Pol. J. Environ. Stud. Vol. XX, No. X (XXXX), 1-12
DOI: *10.15244/pjoes/219362* ONLINE PUBLICATION DATE: 2026-07-31

Original Research

A Case Study on Wind Damage Evaluation of Common Tree Species in Coastal Urban Forests

Yunxuan Deng[1, 2], Kang Liu[3], Weijie Tong[3], Shuai Ma[3], Han Sheng[1], Yuxin Wu[1], Fasih Ullah Haider[1], Zitao Guo[1], Yuhua Ma[3], Xu Li[1]*, Linhua Wang[1]**

[1]Guangdong Province Data Center of Terrestrial and Marine Ecosystems Carbon Cycle, South China Botanical Garden, Chinese Academy of Sciences, Guangzhou 510650, China
[2]College of Life Sciences, University of Chinese Academy of Sciences, Beijing 100049, China
[3]College of Civil and Architecture Engineering, Chuzhou University, Chuzhou 239000, China

Received: 24 December 2025
Accepted: 15 March 2026

Abstract

Assessing the wind resistance of urban coastal trees is crucial for enhancing ecological security in typhoon-vulnerable regions under climate change. This study conducted post-typhoon field investigations in the wake of Typhoon Wipha in Yangjiang and Maoming, China, to evaluate damage to 1,645 trees across 15 common species. Using the Analytic Hierarchy Process (AHP), we developed a weighted wind damage value (WDV) integrating uprooted (weight: 0.637), trunk broken (0.258), and light-moderate damage (including broken branches and defoliation) (0.105). Results showed that 26.50% of surveyed trees suffered typhoon damage. *Casuarina equisetifolia* L. (WDV = 2.20), *Camphora officinarum* Nees (2.49), and *Plumeria rubra* L. (2.30) exhibited the strongest wind resistance, whereas *Ceiba speciosa* (A.St.-Hil.) Ravenna (11.66), *Cassia fistula* L. (11.09), and *Bauhinia variegata* L. (8.12) were most vulnerable. Functional trait analysis revealed that specific leaf area (SLA) (r^2 = 0.59, p<0.01) and leaf force to punch (Fp) (r^2 = 0.82, p<0.01) were the key predictors of WDV. These leaf-level traits mediate whole-tree wind damage through multi-level regulation of canopy wind load, branch mechanical strength, and root-soil interactions. The integrated WDV and trait framework provides a science-based tool for tree species selection and wind damage mitigation in typhoon-prone urban forests, offering a baseline reference for climate-adaptive management in coastal cities with similar environmental contexts.

Keywords: typhoon, urban forest, wind resistance, plant traits, wind damage

Introduction

Tropical cyclones are low-pressure vortex systems that form over tropical or subtropical oceans and are known by different regional names: “typhoons” in the northwestern Pacific and “hurricanes” in the Atlantic and northeastern Pacific [1]. In recent years, under global climate change, the frequency and intensity of typhoons affecting coastal regions have increased significantly. Studies indicate that over the past four decades, the occurrence of strong typhoons in East and Southeast

*email: lixu@scbg.ac.cn
**email: lhwang@scbg.ac.cn
0000-0002-7901-2551

Asia has increased by a factor of 2-3, and 2ºC of future global warming could further enhance both the intensity and frequency of such events [2-4]. This projection will leave forests in coastal areas such as Guangdong Province directly vulnerable to inevitable typhoon events in the future. Against this backdrop, obtaining baseline data on the wind resistance of tree species in coastal urban forests and exploring their adaptive traits have become an urgent prerequisite for formulating regional climate change adaptation strategies and improving the typhoon resilience of urban forest ecosystems under the warming climate. Typhoons not only pose severe threats to human lives, property, and socioeconomic stability, but as major natural disturbances, they also inflict destructive impacts on ecosystems and place coastal forests under sustained and severe pressure [5, 6]. Typhoons predominantly impact coastal forests across various climatic zones, inflicting physical damage on trees through strong winds and heavy rainfall. Common damage modalities include defoliation, branch damage, trunk snapping, and uprooting [7, 8]. Notably, typhoons frequently make landfall along coastlines, which are also highly urbanized areas. In these regions, urban forests serve as essential green infrastructure, playing a vital role in enhancing human well-being and maintaining the stability of urban habitats [9, 10].

Given the critical role of urban coastal forests in urban resilience, research on the effects of typhoon disturbance on these ecosystems and their response mechanisms has gradually become a focus in ecology, with a marked increase in related publications [11-13]. Bibliometric analysis of publications from 2010 to 2024 reveals a growing global research interest, led by institutions from the United States and China, with thematic clusters focusing on wind damage mechanisms, remote sensing monitoring, long-term recovery, and functional trait responses [14]. For instance, Duryea et al. (2007) systematically revealed wind damage response patterns of tree species along the southeastern coastal plain of the United States, while long-term observations following hurricanes in coastal forests of the southern United States showed that larger and taller trees (greater diameter at breast height and tree canopy height) experienced more severe damage, highlighting these structural dimensions as primary factors of stand vulnerability. Additionally, some studies have addressed damage to urban forest ecosystems and preventive strategies for specific tree species [15-17]. However, existing research has predominantly focused on natural forest ecosystems. Consequently, the wind resistance and species-specific vulnerability of urban forests, which serve as critical ecological barriers in highly urbanized coastal zones, have received relatively insufficient attention [18]. This knowledge gap is particularly concerning because urban forests differ from natural forests in species composition, stand structure, and management regimes, and thus are likely to exhibit distinct responses to typhoon disturbance [19]. This gap is especially pronounced in western Guangdong, a coastal region that bears the brunt of typhoons in China. Statistics indicate that nearly 70% of typhoons making landfall in China strike Guangdong Province, and cities along the western Guangdong coast, such as Yangjiang and Maoming, are among the most frequently impacted [20]. However, in contrast to coastal urban forests in regions with intense human development, scarce and unevenly distributed natural vegetation, and low ecosystem resilience, research on the post-typhoon responses of forests in the coastal areas of western Guangdong, an area featuring a mild, suitable climate, fertile soil, low population density, and low construction coverage, remains relatively limited; field-based, quantitative assessments of tree species' wind resistance and science-based species selection recommendations remain scarce [21, 22]. Furthermore, research on typhoon disturbances in China is far less advanced than that on other natural disasters, such as wildfires and droughts.

In East Asia, approximately 30% of typhoon tracks make landfall in China, causing severe natural disasters that result in billions to tens of billions of US dollars in infrastructure losses, alongside significant ecological disruption [23]. The coastal areas of Guangdong Province have experienced particularly severe vegetation damage since 2000, with forest ecosystems suffering extensive destruction, establishing this area as a high-frequency and high-impact zone for typhoon disturbances [24]. A targeted post-survey of a single typical typhoon event is the fundamental step to acquire baseline data that contributes to climate change adaptation, enabling future research to quantify how shifting typhoon regimes under global warming alter forest damage patterns and to inform proactive, resilient species selection for urban planning, while laying a solid foundation for subsequent long-term monitoring and multi-typhoon comparative analysis in this region. To address these challenges, this study takes Typhoon Wipha (2025) in Yangjiang and Maoming (Guangdong Province) as a case study to: (1) analyze post-typhoon tree damage rates and rank the wind resistance of common tree species in urban coastal forests of Guangdong; (2) identify the key plant traits that predict tree wind resistance. To this end, we conducted field surveys in Yangjiang and Maoming (Guangdong Province) shortly after Typhoon Wipha in 2025, collecting damage data for 15 common tree species. Using the Analytic Hierarchy Process (AHP), we assigned weights to three damage indicators: light-moderate damage (defoliation and branch damage), broken trunk, and uprooted. These weights were then used to calculate species-specific Wind Damage Values (WDV), which serve as a quantitative index of wind resistance. The findings aim to provide a scientific basis for species selection and practical strategies for disaster prevention and ecological restoration in urban coastal forests of typhoon-prone South China.

