particular, it suggests that the use of aerial imagery from immediately poststorm to document storm-associated disturbance may result in underestimation of storm impacts via lightning. Developing more accurate and precise quantification of storm-associated disturbance is important to understanding its role in regulating forest dynamics and carbon fluxes, especially given evidence that electrical storms are becoming stronger and more common (Harel and Price 2020).

Lightning-caused gaps differ from those caused by other disturbance mechanisms (Araujo et al. 2021b; Simonetti et al. 2023), and thus they contribute to variation in forest structure and heterogeneity in regeneration opportunities that may play a role in maintaining forest diversity. The vast majority of disturbances caused by lightning arise from the decomposition of standing dead trees, whereas the majority of disturbances in this site overall arise from treefalls (Araujo et al. 2021b). The average lightning-caused disturbance (236.5 m^2) was 206%–416% greater in area than an average canopy disturbance in this forest (56.9 or 115 m^2 from Araujo et al. (2021b) and Cushman et al. (2022), respectively). Larger treefall gaps are more effective at supporting the recruitment of pioneer species (N. V. L. Brokaw 1987; Dalling 2024; Terborgh et al. 2020), suggesting that lightning strikes could increase pioneer abundance and diversity due to their size. However, the effects of lightning-caused disturbances could differ because of their slow formation, and the presence of standing dead trees and more surviving understory trees could result in unfavorable light conditions relative to treefalls, thereby disadvantaging pioneer species in lightning gaps (Dalling 2024; Terborgh et al. 2020; Yanoviak et al. 2020). Field assessments of forest regeneration in lightning-caused and nonlightning-caused gaps would illuminate their contributions to tree diversity.

Drone-derived measurements of canopy disturbance areas were strongly correlated with ground-based assessments of biomass loss across sites. The agreement would likely be even greater if we had longer drone survey time for all lightning-caused disturbances. Nonetheless, there were systematic differences between drone and ground-based estimates of canopy disturbance areas, which we attribute to multiple causes. First, drone-estimated disturbance area continues to increase over time (Figure S13), and the short drone monitoring duration of many strikes (18% monitored for $<$ 7 months and 32% for $<$ 2 years) likely causes an underestimate of total drone-based canopy disturbance area in this dataset (Figure 2). Second, drone-based estimates may be more likely to miss damage that is obscured by overhead liana growth or branching growth from neighboring trees. Finally, the ground-based approach likely overestimates the disturbance area by failing to account for overlap among adjacent tree crowns. These opposing biases suggest that the true disturbance area, which also depends on its definition, likely falls between the ground-based and drone-based estimates presented here.

Our findings on the noncircular shape of most lightning-associated canopy disturbances in this forest have implications for interpreting imagery more generally. Lightning-caused disturbance in mangrove and swamp forests is often quantified by counting circular gaps detectable in aerial imagery under the assumption that lightning causes circular gaps (Amir 2012; Amir and Duke 2019; Sherman et al. 2000). Given that the lightning disturbances identified in our study were highly irregular in shape and total lightning canopy gaps (low-canopy area) also appeared irregular to ground observers and in the drone imagery, it seems the shape of lightning-caused gaps may differ between terrestrial and flooded forests (Anderson 1964; Brünig 1964). Validated lightning strikes with both ground and aerial data are needed to confirm the characteristics of lightning disturbances in flooded forests.

The patterns presented here highlight avenues for future research. This study is unusual in that it paired drone-mapped canopy disturbances with ground data on patterns of tree damage and death for a known agent of disturbance. Future studies performing similar quantification of other agents of disturbance would shed light on how different agents of disturbance combine to shape forest dynamics. Additionally, we show that drone imagery can capture structural damage in most lightning strikes, but we do not know whether additional strikes could be detected with different types of imagery (e.g., multi- or hyperspectral data). Overall, this study highlights the potential for using drone-based and airborne imagery to detect and quantify lightning damage, but more work is needed to develop and evaluate these methods.

Author Contributions

R.F.A., E.M.G., and H.C.M.L. planned and designed the research. R.F.A., E.M.G., and C.H.S.C. performed the analysis. R.F.A., E.M.G., H.C.M.L., and S.P.Y. wrote the manuscript. S.P.Y. and E.M.G. provided the lightning-strikes dataset.

Acknowledgments

We gratefully acknowledge financial support from the Smithsonian Tropical Research Institute fellowship program (R.F.A. and C.H.S.C.), the National Science Foundation (DEB-1354060, DEB-1655346, and DEB-2213246 to S.P.Y., and DEB-2213245 and GRF-2015188266 to E.M.G.), the National Geographic Society (9703-15 to E.M.G.), Smithsonian Scholarly Studies (to H.C.M.L.), and a Smithsonian Tropical Research Institute Tupper Postdoctoral Fellowship (to E.M.G.).

Conflicts of Interest

The corresponding author confirms on behalf of all authors that there have been no involvements that might raise the question of bias in the work reported or in the conclusions, implications, or opinions stated.

Data Availability Statement

The data that support the findings of this study are openly available at https://github.com/Raquel-Araujo/Python_Strikes_GitHub and in the Smithsonian Research Data Repository at http://doi.org/10.60635/C3131N (Araujo et al. 2025).

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Data S1:** Supporting Information.