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Winds with destructive potential across a topographic and seasonal gradient in a Central Amazon forest

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Abstract. Winds can exceed the mechanical stability of trees, leading to snapping or uprooting. In large portions of the Amazon, storms propagating winds with destructive potential (WDP) are key drivers of tree mortality, affecting forest structure, biomass stocks, and species composition. Our understanding of WDP primarily comes from tree damage observations, as meteorological records assessing wind patterns exist in few locations and are often made with insufficient time resolution. Consequently, the temporal and spatial patterns of WDP remain poorly understood. Using 24 months of meteorological data recorded at canopy height across a topographic and rainfall gradient, we developed an innovative method for detecting and describing WDP in a central Amazon forest. We assessed the frequency, speed, and critical duration of WDP and possible relationships with local topography and rainfall seasonality/intensity. We recorded 424 WDP events, with speeds ranging from 10 to 17.9 m s^{-1} and critical durations from 1 to 90 seconds. WDP occurred approximately 4% of the analyzed time, representing daily and monthly means (± standard deviation) of 3.1 ± 2.9 and 17.2 ± 9.6 events, respectively. Topography influenced the fastest, longest-lasting, and least frequent gusts but did not affect the more frequent, slower, and shorter ones. Elevated and relatively more exposed areas were particularly vulnerable to the speediest and longest-lasting WDP. The 87th percentile of rainfall rate (~0.7 mm min^{-1}) correlated most strongly with the frequency and duration of observed events, highlighting the role of extreme rainfall in propagating destructive winds. Our findings indicate that WDP are more common during the transition from the dry to the wet season and confirm previous studies in different Amazon regions that extreme winds are important mechanisms of tree damage and mortality, influencing turbulence and associated processes like gas and energy fluxes.

Keywords: Forest canopy; turbulence; meteorological tower; rainfall seasonality; tree mortality; shelter effect; convective systems.

1 Introduction

Winds with destructive potential (WDP) can reach critical speeds that exceed the mechanical stability of trees and lead to branch fall and/or tree toppling via trunk snapping and uprooting (Gardiner et al., 2008; Mitchell, 2013; Moore et al., 2018; Peterson et al., 2019; Ribeiro et al., 2016). In the Amazon, storms and heavy rainfall can propagate WDP, which are an important driver of tree damage and mortality, affecting forest structure, biomass, carbon stocks, and species composition (Marra et al., 2018; Marra et al., 2014; Urquiza Muñoz et al., 2021).

WDP are often associated with intense short-lived downbursts, which according to Fujita (1981), are divided into *dry downbursts* or *wet downbursts* (associated with less and higher than 2.5 mm of rain between the onset and the end of high winds, respectively). Regarding the outflow size, these author also divided these events into *microbursts* and *macrobursts* (<4 and ≥4 km in outflow diameter, with peak winds lasting 2 – 5 and 5 – 20 minutes, respectively). Garstang et al. (1998) considered that ambient conditions prior to the WDP in the Central Amazon are characterized by sudden increases in wind speed ≥10 m s^{-1} right above the canopies. These authors argue that extreme speeds close to 31 m s^{-1} can be reached where the

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moist convection is intense enough, which is fairly higher than values reported as associated to widespread damage and mortality of trees (Negrón-Juárez et al., 2010; Peterson et al., 2019; Ribeiro et al., 2016).

WDP impact trees in different scales, varying between the more frequent single or small-clusters to the rare catastrophic large windthrows often associated with squall line events (Araujo et al., 2017; Chambers et al., 2013; Negrón-Juárez et al., 2010; Nelson et al., 1994; Simonetti et al., 2023). The severity of wind damage and mortality is influenced by the combination of species traits, such as wood density, leaf area, and canopy architecture, as well as the frequency, duration, and speed of the gusts (Geitmann and Gril, 2018; Quine et al., 2021). WDP are related to climatic and environmental factors such as local atmospheric stability, rainfall intensity, topography, and canopy roughness (Belcher et al., 2012; Garstang et al., 1998; Jackson et al., 2019a; Ruel et al., 1998). The topography modulates the wind speed on complex reliefs by differences in elevation and exposure, and the orientation of valleys and slopes relative to the prevailing wind direction (Jiang et al., 2021; Ruel et al., 1998). More elevated surfaces generally experience more intense wind regimes compared to slopes and valleys (Belcher et al., 2012). These complex reliefs are common in the Central Amazon (Rennó et al., 2008), where variations in wind speed due to elevation and orientation have been scarcely reported (Tóta et al., 2012).

Previous research indicates that large windthrows were formed by WDP propagated by extreme storms associated with convective systems (Negrón-Juárez et al., 2017, 2010). In the Amazon, these storms occur most frequently during the rainy season (e.g., from October to April). Some may last between 3 to 5.5 hours, and rainfall intensities can reach values higher than 30 mm h^{-1} (Araujo et al., 2021; Funatsu et al., 2021; Negron-Juarez et al., 2023; Negrón-Juárez et al., 2017; Rehbein et al., 2018; Sikora de Souza et al., 2020). However, in the equatorial region, the heat and humidity near the surface provide favorable conditions for convective activity all year long (Gonçalves et al., 2024; Rehbein et al., 2018).

At the Amazon basin, studies using remote sensing data have shown that extreme precipitation, rainfall seasonality, surface elevation, and soil characteristics explain 20 – 50% of the variability in the occurrence of large (>5 ha) windthrows (Negron-Juarez et al., 2023; Negrón-Juárez et al., 2017). However, due to the relatively small spatial- and temporal-resolution, meteorological satellite data tend to underestimate local variations in wind and rainfall regimes at both subpixel (~hectare) and larger scales (Harris et al., 2020; Hersbach et al., 2020; Huffman et al., 2020; Poggio et al., 2021; Takaku et al., 2020). This is critical over landscapes with intense environmental gradients like in the Central Amazon (Jiang et al., 2021; Rennó et al., 2008; Simard et al., 2011).

Most of what we know about WDP comes from observations of their damage to trees and forests, as meteorological records to assess wind speeds, their spatial and temporal distribution only exist in comparatively few locations. Despite the well-known meteorological processes that create WDP (Dunlop, 2017), a scarcity of observational studies with meteorological data means their patterns of occurrence and actual severity of the WDP remain poorly understood. Wind is considered a regional mechanism of tree mortality due to heterogeneity of environmental and meteorological factors that influence disturbance regimes (McDowell et al., 2018). This idea is supported by recent observations showing windthrow hotspots in Central and Western Amazon (Negron-Juarez et al., 2023; Urquiza-Muñoz et al., acepted). Further, convective storms propagating WDP may become more common and intense with future climate system warming (IPCC, 2021). Describing local-to-regional

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patterns of WDP can expand the current scarce-knowledge on how topographic attributes moderate tree damage and mortality associated with destructive winds (Ruel et al., 2001). Assessing possible relationships between rainfall and other weather variables can also contribute to more reliable predictions of the occurrence and severity of destructive winds from local to regional scales (Allen et al., 2010; Berzaghi et al., 2020; Forkel et al., 2019; Roberts et al., 2018; Swain et al., 2020).

In this study, we described for the first time the patterns of WDP in an old-growth forest in Central Amazon known to be in a windthrow hotspot (Negrón-Juárez et al., 2017; Urquiza-Muñoz et al., acepted). We used long-term (24 months) and high-frequency meteorological data recorded at the canopy height, and an innovative analytical approach to identify WDP across a topographic and seasonal gradient answering the following questions: (i) What are the WDP patterns in the forest canopy? (ii) How are WDP affected by topography? and (iii) How do seasonality and rainfall intensity affect WDP?

2 Material and methods

2.1 Study area

Our study was conducted in an old-growth forest in Central Amazon located ~100 km north of Manaus, Brazil, at the Tropical Silvicultural Experiment Station (EEST, coordinates 2°38'16"S/60°11'39"W) of the National Institute for Amazonian Research (INPA) (Fig. 1b). Our study is part of the INVENTA project (i.e., Wind-Tree Interactions in the Amazon, *Interação Vento-Árvore na Amazônia* [Portuguese]; Marra et al., 2018; Peixoto et al. 2023), which aims to integrate research on tree architecture and biomechanics with atmospheric and biogeochemical processes that affect the forest dynamics. INVENTA incorporates a 18-ha permanent plot installed in 2000 (Pinto et al., 2003) covering the topographic variation typical of Central Amazon *terra-firme* forests. The site elevation above the canopy surface ranges from 67 – 145 m above sea level (Fig. 1c), with undulating relief including plateaus, steep slopes and narrow valleys associated with perennial drainages (Ferraz et al., 1998; Rennó et al., 2008). Gap dynamics has also been monthly monitored as part of our study site using drone RGB-photogrammetry (Simonetti et al., 2023).