Materials and Methods

Study Area

The study area is located in Yangjiang and Maoming cities in southwestern Guangdong Province, China, geographically adjacent to each other and collectively forming an important coastal region in western Guangdong. Yangjiang spans from 21°28′45″N to 22°41′02″N and 111°16′35″E to 112°21′51″E, while Maoming lies between 21°22′N to 22°42′N and 110°19′E to 111°41′E. Both cities are situated south of the Tropic of Cancer and experience a south subtropical monsoon climate characterized by warm temperatures and abundant rainfall. The mean annual temperature ranges from 22-23°C. The average annual precipitation is approximately 2345 mm in Yangjiang and 1530-1770 mm in Maoming, with uneven spatiotemporal distribution. Rainfall occurs predominantly during the summer and autumn typhoon season. The area enjoys a long frost-free period and sufficient sunshine.

Topographically, the region slopes from north to south. In Yangjiang, mountains, hills, and plains account for 41.97%, 25.57%, and 21.77% of the total area, respectively. Maoming is dominated by hilly and mountainous terrain in its central and northern parts, with a coastal southern area featuring diverse landforms. The coastline is extensive, with the Yangjiang section alone stretching 458.6 km. The southeastern area is relatively low and flat, making it highly vulnerable to typhoon impacts. Both Yangjiang and Maoming have high forest coverage rates (59.28% and 58.48%, respectively), indicating a good ecological environment [25].

Typhoon Wipha

Typhoon Wipha (International designation 2506), the sixth typhoon of 2025, was characterized by abundant moisture supply, extensive circulation, a loose structure, significant forecast uncertainty, and a broad impact area. It made landfall along the coast of Hailing Island in Yangjiang City, Guangdong Province, on July 20, 2025. At landfall, the maximum wind speed near the center reached Force 10 (25 m s^{-1}), with a minimum central pressure of 980 hPa. After landfall, the typhoon moved westward and gradually weakened, causing damage to urban forest ecosystems along its path. Compared to super Typhoon Mangkhut (International designation 1882), which directly struck Guangdong Province in 2018, Typhoon Wipha exhibited substantially lower intensity. Mangkhut made landfall with maximum wind speeds of 45 m s^{-1} and an average translation speed of 8 m s^{-1}, substantially exceeding the Typhoon Wipha's translation speed of 4-5 m s^{-1}. It was characterized by extreme intensity, rapid movement, and severe wind and rainfall impacts. In contrast, Wipha's relatively modest intensity, loose structure, and slower movement provide a unique opportunity to investigate urban forest damage patterns under moderate typhoon conditions. Data regarding the trajectory and hourly maximum wind speeds of Typhoon Mangkhut and Wipha were obtained from the China Meteorological Administration Typhoon Network (http://typhoon.nmc.cn).

Field Survey Method and Damage Classification

The field investigation was conducted in July 2025, using a transect survey method. A total of 11 representative sites were selected in Yangjiang and Maoming cities, China, including urban parks, roadside green spaces, and coastal green spaces (Fig. 1). These sites encompassed 15 common tree species, with a total of 1,645 individual trees surveyed (Table S1). For each sample tree, species and typhoon-induced damage conditions were accurately recorded, with photographic documentation of representative cases for typical damage patterns (Fig. S1).

With reference to previous methodologies [26, 27], the damage to individual trees was classified into three levels: light-moderate damage (A3, including defoliated and broken branches); broken trunk (A2); uprooted (A1). A1 and A2 are considered severe damage, and A3 indicates light-moderate damage. Damage to urban forest trees following Typhoon Wipha is illustrated

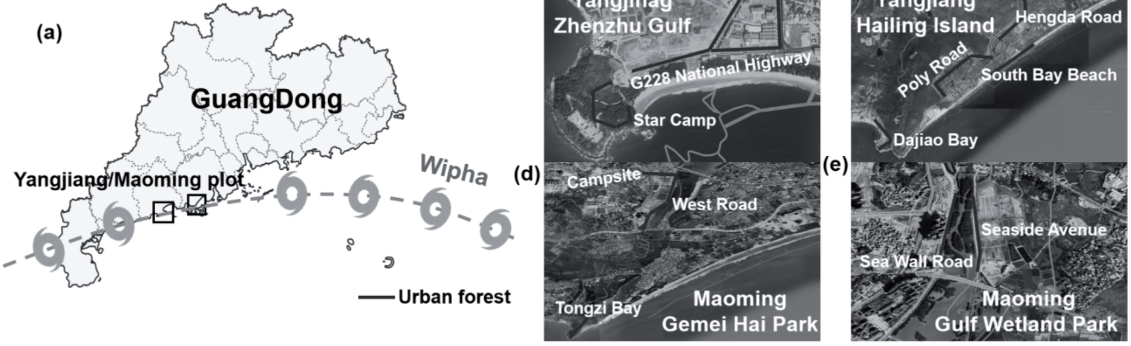

Fig. 1. a) Locations of the survey regions in Yangjiang and Maoming, and the route of Typhoon Wipha across Guangdong Province in southern China. (b, c) Distribution of the survey sites in Yangjiang. (d, e) Distribution of the survey sites in Maoming.

in Fig. S1. To facilitate subsequent analysis, the 15 tree species involved in the study are referred to by the initial abbreviations of their genus and species names, as listed in Table S1.

Measurement of Plant Functional Traits and Tree Structural Traits

Plant functional traits include specific leaf area (SLA), leaf force to punch (Fp), and wood density (WD). Leaf collection was conducted during field surveys following standardized protocols [28]. For each species, 20-30 fully expanded, sun-exposed, mature, and healthy leaves without insect herbivory or mechanical damage were selected. The collected leaves were placed in ziplock bags with moistened paper towels, stored under cool conditions, and transported to the laboratory for subsequent morphological and mechanical trait measurements. Leaf area (LA, cm^2) was measured using a portable leaf area meter (Li-3000A, Li-Cor, USA) equipped with an LI-3050C transparent conveyor belt. Subsequently, leaves were oven-dried at 65°C for 72 h until constant mass was achieved. Leaf dry mass (W, g) was then measured, and SLA (g^2 cm^{-1}) was calculated for each species. Fp (kN m^{-1}) was determined using an IMADA-DST-50N digital force gauge fitted with a 2 mm diameter needle. Fresh leaves were punctured at locations avoiding midribs and secondary veins, and the maximum penetration force was recorded. Fp was calculated according to Equation (1) [29]. WD (g cm^{-3}) was measured following standard protocols [30]. For each surveyed species, healthy twigs were collected, and 3-5 segments were randomly selected per species. These segments were placed in sealed plastic bags with moistened paper towels, refrigerated, and transported to the laboratory for determination. Sample volume was measured using the water displacement method: a beaker containing distilled water was placed on an electronic balance with an accuracy of ≥0.001 g, tared to zero, and then the twig segments were completely immersed in water using a fine needle. The mass of displaced water (m_1, g) was recorded. The samples were then oven-dried at 65ºC for 72 h until constant mass was achieved. Dry mass (w_1, g) was measured immediately to prevent moisture absorption. WD was calculated using Equation (2). In addition, WD data for some tree species were obtained from the BIOMASS R package [31].

