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Regional distribution of large blowdown patches across Amazonia in 2005 caused by a single convective squall line

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Abstract

In mid-January 2005 a convective squall line traversed 4.5 × 10^6 km^2 of Amazonia from southwest to northeast. As seen in Landsat images, this atypical convective storm left blowdown imprints with diffuse geometry, unlike the fan-shaped wind disturbance of much more frequent east-to-west propagating squall lines. Previous work reported 0.2% of the forest area damaged by this one relatively rare event within one Landsat image and assumed similar disturbance across the entire traverse. We mapped convective wind damage impact to the region in 2005 by identifying large-scale (>4 ha) blowdown imprints in 30 Landsat images. The diffuse-type imprints associated with this single squall line contributed up to 60–72% of total 2005 wind-disturbed area detected across the region, but damage was highly concentrated in central Amazonia. Consequently, the distribution of large wind damage patches in 2005 across Amazonia was very different from long-term average. Regional distribution of wind-driven tree mortality for smaller patch sizes remains unknown.

1 Introduction

During ~72 h in mid-January of 2005 a convective squall line propagated from SW to NE across 4.5 × 10^6 km^2, which is most of the Amazon forest (Figure 1a). The Manaus region in the central Amazon was hit in the late afternoon of the second day. An associated mortality of 0.32 ± 0.05 million trees was reported within an area of 13,400 km^2 of forest examined near Manaus [*Negrón-Juárez et al*., 2010]. This damage for the Manaus region was then extrapolated across the full extent of the area traversed by the squall line, assuming a similar and homogeneous disturbance rate [*Negrón-Juárez et al*., 2010]. In this study, we measured large blowdown disturbances for the year 2005 across the same 4.5 × 10^6 km^2 of squall line traverse to rigorously explore the continental-scale spatial variability of the associated large forest blowdowns. We ask (1) if the area of a single squall line traverse is a good proxy for inferring area of occurrence of associated large blowdowns and (2) what fraction of total annual large blowdown area in 2005, across 4.5 × 10^6 km^2 of Amazonia, was attributable to this single 3 day event. To answer both questions, we use blowdown imprint geometry on Landsat satellite images to determine whether each blowdown imprint was or was not associated with the unusual SW to NE propagating squall line.

