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Predictors of tropical cyclone-induced urban tree failure: an international scoping review

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Background: Trees are critical components of rural and urban ecosystems throughout the world. While they have adapted to the historic conditions of their native environments, climate change, urbanization, and human-assisted range expansion may test the storm resiliency of many tree species.

Objective: In this global multilingual scoping review, we investigate a range of intrinsic (i.e., tree characteristics) and external (i.e., environmental and management) factors which have been used to predict tree failure during tropical cyclones.

Design: We searched online databases and journals in English, Chinese, French, Japanese, Portuguese, and Spanish to find peer-reviewed papers and dissertations. We retained papers that used ground-based methods to study tree damage following a tropical cyclone and conducted a statistical analysis of factors that influence tree resistance to damage. From each paper we extracted details of study methods, and the relationships between damage and predictors.

Results: Our efforts generated 65 peer-reviewed papers and dissertations that met our final criteria for inclusion (i.e., data on the relative proportion of trees failed/intact as assessed no more than a year after the storm event). Of these papers 37 independent variables were assessed to predict tree failure. Research in both urban and rural settings tends to be concentrated in regions frequently impacted by tropical cyclones. Characteristics of species such as wood density have been studied in rural environments and are also relevant predictors for tree failure in urban trees. Environmental characteristics unique to urban settings such as planting areas surrounded by pavement need further research. Several urban studies demonstrate that risk assessment methods can predict tree failure during a storm.

Conclusion: Results can be used by future storm researchers to identify both predictors may warrant inclusion in their models as well as predictors which have yet to be tested. Results can also inform planning and activities that can mitigate tropical cyclone damage to the urban forest.

KEYWORDS

hurricane, mitigation, species selection, storm damage, tree size, trunk snapping, typhoon, uprooting

1. Introduction

Tropical cyclones are extreme weather events that affect many regions across the planet (Figure 1). Called hurricanes in the Atlantic region and typhoons in the western Pacific, tropical cyclones are large, rotating storms centered on an area of low pressure (World Meteorological Organization, 2022). These storms can generate winds that exceed 119 km per hour and are often accompanied by torrential rains. Tropical cyclones vary in intensity, frequency, and size and are a major driver of disturbance in coastal ecosystems and urban environments. Unlike other extreme wind events such as downbursts or derechos, tropical cyclones can cover immense areas, with some storms having a diameter of over 1,000 km and affecting large swaths of developed and undeveloped areas where they make landfall.

Tens of millions of people living in coastal communities face elevated risks from exposure to tropical and extratropical cyclones (Crowell et al., 2007). After adjustment for inflation and changes in population, wealth, and housing density, tropical cyclone damage-related costs average approximately $17 billion (2017 USD) per year in the continental U.S. alone (Weinkle et al., 2018). Additionally, urban forest damage from tropical cyclone wind, flooding, landslides, and salt-water intrusion can be substantial. A study in Florida, USA revealed that an average of 232 cubic meters of urban tree debris was produced per kilometer of street during an active hurricane season (Staudhammer et al., 2009). The loss of urban trees to tropical cyclones leads to a loss of benefits such as reducing air pollution, mitigating the urban heat island effect, improving physical and mental health, and reducing stormwater (Turner-Skoff and Cavender, 2019).

Tropical cyclones have shaped many forest ecosystems for hundreds to thousands of years by profoundly altering the structure, composition, and function of forest ecosystems and their patterns of succession (Lugo, 2008; Xi, 2015). Yet in both urban and rural forests, tree damage patterns can be highly variable (Franklin et al., 2004; Landry et al., 2021). Tree resistance to tropical cyclone wind damage has been examined through observational studies of damage to rural and urban forests (Saito, 2002; Wiersma et al., 2012) and experimental work examining the biomechanical properties of trees in the context of high winds (Gilman et al., 2008). Many biotic and abiotic factors influence the resistance of individual trees to damage by severe winds within rural forests and tree plantations. Everham and Brokaw (1996) synthesized these factors based on several decades of research in wind-damaged forests (Figure 2). The authors identified biotic factors, including stem size, stand conditions (e.g., age structure, species composition, stand density, thinning history and other silvicultural treatments), species characteristics (e.g., wood properties, slenderness, crown shape, root architecture), and pathogens associated with weakened wood. Abiotic factors included storm characteristics (e.g., intensity, duration, frequency, rainfall depth), topography, soil characteristics, disturbance history (i.e., natural and anthropogenic), and other miscellaneous factors such as salt stress or wave damage.