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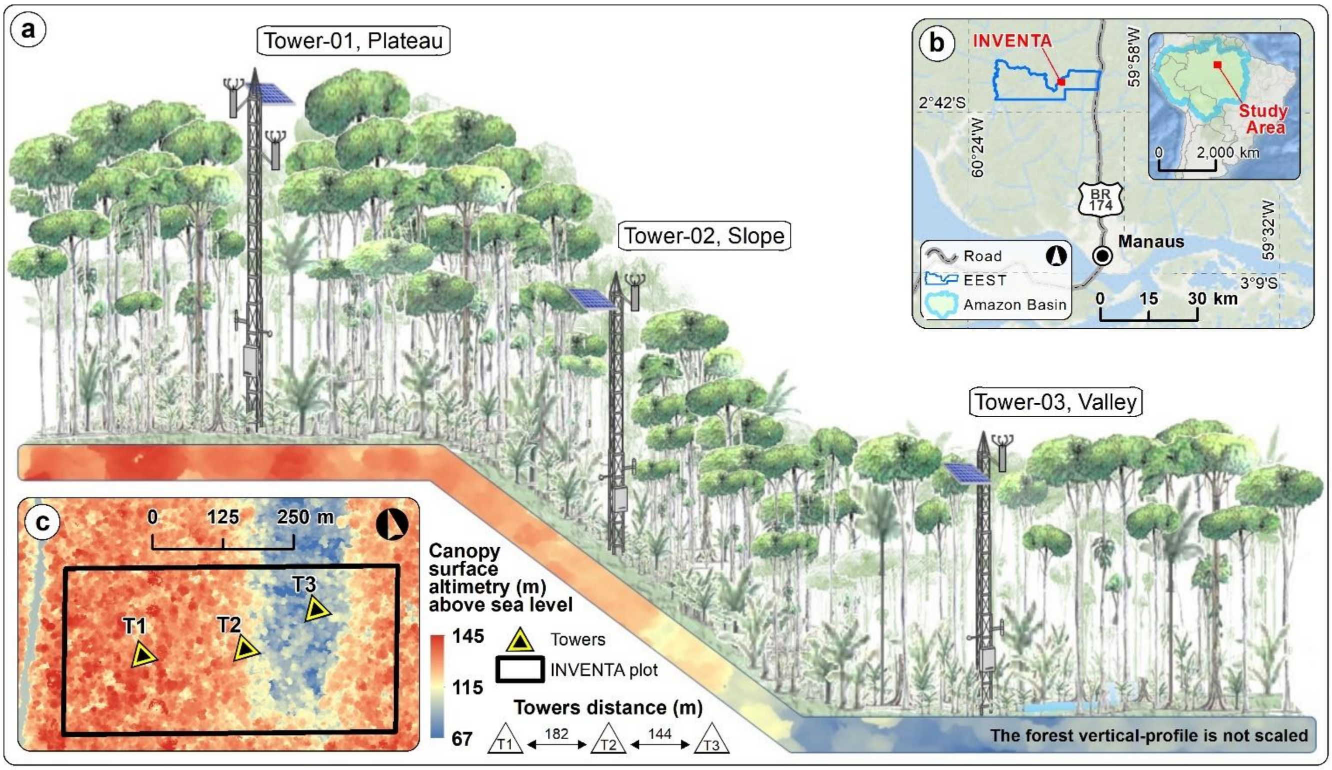

Figure 1. Location and data collection arrangement of the study area. (a) Schematic profile of the meteorological towers across the topographic gradient. (b) Location of the EEST and INVENTA project. (c) Digital surface model generated from drone imagery representing the altimetry of the canopy surface relative to sea level, and the location of the towers on the 18-ha permanent plot.

Soils on the plateaus have generally high clay content transitioning to sandy soils in the lower portions, which can be seasonally flooded (Chauvel et al., 1987; Ferraz et al., 1998; Luizão and Schubart, 1987). In general, the soils have relatively low fertility, low pH, low phosphorus availability, high aluminum concentration and low organic carbon content (Cunha et al., 2022; Telles et al., 2003).

The climate in the region is "Am" tropical according Köppen-Geiger, with a dry and rainy seasons modulated by monsoons (Peel et al., 2007). The rainy season lasts from December to May and the dry season lasts from June to November, with an evident dry period from July to September with monthly precipitation less than 100 mm (Marengo et al., 2001; Sombroek, 2001). Mean annual temperature and annual precipitation in the region of Manaus is 26.9 ± 0.17º C and 2,231 ± 118 mm (mean ± 95% confidence interval from 1970-2016, Marra et al., 2018). The mean annual temperature in our study site is 26.2 ± 3.2º C (mean ± standard deviation from 2021-2023), and mean annual precipitation is 2,304.1 ± 50.3 mm, (Fig. S1 in the Supplement).

The *terra-firme* forest is the most common forest type in the Amazon basin (Braga, 1979) and is characterized by a continuous canopy, dense understory, and high diversity, where >280 species can occur in a single hectare (Chambers et al., 2009b; De

Oliveira et al., 1999; Marra et al., 2014). The INVENTA region is covered by an old-growth forest with closed canopy, where the mean (± standard deviation) density and height of the trees are 623 ± 66 trees ha^{-1} and 28.65 ± 0.46 m, respectively (Araújo, 2019; Carneiro, 2004; Lima, 2010; Pinto et al., 2003). The old-growth *terra-firme* forest covering the INVENTA plot was not affected by severe human or natural disturbances for at least 60 years.

2.2 Acquisition of meteorological data

INVENTA includes three triangular mast meteorological towers, each one installed on the plateau, slope, and valley (Fig. 1a). The plateau tower (T1) is 36-m tall and equipped with two 2D sonic anemometers installed at 33 m and 36 m height. T1 is also instrumented with a tipping bucket rain gauge, temperature-humidity-sensor, and a pressure transmitter (see details on instruments in the Fig. S2). These instruments were installed at ~33 m height in order to capture the meteorological conditions at the canopy height, i.e., 28.65 m ± 0.46 m (mean ± standard deviation) (Araújo, 2019; Lima, 2010). The slope and valley towers (T2 and T3, respectively) are both 33-m tall and equipped with a single 2D sonic anemometer installed at 33-m height. In this study, we only used wind data collected at 33-m height.

All towers are equipped with a datalogger (CR6, Campbell Scientific) that records, preprocesses and stores the data. Instruments and dataloggers are powered by a solar panel attached to the tower above the canopy and connected to a 12 V/50 Ah stationary-battery. The solar energy system provides operational autonomy for the towers, given the remote conditions and lack of integrated power-transmission infrastructure in the study area.

All instruments record data continuously at a frequency of 1 Hz. Here, we used wind data recorded at the three towers, and rainfall data measured by the rain gauge at T1. The anemometer data is stored at the rough frequency (i.e., one data point every second), while the rainfall data are pre-processed and stored by total rainfall volume at 5-minute intervals. The towers were built in September 2019 and the instrumentation completed by March 2020. Data has been collected continuously since then, but here we used data covering the period from 01 October 2021 to 31 September 2023.

Meteorological time-series data can be influenced by problems like instrument malfunctioning, external influences, and registration errors (Faybishenko et al., 2022). To minimize these possible non-sampling errors, we performed the data quality-control protocol described by Zahn et al (2016). This protocol uses visual graphical analysis of the data time series to identify patterns and inconsistencies, and applies treatments using missing values or flags (Rollenbeck et al., 2016), identification of impossible and implausible values, bounds tests, (Mauder et al., 2013), and removal of random electronic spikes (Vickers and Mahrt, 1997).

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2.3 Data analysis

2.3.1 Defining WDP

We first defined gust as winds with a relative large positive increase in speed (i.e., higher deviations) in relation to the mean (Kristensen et al., 1991). Only events that persisted for a minimum of three seconds (Harper et al., 2010) prior to return to a condition similar to the pre-gust mean speed were considered (Beljaars, 1987; Gomes and Vickery, 1978; Kantz et al., 2004; Kristensen et al., 1991; Mitsuta and Tsukamoto, 1989). Among detected gusts, we distinguished WDP as those propagating at a minimum speed of 10 m s^{-1}. This threshold was set close to the minimum critical wind speed of 10.75 m s^{-1} estimated by Peterson et al. (2019), from which canopy trees in our study site experience sufficient force to potentially be broken or uprooted. The critical wind speeds were estimated by Peterson et al. (2019) by using a dynamic profile model and observational data from a mechanical winching test performed with 60 canopy trees in an area adjacent to the INVENTA plot (Ribeiro et al., 2016). Our 10 m s^{-1} threshold was also defined based on the strongly asymmetric wind speed distribution of our data (Fig. S3). A sudden increase of ≥10 m s^{-1} measured at 40 m height (i.e., close to our measurements) in relation to the mean wind speed is also considered as a prior downburst condition (Garstang et al., 1998) from which tree damage or mortality have also been reported (Negrón-Juárez et al., 2017, 2010).

We created a three-step analytical method to identify and process WDP from our data, calculating their attributes of speed, direction, and critical duration. First, we defined a minimum threshold of wind speed of 1.85 m s^{-1} based on the mean and one standard deviation (1.06 m s^{-1} + 0.79 m s^{-1}) observed for our 2 years' time-series. Considering one standard deviation allowed us to reliably selected gusts that exceeded the speed typically observed right above the canopy (~1 m s^{-1} at 35-55 m height) (Andreae et al., 2015; Garstang et al., 1998; De Santana et al., 2017; Tóta et al., 2012) (Fig. 2a). Second, the time between the propagation of the gust and return to the predefined minimum of 1.85 m s^{-1} (i.e., non-wind condition) was computed as the "total duration" of the gust. We further focused on WDP with at least three seconds of total duration according to the definition given by the World Meteorological Organization (Harper et al., 2010). WDP more than three seconds apart were considered as single events. We calculated the maximum speed and mean direction for all identified WDP (Fig. 2b). Further, we computed the "critical duration" of each selected gust as the time during which the gust sustained speeds ≥10 m s^{-1} (Fig. 2c). Our preliminary analyses indicated that the critical duration explained 70% of the variation in the speed of the WDP in comparison to only 6% explained by their total duration (Text S1 and Fig. S4). This suggests that critical duration is a better attribute to access the destructive potential of winds to cause tree damage or mortality. This finding is consistent with tree mechanical tests conducted under controlled conditions of wind speed (England, 2000; Gardiner, 2021; Holmes et al., 2014; Moore and Maguire, 2004; Quine et al., 2021). Therefore, our subsequent analysis was conducted by using the WDP attributes of number, wind speed, wind direction, and critical duration.