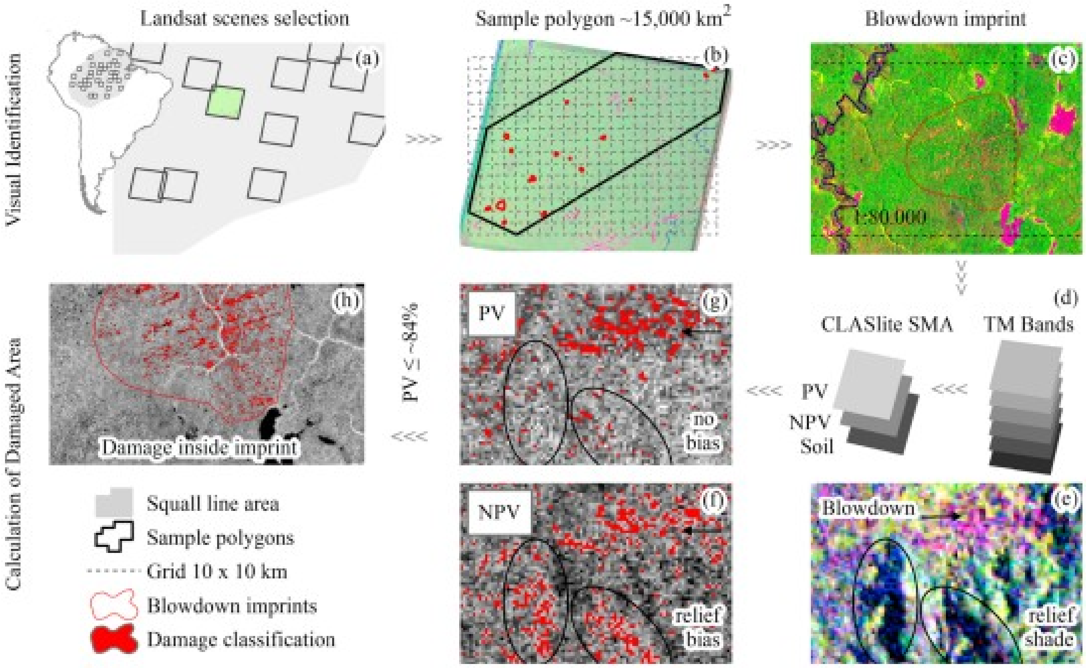

Figure 1. Method workflow showing (a) 30 Landsat TM satellite image areas outlined in black, spread over the 4.5×10^6 km^2 of the mid-January 2005 squall line's traverse, which is the grey area covering most of Amazonia; (b) delimitation of blowdown imprint vicinities (many small red outlines) within the 15,000 km^2 sample of one Landsat image (single black outline); (c) 10 × 10 km search grid and fixed scale of 1:80.000 used in step b; (d) subpixel fractional cover by photosynthetic vegetation—PV, nonphotosynthetic vegetation—NPV, and bare soil, obtained by CLASlite SMA (spectral mixture analysis) from the six Landsat TM bands of each pixel; (e) close-in view of RGB color composite of Landsat bands, showing an area with topographic relief shade; (f) overestimate of wind damage (concentration of red pixels) within this same area of relief shade if using an NPV fraction threshold; (g) no bias in estimate of wind damage in this same area of relief shade when using a PV fraction threshold; and (h) PV threshold and classified wind damaged pixels inside blowdown imprints.

Because the Amazon region is covered with a nearly continuous carpet of forest, the spatial distribution of large blowdown damage can be mapped from the spectral characteristics of felled trees and the geometry of blowdown imprints on satellite images [*Espírito-Santo et al*., 2010, 2014; *Negrón-Juárez et al*., 2010, 2011; *Nelson et al*., 1994]. Damage imprints caused by the typical organized convective systems, or squall lines, propagating from the east [*Cohen et al*., 2009; *Garstang et al*., 1998], as seen in 30 m resolution Landsat Thematic Mapper (TM) false-color composites, are mostly fan shaped with linear fingers of felled forest indicating wind direction [*Nelson et al*., 1994]. These squall lines form at about weekly intervals on the northeast coast of Brazil in the afternoon [*Cohen et al*., 2009]. Convection weakens as they cross the eastern Amazon at night and then strengthens during daylight hours on the second day [*Garstang et al*., 1998]. They may therefore explain the concentration of convective downburst wind damage between 63° and 68°W in the central and western Amazon, as seen in a map of ~15 years of accumulated blowdown imprints [*Nelson et al*., 1994].

The January 2005 squall line was different in at least two aspects. First, strong convective winds propagating from the southwest are uncommon, occurring only about twice per year [*Negrón-Juárez et al*., 2010]. Second, the blowdown imprints associated with the mid-January event that were field verified near Manaus by this and other studies [*Negrón-Juárez et al*., 2010; *Marra et al*., 2014] had a diffuse geometry rather than fan shaped or linear features which are typical of westward propagating squall lines [*Nelson et al*., 1994].

2 Methods

Interpretation of blowdown imprint geometry requires at least 40–50 Landsat TM pixels of forest damage. We therefore use a minimum detection size of ~4 ha of spatially clustered Landsat pixels forming each blowdown imprint (Figure 1c) and having a spectral signature of recent damage. The 4 ha minimum size is the sum of contiguous and noncontiguous damaged pixels, and each imprint typically includes a large number of single-pixel patches of damage. Recent blowdowns are those less than about 12 months old [*Negrón-Júarez et al*., 2010], the time it takes for new leafy regrowth to cover the dry parts of fallen trees—dried bark of trunks and branches and dry dead leaves—changing the spectral characteristics of damaged pixels. To address our two questions above, we produce an interpolated surface across the entire 4.5 × 10^6 km^2 area of squall line traverse, showing percent forest damage by all blowdown types in 2005 and compare this to a similar interpolated surface for only those blowdowns likely to be associated with the January 2005 event. The workflow for deriving these two maps is shown in Figure 1 and is described below.

2.1 Wind Disturbance Samples Across Amazonia

We selected 30 Landsat TM images spread over the 4.5 × 10^6 km^2 area traversed by the mid-January 2005 squall line. Figure 1a shows the traverse area based on interpretation of 3-hourly meteorological images of the squall line [*Negrón-Juárez et al*., 2010, supporting information]. All Landsat images were acquired in the dry season of 2005, 5–9 months after the mid-January event, before new regrowth covered the fallen trees (Table S1 in the supporting information). For each image, we prepared an R-G-B color composite using the respective TM spectral bands shortwave infrared, near infrared, and visible red. Contrast stretch was applied to optimize visual detection of patches of recently felled trees in primary forest. On each of the 30 Landsat images we visually inspected for recent large blowdown imprints in an area of continuous forest covering about 15,000 km^2, which is half of each satellite image's area. This sample area in each image was placed to minimize the inclusion of floodplain forest, rivers, roads, deforestation, forest fire scars, or evidence of mechanized logging (Figure 1b).