Tree structural traits were measured simultaneously during the field survey. All standing trees with a diameter at breast height (DBH, cm) ≥1.0 cm and tree canopy height ≥ 1.3 m within the plots were measured and recorded. DBH was measured at 1.3 m above ground level using a diameter tape. Tree canopy height (H, m) was estimated through visual observation combined with a telescopic staff. These traits encompass stem dimensional characteristics (H and DBH) and material properties (WD, SLA, and Fp), which are closely related to tree responses to typhoon disturbance [32].

$$Fp = max\ Fp / needle\ perimeter \tag{1}$$

$$WD = w_1/(m_1 \times \rho) \tag{2}$$

Data Analysis

All field survey data were initially recorded, organized, and subjected to basic statistical analysis using Microsoft Excel 2024. The tree damage rate was calculated using Equation (3), and the damage rate for each species was determined using Equation (4). The uprooted rate, trunk broken rate, and light-moderate damage rate were calculated by replacing the "number of damaged trees by species" in Equation (4) with the "number of uprooted trees," "number of broken trunks," and "number of trees with light-moderate damage," respectively.

The comprehensive wind resistance of tree species was evaluated using a wind damage value (WDV), which was derived through the AHP. The three damage levels, A1 (uprooted), A2 (trunk broken), and A3 (light-moderate damage, including broken branches and defoliation), served as evaluation indicators. A judgment matrix was constructed, and pairwise comparisons of the relative importance among these indicators were conducted using the Saaty 1-9 scale. The consistency ratio of the matrix was 0.0375<0.1, indicating acceptable consistency. The weights assigned to A1, A2, and A3 were determined as 0.637, 0.258, and 0.105, respectively [33-35]. The WDV for each species was subsequently calculated using Equation (5). For ease of comparison, the final WDV were multiplied by 100. Normality tests and correlation analyses were performed using SPSS 20.0, and data visualization was conducted with Origin 2021 software.

$$Damage\ rate\ (\%) = \left(damaged\ trees / total\ number\ of\ trees\right) \times 100 \tag{3}$$

$$Species\ damage\ (\%) = (damaged\ species / total\ species) \times 100 \tag{4}$$

$$WDV = (0.637 \times A1 + 0.258 \times A2 + 0.105 \times A3) \times 100 \tag{5}$$

Partial Least Squares Path Modeling (PLS-PM) was implemented in R version 4.5.1 (R Core Team, 2021) using the plspm package to evaluate complex causal relationships among variables [36]. Missing values were handled through linear interpolation and averaging. The model demonstrated an acceptable goodness of fit (GOF = 0.52). Furthermore, to identify the key indicators associated with different species, a random forest prediction model was built using the randomForest package (v4.7-1.1) in R (version 4.5.1). This model integrated leaf physiological traits and tree characteristics to screen for the driving factors that contributed most to prediction accuracy.

Results

Tree Damage Rates and Characteristics in Coastal Urban Forests

Statistical analysis results (Fig. 2 and Table S2) indicate that among the total of 1,645 trees surveyed in Yangjiang and Maoming cities following Typhoon Wipha, 436 trees sustained varying degrees of damage, resulting in an overall damage rate of 26.50%. Among these, the rate of light-moderate damage was 19.57%, significantly higher than the severe damage rate of 6.93%. In terms of regional differences, the total tree damage rate across 6 survey sites in Yangjiang City was 24.57%, while it was 28.65% across 5 sites in Maoming City. The damage rates between the two regions were relatively similar, showing no significant difference.

Damage Rates and Wind Damage Values of Common Tree Species

Significant differences in damage degree and WDV were found among the 15 investigated tree species after Typhoon Wipha (Fig. 3, Table S3). Overall, *Ceiba speciosa* (A.St.-Hil.) Ravenna had the highest damage rate (50.85%) and the highest WDV (11.66), indicating its high susceptibility to damage in strong winds. While light-moderate damage was predominant (30.51%), the proportions of trunk breakage and uprooting were also considerable (collectively 20.33%). Although *Cassia fistula* L. had a slightly lower total damage rate (46.81%), its trunk breakage rate was the highest among all species (25.53%), suggesting weak resistance of its trunk structure to wind. *Bauhinia variegata* L. and *Hibiscus tiliaceus* L. showed similar damage rates (close to 30%), with WDV of 8.12 and 6.58, respectively.

Despite a relatively high total damage rate (42.22%), *Senna surattensis* L. was primarily characterized by light-moderate damage (37.78%), with a low proportion of severe damage (4.44%). Its WDV was 5.96, categorizing it as medium risk. Species such as *Leucaena leucocephala* L., *Ficus concinna* L., *Terminalia neotaliala* L., and *Handroanthus chrysanthus* (Jacq.) S.O.Grose had damage rates ranging between 21% and 33%, with WDV between 3.84 and 4.23. These species demonstrated an intermediate overall damage level, predominantly featuring light-moderate damage. *Alstonia scholaris* L., *Bischofia javanica* Blume, *Camphora officinarum* Nees, *Plumeria rubra* L., and *Casuarina equisetifolia* L. performed relatively well, with total damage rates all below 29% and low WDV (all below 3.66). Among them, *Casuarina equisetifolia* L. had the lowest damage rate (14.96%) and the lowest WDV (2.20), indicating strong wind resistance.

Associations of Wind Damage Values with Functional and Structural Traits in Common Tree Species

According to the analysis, distinct patterns emerged between WDV and plant traits. A highly significant positive correlation was observed between WDV and SLA (r^2 = 0.59, p<0.01), whereas Fp showed a strong negative correlation with WDV (r^2 = 0.82, p<0.01) (Fig. 4a); Fig. 5(a-b). In contrast, WD, H, and DBH exhibited no significant relationship with WDV (Fig. 5(c-e). Given the small sample size (15 tree species), Random Forest analysis was performed using out-of-bag (OOB) error

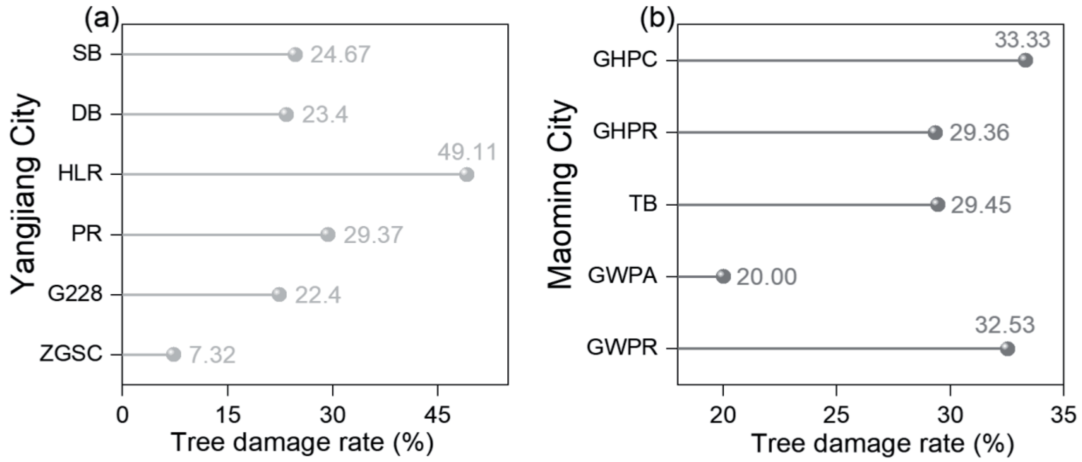

Fig. 2. Tree damage rates at survey sites in coastal urban forests of a) Yangjiang and b) Maoming.
Note: Survey sites and their abbreviations, Yangjiang City: ZGSC: Zhenzhu Gulf Star Camp; G228: Zhenzhu Gulf G228 National Highway; PR: Hailing Island Poly Road; HLR: Hailing Island Hengda Landscape Road; DB: Hailing Island Dajiao Bay; SB: Hailing Island South Bay Beach. Maoming City: GWPR: Gulf Wetland Park Seawall Road; GWPA: Gulf Wetland Park Seaside Avenue; TB: Tongzi Bay; GHPR: Gemei Hai Park West Road; GHPC: Gemei Hai Park Campsite.