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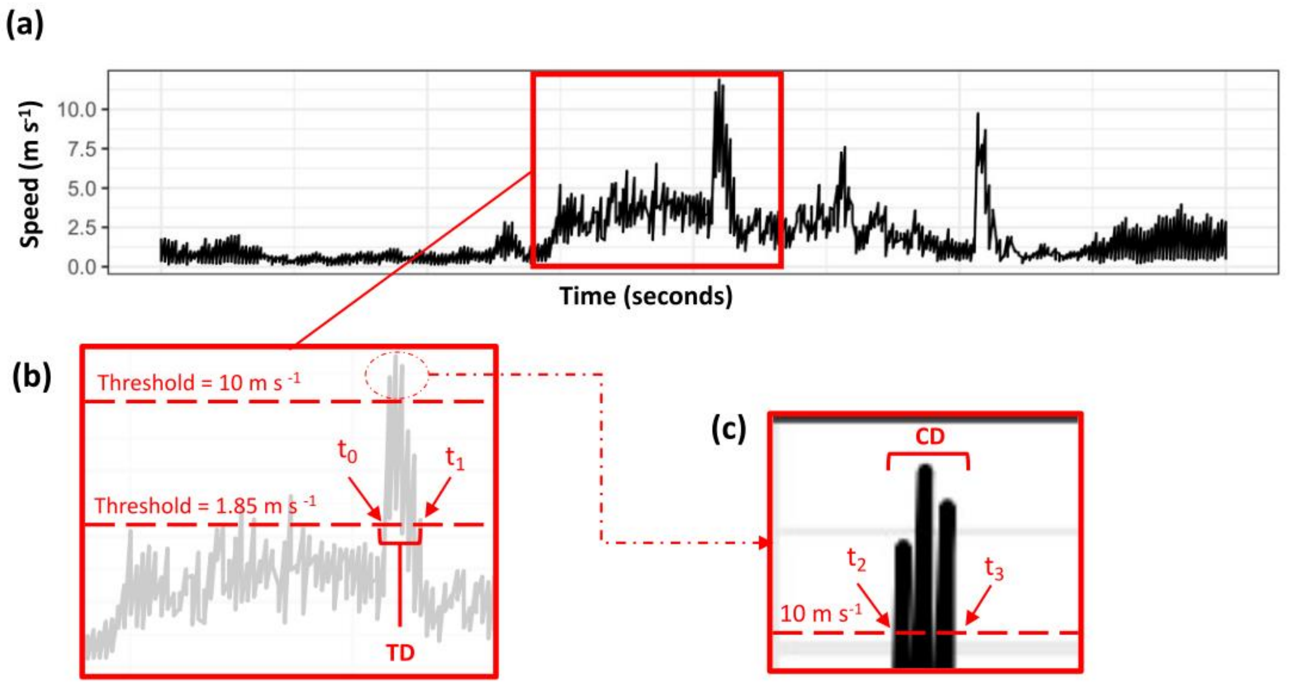

Figure 2. Scheme of the analytical process used to define WDP in our dataset. (a) Example of the wind speed time series where the WDP are found; (b) Gusts that exceeds a minimum threshold of 1.85 m s^{-1} and reached or exceed 10 m s^{-1} were considered as an WDP. The time of begin (t_0) and end (t_1) of the gusts were recorded and the total duration (TD) of the WDP was calculated as the time in seconds from t_0 to t_1; (c) From TD, the critical duration (CD) was calculated as the time in seconds from t_2 to t_3 (i.e., the time that the gust sustains speeds ≥10 m s^{-1}). In the panels b and c, thresholds lines were not scaled to easy the understanding of the analytical process.

2.3.2 Relating WDP and meteorological variables

We summarized the WDP attributes of number, maximum wind speed, mean wind direction, and maximum critical duration recorded at 1 Hz frequency to match the rainfall data in a 5-min frequency. We analyzed the data separately for each of the topographic positions (i.e., plateau, slope, and valley). We also tested for possible patterns related to daytime (i.e., day period from 06:00:00 to 17:59:59; night period from 18:00:00 to 05:59:59 LT), and dry/wet seasons. The wet and dry seasons were defined as the periods from December to May and June to November, respectively (Liebmann and Marengo, 2001; Marengo et al., 2001).

2.3.3 Statistical analysis

All statistical analysis were conducted in R 4.4 (R Core Team, 2024) and we report results based on a probability level of 95%. We tested the normality and variance homogeneity of the data using Shapiro-Wilk and Levene-Brown-Forsythe tests using

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RVAideMemoire and *onewaytests* packages, respectively (Dag et al., 2018; Herve, 2023). As our data were not normally distributed and had a non-homogeneous variance, we conducted a non-parametric approach using the median as a central tendency measure for the WDP patterns (Gotelli and Ellisson, 2013).

To address question one on overall patterns of WDP, we assessed differences on the medians of selected attributes between daytime periods by using the Mann-Whitney-Wilcoxon test from *rstatix* package (Kassambara, 2023). To address question two on how topography affects observed patterns, we assessed differences on the selected attributes among topographic positions using Kruskal-Wallis and Dunn Bonferroni post-hoc tests for medians through the *stats* and *FSA* packages, respectively (Ogle et al., 2023; R Core Team, 2024). To address question three on how rainfall seasonality influences WDP, we analyzed the relationship between rainfall rate (mm min^{-1}) (predictor variable) with all WDP attributes (response variables) by using a cross-correlation function (Zebende, 2011) from the *forecast* package (Hyndman et al., 2024).

The relation between rainfall and wind speed is an example of highly non-stationary atmospheric process (Barry and Chorley, 2003; Dunlop, 2017) that often involve complex changes that do not necessarily occur at the same time between these two variables (dos Anjos et al., 2015; Kavasseri and Nagarajan, 2004; Koçak, 2009; de Oliveira Santos et al., 2012). The cross-correlation analysis indicates the time lag where the highest (positive or negative) correlation between the response and predictor variables occurs (Kristoufek, 2014; Podobnik and Stanley, 2008), allowing us to evaluate possible correlations between rainfall and WDP. Positive lags indicate that changes (i.e., increase or decrease) in the response variable occur before the changes in the predictor variable. Negative lags indicate the opposite and zero lag indicates that changes in both variables occur at the same time. We evaluated a two-hour window time before and after each WDP. Once we identified the lag with the highest correlation between the precipitation rate and each of the WDP attributes, we adjusted the time lag between the predictor and response variables using the *DataCombine* package (Gandrud, 2016). Further, we analyzed the relation among log-transformed number of WDP, speed, critical duration, and rainfall rate (mm min^{-1}) using linear models (i.e., log(y+1) ~ log(x+1)) for the time-lagged adjusted data. We fitted a simple linear model for each combination of predictive and response variables (e.g., log(speed+1) ~ log(rainfall rate +1)) along different rainfall percentiles varying between 0th and 99th. These percentiles were used for testing the magnitude of the effect of different rainfall severities on the response variables. For each model combination along the percentiles, we calculated the Pearson correlation (r), adjusted coefficient of determination (R^2) and p-value from the regressions using the *stats* package (R Core Team, 2024) as measures of the robustness of the relationship between the rainfall rate and the WDP attributes. Higher r and R^2, and lower p-value indicate the percentile where the best relationship was found.

3 Results

3.1 What are the WDP patterns in the forest canopy?

We analyzed 17,348 hours of data, of which around 4% contained WDP. We recorded 424 events of WDP during the study period. Wind speed and critical duration ranged from 10 to 17.9 m s^{-1}, and from 1 to 90 seconds, respectively (see details in

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Table 1). The WDP occurred on only 133 (~18%) of the 730 days analyzed. Nonetheless, these represent a daily mean of 3.1 ± 2.9 (± standard deviation) events, monthly mean of 17.2 ± 9.6 events, 213 events in Oct/2021 – Sept/2022 period, and 211 events in Oct/2022 – Sept/2023 period.

Table 1. Attributes and descriptive statistics of the WDP recorded in the INVENTA from Oct 2021 to Sep 2023. The letters inside the brackets show the results of the Mann-Whitney-Wilcoxon and Dunn Bonferroni tests for comparing the medians between the levels of the predictor variables. Equal letters indicate statistically similar medians, and different letters indicate the opposite.

Position	Number of WDP	Speed (m s^{-1})			Critical duration (s)		
		Min	**Max**	**Median**	**Min**	**Max**	**Median**
Plateau	302	10	17.9	11.1 (a)	1	90	3 (a)
Slope	98	10	16.2	10.9 (a)	1	30	2 (b)
Valley	24	10.1	13.5	10.7 (a)	1	16	1 (b)
Daytime	**Number of WDP**	**Min**	**Max**	**Median**	**Min**	**Max**	**Median**
Day	358	10	17.9	11 (a)	1	90	2 (a)
Night	66	10	14.7	11.1 (a)	1	30	2 (a)
Season	**Number of WDP**	**Min**	**Max**	**Median**	**Min**	**Max**	**Median**
Dry	249	10	17.9	11.1 (a)	1	90	3 (a)
Wet	175	10	14.8	10.9 (a)	1	30	2 (a)

We found that 358 (84.4%) and 66 (15.6%) WDP occurred in the day and night periods, respectively (Fig. 3a). However, there was no statistical differences between the medians of speed ($p = 0.83$) and critical duration ($p = 0.41$) between day and night periods (Fig. 3b and c; Table 1). Still, the highest values of speed and critical duration were recorded during day period, mainly between 10:00 and 16:00 local time (LT) (Fig. 3d and e). Despite the similar patterns, these results suggest that the day and night periods show a distinct variation of these attributes.