2.2 Forest Damage in Blowdown Imprints

Each of the 30 Landsat image's 15,000 km^2 search area was overlain with a search grid of 10 × 10 km and examined systematically at a fixed scale of 1:80.000 (Figure 1c). Blowdown imprints from wind disturbances, contained within a 15,000 km^2 sample area and being less than ~12 months age, were visually identified by their spectral and spatial characteristics [*Espírito-Santo et al*., 2010; *Nelson et al*., 1994]. The vicinity of each blowdown imprint was delimited out to where single-pixel patches of damaged forest became so rare that they were no longer clearly associated with the geometry of that blowdown (Figure 1c). Damaged pixels contained in all the blowdown imprints of each Landsat image were summed, and their total area was expressed as a fraction of all the forest area in each of the 30 samples of 15,000 km^2. This provided 30 data points for the spatially interpolated maps of damage by blowdown type across the entire 4.5 × 10^6 km^2.

To measure forest damage contained within the vicinity of each blowdown imprint, we transformed the six optical bands of each pixel of the Landsat image into estimates of subpixel fractional cover by photosynthetic vegetation (PV), nonphotosynthetic vegetation (NPV), and bare soil (Figure 1d). These fractions sum to 1.0 within each pixel. Subpixel cover fractions were obtained with CLASlite (Carnegie Landsat Analysis System–Lite) version 2.3 [*Asner et al*., 2009]. Topographic shade is removed from consideration as a fractional cover by the CLASlite spectral unmixing method. Field checking showed that exposed soil is also absent from areas of both intact forest and recent blowdowns. This leaves only PV and NPV to vary in a complimentary fashion, as a function of tree mortality in wind-disturbed pixels. So either PV or NPV fraction images from CLASlite could, in principle, be used as a metric of recent forest damage within a pixel. However, a residual topographic relief effect was detected in the estimates of NPV fractions, with a small fraction of NPV being interpreted as present on the shaded side of slopes (Figures 1e and 1f). Only the PV fraction is unaffected by topography. Consequently, we chose the PV fraction to define a threshold below which a pixel was classified as having forest damage (Figure 1g). Clouds were masked where soil fraction exceeded 5%, as white clouds are interpreted by the model as having some bright soil.

Small systematic errors in the estimates of radiance and reflectance in each band lead to a small upward or downward bias in the PV fraction across an image. This bias is different for each of the 30 Landsat images. We therefore chose the PV threshold separately for each image, selecting that threshold value which minimized errors of inclusion and omission of damaged pixels. These errors were evaluated visually in the RGB false color composites of three TM spectral bands for each of the 30 images. For each image, we tested PV thresholds in 1% increments and found that the ideal PV fraction threshold, below which a pixel was considered damaged, was always in the range 0.83 to 0.85. We applied the image-specific PV threshold to obtain a binary image of forest damage for each image. We then summed the area of damage pixels contained in the vicinities of all the blowdown imprints found across the 15,000 km^2 area of each Landsat image. We evaluated our choice of PV threshold by comparing with the damage detected by *Negrón-Juárez et al*. [2010] in a single Landsat scene. They used image differencing of NPV fractional cover (Text S1).

2.3 Classification of Blowdown Imprints

We classified all large blowdowns formed in 2005 into three groups by their geometry. Group A included all those with diffuse geometry, lacking directional linear damage features. This pattern is typical of field-checked disturbances near Manaus known to be caused by the mid-January squall line propagating from the SW (Figure 2a). Group B included additional blowdowns that might have been caused by the January 2005 event—those with parallel lineaments oriented SW/NE and the smaller imprints with undefined wind direction due to their size (Figure 2b). Group C had all blowdowns whose geometry clearly excluded the possibility of being caused by winds from the SW (Figure 2c). Groups A + B + C constitute all blowdowns formed over a full year prior to the 2005 dry season, while groups A + B include all blowdowns potentially caused by the January 2005 squall line.