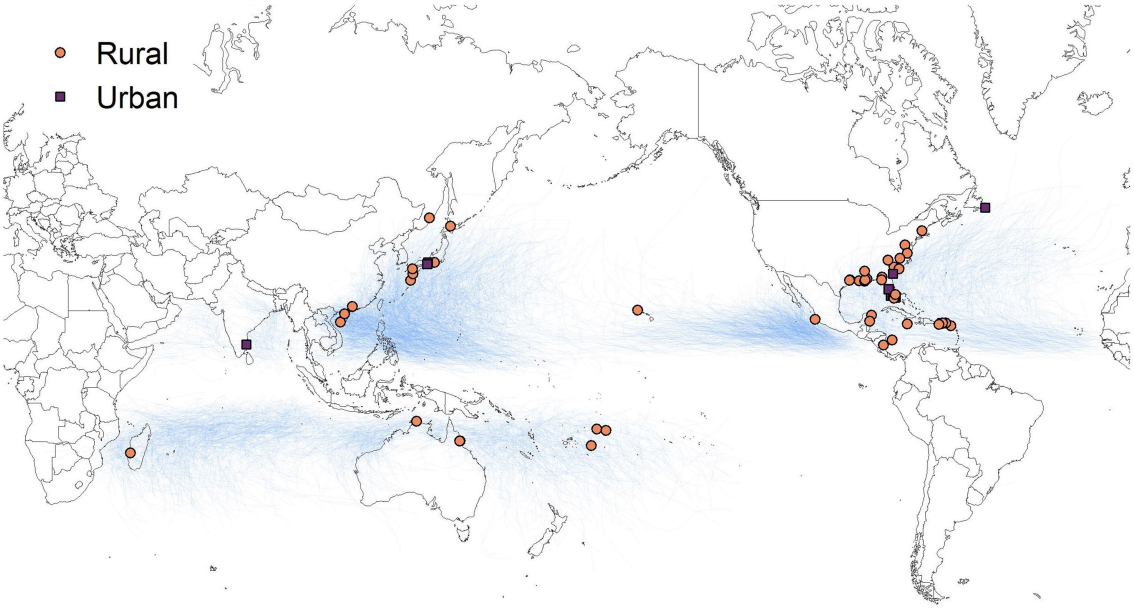

FIGURE 1
Tracks of tropical cyclones which have made landfall since 1970 (light blue lines) and the location of urban and rural studies (purple squares and orange circles, respectively) selected for inclusion in the literature review. Hurricane track data from Knapp et al. (2010, 2018).

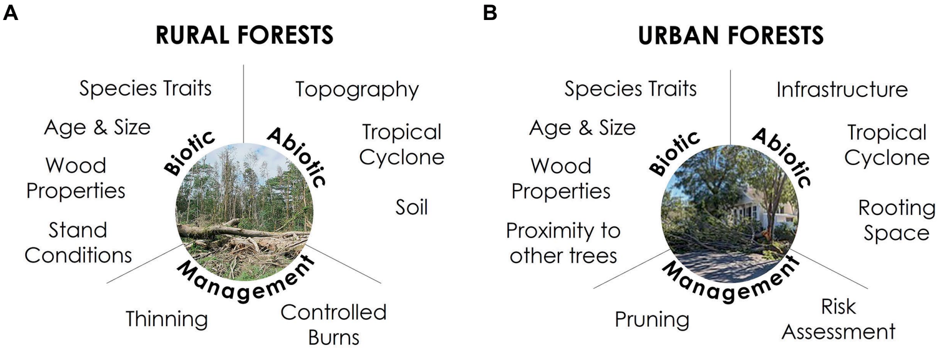

FIGURE 2
Conceptual diagram of factors that affect tropical cyclone damage to trees in rural **(A)** and urban **(B)** settings. Photo credit: Bob Linsdell, CC BY 3.0, and Bart Everson, CC BY 2.0, via commons.wikimedia.org.

Isolating the impacts and relative importance of these factors is substantially complicated by their interactions. For example, as ridgelines (an abiotic factor) may favor species that are already resistant to wind damage (a biotic factor), storms may cause less damage on ridgelines despite greater exposure (Bellingham et al., 1992).

In addition to the biotic and abiotic factors influencing tree wind resistance in rural contexts, other characteristics impact tree tropical cyclone resistance in urban environments (Figure 2). Urban forests contain multiple habitat types: natural areas where trees are the dominant vegetation type and are minimally managed, managed park-like landscapes, private property, plazas, and roadside planting strips in close proximity to hard infrastructure (Piana et al., 2021). In many of these managed landscapes, urban trees can be found growing in open settings, clusters, or rows rather than closed stands. These open–grown trees lack the wind protection afforded to trees growing in larger forest stands (MacFarlane and Kane, 2017). Additionally, urban street trees are often planted into small soil volumes or near infrastructure (e.g., streets, curbs, sidewalks, buildings) which can influence root growth and tree canopy size in addition to generating potential conflicts with infrastructure (Day et al., 2010). In highly managed settings, urban trees can be pruned to meet esthetic or safety goals or to reduce conflicts with infrastructure. Pruning practices such as reduction cuts and thinning can increase a tree's resistance to wind damage (Gilman et al., 2008). Urban forests can also contain high proportions of non-native species that may influence both susceptibility to and recovery from tropical cyclones (Zhao et al., 2010). Finally, urban natural areas also tend to have a high degree of fragmentation (Doroski et al., 2022), which creates more forest edges exposed to wind. Given these noted differences, reliance upon core works such as Everham and Brokaw (1996), derived from tropical cyclone research in rural forest environments may not be prudent when making research-based urban forest and emergency management decisions.

The primary goal of this scoping review is to examine the state of research as it relates to factors that influence tree resistance to tropical cyclone damage in urban settings. We included rural studies in our search to provide context for assessing the state of urban tropical cyclone tree research. We focus on damage to trees driven by high winds as opposed to other destructive elements of tropical storms (e.g., storm surge or saltwater inundation). To this end, we conducted a global, multilingual review of scholarly literature to identify studies using ground-based observations of tropical cyclone-related tree damage to test the impacts of different factors (e.g., tree height) on damage resistance. Our review is unique from other literature reviews on the impacts of tropical cyclones on forests (Xi, 2015; López-Marrero et al., 2019; Lin et al., 2020; Heartsill-Scalley and López-Marrero, 2021) because of our focus on tree damage urban settings. A scoping review approach enables us to document the amount and global distribution of tropical cyclone urban tree damage research, synthesize key themes, identify key knowledge gaps, and develop preliminary recommendations.

For this review we focused on studies which made observations of damage at the tree-level since many management decisions are made at the level of the individual tree in urban forestry, such as choosing a species to plant along a street. We hypothesized that urban studies identified in our review would evaluate a broader range of factors affecting tropical cyclone tree resistance than rural studies since urban environments incorporate additional infrastructure and management activities. This review identifies areas in need of additional research regarding tropical cyclone damage to urban trees. It also offers insights into tree characteristics and management practices that can improve the ability of urban forests to resist wind damage from tropical cyclones. While tropical cyclones are by no means a new phenomenon, the potential for more intense storms in the future (Knutson et al., 2019) adds urgency to understanding tropical cyclone impacts on urban trees, especially since hurricane intensity tends to exacerbate damage to trees (e.g., Middleton, 2009). Research in urban settings also has the potential to benefit forests impacted by fragmentation from human development (López-Marrero et al., 2019).