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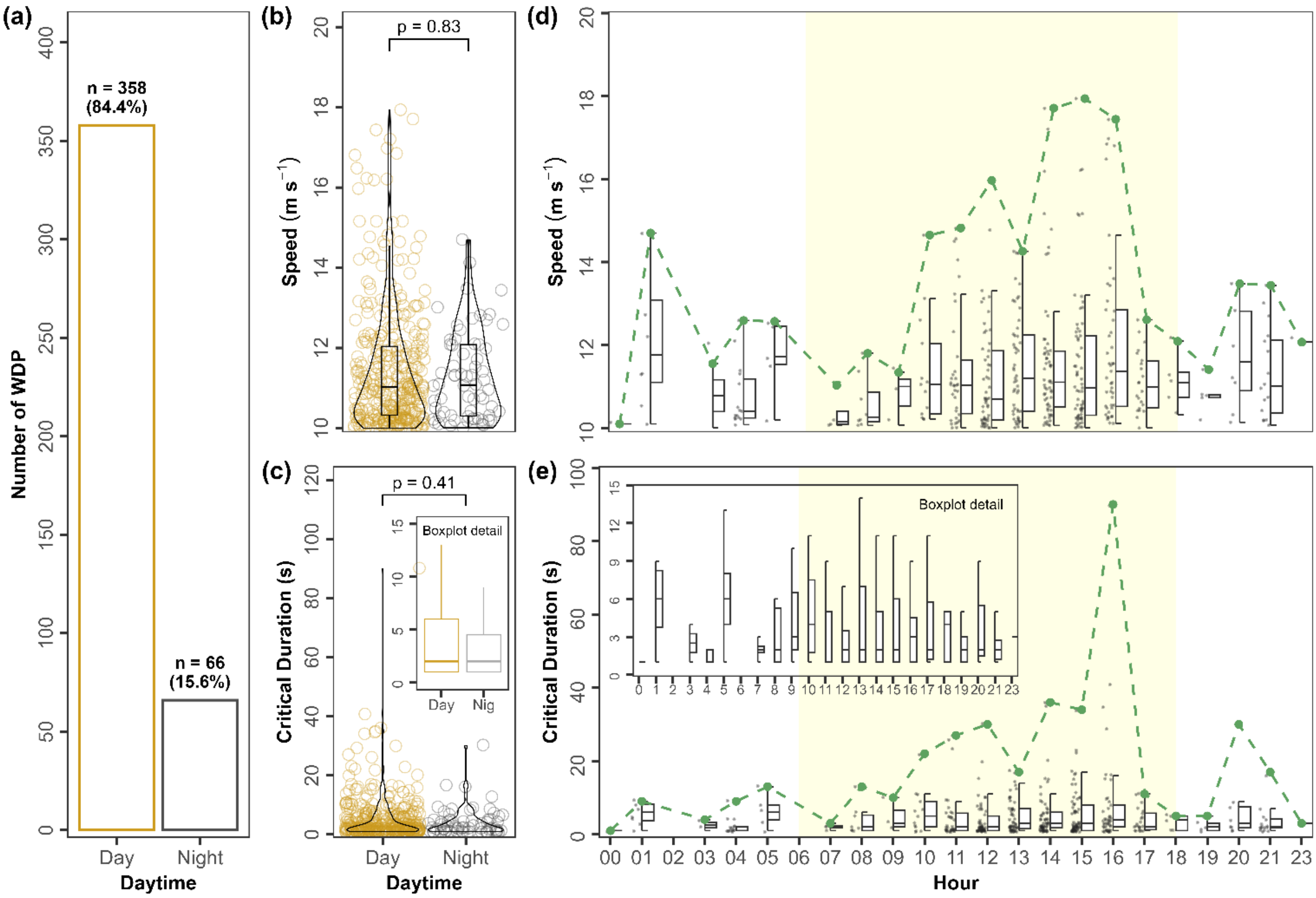

Figure 3. Daytime effects in the WDP attributes. (a) Number of gusts; (b) Speed; (c) Critical duration; (d) Speed along of hours of the day; (e) Critical duration along of hours of the day. In panels b and c, the p-value of Mann-Whitney-Wilcoxon test is shown above the brackets. In panels d and e, the light-yellow bands represent the day period. In all the panels, the attributes were computed without distinction of topographic position.

3.2 How are WDP affected by topography?

From the total number of WDP (n = 424), 302 (66%) were recorded on the plateau, 98 (21%) on the slope, and 24 (5%) in the valley (Fig. 4a). Although the number of events reduced greatly from plateau to valley, the median wind speed of recorded events did not differ significantly among the three topographic positions (p= 0.35, Fig. 4b; Table 1). Still, the median critical duration declined significantly with topographic position (p = 0.02, Fig. 4c; Table 1). Nevertheless, these differences were only observed between plateau and slope (p = 0.03) and between plateau and valley (p = 0.02) with slope and valley being similar (p = 0.18).

We recorded a systematic decrease of the maximum values of speed and critical duration reached by the WDP from the plateau to the valley (Table 1). Our results suggest that the topographic effect of the WDP is attributable to fewer and shorter events, with only those reaching the highest recorded speeds propagating down to the lower portions of the relief (i.e., lower portions of slope and valley). Wind direction was also affected by topography. Overall, WDP blew predominantly from the east quadrant in all topographic positions. However, at the plateau and slope (Fig. 4d and e), WDP had a distribution relatively constrained from east to west. This contrasts the distribution observed at the valley, where WDP were predominantly aligned from south to north (Fig. 4f, see the valley orientation in the Fig. 1c).

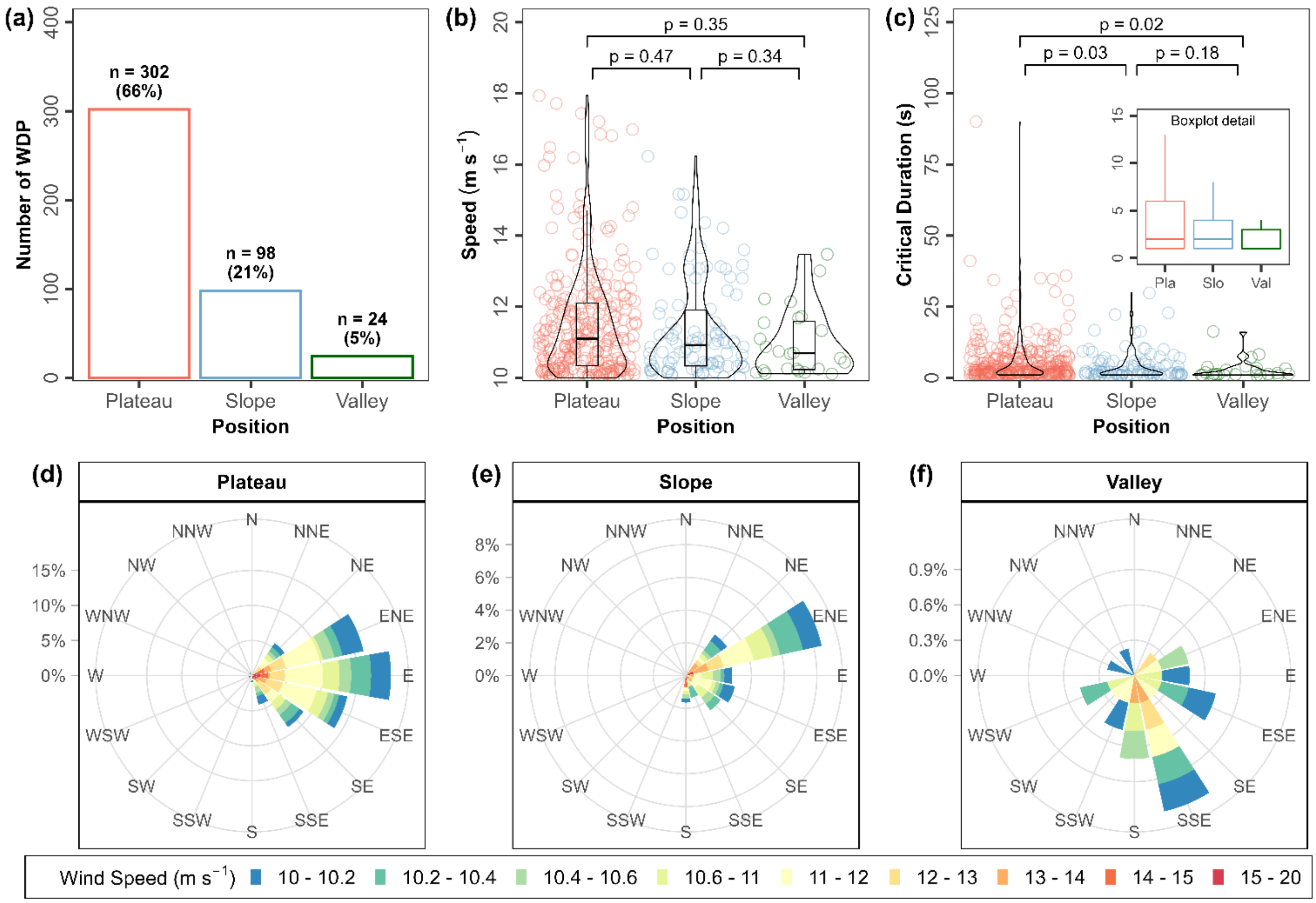

Figure 4. Topographic effects in the WDP attributes. (a) Number of gusts; (b) Wind speed; (c) Critical duration; (d) Wind direction in the plateau; (e) Wind direction in the slope; (f) Wind direction in the valley. In panels b and c, the p-value of the Dunn Bonferroni post-hoc test for multiple comparations among the topographic positions is shown in the top and the brackets. In panels d to f, the y axis represents the frequency (%) of WDP according with wind speed levels legend below the panels.