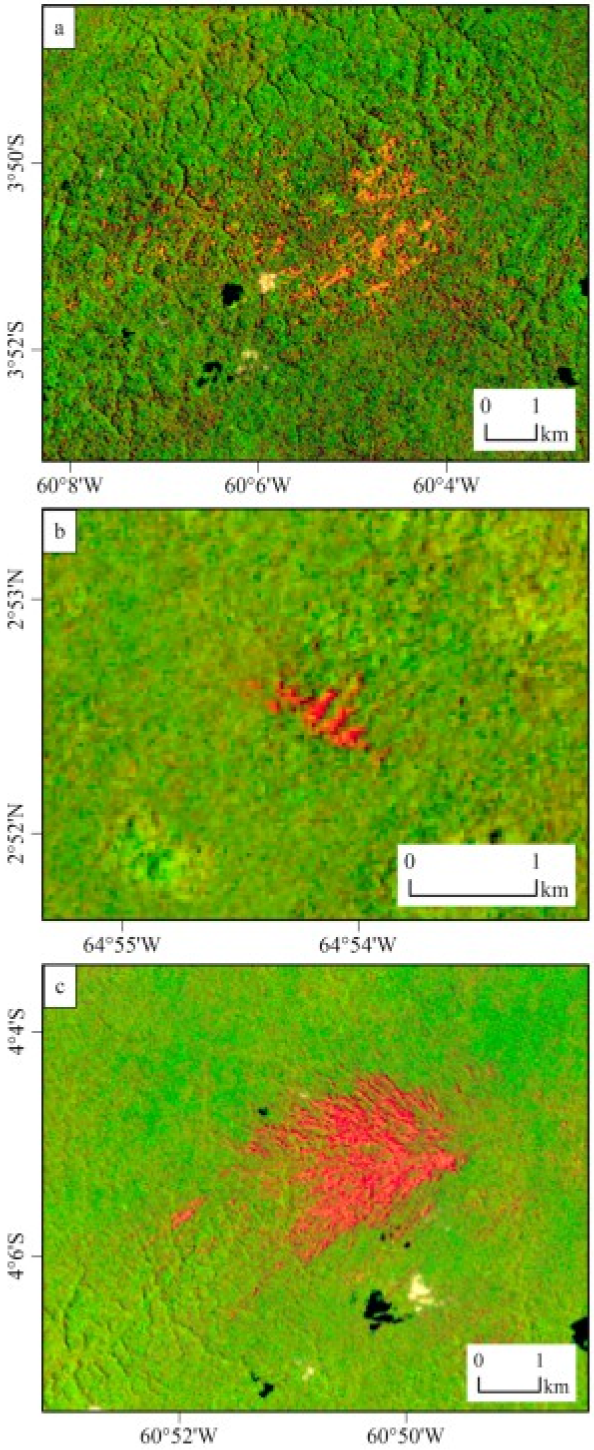

Figure 2. Examples of blowdown geometries: (a) diffuse geometry, typical of the mid-January 2005 squall line, (b) lineaments oriented SW/NE, and (c) caused by winds from the east.

For each of the groups A, B, and C, we obtained the percentage of forest area damage found in recent blowdown imprints in 2005, for each of the 30 areas of ~15,000 km^2 spread across Amazonia (Table S2). We obtained the forest area in each of the 15,000 km^2 samples by masking water bodies, natural nonforest areas, and deforestation using the International Geosphere-Biosphere Programme vegetation map for 2005, from Moderate Resolution Imaging Spectroradiometer product MCD12Q1 [https://lpdaac.usgs.gov/products/modis_products_table/mcd12q1]. We then attributed the percent of forest damaged in each of the 30 areas to its respective centroid point. We then interpolated two raster surfaces of percent forest damage at a cell resolution of 1 km^2, over the full 4.5 × 10^6 km^2 area of the January 2005 squall line traverse. Surface A + B represented wind damage potentially attributable to the January squall line. Surface A + B + C was all wind damage caused by all recent blowdowns detected that year. Interpolation was by inverse distance weighting (1/distance^2) of the 12 centroids within a radius of 1000 km from each 1 km^2 cell being estimated.

3 Results and Discussion

A total of 149 recent large blowdown imprints were found across the 30 Landsat image areas examined. These were divided about equally among the three geometry types A, B, and C. By area, however, the diffuse group (type A) contributed 60% of total annual damaged forest area in the 30 samples (Table 1). Adding small nondiffuse blowdowns with undefined geometry and blowdowns with SW/NE lineaments (types A + B) accounts for 72% of the total blowdown damage area for 2005. Blowdowns with geometry that was clearly not associated with the squall line propagating from the SW (type C) contributed only 27% of total annual blowdown damage area for 2005.