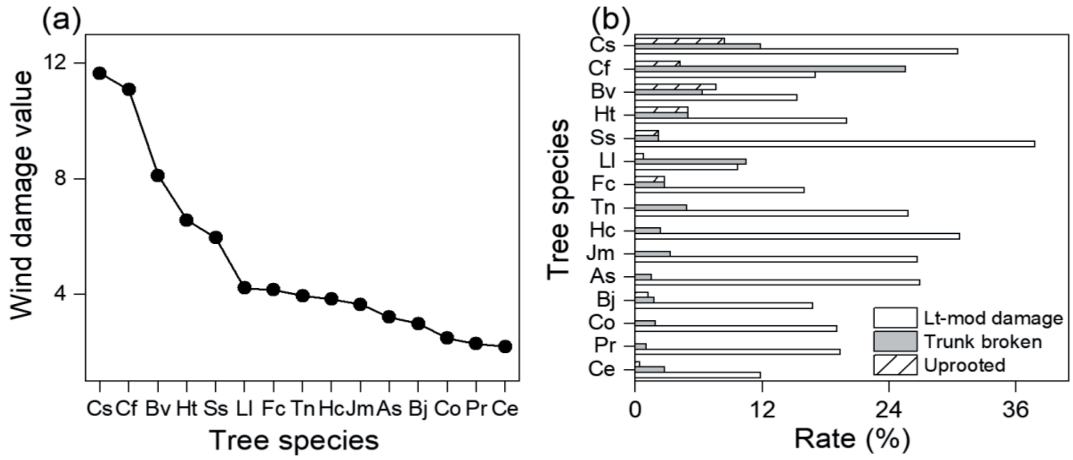

Fig. 3. Wind damage values of tree species in Yangjiang City and Maoming City. a) tree species ranked by wind damage value in descending order, and b) damage status of tree species. The damage rate of each surveyed tree species is the sum of the three damage types.
Note: Lt-mod damage: light-moderate damage; WDV: wind damage values.

to avoid overfitting and ensure reliable validation. avoid overfitting and ensure reliable validation, and was coupled with out-of-bag (OOB) error testing (Fig. 4b)). Fp emerged as the most important variable for predicting WDV (IncMSE = 10.49), followed by SLA (IncMSE = 9.91). While H contributed moderately to the model, its effect was not statistically significant; WD and DBH showed no meaningful predictive contribution. These results indicate that tree species with higher SLA and lower Fp generally incurred more severe typhoon damage. The relationship was further validated by PLS-PM analysis, which explained over 85% of the variance in WDV. The model confirmed significant path coefficients from Fp to WDV (-0.65) and from SLA to WDV (0.49), reinforcing both traits as key predictors of wind damage (Fig. 6).

Specifically, species such as *Ceiba speciosa* (A.St.-Hil.) Ravenna, *Cassia fistula* L., and *Bauhinia variegata* L., which exhibit high SLA and low Fp, showed the highest WDV of 11.66, 11.09, and 8.12, respectively. In comparison, species with lower SLA and higher Fp, such as *Casuarina equisetifolia* L., *Plumeria rubra* L., *Camphora officinarum* Nees, and *Bischofia javanica* Blume, demonstrated lower WDV and greater wind resistance.

Discussion

This study conducted field investigations and assessments using the specific impact of Typhoon Wipha on urban forests in Yangjiang and Maoming as a case study. The survey and calculation of WDV

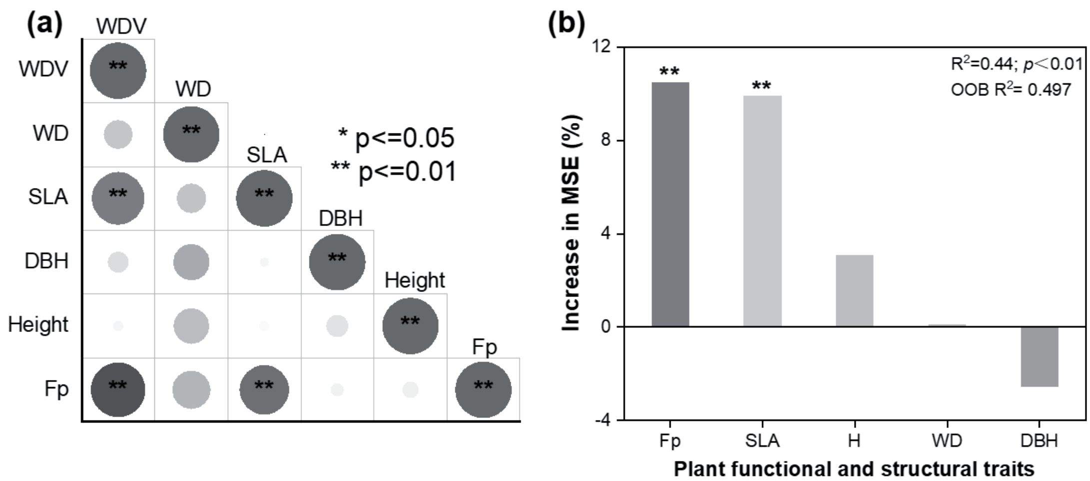

Fig. 4. Relationships between wind damage values and plant functional and structural traits. a) Correlation matrix among traits and wind damage values. b) Random Forest analysis identifying key traits predicting wind damage values.
Note: WDV: Wind damage values, WD: wood density, SLA: specific leaf area, DBH: diameter at breast height, Height: tree canopy height, Fp: leaf force to punch; OOB R^2: out-of-bag error.

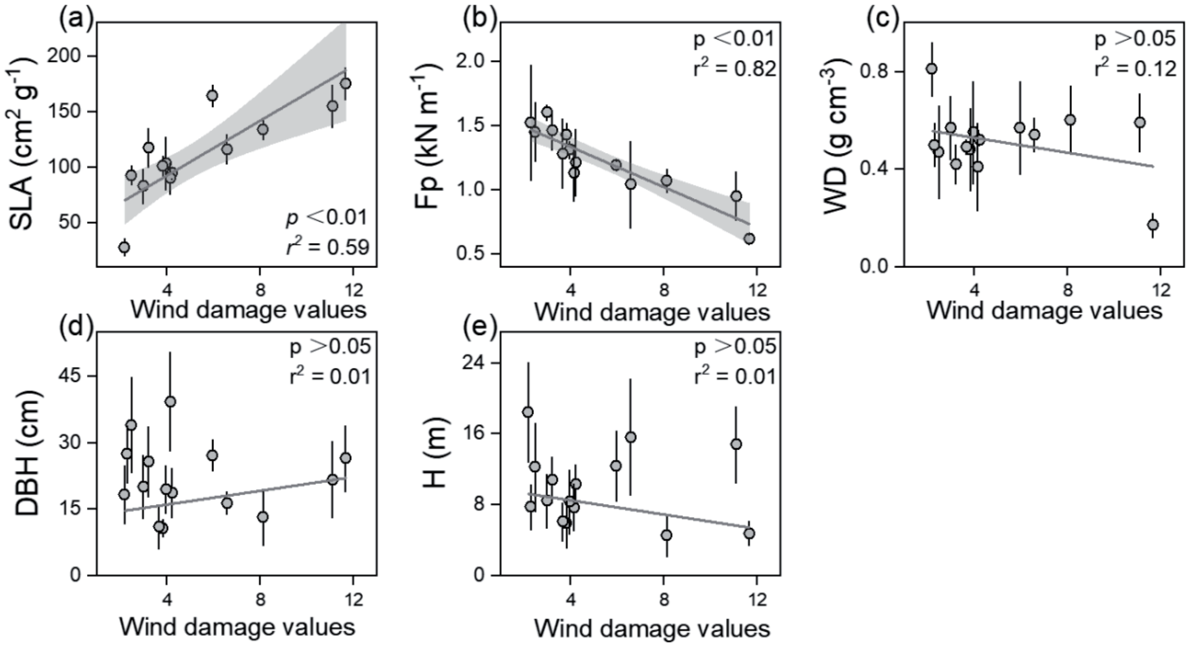

Fig. 5. Relationships between plant functional traits and tree structural traits with wind damage values. In fig. 5a) and b), solid lines indicate statistically significant relationships (p<0.05 or 0.01), with shaded areas representing 95% confidence intervals.
Note: SLA: specific leaf area; H: tree canopy height; DBH: diameter at breast height; Fp: leaf force to punch; WD: wood density.