2. Methods

2.1. Literature search

We conducted a literature review to identify studies that tested the effects of different factors on tree damage by tropical cyclones in urban and rural settings, for both managed and natural forests. We report our review process following the Preferred Reporting Items for Systematic reviews and

Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) guidelines (Tricco et al., 2018), though a review protocol was not published for this study (Supplementary Table S1; Figure 3). Studies were classified as urban if they were conducted within a city or town, including those natural areas that were embedded within an urban matrix. All other studies were classified as rural. Since tropical cyclones impact multiple regions of the world, we searched for peer-reviewed research written in English, Chinese, French, Japanese, Portuguese, and Spanish. We used the following search string and its translation and synonyms into the five additional languages (Supplementary Table S2): forest AND (hurricane OR cyclone OR typhoon). We captured peer reviewed research and dissertations in the six target languages utilizing multiple search engines and databases, including Google Scholar, SciELO, J-Stage, and CNKI (China National Knowledge Infrastructure Database). For publications in French, Portuguese, and Spanish, we also directly searched within forestry-related journals in those languages that may not have been indexed in a database (full search details provided in Supplementary Table S3). The searches were conducted to include studies published between 1900 and 2022. The last search was conducted on May 5, 2022. Backward and forward chaining were also used to identify literature we might have missed during the formal search engine and database search processes.

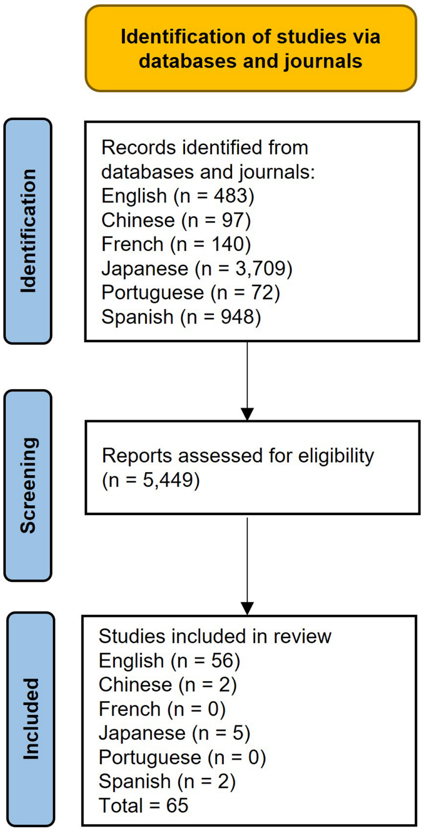

FIGURE 3
Diagram documenting the literature review search and screening process.

2.2. Screening

Research documents were required to meet the following eligibility criteria to be considered for inclusion in the literature review: (1) study tree damage following a tropical cyclone within one year of the weather event, assuming a second extreme weather event did not impact the study site sooner; (2) examine only one type of natural disaster (e.g., a study of tropical cyclone and a concurrent landslide or subsequent forest fire would be excluded); (3) base their analysis on ground-based observations of tree damage; and (4) analyze factors that may influence the resistance of trees to tropical cyclone wind damage, such as wood density or topographic position. Studies of tropical cyclone damage to mangrove ecosystems were excluded since these unique habitats have no analog in managed urban settings such as parks or roadways. None of the documents published in French or Portuguese identified by the search process satisfied the review criteria.

2.3. Data extraction

After screening, one member of the researcher team collected the following information from the selected papers into a spreadsheet: study location, classification as an urban or rural site, data collection and statistical analyses methodologies, the time elapsed between the tropical cyclone and data collection, the type of damage used as a response variable (e.g., snapped trunk; Table 1), and the type(s) of predictor variables (e.g., trunk diameter at breast height (DBH); Table 2). Multi-lingual team members checked data extraction for sources in languages other than English. Each study was assigned a climate classification according to an updated version of the Köppen–Geiger system (Peel et al., 2007).

The studies' methodologies were also evaluated using a five-point methodology rating system based on the following criteria: (1) used a randomized study design or conducted a complete inventory of an area; (2) reported results as a proportion of a population; (3) differentiated between types of storm damage (e.g., branch failure and uprooting); (4) assessed risk or condition; and (5) measured tree size (e.g., DBH, height, etc.). A study received a point for each criterion it met, for a potential maximum of five points. Studies with a score of zero were excluded from further analysis.

For the purpose of counting the frequency of predictor and response variables used in tropical cyclone tree studies, four papers were assigned as two pairs. McGroddy et al. (2013) and Vandecar et al. (2011) were counted as a single study as the two articles tested the same research sites (assessing different predictors of damage). Duryea et al. (2007a,b) were also counted as a single study since they applied the same analysis methodology to overlapping study regions (although each manuscript examined different sets of species).

After data extraction, we determined the frequency of studies and/or analyses by region, country, year, urban and rural context, climate type, damage type, predictor type, and the relationship between predictors and damage. We compared the frequencies of damage and predictor variables between urban and rural studies using a χ^2 test. We also compared the number of predictive factors evaluated by urban and rural studies using a *t*-test. All summaries, analyses, and associated Figures were created using R v.4.2.1 (R Core Team, 2022).

3. Results

3.1. Summary of screened papers

Our initial search generated 5,449 papers, of which 65 met our screening criteria. We attribute this low return rate to our use of very broad search terms (forest AND hurricane OR cyclone OR typhoon; Supplementary Table S2) which returned a large number of studies, most of which had no relevance to our study objectives. For some search platforms such as J-STAGE, Boolean operators appeared to be limited in their effectiveness as most search results were only relevant to forestry or tropical cyclones, not both. Out of the 65 papers meeting our criteria, 13 urban and 52 rural met our screening criteria (Figure 3). Of the urban studies, 9 studies examined trees growing in managed areas (e.g., street trees, landscaped parks, residential areas), 1 was in unmanaged urban forest fragments, and 3 contained both managed and unmanaged areas. Out of the 52 rural studies, only 6 involved actively managed forests (recent timber harvests, controlled burns, etc.). Publication frequency of the topic did not show any trends over time (Figure 4).