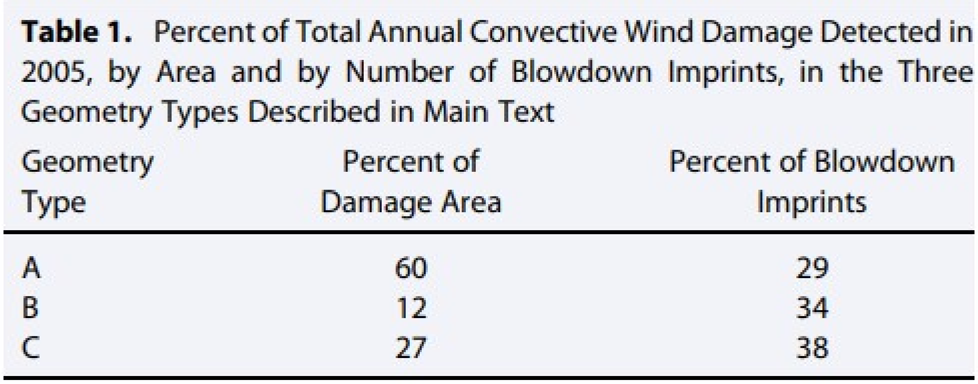

Table 1. Percent of Total Annual Convective Wind Damage Detected in 2005, by Area and by Number of Blowdown Imprints, in the Three Geometry Types Described in Main Text

Geometry Type	Percent of Damage Area	Percent of Blowdown Imprints
A	60	29
B	12	34
C	27	38

The raw data map of wind damage (Figure 3a) shows that among the 30 data points spread over the Amazon forest, those points which are closer together tend to have similar values. Thus, we have spatial autocorrelation at the sampling density we used, which is a prerequisite for use of spatial interpolation. Our interpolated maps of the three geometry classes show that blowdowns with diffuse geometry were highly concentrated in the central Amazon (Figure 3b) and caused most of the total wind damage across the

Amazon region in 2005 (Figure 3c). A cluster of diffuse blowdown imprints within three central Amazon Landsat images contributed 96% of all the diffuse blowdown area across Amazonia (Figure 3a). This suggests that almost all the total damaged area detected for 2005 within diffuse blowdown imprints was associated with the SW to NE moving January 2005 squall line.