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3.3 How do seasonality and rainfall intensity affect WDP?

The majority of WDP occurred in the dry season (249 or 58.7% compared to 175 or 41.3% in the wet season) (Fig. 5a). Although the median critical duration of WDP was similar (p = 0.14, Fig. 5c; Table 1), the median wind speed in the dry season marginally exceeded that of the wet season (p = 0.05, Fig. 5b; Table 1). The maximum values of wind speed and critical duration of WDP were higher in the dry season (Table 1). July had the highest frequency of WDP (n=73) among all months (Fig. 5d). The highest wind speeds (Fig. 5e) and critical durations (Fig. 5f) were observed during the transition from the dry to the wet season (i.e., September and October).

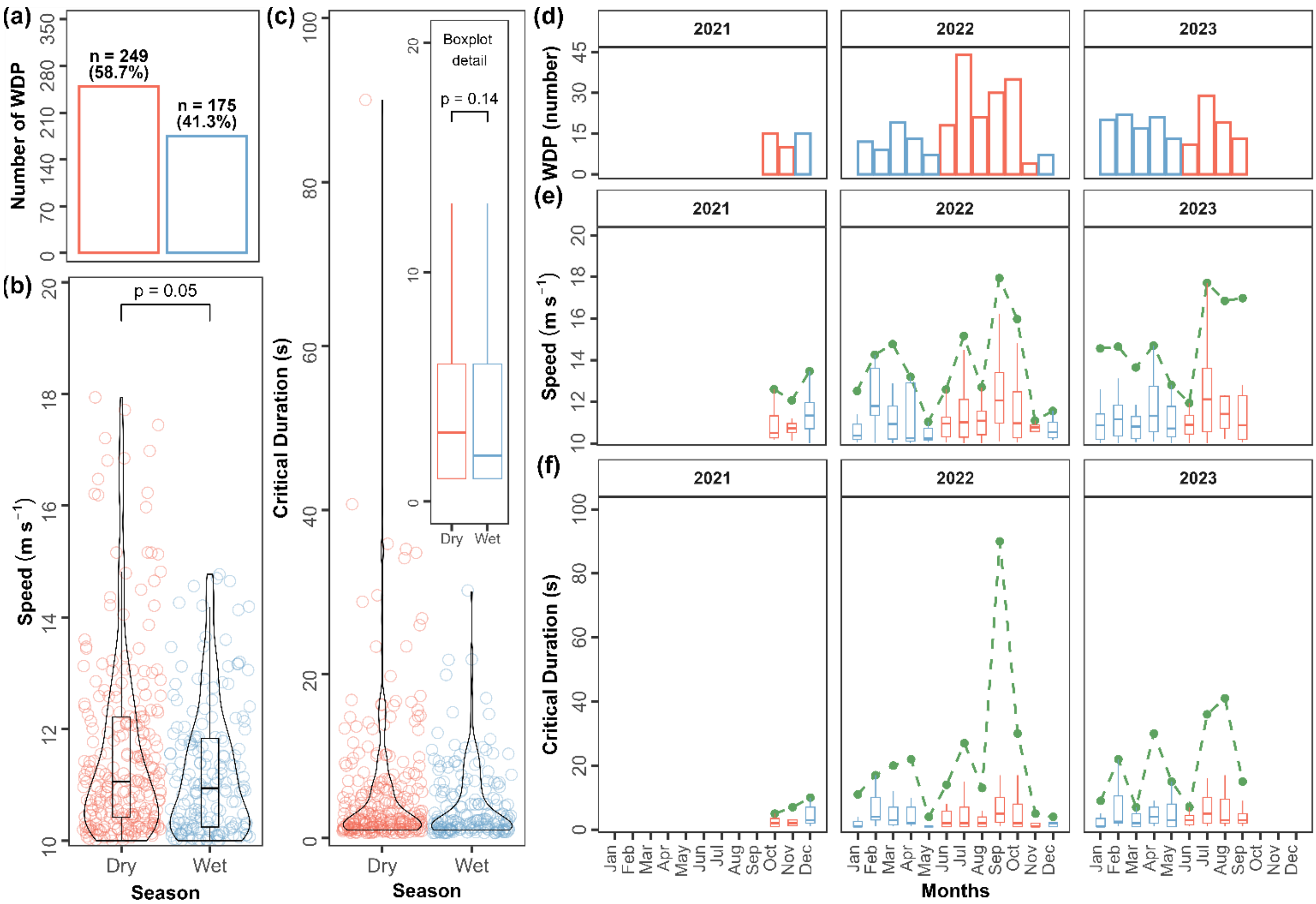

Figure 5. Seasonality effects in the WDP attributes. (a) Number of gusts; (b) Wind speed; (c) Critical duration; (d) Number of gusts during the months; (e) Wind speed during the months; (f) Critical duration during the months. In panels d to f, the months are distinguished in relation to the Dry and Wet seasons by red and blue colors, respectively. For the panels e and f, the maximum values of WDP attributes recorded in the months are represented by the green points connected by the dashed green lines. In all the panels, the attributes were computed without distinction of topographic position.

Recorded WDP were predominantly aligned to the east quadrant, both in the dry and wet seasons (Fig. 6a and b). Nonetheless, we observed a change in direction of WDP during the dry season, with events predominantly aligned to the southeast sub-

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quadrant (Fig. 6a). In the wet season, most WDP were aligned to the northeast quadrant (Fig. 6b). These changes in sub-quadrant direction were more evident monthly (Figure 6c), with largest shifts evident in May and October, the months marking the end and onset of wet season in the region (Fig. 6c).

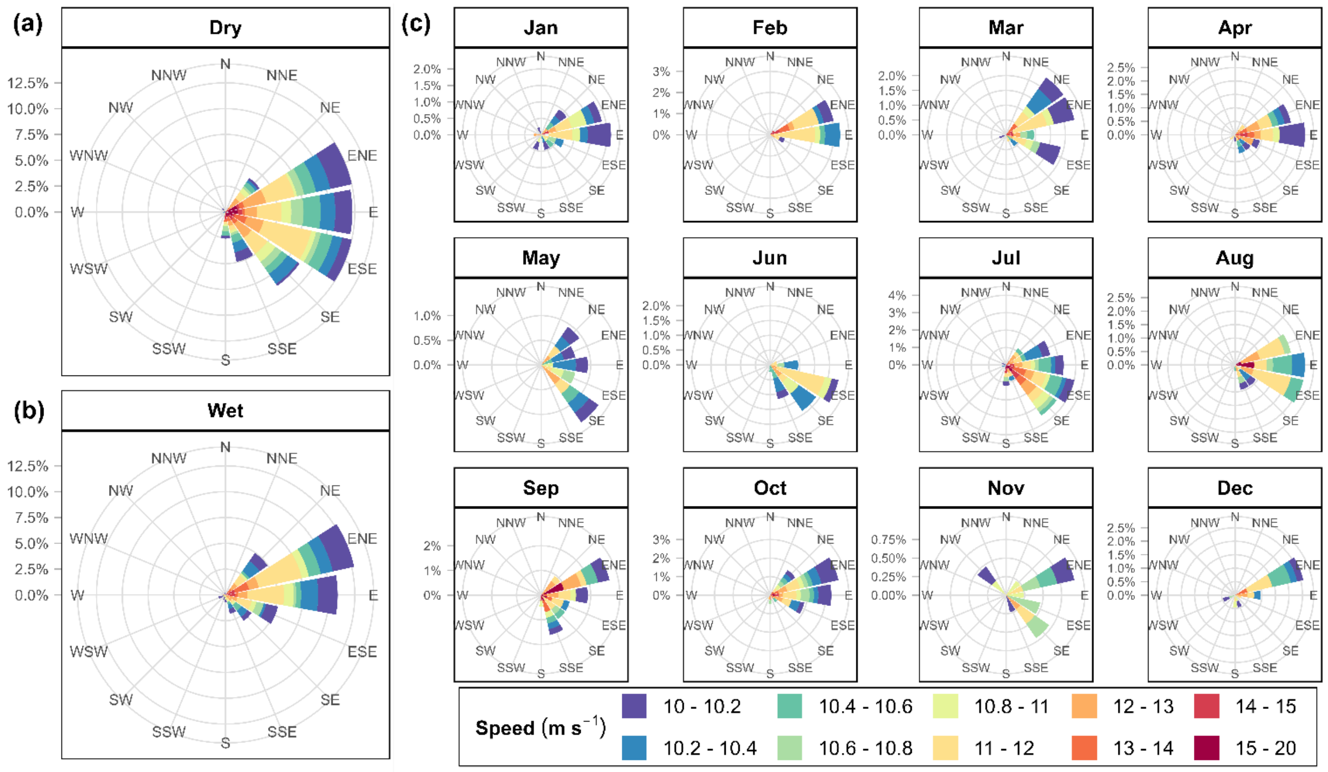

Figure 6. Seasonal and monthly direction of the WDP. (a) Distribution direction in the dry season; (b) Distribution direction in the wet season; (c) Distribution direction of the WDP during the months. The y-axis in the panels a-c indicates the frequency (%) of gusts according to the direction. In all the panels, the attributes were computed without distinction of topographic position.