These papers represent research conducted in six countries and territories for urban forests and 17 countries and territories for rural forests (Figure 1; Supplementary Table S4). The majority of urban and rural studies were conducted in the North Atlantic tropical cyclone basin (77 and 62%, respectively). While the search process did identify several urban studies in China, these articles did not meet eligibility requirements because they lacked sufficient methodological details and were consequently excluded from further analysis. Seven urban forest research studies were classified as tropical according to the updated Köppen–Geiger Climate Classification (Peel et al., 2007), five were temperate, and one was cold. For rural forest research, 25 were tropical, 23 were temperate, and three were cold. The studies included damage due to 50 storms, most commonly Hurricane Hugo (seven studies), followed by Hurricane Irma (six), and Hurricane Katrina (five). Notably, 63% of the rural studies collected tropical cyclone damage data at long-term study sites, places where forest monitoring plots had been established for other research purposes prior to the occurrence of the tropical cyclone of interest. Only 31% of the urban studies utilized long-term research locations.

We found that studies evaluated damage to trees using a range of different metrics, some focused on specific tree parts while other studies documented damage more generally (Figure 5). The most frequently analyzed type of damage to urban trees was the response variable "All Damage," a variable that combines multiple types of tropical cyclone damage (23% of urban analyses). Unlike data collection in rural settings, urban studies often collected defoliation and branch damage data as a proportion of the crown lost for individual trees. Though there was no significant difference between the distribution of damage variables in urban and rural studies ($\chi^2 = 14.5$, $p = 0.21$). By contrast in rural studies, defoliation and branch damage were more frequently recorded as a presence–absence metric on individual trees within a population. Leaning, a condition whereby the tree bole is no longer vertical but is not resting on the ground, is the only other variable that appeared in rural but not urban forests. In urban studies, root, stem, and branch failure/crown loss were analyzed at similar frequencies, however in rural studies, root failure was more frequently evaluated than branch and stem damage. Urban studies collected data regarding an average of three and a maximum of seven damage categories per study, whereas rural studies included data on an average of four and a maximum of nine damage categories per study.

For both urban and rural forest studies, diameter at breast height (DBH) was the most frequently studied factor affecting damage, while Species was the second (Figure 6). Overall, urban studies tested a similar quantity of factors than rural (31, versus 36 for rural, including factors in the "Other" category). Fifteen factors were examined in more than one urban study, including DBH, Height, Leaf Properties, Native Status, Species, Stand Composition, Wind Speed, and Wood Density, among others. In contrast, 22 factors were examined in multiple rural studies. Urban and rural studies on average examined 4 and 3 factors, respectively, within a given study ($t = -1.3$, $p = 0.22$). Though the distribution of predictor types was significantly different between urban and rural studies ($\chi^2 = 69.0$, $p = 0.002$). Factors unique to urban studies included volume of rooting space, the presence of

TABLE 1 Types and definitions of tropical cyclone tree damage identified in the literature review.

Damage Type	Definition
All Damage	A single variable that includes all types of tropical cyclone damage. Can include mortality as well as living trees with branch damage.
Mortality (%)	Percent of trees that died from primarily tropical cyclone-related wind within one year of a hurricane. Note: includes studies that reported results in terms of survival (proportion of living trees)
Multiple Damage Categories	Tropical cyclone-related damage is assessed by multiple categories.
Failure – Stem (%)	Percentage of trees with a stem (aka trunk or bole) broken between ground level and the crown.
Failure – Branch (%)	Percentage of trees with large broken branches or general damaged crown. Based on presence or absence of damaged branches.
Failure – Root (%)	Percentage of trees uprooted or tipped over resulting in the tree lying on the ground or leaning less than 45 degrees.
Failure – Root and Stem (%)	Percentage of trees with root or stem failure.
Defoliation (%)	Percentage of trees with a completely or partially defoliated crown. Tree may still be alive.
Leaning (%)	Percentage of trees that lean but have not completely fallen to the ground.
Other	Other damage-related variables not included in the previously defined categories.
Percent Crown Loss – Branch	Percentage of the crown that has lost branches.
Percent Crown Loss – Defoliation	Percentage of crown that has defoliated.

TABLE 2 Types and definitions of factors that affect tropical cyclone damage to trees identified in the literature review.

Factor type	Definition
Age	Tree age or stand age
Aspect of slope or exposure	Direction of slope relative to prevailing tropical cyclone winds
Buttress presence	Presence or absence of buttress or stilt roots
Canopy position	Classification of tree as dominant, intermediate, suppressed, etc. also called crown class
Crown properties	Crown shape defined as a category or a numerical relationship between crown size and other tree properties (e.g., crown to bole ratio)
DBH	Trunk diameter at breast height
Defects	Tree contained structural defects, cavities, poor branch attachment, cut roots, and/or decay
Distance to hurricane eye	Distance between study site and hurricane track or eyewall
Elevation	Stand elevation
Failure likelihood rating	Professional risk assessment rating estimating the likelihood of a tree breaking prior to the storm
Forest type	Compares forests with different compositions and/or land use histories
Grouped trees	Trees planted in groupings of five or more
Growth form	Excurrent or decurrent growth form
Growth rate	Tree growth rate
Height	Tree height
Leaf properties	Leaf level properties including the propensity to retain leaves in high winds, specific leaf area, etc.
Management history	Previous management activities such as clear cutting
Maximum height	Maximum height of a species used as a species trait
Modulus of elasticity	Resistance of wood to deformation, the ratio of stress to strain (higher value indicates stiffer material)
Modulus of rupture	Strength of wood prior to breaking, also called bending strength (higher value indicates stronger material)
Native status	Tree species is native to study area
Other predictors	Additional predictors of tree mortality and damage by tropical cyclones not included in other classifications. Includes: branch resistance to flexing, canopy unevenness, coefficient of variation of DBH within a plot, crown width, distance from canopy opening, exposure to previous hurricane, extent of canopy cover, percent of crown missing, plot fragmentation, size of tree island in wetland, sociodemographic characteristics, stand basal area, stand stem quantity, and wind protection by structure.
Precipitation	Antecedent precipitation
Pruning	Branches have been removed from tree to reduce size or density of crown
Rooting space	Area of exposed (unpaved) soil surrounding a tree
Shade tolerance	Species tolerance or intolerance to shade
Slenderness	Ratio of height to trunk diameter
Soil	Soil properties (e.g., texture, drainage) or a composite metric that aggregates multiple soil properties into a single number
Species	Tree species
Stand basal area	Basal area of a stand
Stand composition	Number or composition of species within a stand, including proportions of hardwoods and softwoods
Stand density	Quantity of trees per area within a stand
Topography	Composite metric or classification of multiple topographic characteristics, including slope
Utility line	Overhead utility lines were observed near a tree
Vine presence	Presence or absence of vines
Wind speed	Wind speed reported as maximum sustained wind speed or maximum gust speed
Wood density	Average wood density for a species based on field measurements or literature values