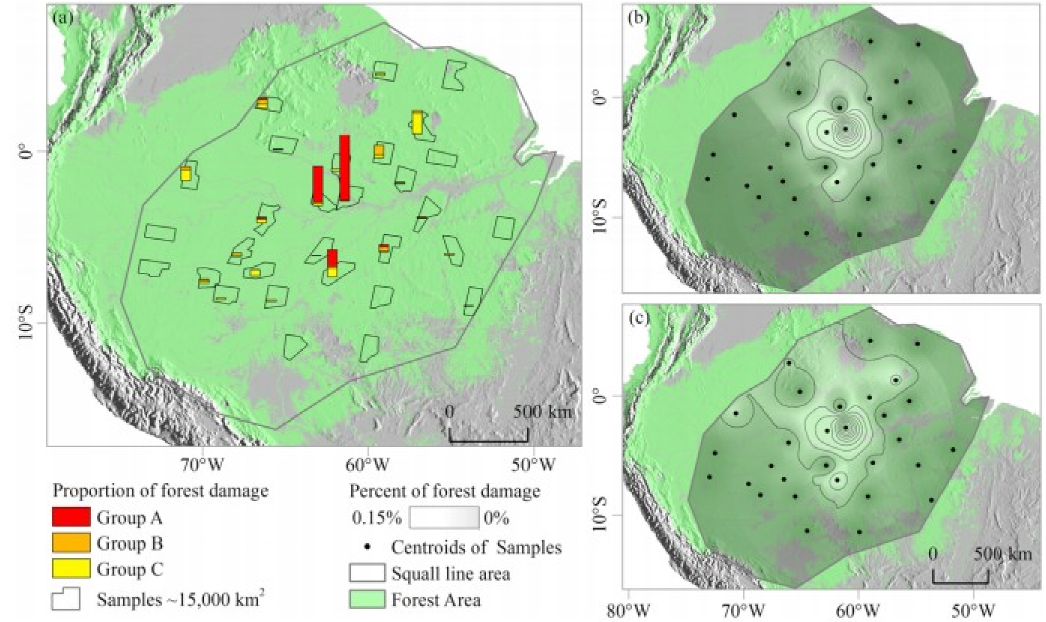

Figure 3. Spatial distribution of blowdown damage across the area traversed by the mid-January 2005 squall line (grey outline). (a) Stacked columns show the percent of forest damaged in 2005 by each geometry type within each of the 30 Landsat image areas of 15,000 km^2 (thin black outlines); range of wind damaged area was 0–0.15% of the forest. (b) Interpolated surface showing percent damage by all blowdowns potentially attributable to the January 2005 squall line (geometry types A + B, described in main text); damage is highly concentrated in the central Amazon. (c) Interpolated surface as in Figure 3b but showing blowdown damage from all convective winds for full 12 months preceding the 2005 dry season Landsat image dates (geometry types A + B + C, described in main text).

Furthermore, because diffuse blowdowns account for most of the total blowdown area across Amazonia in 2005, the map of damage from all types of convective events for that year (Figure 3c) is very different from the long-term spatial pattern. Two previous maps of damage across Amazonia by large blowdowns, covering time windows of ~3 years and of ~15 years, respectively [*Espírito-Santo et al*., 2010; *Nelson et al*., 1994], showed wind damage more widely spread across the central and western Amazon. This more typical spatial pattern is attributable to convective systems that initiate on the Atlantic coast and intensify on the afternoon of their second day of westward transit [*Garstang et al*., 1998].

For the 4.5 × 10^6 km^2 area traversed by the squall line, and using our spectral and blowdown size thresholds for Landsat-detectable damage, the maximum disturbed area as large blowdowns potentially attributable to the January squall line (groups A + B) was 324 km^2. This is the sum of wind-damaged fractions across all 1 km^2 cells of forested area in Figure 3b. The

Landsat-detectable damage area increases by a factor of 1.33 times when corrected to make our method comparable to that of *Negrón-Juárez et al*. [2010]. This is the ratio of their detected damage (0.2% of the forest) to ours (0.15%) for the same July 2005 Landsat image near Manaus (see Text S1). With this adjustment, their estimate of wind-damaged area across the 4.5×10^6 km^2 traversed by the January 2005 squall line is still high by 2 orders of magnitude, compared to ours. Analyzing large blowdown disturbances, we do not find support for homogeneous extrapolation of Manaus damage levels across the entire area of transit of the January 2005 squall line. Calculations comparing the two studies are given in Table S3.

We draw three main conclusions. First, the area of a squall line's traverse is a poor proxy for mapping the extent of associated large Landsat-detectable blowdown damage (i.e., imprints having damage >4 ha). Damage was even more spatially concentrated than expected from nocturnal weakening of convection during the lifetime of a squall line [*Garstang et al*., 1998]. Only one of the three diurnal periods in the 72 h transit of the January 2005 squall line showed up as a high damage area in our maps. Second, despite the damage from this one squall line being highly concentrated in a single day and confined to a small portion of Amazonia, it appears to have contributed most (up to 60–72%) of Landsat-detectable forest blowdown area across Amazonia in all of 2005. Third, due to this anomalously high spatial and temporal concentration of wind damage by a single event, the map of total annual damage for a single year of observation may not be a faithful representation of the long-term spatial distribution of large blowdown risk [*Nelson et al*., 1994, Figure 2].

There is also the issue of how much of total wind disturbance is captured in these large blowdowns and to what extent large visible blowdowns are indicative of treefalls in smaller patches. For example, it is important to note that Landsat pixel resolution is 900 m^2. The vast majority of treefalls from wind disturbance occur in spatial resolutions that are well below the single pixel size [*Chambers et al*., 2013; *Negrón-Juárez et al*., 2010]. Wind disturbances ranging in size from one to six tree clusters are not detectable by Landsat but account for 84% of the biomass mortality flux across a central Amazon landscape [*Chambers et al*., 2013]. Including patches comprising 6–10 treefalls (i.e., single pixel disturbance) increases the total wind mortality unaccounted for in our study to above 95% when compared to *Chambers et al*. [2013]. For example, our blowdown imprints capture only about 5% of the single- and double-pixel wind-damaged patches in their model (Table S4). Clustered treefalls in wind-caused gaps cause mortality to be very sparse in time and space and thus are also underdetected by permanent inventory plots [*Fisher et al*., 2008]. Overall, large blowdown disturbance patches (i.e., > 4 ha) are rare in Amazonia, and more work is needed to better understand how total wind-driven landscape mortality is related to these large visible gaps, including the full range of return frequencies across all event size classes.

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