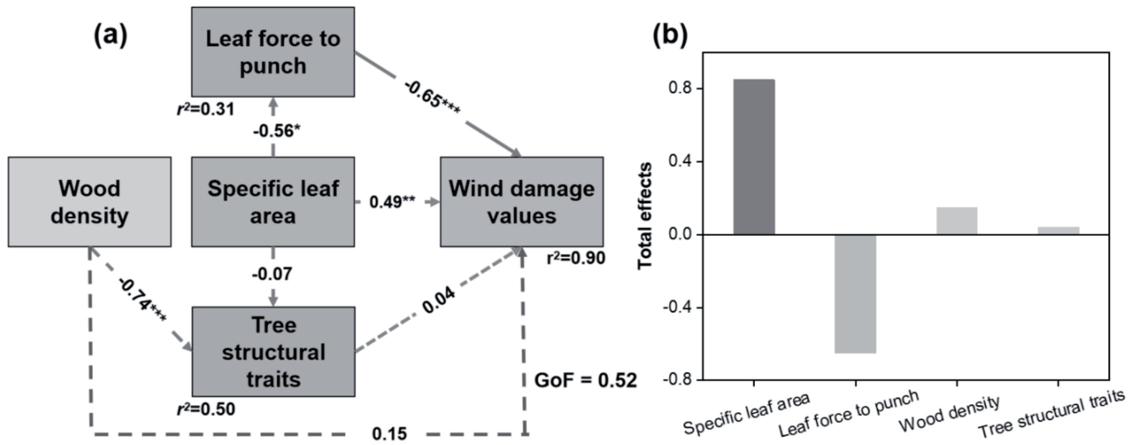

Fig. 6. The partial least squares path (PLS-PM) modeling. a) shows the influence of different plant functional and structural traits on the tree species wind damage values and b) total effects. Solid lines with "-" denote negative correlation, otherwise they indicate a positive correlation; dashed lines denote no significant correlation. *, **, and *** represent path coefficient significant at p<0.05, p<0.01, and p<0.001, respectively.
Note: Tree structural traits include diameter at breast height (DBH) and tree canopy height (H). Their standardized path coefficients (weights) are 0.97 for H and -0.35 for DBH.

revealed that *Bischofia javanica* Blume, *Camphora officinarum* Nees, *Plumeria rubra* L., and *Casuarina equisetifolia* L. exhibited low WDV, indicating minor damage during the typhoon and strong wind resistance. Among them, *Casuarina equisetifolia* L. had the lowest WDV, a finding consistent with studies on its functional traits under long-term wind stress [2]. The strong wind resistance of *Camphora officinarum* Nees and *Plumeria rubra* L. is also aligned with conclusions from post-Typhoon "Mangkhut" evaluations of wind resistance in greening tree species in Shenzhen City, China [35]. It is worth noting that some studies have reported medium wind resistance for *Bischofia javanica* Blume, citing instances of row-wise falling and tilting after Typhoon Mangkhut. This discrepancy may be related to stand age [37]. As trees age, their root and trunk structures strengthen, significantly enhancing mechanical support capacity and thereby improving wind resistance [38, 39].

In contrast, *Ceiba speciosa* (A.St.-Hil.) Ravenna, *Cassia fistula* L., *Bauhinia variegata* L., and *Hibiscus* *tiliaceus* L. exhibited high WDV, indicating poor wind resistance. This finding is consistent with post-typhoon survey results from Xiamen, Guangzhou, and Zhuhai Cities, China [18, 40, 41]. These species are prone to trunk breakage and uprooting during typhoons, making post-disaster restoration difficult and costly [42]. This study further revealed significant correlations among the WDV of the investigated tree species and their leaf functional traits: a positive correlation with SLA, a negative correlation with Fp, and a significant negative relationship between SLA and Fp. These findings are consistent with measurements and statistical analyses conducted on over 30 dicotyledonous plant species, which indicated that higher SLA is associated with lower Fp [43].

This trait association provides a critical functional ecological mechanism for explaining interspecific differences in wind resistance among tree species. Tree species with higher SLA typically produce thin, broad leaves, and their above-ground biomass investment strategy prioritizes rapid growth and resource acquisition. Such leaf morphological characteristics directly increase the canopy's wind catch area and wind load: the elevated wind pressure on the canopy is further transmitted to branches and trunks, amplifying the risk of branch breakage and leaf abscission under typhoon conditions [44]. Moreover, these leaves often lack sufficient structural toughness, rendering the trees more susceptible to mechanical damage (e.g., branch damage and leaf defoliation) in strong winds, which ultimately results in higher WDV [45]. In contrast, tree species with lower SLA exhibit slower growth rates, with a larger proportion of leaf volume allocated to mesophyll cell walls and cuticles. These plants invest more resources in constructing protective leaf structures and robust mesophyll tissues, which translates to greater Fp, a key indicator of leaf mechanical toughness. High Fp effectively mitigates direct leaf damage caused by strong wind scouring and physical impact. Notably, the combination of low SLA and high Fp is accompanied by a more conservative plant resource allocation strategy: more photosynthates are diverted to the development of branch xylem and root systems, which enhances the mechanical strength of branches and improves root-soil bonding [46, 47]. This multi-level enhancement of mechanical stability across leaves, branches, and roots collectively reduces the likelihood of severe damage (e.g., trunk breakage and uprooting), leading to lower WDV. Evolutionarily, such species are more inclined to adapt to and resist environmental disturbances, thereby exhibiting superior wind resistance [32, 48, 49]. Therefore, SLA and Fp can serve as effective functional indicators for predicting the wind resistance of subtropical urban tree species.

However, this study did not find a significant correlation between WD, DBH, and H with WDV, a result further supported by PLS-PM analysis (Fig. 6). Numerous previous studies have indicated a significant negative correlation between WD and post-typhoon severe structural damage (such as trunk breakage and uprooting) as well as tree mortality. It is generally accepted that trees with higher WD, due to their sturdy structure, possess greater resistance to bending and breaking, thereby maintaining mechanical stability more effectively under strong wind conditions [50, 51]. The absence of a similar correlation in our study may be related to the relatively low intensity of the typhoon investigated. Typhoon Wipha was a relatively weak event, and the surveyed samples were predominantly composed of undamaged or lightly to moderately damaged trees, with a low proportion of individuals suffering severe damage (trunk breakage and uprooting) (Fig. 3 and Table S4). Under weaker wind conditions, the contribution of WD to wind resistance may not be fully manifested, which could be the main reason for the lack of a significant correlation with WDV [52]. Furthermore, the absence of significant correlations between DBH, H, and WDV may be attributed to species-specific relationships between tree size and damage extent, which could have diluted the overall trend. On the other hand, the intensity of this typhoon may not have reached the threshold required to induce severe mechanical responses in trees. Previous studies have shown that in intense typhoons, trees with small to medium DBH typically exhibit higher breakage rates than larger trees [53]. The relatively weak intensity of the typhoon in this study may have been insufficient to trigger this response mechanism.