overhead utility lines, protection provided by other structures, grouping (trees planted near other trees), risk assessment rating for likelihood of failure, previous pruning, growth form (decurrent or excurrent), and modulus of rupture (the amount of stress a material can experience before breaking). Rural studies more commonly assessed factors occurring at multiple scales in relation to tree damage, such as stand density or basal area (stand level), and topographic position or elevation (landscape level).

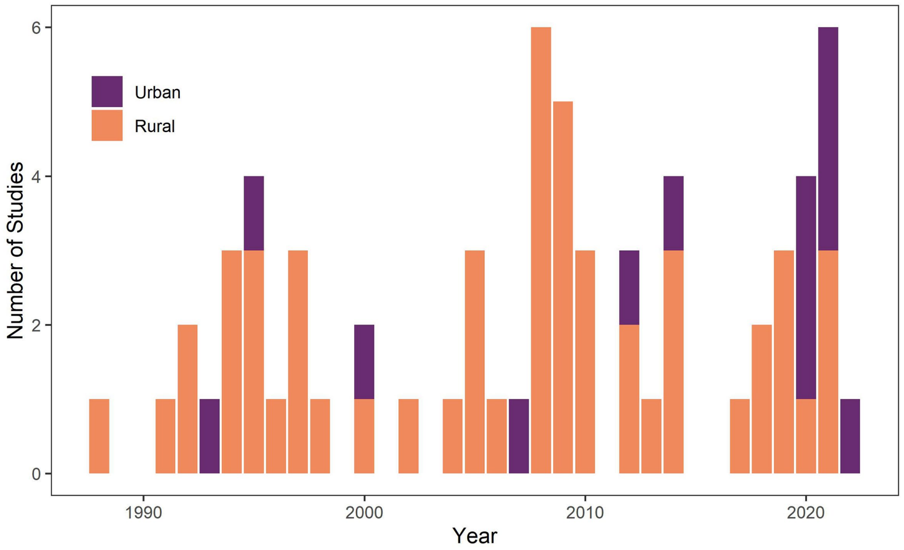

FIGURE 4
Distribution of studies identified in the literature review search and screening process based on publication year.

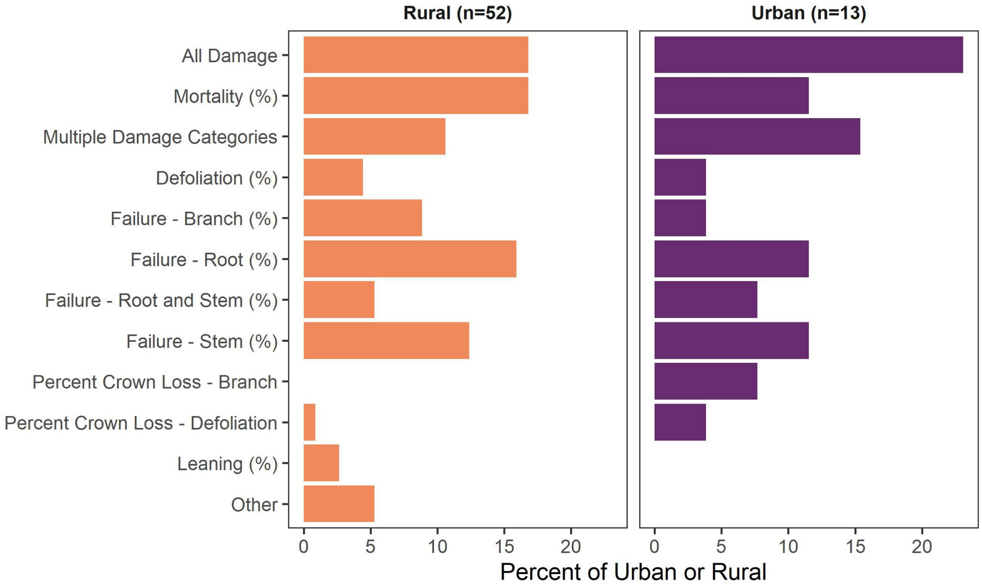

FIGURE 5
The percentage of tropical cyclone tree damage type categories used in the data analyses of the literature review studies.

Several different types of statistical analysis approaches were used in the studies. When damage was treated as a categorical variable with multiple groups many studies utilized a contingency table-based approach such as a chi-squared test or *G*-test (23% of urban, 30% of rural). If a study evaluated a continuous predictor variable such as DBH, that predictor would be binned into groups for use in the contingency table-based analysis. Generalized linear models (e.g., logistic regression) were used by 46% of urban and 27% of rural studies, quantifying damage as either presence–absence within an individual tree or as the proportion of damaged trees within a plot. By location, 42% of urban and 31% of rural studies tested multiple types of damage (variables: All Damage, Multiple Damage Categories, and Failure – Root and Stem) in a single statistical model as opposed to testing each damage type (e.g., Failure – Root) individually.