We found a positive lag ranging from 5 to 20 min between rainfall rates (mm min^{-1}) and all WDP attributes (Fig. 7a-c). There was a positive effect between rainfall rate in the number of WDP (Fig. 7d) and their critical duration (Fig. 7f). Wind speed (above the WDP threshold) was not affected by the rainfall rates (Fig. 7e). The 5-min lags indicated that increases in the number and critical duration of the WDP were linked to subsequent rainfall events. However, most of WDP (291 or 68.8%) were not accompanied simultaneously by rainfall in a time lag ≥5 min, and another expressive number (122 or 29%) were not accompanied by rain in a time lag ≥20 min. A relatively lower number of WDP (133 or 31,3%) occurred simultaneously with rainfall in a time lag ≤5 min. For the number and critical duration, there was a general upward trend in the relationship with the rainfall rate during the rainfall events, where the highest Pearson's correlations were recorded at the 87th percentile both for number of WDP ($r = 0.92$, $p < 0.01$, Fig. 7g) and critical duration ($r = 0.83$, $p = 0.01$, Fig. 7i). This percentile corresponded to a mean rainfall rate of 0.7 mm min^{-1} and explained 84% and 68% of the variation in number and critical duration of WDP, respectively. In both these attributes, this relationship was mainly driven by events occurred during the dry season (Fig. 7j and

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l). We found no clear relationship between WDP attributes and monthly maximum rainfall rate (Fig. S5c-e). Median rainfall rate also did not differ between dry and wet seasons (Fig S5a). However, we recorded 30% more extreme rainfall events with rainfall rate ≥0.7 mm min^{-1} (87^{th} percentile) during the wet season, especially in February and March (Fig. S5b).

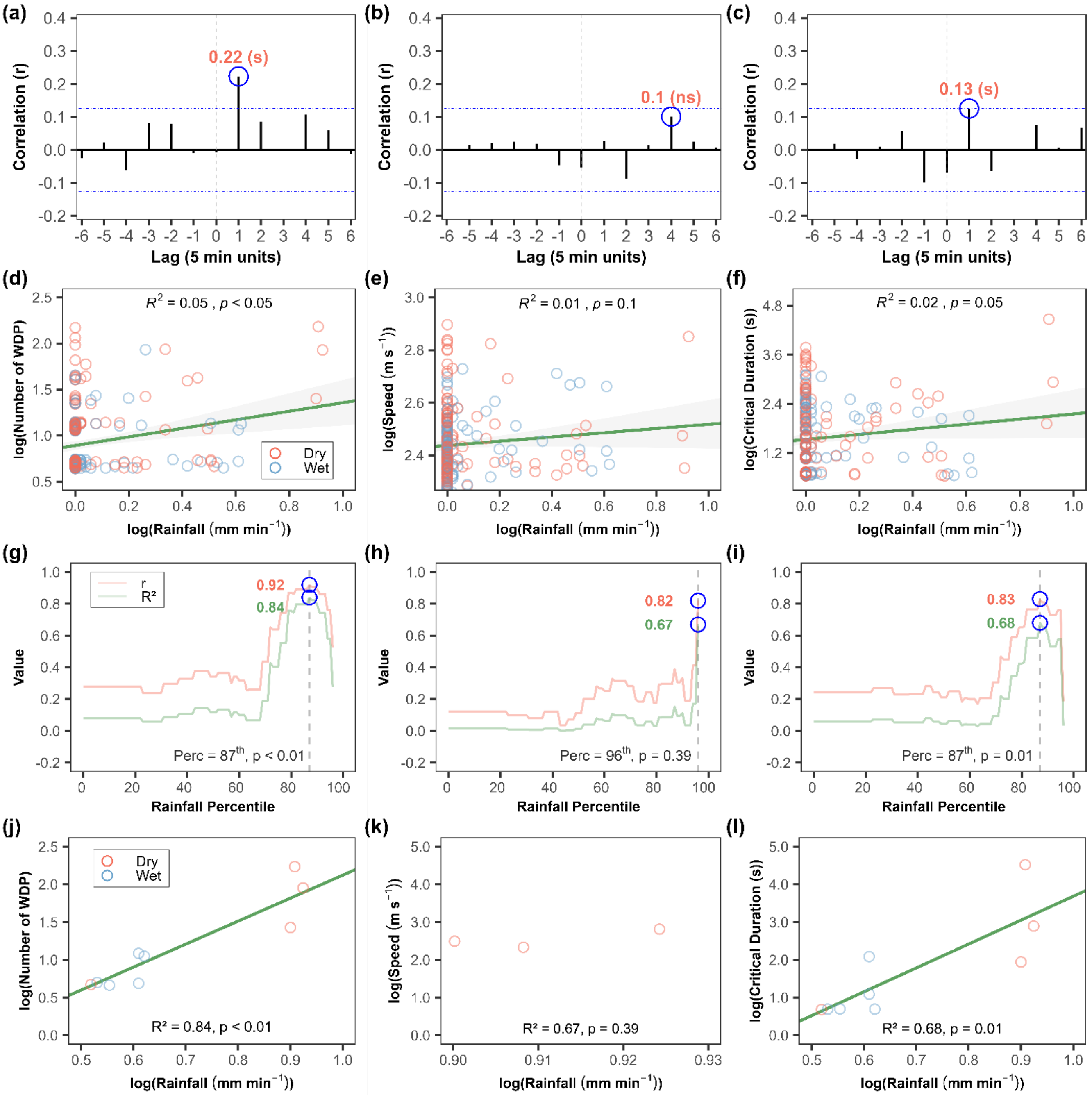

Figure 7. Relationship between rainfall and the WDP attributes. Panels a-c: Cross-correlation analysis between log-transformed rainfall rate (mm min^{-1}) and log-transformed (a) Number of WDP, (b) Speed, and (c) Critical duration. In the a-c panels, the x-axis is a time lag in which

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the highest significative Pearson correlation is observed between rainfall rate and the WDP attributes. This time lag is measure by 5-min units of frequency (e.g., 4 lag is equivalent to 20 min). Blue circles in the top of bars indicate the highest Pearson's correlations (r) found for the relationship. Pearson's Correlations numbers are followed by "(ns)" indicating non-significative or "(s)" indicating significative p-values. Dashed blue lines are the limits of confidence intervals. Panels d-f: Linear models indicating the relationship between log-transformed rainfall rate and log-transformed (d) Number of WDP, (e) Wind Speed, and (f) Critical duration. Grey bands are the confidence intervals; Panels g-i: Pearson's correlation (r) and adjusted coefficient of determination (R^2) between log-transformed rainfall rate and log-transformed (g) Number of WDP, (h) Wind Speed, and (i) Critical duration along 0 to 99th percentiles of rainfall rate. The y-axis is the values of Pearson correlation and R^2. Blue circles indicate the percentile which the highest significative Pearson's correlation and R^2 were found; Panels j-l: Linear models describing the relationship between log-transformed rainfall rate and log-transformed (j) Number of WDP, (k) Wind Speed, and (l) Critical duration in the selected percentile where the highest significative Pearson correlation and R^2 were found (panels g-i). Grey bands in the panels d-f are the confidence intervals. In all the panels, the attributes were computed without distinction of topographic position.

4 Discussion

4.1 The effects of topography and seasonality on the patterns of WDP

We found that the WDP patterns were affected by topographic attributes, which has also been previously reported by studies assessing wider speed ranges and relatively more complex reliefs in temperate and tropical forests (Belcher et al., 2012; Mikita and Klimánek, 2012; Mitchell, 2013; Ruel et al., 2001; Tóta et al., 2012). In our study site, differences in the attributes of WDP among topographic positions were more pronounced for maximum than for median values, suggesting that topography interacts mainly the dissipation of the speediest and longest WDP registered in the lowest parts of the relief (Fig. 2b-d).

Wind speed generally increases with altitude (Dunlop, 2017; Mitchell, 2013). Further, the orientation of terrain in relation to the predominant wind direction, variability in elevation, and canopy roughness also affect the wind regime in a forested location (Chapman, 2000; Finnigan, 2004; Gardiner, 2021; Ruel et al., 2001; Santana et al., 2018). Trees and relief breaks impose barriers to air flow, or sheltering effects (Chapman, 2000) that reduce the speed and duration of wind gusts passing through these obstacles (Awol et al., 2022; Dupont and Brunet, 2009; Finnigan et al., 2009; Gardiner et al., 2019; Guo et al., 2021; Holmes et al., 2014). The higher the speed of the gusts before they encounter an obstacle, the lower the loss of wind speed after passing the obstacle, i.e. the lower the secondary flow speed (Joshi and Anderson, 2022; Terziev et al., 2021). Here, we recorded WDP with anemometers placed at canopy height, which captures the wind speed influenced by turbulent interaction with the canopy roughness (Awol et al., 2022; Bannister et al., 2022; Belcher et al., 2008; Chen et al., 2019; Corrêa et al., 2021; Finnigan, 2000, 2004; Repina et al., 2021). Thus, the wind speeds we recorded were likely affected (reduced) by interaction with the canopy and lost some energy. Around 74% of the WDP we recorded at all topographic positions were in the lower speed range, between 10 – 12 m s^{-1} (median = 11 m s^{-1}, Fig. S3), which are more prone to substantial speed losses when they interact with the canopy than higher speed WDP. The vast majority of WDP fits into this lower speed range, which explains no speed differences among topographic positions (Fig. 2b). Conversely, we observed a systematic decrease of speed and number of gusts, particularly in the speediest WDP from the plateau to the valley. This indicates that valleys may be generally less exposed to WDP. In fact, our valley is oriented from south to north in relation to the prevailing east to west winds in our region (Rehbein et al., 2018, 2019). Theoretically, wind gusts lose speed when entering valley formations because the wind encounters resistance from the trees, which reduces its strength (Quine et al., 2021). In addition, the orientation of

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our valley (south to north) forces a change in wind direction, from east to west to south to north. This orientation perpendicular to the prevailing winds makes the lower parts more protected from the action of extreme winds, especially the east side of the valley. If the orientation of the valley affects the critical duration of gusts, we can infer that valleys with a predominantly south-to-north alignment are generally less vulnerable to strong winds compared to plateaus or east-west valleys.