Wind resistance is a critical screening trait for coastal urban forests in disaster prevention and mitigation [54]. Based on the WDV assessment, we propose targeted management strategies for coastal urban forests in South China. Species with strong wind resistance, such as *Casuarina equisetifolia* L., *Camphora officinarum Nees*, and *Plumeria rubra* L., exhibit low SLA, high Fp, well-developed root systems (deep-rooted or plate-root characteristics), and superior wood quality (longer wood fibers, greater compressive strength, and higher flexural elasticity). These species should be prioritized as backbone species in high-wind-stress areas, including coastal shelterbelts, windward slopes, and urban ventilation corridors, following the "matching tree species with site conditions" principle [55]. For species with moderate wind resistance (e.g., *Bischofia javanica* Blume, *Terminalia neotaliala* L., *Alstonia scholaris* L.), proactive management before typhoon seasons is essential. This includes scientific pruning, specifically crown thinning to increase canopy transparency and reduce wind load, and crown reduction to suppress apical dominance and balance the root-to-crown ratio, along with standardized tree supports using three or four-legged brackets and elastic binding materials [56, 57]. Soil management should involve expanding tree pits, improving aeration through regular loosening, replacing compacted backfill with suitable planting media, addressing coastal soil salinization, and applying potassium and phosphorus fertilizers to strengthen root systems and enhance the root-to-crown ratio [58]. For community-level configuration, multi-layered tree-shrub-herb mixtures should be adopted to leverage collective wind resistance, with clustered or array plantings preferred over solitary or linear arrangements, especially in open coastal areas [59, 60]. Differentiated strategies should be applied across urban functional zones; coastal shelterbelts and high-wind-exposed areas should prioritize high wind-resistance species as dominant canopy trees; urban parks and residential areas can integrate both wind-resistant and high-value ornamental species in sheltered locations; main roads and avenues require species with inherent wind resistance and moderate crown size, with regular crown thinning essential [61]. By integrating science-based species selection with precise cultivation and management (including standardized pruning, soil improvement, appropriate support systems, and differentiated configuration), we can construct resilient, stable urban forest ecosystems capable of withstanding intensifying typhoon pressures under climate change [62, 63]. Future urban forest planning should rationally allocate species with varying wind resistance to form organic wholes, while ensuring landscape value. This approach will comprehensively enhance the forest's overall typhoon resilience and minimize post-typhoon damage to urban forest ecosystems.

It should be noted that this study has a limitation regarding phylogenetic independence: the 15 surveyed tree species belong to different families and genera, and shared evolutionary history may potentially influence trait-wind damage associations. However, due to the small sample size, reliable phylogenetic comparative analyses (e.g., PGLS and PIC) could not be performed, as these methods typically require at least 20-30 species to obtain stable parameter estimates and sufficient statistical power [64, 65]. Nevertheless, the strong linear correlations between SLA, Fp, and WDV (r^2 = 0.59 and 0.82, respectively) and consistency with functional trait theory suggest that ecological and mechanical mechanisms dominate the observed relationships, with phylogenetic signals having limited confounding effects. Future studies with expanded species sampling should incorporate phylogenetic corrections to further verify the generality of the identified trait-wind resistance patterns.

Conclusions

This study provides a critical assessment of wind resistance in urban coastal forests under escalating typhoon risks driven by climate change. Through post-typhoon field surveys following Typhoon Wipha in Yangjiang and Maoming cities, China, we evaluated damage to 1,645 trees across 15 common species and developed an integrated framework combining Analytic Hierarchy Process (AHP) modeling and functional trait analysis. Our approach quantified species-specific wind resistance using WDV and identified key plant functional traits as mechanistic predictors of wind damage. Key findings demonstrate that *Casuarina equisetifolia* L. (2.20), *Camphora officinarum* Nees (2.49), and *Plumeria rubra* L. (2.30) exhibit superior wind resistance, while *Ceiba speciosa* (A.St.-Hil.) Ravenna (11.66), *Cassia fistula* L. (11.09), and *Bauhinia variegata* L. (8.12) are highly susceptible. Crucially, plant functional traits, specifically SLA and leaf Fp, emerged as robust predictors of WDV (r^2 = 0.59 and 0.82, respectively; p<0.01). These leaf-level traits mediate whole-tree wind damage through multi-pathway regulation of canopy wind resistance, branch mechanical stability, and root-soil interactions, which highlights the key role of leaf-level adaptations in mitigating typhoon wind damage at the whole-tree scale.

For urban forestry practice, we propose a "wind-resistance prioritization" strategy: (1) Prioritize high-resistance species (e.g., *Casuarina equisetifolia* L., *Camphora officinarum* Nees) in coastal wind corridors and shelterbelts; (2) Implement pre-typhoon management (e.g., pruning, support systems) for moderately resistant species; (3) Restrict vulnerable species to sheltered urban zones. This approach enhances ecological security in vulnerable coastal regions, while balancing landscape aesthetics. Our findings offer a science-based reference for species selection and resilience planning in typhoon-exposed cities with similar environmental contexts, addressing an urgent need for adaptive urban forest management under climate change. We acknowledge that the generalizability of our results may be constrained by the specific environmental conditions of western Guangdong; thus, future research should validate these findings across other climate zones, typhoon intensity gradients, and soil types to further refine the adaptive management framework for broader application.

Acknowledgments

We gratefully acknowledge the financial support from the National Key R&D Program of China (Key Special Project for Marine Environmental Security and Sustainable Development of Coral Reefs 2022-102).

AI Usage Disclosure Statement

During the preparation of this manuscript, the authors used ChatGPT only for language polishing, grammar checking, and improving the clarity of English expression. The AI tool was not used for research design, data collection, data generation, data analysis, figure preparation, interpretation of results, or drawing conclusions. All AI-assisted content was carefully reviewed, revised, and verified by the authors, who take full responsibility for the content of the published article.

Data Availability Statements

The data will be made on request.

Conflict of Interest

The authors declare no conflict of interest.