Rural studies tended to score slightly higher on our five-point methodology rating system compared to urban studies (3.0 versus 2.8; Supplementary Table S5). Urban studies more often measured tree size and assessed tree risk of failure, while rural studies more frequently utilized a randomized study design, differentiated between types of storm damage, and reported results as a proportion of the population.

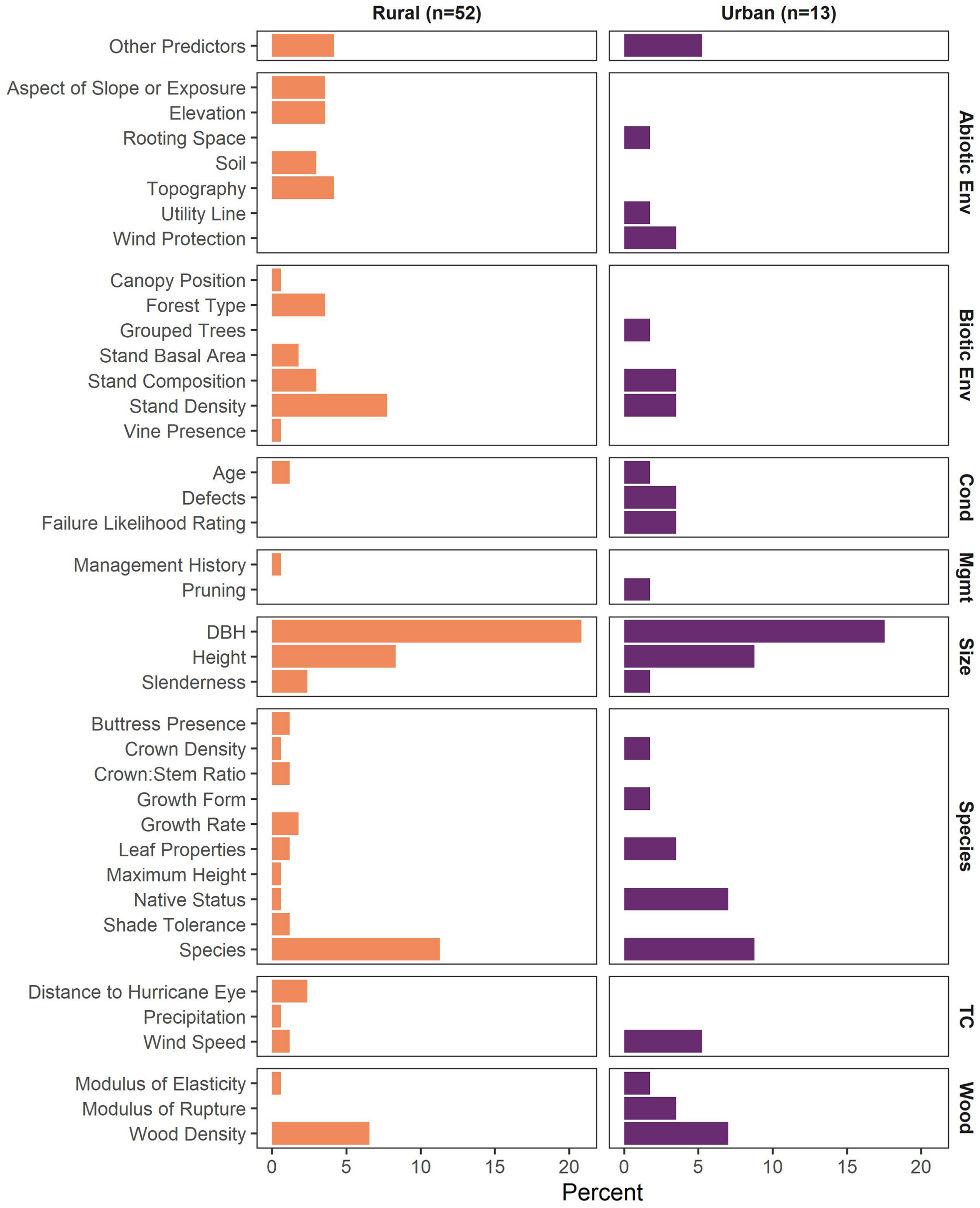

FIGURE 6
The frequency of each type of predictor examined in the studies identified by the literature review. Data are presented as a percentage of the total number of rural or urban studies and are grouped by theme. Categories with no bar were not analyzed by any urban or rural study. Denominator=number of urban or rural studies. Cond, condition; Env, environment; Mgmt, management; TC, tropical cyclone. Categories included in "Other Predictors" are listed in Table 2.

3.2. Biotic factors

3.2.1. Tree size

Research on the relationship between DBH and tropical cyclone damage has produced mixed results (Figure 7; Supplementary Table S6). Trees with larger DBH were more likely to experience any kind of damage (All Damage) in studies of managed and unmanaged urban landscapes in several Caribbean islands (Francis and Gillespie, 1993) and Florida, USA (Koeser et al., 2020; Landry et al., 2021). DBH had a positive relationship with Stem Failure (snapped boles) and Root Failure (uprooted trees) when tree type (deciduous or coniferous) was included in a model of tropical cyclone damage to trees in Newfoundland, Canada (Wiersma et al., 2012). Though in this same study, tree age did not predict damage. Larger DBH trees were also more likely to have Root and Stem Failure in remnant forests in urban Florida (Horvitz et al., 1995). Klein et al. (2020) observed larger DBH trees were less likely to be severely damaged (Multiple Damage Categories) in a survey of open grown trees in a city in Florida, though this effect was small and may have been confounded by differences among species. Additionally, when assessing damage to branches (since large trees have more branches than smaller trees) the loss of a branch in a large tree can lead to a smaller proportion of crown loss compared to a smaller tree. Francis and Gillespie (1993) also observed a weak negative relationship between DBH and Stem Failure and no