The shelter effect creates more recirculation eddies after the wind has passed the obstacle (Cassiani et al., 2008; Detto et al., 2008). In high-slope valleys, as typically found in our study region (Rennó et al., 2008), the rapid change in altitude overcome the sheltering effect produced by trees (Bannister et al., 2022; Belcher et al., 2012). Abrupt changes in topography in forested hills and valleys also create recirculation zones, usually associated with vertical shear and turbulence (Chen and Chamecki, 2023; Diebold et al., 2013; Kutter et al., 2017), as well as changes in the vertical mixture of energy, direction, and magnitude of fluxes (Chamecki et al., 2020; Staebler and Fitzjarrald, 2005; Xu and Yi, 2013). Further, valleys are susceptible to downward inflows of air, which can be channeled, creating more complex areas of turbulence (Belcher et al., 2012; Gardiner et al., 2013, 2019) that in our study apparently affected more the duration than speed of the WDP. In fact, our results show that the predominant wind direction recorded at the valley tower was notably distinct from the others and influenced by inflows oriented parallel to the valley (Fig. 2g). This process has already been described in adjacent forests with similar structure (Tóta et al., 2012) and corroborates that turbulent flows from tree and wind drag may have influenced more the critical duration of gusts than their speed. As in our study region the topography becomes flatter at higher elevations, the sheltering effect decreases (Belcher et al., 2012) and the canopy surface becomes more susceptible to the entry of faster winds associated with convective systems and low-level jets, which are less dependent of direct interactions with the surface features such as roughness, slope and aspect (Anselmo et al., 2020; Garstang et al., 1994; Greco et al., 1994; Mendonça et al., 2023). In fact, nine of the 10 fastest WDP were recorded on the plateau. As the topographic sheltering effect decreased (i.e. from the valley to the plateau), the predominant wind direction recorded in our study area (Fig. 2d and f) converges with the prevailing east-to-west wind direction reported for the Central Amazon (Andreae et al., 2015; Espinoza et al., 2012; Pöhlker et al., 2019; Rehbein et al., 2018, 2019; dos Santos et al., 2014; Tóta et al., 2012; Zhuang et al., 2017).

While found no day-night differences in the median velocity and critical duration of WDP (Fig. 3b and c), the events were concentrated in the daytime (Fig. 3a), including a systematic increase of all WDP metrics in the hottest hours of the day (Fig. 3d and e). These results are consistent with previous studies conducted in the same region (Fuentes et al., 2016; Mendonça et al., 2023; dos Santos et al., 2014; Tóta et al., 2012; Zhuang et al., 2017), which attributed these patterns to decoupling of airflow between upper and sub canopy layers at night due to the decrease of transport efficiency with cooling. This implies a low-intensity wind regime at night (Cava et al., 2022; Freundorfer et al., 2019; Thomas et al., 2013). Our results also agree with regional observations of more intense winds during daytime due to surface solar heating, intensification of convection, and consequently higher air pressure gradients (Fuentes et al., 2016; Garstang et al., 1994, 1998; Mendonça et al., 2023; Rehbein et al., 2019; Rehbein and Ambrizzi, 2023; Tóta et al., 2012; Zhuang et al., 2017).

The highest number and mean wind speed of the WDP in our study region occurred during the dry season months, especially in the transition from dry to wet season (Fig. 4c). This is in accord with records in other tropical forests located at Barro

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Colorado, Panamá (Araujo et al., 2021), and the Central Amazon (Ahlm et al., 2010; Andreae et al., 2015; Mendonça et al., 2023). However, our records also showed that the strongest WDP (i.e., the fastest and longest-enduring gusts) coincided with the average passage period of short- (lifetime 3 to 5.5 h) and long-lived (lifetime ≥6 h) continental MCSs over our study region described by previous studies, mainly between September and March and also during the transition of the dry to the wet season when heavy rainfall events are more frequent (Negrón-Juárez et al., 2017; Rehbein et al., 2018, 2019). This pattern should be confirmed with a more extensive temporal observations, as in our data the median critical duration of WDP was similar between the dry and wet seasons (Fig. 4c). In fact, we did not observe significant differences in the median precipitation rate between the seasons (Fig. S5a), although we observed a clear concentration of extreme rainfall events (≥0.7 mm min^{-1}, 87^{th} percentile) in the February to April months of the wet season (Fig. S5b). During the wet season in most of Amazon basin, the active phase of the South Atlantic Convergence Zone (SACZ) and the Intertropical Convergence Zone (ITCZ) in your southernmost position represent the dominant features. They bring more stratified extreme rainfall from tropical ocean for several days (Carvalho et al., 2004), and intensification of westerly wind regime (Nobre et al., 2009). During the dry season, the cloud systems have a more continental-type behavior (Williams et al., 2002), with most rainfall events generated by localized deep convection due the northernmost position of the ITCZ and the weakening or breaking of the SACS (Nunes et al., 2016). The highest number of WDP was recorded in July for both 2022 and 2023 years, which also coincided with highest number of MCS documented in Central Amazon sites for the 2014 and 2015 years (Rehbein et al., 2019). However, our results showed that September had highest values of wind speed and critical duration of the WDP, coinciding with the average period where MCSs substantially reduced their activity in the Central Amazon (Rehbein et al., 2019). This reduction is due to the acceleration the dissipation time by strong winds at all levels, which are created by the intensification of the diurnal cycle of radiative heating (Machado et al., 1998; Nunes et al., 2016; Raupp and Silva Dias, 2010; Salio et al., 2007). The radiative heating is higher in driest months, intensifying the wind regime, mainly from August to October in the Central Amazon (Liebmann and Marengo, 2001; Marengo et al., 2001). Therefore, our results suggest that the period of highest intensification of WDP in our study region is probably related to MCSs activity, but also with other transients systems, such as frontogenesis, river breezes, low level jets, and cold fronts (Filho et al., 2015; De Oliveira and Fitzjarrald, 1994; Silva Dias et al., 2004), which take force in the onset of the South American Monsoon System in the Central Amazon (Carvalho et al., 2011; Garcia and Kayano, 2010; Liebmann and Marengo, 2001; Marengo et al., 2001).

4.2 Linking WDP and rainfall events

In lower percentiles (i.e., in most cases), the rainfall rate had a weakly positive relationship with WDP attributes in our study area (Fig. 6a-f), demonstrating the high complexity of the weather processes that involve the interaction of local and large-scale environmental variables (Dunlop, 2017; Garstang et al., 1994; Maslin, 2013; Sombroek, 2001). On other hand, these relationships became stronger for the few events associated with extreme rainfall (Fig. 6g-i), highlighting the importance of organized convection for the windthrow tree-mortality in the tropical forests (Araujo et al., 2021; Marra et al., 2018; Marra et al., 2014; Negrón-Juárez et al., 2018; Dos Santos et al., 2016; Urquiza-Munoz et al., 2024; Urquiza Muñoz et al., 2021).

The higher number of extreme rainfall events recorded in the wet (Fig. S5b) gives us evidences that these season concentrated more events with a dangerous combination of heavy rainfall and destructive winds for the trees than the dry season (Gardiner, 2021; Geitmann and Gril, 2018; McDowell et al., 2018; Quine et al., 2021; Rau et al., 2022). Our results are consistent with previous studies in tropical forests in Central America and Amazon Basin that reported more rainfall events with higher rates in the wet season compared to the dry season (Angelis et al., 2004; Araujo et al., 2021; Jaramillo et al., 2017; Marengo et al., 2001; Oliveira et al., 2016; dos Santos et al., 2014). However, our results partially contrast with previous studies carried at larger scales that found a strong positive correlation between wind speed and rainfall along the ITCZ of the eastern Pacific and tropical America (Back and Bretherton, 2005; Espinoza et al., 2015; Hall et al., 2020; Mendonça et al., 2023).

The association of high rainfall rates with WDP is not always observed (Fujita and Wakimoto, 1983; Wakimoto, 1985). Other research has shown that these association is complex, and highly depend on seasonality and the interaction between local and large-scale factors (Espinoza et al., 2015; Kumar et al., 2019). MCSs such as squall lines propagating extreme winds and strong rainfall rates have been reported as the most distinct example of the association between rain and destructive winds in the Amazon Basin (Garstang et al., 1994; Negrón-Juárez et al., 2017, 2010; Nelson et al., 1994). Negrón-Juárez et al. (2018, 2010) reported MCSs propagating winds with 19 - 31 m s^{-1} and rainfall rates ≥ 10 mm hr^{-1} (~0.17 mm min^{-1}, in a constant rate). Garstang et al. (1998) recorded maximum wind speed of 17.2 m s^{-1} and rainfall rate ~0.8 mm min^{-1} for the Central and Western Amazon. We recorded 122 WDP (~29% of total) not accompanied by rain in a time lag ≥20 min, being one of them with speed of 17.94 m s^{-1}. Downward wind flows from MCSs can be propagated for kilometers beyond the point of origin of a storm (Fujita, 1981; Negrón-Juárez et al., 2010). This implies that wind gusts can be detected without the direct incidence of rainfall in geographically restricted measurement situations (Garstang et al., 1998).