References

1. IPCC Annex IV: Modes of Variability. Cambridge University Press, Cambridge, **2023**.
2. LI K., LI G.S. Risk assessment on storm surges in the coastal area of Guangdong Province. Natural Hazards, **68** (2), 1129, **2013**.
3. WANG H., WANG C. What caused the increase of tropical cyclones in the western North Pacific during the period of 2011–2020? Climate Dynamics, **60** (1), 165, **2023**.
4. YU M., GAO Q. Topography, drainage capability, and legacy of drought differentiate tropical ecosystem response to and recovery from major hurricanes. Environmental Research Letters, **15** (10), **2020**.
5. CHIRICI G., BOTTALICO F., GIANNETTI F., DEL PERUGIA B., TRAVAGLINI D., NOCENTINI S., KUTCHARTT E., MARCHI E., FODERI C., FIORAVANTI M., FATTORINI L., BOTTAI L., MCROBERTS R. E., NAESSET E., CORONA P., GOZZINI B. Assessing forest windthrow damage using single-date, post-event airborne laser scanning data. Forestry, **91** (1), 27, **2018**.
6. KRAUSS K.W., OSLAND M.J. Tropical cyclones and the organization of mangrove forests: a review. Annals of Botany, **125** (2), 213, **2020**.
7. LONG J., GIRI C., PRIMAVERA J., TRIVEDI M. Damage and recovery assessment of the Philippines' mangroves following Super Typhoon Haiyan. Marine Pollution Bulletin, **109** (2), 734, **2016**.
8. VOZMISHCHEVA A.S., BONDARCHUK S.N., GROMYKO M.N., KISLOV D.E., PIMENOVA E.A., SALO M.A., KORZNIKOV K.A. Strong Disturbance Impact of Tropical Cyclone Lionrock (2016) on Korean Pine-Broadleaved Forest in the Middle Sikhote-Alin Mountain Range, Russian Far East. Forests, **10** (11), **2019**.
9. PENG W., WANG R., DUAN J., GAO W., FAN Z. Surface and canopy urban heat islands: Does urban morphology result in the spatiotemporal differences? Urban Climate, **42**, 101136, **2022**.
10. HERNÁNDEZ E., CUEVAS E., PINTO-PACHECO S., ORTÍZ-RAMÍREZ G. You Can Bend Me but Can't Break Me: Vegetation Regeneration After Hurricane Maria Passed Over an Urban Coastal Wetland in Northeastern Puerto Rico. Frontiers in Forests and Global Change, **4**, **2021**.
11. FEEHAN C.J., FILBEE-DEXTER K., THOMSEN M.S., WERNBERG T., MILES T. Ecosystem damage by increasing tropical cyclones. Communications Earth & Environment, **5**, 674, **2024**.
12. IBANEZ T., PLATT W.J., BELLINGHAM P.J., VIEILLEDENT G., FRANKLIN J., MARTIN P.H., MENKES C., PEREZ-SALICRUP D.R., RUSSELL-SMITH J., KEPPEL G. Altered cyclone-fire interactions are changing ecosystems. Trends in Plant Science, **27** (12), 1218, **2022**.
13. LI L., CHAKRABORTY P. Slower decay of landfalling hurricanes in a warming world. Nature, **587** (7833), 230, **2020**.
14. GAO W., LARJAVAARA M. Wind disturbance in forests: A bibliometric analysis and systematic review. Forest Ecology and Management, **564**, 122001, **2024**.
15. YI Q., YE W., WANG F., XING F., HARRIS A.J., DUAN L., CHEN H. Damage by typhoon Hato compared among three different plant communities in Macau, China. Ecology and Evolution, **13** (10), e10574, **2023**.
16. DURYEA M.L., KAMPF E., LITTELL R.C. Hurricanes and the urban forest: I. Effects on southeastern United States coastal plain tree species. Arboriculture & Urban Forestry, **33** (2), 83, **2007**.
17. SHARMA A., OJHA S.K., DIMOV L.D., VOGEL J.G., NOWAK J. Long-term effects of catastrophic wind on southern US coastal forests: Lessons from a major hurricane. PLOS ONE, **16** (1), e0243362, **2021**.
18. TANG H., SONG L., LI Y., YANG Q., DONGXIAN X., WANHUI Q., MINCONG T., QING Z. Impacts of Typhoons with Different Wind Scales on the Urban Greening Trees in Zhuhai City. Forestry and Environmental Science, **37** (2), 1, **2021** [In Chinese].
19. XU S., ZHU X.L., HELMER E.H., TAN X.Y., TIAN J.Q., CHEN X.H. The damage of urban vegetation from super typhoon is associated with landscape factors: Evidence from Sentinel-2 imagery. International Journal of Applied Earth Observation and Geoinformation, **104**, **2021**.
20. WANG J., YU Y., WU Y., GOU A. Ecological vulnerability assessment of coastal cities in Guangdong Province under the background of storm surge disaster. Environmental and Development, **36** (4), 26, **2024** [In Chinese].
21. WU W. Characteristics and Empirical Forecasting Case Study of Storm Surges in the Coastal Areas of Western Guangdong: A Case Study of the Bohe Port Tide Gauge Station. Groundwater, **47** (6), 267, **2025** [In Chinese].
22. AI B., MA C., ZHAO J., ZHANG R. The impact of rapid urban expansion on coastal mangroves: a case study in Guangdong Province, China. Frontiers of Earth Science, **14** (1), 37, **2020**.
23. LIU K.S., CHAN J.C.L., CHONG B., WONG H. Projections of future tropical cyclone landfalling activity in the East Asia region. Tropical Cyclone Research and Review, **13** (4), 328, **2024**.
24. LU L., WU C., DI L. Exploring the Spatial Characteristics of Typhoon-Induced Vegetation Damages in the Southeast Coastal Area of China from 2000 to 2018. Remote Sensing, **12** (10), **2020**.
25. CHEN S., SUN Y., TANG K., ZHANG F., DING W., WANG A. Distribution Characteristics and Restoration Application of Vegetation in Chengcun Bay Surrounding Areas of Yangjiang City. International Journal of Environmental Research and Public Health, **19** (16), 10399, **2022**.
26. TONG C., YANG Y. A review of the impacts of hurricanes and typhoons on forest ecosystems in coastal areas. Acta Ecologica Sinica, (12), 5337, **2007** [In Chinese].
27. WEI Y., WEI D., WEN C., ZHANG G., DAI S., YANG H. Effect of Typhoon on Greening Tree Species Such as Bauhinia variegata in Guangzhou and Its Countermeasures. Forestry and Environmental Science, **36** (3), 86, **2020** [In Chinese].
28. LOHBECK M., POORTER L., LEBRIJA-TREJOS E., MARTÍNEZ-RAMOS M., MEAVE J.A., PAZ H.,