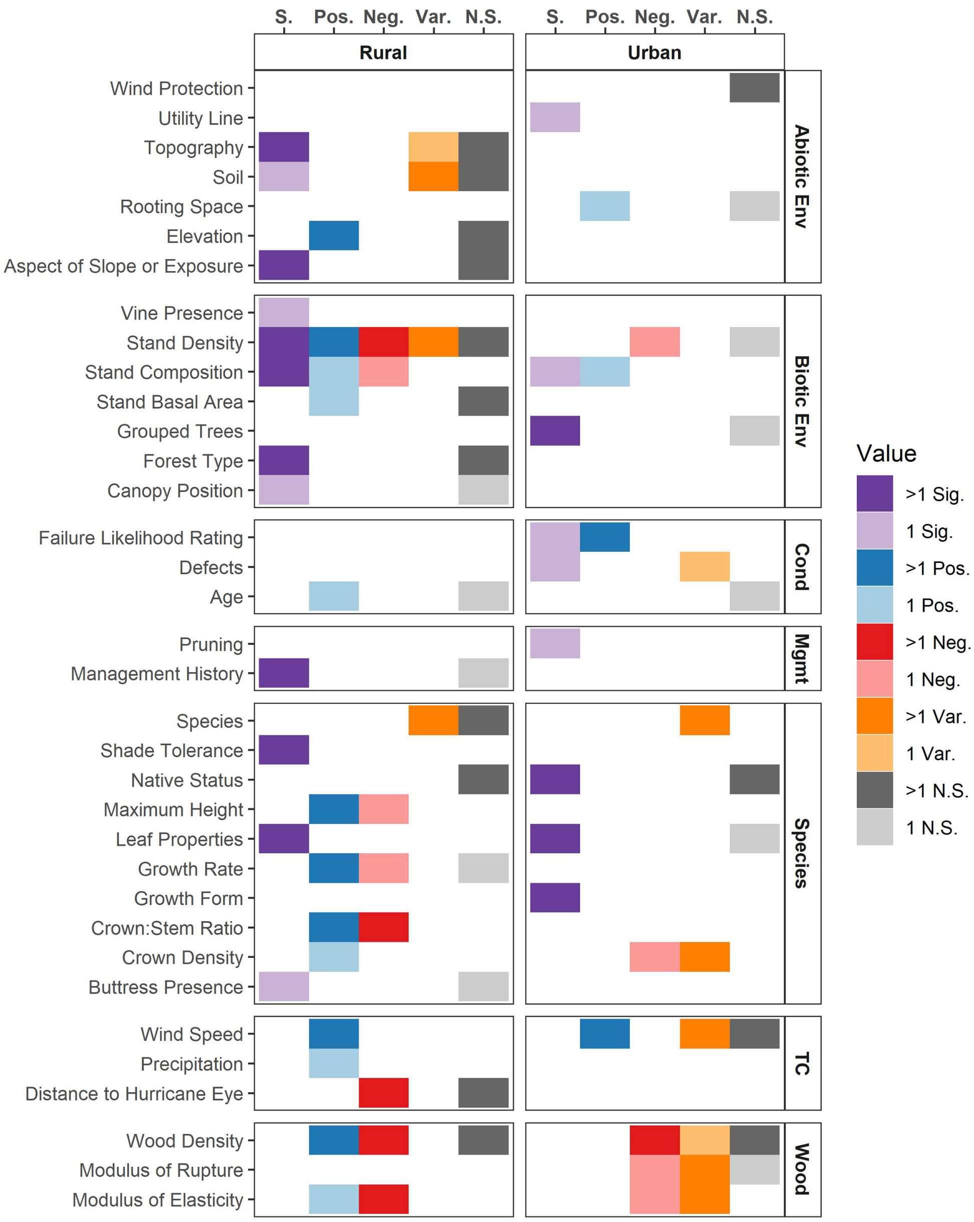

FIGURE 7
The number of studies that observed positive, negative, variable, or non-significant relationships between tree size factors and different types of tropical cyclone damage to trees. >1 indicates relationship type was observed in more than one study. Pos., positive relationship; Neg., negative relationship; Var., variable relationship (e.g., non-linear); N.S., no significant relationship.

relationship between Root Failure and DBH. Height was not a significant predictor of damage in managed and unmanaged urban forests affected by tropical cyclones in Florida (Landry et al., 2021) and Newfoundland (Wiersma et al., 2012). Conversely, taller trees and trees with wider crowns were more likely to have died or been damaged in San Juan, Puerto Rico (Torres-Martínez et al., 2021). Slenderness, the ratio of height to trunk diameter, also increased the likelihood of damage to one common species found in an urban shrine forest in Kyoto, Japan, but not other species (Tabata et al., 2020).

Several rural studies observed that the DBH–damage relationship can vary among species (e.g., Greenberg and McNab, 1998; Franklin et al., 2004). Other rural studies observed no relationship between tree size and damage (e.g., Xu et al., 2008; Ruiz and Fandiño, 2010). The DBH-damage relationship can also be influenced by tree height. For example, Paz et al. (2018) observed slenderness (the ratio of height to stem diameter) was positively associated with Root Failure. Biomechanical models of tree resistance to wind damage based on observations of natural and managed forest stands also highlight the occasionally contrasting influences of DBH and height (Gardiner, 2021). These models suggest that while greater DBH is associated with greater resistance to Stem Failure and Root Failure, greater height is associated with reduced resistance to damage. Some studies in rural forests indicate that tree size may be a less important predictor in areas where previous storms have culled less wind resistant trees, leading to a population with overall greater wind resistance (Elmqvist et al., 1994; Uriarte et al., 2019). Some authors also posit that at extremely