4.3 Linking the patterns of WDP and tree mortality

Storms were responsible by 45 to 51% of individual tree-mortality recorded by forest inventories in the Central Amazon (Esquivel-Muelbert et al., 2020; Fontes et al., 2018b). During our monitoring period, the INVENTA project was not affected by large-scale windthrows (Simonetti et al., 2023). Therefore, the recorded WDP are probably related to individual or small-grouped tree-mortality and branch falls (Negrón-Juárez et al., 2011; Simonetti et al., 2023). While our results reveal a more intense WDP regime (i.e., higher frequency, speed, and duration) at more elevated portions of the relief, a monthly forest inventory conducted by Fontes et al. (2018) in a subjacent area found higher tree mortality in less elevated areas. Despite the scarcity of studies at this topographic scale, the hypothesis that the frequency of extreme wind events alone has a significant relationship with the rate of canopy disturbance from individual or small clustered trees was refuted in a tropical forest in Panama (Araujo et al., 2021) and a temperate forest located in England (Abd Latif and Blackburn, 2010).

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We found that WDP regime were slightly more intense in the dry season than wet season. Previous studies found higher rates of individual and small group windthrow tree-mortality and canopy disturbances in the wet season in areas close to the INVENTA (Aleixo et al., 2019; Araujo et al., 2021; Fontes et al., 2018b). During a monthly monitoring period from September 2018 to January 2021 (28 months) in INVENTA, Simonetti et al (2023) recorded 32 gaps, of which approximately 34% were small (<39 m²). In comparison, during a similar subsequent period (October 2021 to September 2023, 24 months), we recorded 424 WDP. Our results suggest that most of the gusts we observed may not be causing damage to trees. This is corroborated by the strong variation in the critical wind speeds estimated by Peterson et al. (2019) in an area close to INVENTA, which ranged from 10.75 m s^{-1} to >120.0 m s^{-1}. However, these authors found relatively higher rates of gap formation in the onset of the wet season, especially in August, September and October, which are similar with our most intense WDP regime. We hypothesize that the combination of WDP and higher amount of heavy rainfall events in the wet season may also increase the vulnerability of the trees to wind-related mortality compared to the dry season. Damage can be caused not only by forces from extreme winds, but also repeated cycles under different gust durations (Miller et al., 1987; Mitchell, 2013; Moore and Maguire, 2004; Peltola, 2006). These cycles generate continuous and longer sway of the trees with consequent stress and increased vulnerability to mechanical failure that can result in the breakage of branches, snapping and uprooting (Cannon et al., 2015; Jackson et al., 2019b; Moore et al., 2018; Yang et al., 2020). Similar gust speeds can have different impacts on the trees failure if they have different durations, even if these differences are small in magnitude (Holmes et al., 2014; Krayer and Marshall, 1992). For example, at the same turbulence intensity, site conditions and tree size, hypothetical estimates showed that the tree could fall with a gust speed of 27.8 m s^{-1} for a duration of 5s, which, recalculated to 1s, is similar to a gust impact with a speed of 37 m s^{-1} (England, 2000). Beyond the wind, trees can suffer with higher loads generated by the raindrops retention by the canopy (Brandt, 1988; Hall and Calder, 1993; Mulkey et al., 1996), which can reach relatively high retention capacities in tropical forests (Lenz et al., 2022). Despite similar rainfall rates in both seasons (Fig. S5a), we recorded substantially more rainfall volumes in the wet season, suggesting more static rain loadings over the crowns (Pickett and White, 1985) per time unit combined with WDP than dry season (Fig. S5b). The tree mortality is complex and frequently involve many combined factors, which sometimes imply in immediate tree death, but can also result in delayed death (Aleixo et al., 2019; McDowell et al., 2018). In the dry season, tree can suffer mechanical stress by dynamic loads regime due to the high frequency of the gusts, which can be exacerbated by hydraulic failure due the drought stress and warmer temperatures (Adams et al., 2017; Anderegg et al., 2015; Fontes et al., 2018a; Geitmann and Gril, 2018). Sequentially, trees already mechanically and physiologically stressed in the dry season can suffer again in the wet season due to severe storms, which intensify the regime of static and dynamic loadings on the trees, consequently reducing the tree stability (van Emmerik et al., 2018b, a; Van Emmerik et al., 2017; Gardiner et al., 2016; Jackson et al., 2019b; Lorenz et al., 2024; Mitchell, 2013).

4.4 Limitations and future opportunities

Windthrow tree-mortality is undoubtedly connected to the WDP regime (Mitchell, 2013), which we demonstrated to be influenced by topography, seasonality, and rainfall. Changes and anomalies in the climate such as warmer temperatures, droughts, intensification of wind storms, extreme rainfall, and El Niño-Southern Oscillation (ENSO) years were frequently correlated with increases in the tree mortality in the Amazon basin (Adams et al., 2017; Aleixo et al., 2019; Allen et al., 2010; Bennett et al., 2015; Feng et al., 2023; Hartmann et al., 2022; Leitold et al., 2018). Here, we locally analyzed a two-year monitoring interval that included 2022 and 2023, strong La Niña and El Niño years, respectively (NOAA, 2024). Based on measurements taken in Manaus (ANA, 2024), the water levels of the Negro River have fluctuated significantly, ranging from 12.7 meters (the lowest level recorded since 1902 on June 16th, 2021) to 30.02 meters (the highest level recorded on October 26th, 2023). These climate anomalies are often associated with changes in the regime of rainfall and extreme winds in relation to years with less intense climate anomalies (Espinoza et al., 2019; Segura et al., 2020; de Souza et al., 2021). Therefore, concomitant climate anomalies may have limited our capability to fully capture landscape patterns of WDP in our study region. In addition, upscaling from our local WDP patterns must be carefully done due the local variations such as valley orientation and altitude (Rennó et al., 2008; Tóta et al., 2012), and the highly local-regional variability of convective storms in the Amazon basin (Negrón-Juárez et al., 2017; Rehbein et al., 2018, 2019). Both aspects are related to reported local-to-regional wind patterns (Gardiner, 2021; Garstang et al., 1998; Ping et al., 2023; Ruel et al., 1998, 2001). Therefore, the representativeness and accuracy of our results reinforce our patterns of WDP in a local footprint, which can be substantially increased with longer monitoring periods (Feng et al., 2023) and new sites with extensive spatial coverage (Andreae et al., 2015; Garstang et al., 1998; Martin et al., 2016). Future studies could evaluate new environment conditions and to extend the monitoring time to encompass climate anomalies, normal conditions, and extreme conditions, which are crucial to understand the future of tropical forests in a climate change scenario.

INVENTA is a multidisciplinary project integrating remote sensing, meteorological data and ground/terrestrial data on tree mortality driven by wind and associated forest responses (Marra et al., 2018). As our results showed, the more intense WDP regime in the dry compared to the wet season corroborates gaps formation rates previously recorded by Simonetti et al (2023) in the INVENTA but partially contrast the higher windthrow tree-mortality recorded in the wet season in nearby areas (Aleixo et al., 2019; Fontes et al., 2018b). These contrast highlight the importance of to integrate other variables, such as tree-species traits and architecture (Rader et al., 2020; Yang et al., 2020), soil moisture and depth (Costa et al., 2023), and wet/dry extreme events (Esteban et al., 2021; Sousa et al., 2020) in future studies to better understand the tree-mortality process and the limitations of the establishment of complex meteorological patterns based in a single site (Tóta et al., 2012). It also opens new opportunities for the future expansion of INVENTA and integration with other research initiatives. Recently in our study area, Simonetti et al (2023) used high-resolution remote sensing and forest inventory data to quantify the relative contribution of mechanisms of gap formation. The authors found positive correlations between the rate of gap formation and the frequency of extreme rainfall events through a month-basis assessment. However, how much variation of individual or small clustered

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windthrow tree mortality is explained by WDP, remains unclear. To answer this question, we encourage future studies in a high-frequency basis to quantify the relative importance of WDP in the canopy gap formation and evaluated our hypothesis of combined action by wind-rainfall loads on the trees, testing new wind speed thresholds that characterizing destructive gusts. Our results also open up opportunities for future researches approaching tree motion sensing, recently tested with some amazon trees, whose results show that tree sway is connected with the wind forcing (van Emmerik et al., 2018a; Van Emmerik et al., 2017). Currently, the INVENTA is assessing the relative importance of the functional and environmental characteristics involved in the adaptive tree biomechanics through a set of motion sensing installed in canopy trees (Marra et al., 2018). This research will provide a better understand of the mechanical stability of trees and their respective vulnerability to winds.

Conclusions

Wind speeds with potential to damage and topple trees occur during the entire year and all over the topographic gradient of a Central Amazon forest. However, their critical duration and frequency are influenced by seasonality and canopy exposure assessed by variations in topography. More frequent and severe winds occur mainly within the transition from the dry to the wet season, potentially through a combination of excessive heat and moisture brought by convective systems, corroborating empirical observations from previous studies. Our results show a positive correlation of extreme rainfall events (storms) and the frequency and critical duration of WDP. However, they also support that WDP are not exclusively propagated during heavy rainfall formed by large-scale convective systems. More frequent and severe WDP during the transition from the dry to the wet season also corroborates the higher number of canopy gaps previously reported for our study region. This suggest that our threshold of 10 m s^{-1} may be robust for assessing patterns of WDP in other *terra-firme* forests in Central Amazon. Our study highlights the importance of long-term and high frequency meteorological data for assessing disturbance regimes at local-to-regional scales, usually not effectively captured by remote sensing.

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Authors contributions

D.M.M., L.E., G.D.P.., R.I.N-J., and S.T. planned and designed the research; D.M.M., O.K., and L.E. installed and instrumented towers; L.E. and D.M.M. collected the data; L.E. analyzed the data with support from D.M.M. and T.E.; L.E.

wrote the manuscript with support from D.M.M.; All authors helped with revising and editing various versions of the manuscript. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analysis, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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