PÉREZ-GARCÍA E.A., ROMERO-PÉREZ I.E., TAURO A., BONGERS F. Successional changes in functional composition contrast for dry and wet tropical forest. Ecology, **94** (6), 1211, **2013**.
29. PEREZ-HARGUINDEGUY N., DIAZ S., GARNIER E., LAVOREL S., POORTER H., JAUREGUIBERRY P., BRET-HARTE M.S., CORNWELL W.K., CRAINE J.M., GURVICH D.E., URCELAY C., VENEKLAAS E.J., REICH P.B., POORTER L., WRIGHT I.J., RAY P., ENRICO L., PAUSAS J.G., DE VOS A.C., BUCHMANN N., FUNES G., QUETIER F., HODGSON J.G., THOMPSON K., MORGAN H.D., TER STEEGE H., VAN DER HEIJDEN M.G.A., SACK L., BLONDER B., POSCHLOD P., VAIERETTI M.V., CONTI G., STAVER A.C., AQUINO S., CORNELISSEN J.H.C. New handbook for standardised measurement of plant functional traits worldwide. Australian Journal of Botany, **61** (3), 167, **2013**.
30. CORNELISSEN J.H.C., LAVOREL S., GARNIER E., DíAZ S., BUCHMANN N., GURVICH D.E., REICH P.B., TER STEEGE H., MORGAN H.D., VAN DER HEIJDEN M.G.A., PAUSAS J.G., POORTER H. A handbook of protocols for standardised and easy measurement of plant functional traits worldwide. Australian Journal of Botany. **51** (4), 335, **2003**.
31. RÉJOU-MÉCHAIN M., TANGUY A., PIPONIOT C., CHAVE J., HÉRAULT B. biomass: an r package for estimating above-ground biomass and its uncertainty in tropical forests. Methods in Ecology and Evolution, **8** (9), 1163, **2017**.
32. JIMENEZ-RODRÍGUEZ D.L., ALVAREZ-AÑORVE M.Y., PINEDA-CORTES M., FLORES-PUERTO J.I., BENÍTEZ-MALVIDO J., OYAMA K., AVILA-CABADILLA L.D. Structural and functional traits predict short term response of tropical dry forests to a high intensity hurricane. Forest Ecology and Management, **426**, 101, **2018**.
33. GUO Z., KE Y., LI H., GENG H., LI Q. Study on Tree Damage Causes in Xiamen CityBased on Typhoon Hazards. Chinese Landscape Architecture, **36** (1), 122, **2020** [In Chinese].
34. VAIDYA O.S., KUMAR S. Analytic hierarchy process: An overview of applications. European Journal of Operational Research, **169** (1), 1, **2006**.
35. GAO Y., MAO J., ZENG P., LI J., GONG Y., SHEN K., WANG Y. Evaluation of Wind Resistance of Greening Tree Species in Shenzhen Based on Analytic Hierarchy Process—Taking the Typhoon "Mangosteen" as an Example. Forestry and Environmental Science, **35** (4), 97, **2019** [In Chinese].
36. LATAN H., HAIR JR J.F., NOONAN R. Partial Least Squares Path Modeling: Basic Concepts, Methodological Issues and Applications. Cham: Springer, **2023**.
37. ZHU X., TAN G., CHEN B., LIANG G. Evaluation and Analysis of Wind Resistance of Garden Trees in Qianwan of Shenzhen. Chinese Journal of Tropical Agriculture, **43** (3), 96, **2023** [In Chinese].
38. ACHIM A., RUEL J.C., GARDINER B.A., LAFLAMME G., MEUNIER S. Modelling the vulnerability of balsam fir forests to wind damage. Forest Ecology and Management, **204** (1), 37, **2005**.
39. PELTOLA H., KELLOMÄKI S., HASSINEN A., GRANANDER M. Mechanical stability of Scots pine, Norway spruce and birch: an analysis of tree-pulling experiments in Finland. Forest Ecology and Management, **135** (1-3), 143, **2000**.
40. LIN S., ZHOU J., QIN Y., DONG J. The Influence of Typhoon Meranti on the Greening Tree Species for Urban Road in Xiamen. Chinese Landscape Architecture, **34** (5), 83, **2018** [In Chinese].
41. YU G., ZHOU G., ZHENG F. Impacts of Typhoon "Mangkhut" on Trees in Huolushan Forest Park, Guangzhou. Chinese Landscape Architecture, **36** (10), 122, **2020** [In Chinese].
42. KLEIN R.W., KOESER A.K., KANE B., LANDRY S.M., SHIELDS H., LLOYD S., HANSEN G. Evaluating the Likelihood of Tree Failure in Naples, Florida (United States) Following Hurricane Irma. Forests, **11** (5), 485, **2020**.
43. OU M., LI H., ZHAO Q., LI J. Relationship Between Leaf Force-to-punch and Leaf Functional Traits under Different Measurement Methods. Bulletin of Botanical Research, **43** (6), 910, **2023** [In Chinese].
44. CURRAN T.J., BROWN R.L., EDWARDS E., HOPKINS K., KELLEY C., MCCARTHY E., POUNDS E., SOLAN R., WOLF J. Plant functional traits explain interspecific differences in immediate cyclone damage to trees of an endangered rainforest community in north Queensland. Austral Ecology, **33** (4), 451, **2008**.
45. RICHARDSON B.A., RICHARDSON M.J., GONZÁLEZ G., SHIELS A.B., SRIVASTAVA D.S. A Canopy Trimming Experiment in Puerto Rico: The Response of Litter Invertebrate Communities to Canopy Loss and Debris Deposition in a Tropical Forest Subject to Hurricanes. Ecosystems, **13** (2), 286, **2010**.
46. DE BATTISTI D., FOWLER M.S., JENKINS S.R., SKOV M.W., BOUMA T.J., NEYLAND P.J., GRIFFIN J.N. Multiple trait dimensions mediate stress gradient effects on plant biomass allocation, with implications for coastal ecosystem services. Journal of Ecology, **108** (4), 1227, **2020**.
47. WANG J.F., WANG X.X., JI Y.H., GAO J. Climate factors determine the utilization strategy of forest plant resources at large scales. Frontiers in Plant Science, **13**, **2022**.
48. HOGAN J.A., ZIMMERMAN J.K., THOMPSON J., URIARTE M., SWENSON N.G., CONDIT R., HUBBELL S., JOHNSON D.J., SUN I.F., CHANG-YANG C.-H., SU S.-H., ONG P., RODRIGUEZ L., MONOY C.C., YAP S., DAVIES S.J. The Frequency of Cyclonic Wind Storms Shapes Tropical Forest Dynamism and Functional Trait Dispersion. Forests, **9** (7), 404, **2018**.
49. KITAJIMA K., POORTER L. Tissue-level leaf toughness, but not lamina thickness, predicts sapling leaf lifespan and shade tolerance of tropical tree species. New Phytologist, **186** (3), 708, **2010**.
50. TAYLOR B.N., STEDMAN E., VAN BLOEM S.J., WHITMIRE S.L., DEWALT S.J. Widespread stem snapping but limited mortality caused by a category 5 hurricane on the Caribbean Island of Dominica. Forest Ecology and Management, **532**, **2023**.
51. URIARTE M., THOMPSON J., ZIMMERMAN J.K. Hurricane Maria tripled stem breaks and doubled tree mortality relative to other major storms. Nature Communications, **10** (1), 1362, **2019**.
52. TAILLIE P.J., ROMAN-CUESTA R., LAGOMASINO D., CIFUENTES-JARA M., FATOYINBO T., OTT L.E., POULTER B. Widespread mangrove damage resulting from the 2017 Atlantic mega hurricane season. Environmental Research Letters, **15** (6), **2020**.
53. LI Y., MWANGI B., ZHOU S., LIU S., ZHANG Q., LIU J., CHU G., TANG X., ZHANG D., WEI S., LIE Z., WU T., WANG C., YANG G., MENG Z. Effects of Typhoon

Mangkhut on a Monsoon Evergreen Broad-Leaved Forest Community in Dinghushan Nature Reserve, Lower Subtropical China. Frontiers in Ecology and Evolution, **9**, **2021**.
54. SHANG X.H., ZHANG P.J., LI X.M., WANG Y.S., WU Z.H. Key traits influencing the resistance of Eucalyptus camaldulensis to wind damage in coastal areas of South China. Frontiers in Plant Science, **15**, **2024**.
55. ZHANG D., LIU M., YAO C., CHEN L. Research Advances of Wind Resistance of Landscape Tree Species in Coastal Areas under Climate Change. Landscape Architecture, **28** (11), 68, **2021** [In Chinese].
56. WANG X. Landscaping strategies for typhoon protection in coastal areas of South Fujian. Journal of Minnan Normal University (Natural Science), **33** (2), 72, **2020** [In Chiese].
57. XU L. Research on the countermeasures of typhoon "Doksuri" resistance for Quanzhou road greening trees. Fujian Construction, **44** (11), 1, **2025** [In Chinese].
58. FAN C.C., LI S.C., LU J.Z. Modeling the Effect of High Soil Moisture on the Wind Resistance of Urban Trees. Forests, **13** (11), **2022**.
59. MACFARLANE D.W., KANE B. Neighbour effects on tree architecture: functional trade-offs balancing crown competitiveness with wind resistance. Functional Ecology, **31** (8), 1624, **2017**.
60. ZU X., ZHANG Y., LI G. Planting Strategies of Road Plant Landscape in Xiamen Island Based on FLUENT Simulation of Wind Environment. Journal of Chinese Urban Forestry, **19** (3), 78, **2021** [In Chinese].
61. HAN M., LUO X., SU C., GAO Y., GONG Y., ZHENG W. Research Progress on Typhoon Resistance of Urban Greening in Coastal Areas. Journal of Zhejiang Forestry Science and Technology, **44** (6), 117, **2024** [In Chinese].
62. JACTEL H., BAUHUS J., BOBERG J., BONAL D., CASTAGNEYROL B., GARDINER B., GONZALEZ-OLABARRIA J.R., KORICHEVA J., MEURISSE N., BROCKERHOFF E.G. Tree Diversity Drives Forest Stand Resistance to Natural Disturbances. Current Forestry Reports, **3** (3), 223, **2017**.
63. RUTLEDGE B.T., CANNON J.B., MCINTYRE R.K., HOLLAND A.M., JACK S.B. Tree, stand, and landscape factors contributing to hurricane damage in a coastal plain forest: Post-hurricane assessment in a longleaf pine landscape. Forest Ecology and Management, **481**, **2021**.
64. MUNDRY R. Statistical Issues and Assumptions of Phylogenetic Generalized Least Squares. In: Garamszegi, L. (eds) Modern Phylogenetic Comparative Methods and Their Application in Evolutionary Biology. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 131-153, **2014**.
65. SYMONDS M.R.E., BLOMBERG S.P. A Primer on Phylogenetic Generalised Least Squares. In: Garamszegi, L. (eds) Modern Phylogenetic Comparative Methods and Their Application in Evolutionary Biology. Springer Berlin Heidelberg, Berlin, Heidelberg, pp 105-130, **2014**.