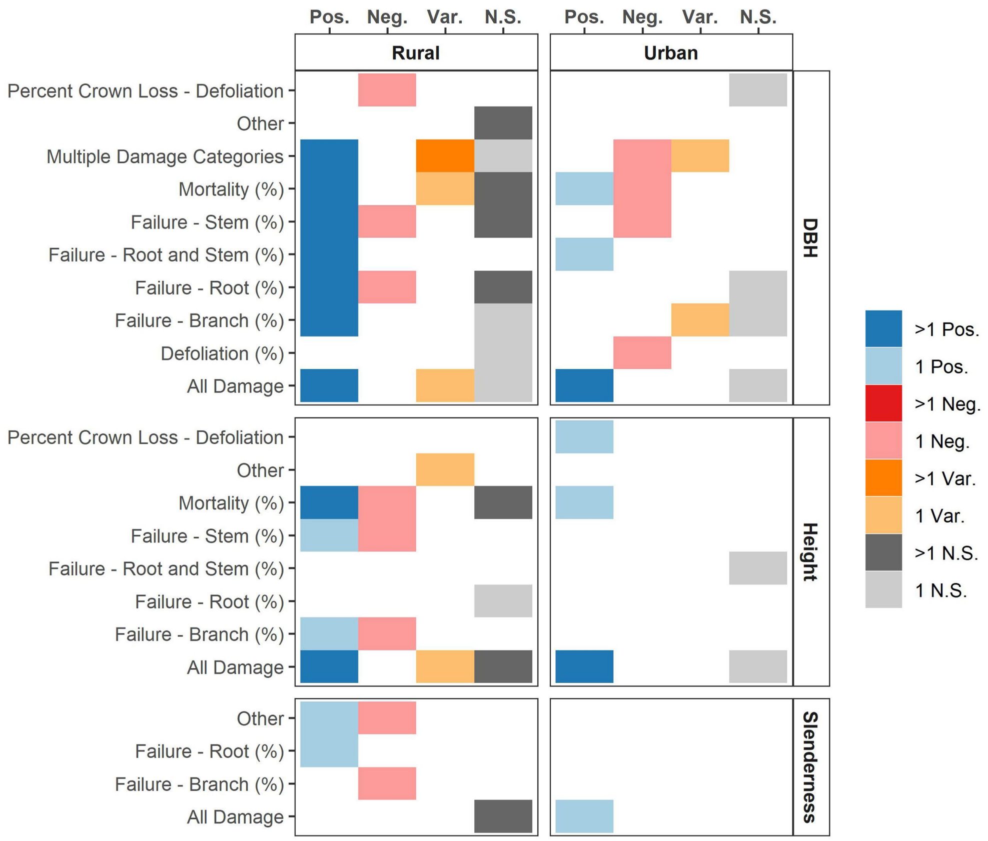

FIGURE 8
The number of studies that observed positive, negative, variable, or non-significant relationships between predicting factors and different types of tropical cyclone damage to trees. >1 indicates relationship type was observed in more than one study. S., significant difference among categories; Pos., positive relationship; Neg., negative relationship; Var., variable relationship (e.g., non-linear); N.S., no significant relationship; Cond., tree condition; Mgmt., management; TC, tropical cyclone.

high wind speeds, tree size and other wind resistance traits may not matter (Everham and Brokaw, 1996; Eppinga and Pucko, 2018).

3.2.2. Species allometric and architectural characteristics

Species was a predictor of damage frequency in multiple urban studies (Figure 8; Supplementary Table S6), though these studies were all conducted in managed urban forests in Florida or the Caribbean (Duryea et al., 2007a,b; Klein et al., 2020; Koeser et al., 2020). Duryea et al. (2007a) conducted the most comprehensive analysis of species-related characteristics which could influence urban tree damage resistance. They conducted separate analyses for species found in coastal plain and tropical/subtropical settings in Florida, and often observed differences between the two groups of trees. Coastal plain trees with greater Crown Density had lower mortality but tended to lose more branches while tropical/subtropical species with moderate Crown Density had the highest mortality. Trees with a decurrent Growth Form (no dominant leader) tended to have lower mortality in both groups. Coastal plain trees with a tendency to defoliate in response to extreme winds (Leaf Properties) had lower mortality, though there was no association between defoliation and mortality in the tropical/subtropical species. In tropical dry forests and tropical rainforests, Paz et al. (2018) and Webb et al. (2014), respectively, observed that trees with greater Crown:Stem ratios (wider crown compared to trunk) were more likely to suffer Root Failure or Stem Failure, respectively. Kitagawa et al. (2010) also found that greater frequency of damage to trees with larger Crown:Stem ratios in conifer tree plantations. Another trait often observed in tropical species were buttresses or stiltroots (Buttress Presence). Elmqvist et al. (1994) observed species with buttresses or stiltroots were more resistant to uprooting in a Samoan rainforest.

3.2.3. Native status

Authors of several studies hypothesized that a species' Native Status to the study region could impact its resistance to damage (Figure 8). There was no difference between native and non-native mortality for coastal plain species in Florida (Duryea et al., 2007b), but sub-tropical native species had lower mortality in three of the four studied storms in the area (Duryea et al., 2007a). Non-native species on a university campus in Sakai, Japan were more likely to be damaged compared to native species (Nakamura, 2020). However, Wiersma et al. (2012) and Landry et al. (2021) did not find differences among native and non-native urban trees damage and survival in Newfoundland, Canada, and Florida, respectively.

3.2.4. Wood properties

Some studies observed species with greater Wood Density are more resistant to damage in the urban forest context, while others found no relationship (Figure 8). Species with denser wood in managed urban forests in Puerto Rico were less likely to have root or stem failure following a tropical cyclone (Francis, 2000). However, in Puducherry, India (Sundarapandian et al., 2014) and Sakai, Japan (Nakamura, 2020) there was no relationship between wood density and root or stem failure. Wood density did not exhibit a linear relationship with percent branch loss, instead branch loss peaked around 0.5 to 0.59 g/cm^3 (out of a population range of 0.4 to 0.89 g/cm^3) for coastal plain species in urban Florida (Duryea et al., 2007b). However, wood density did have a negative relationship with mortality for this same group of trees (Duryea et al., 2007b). Yet for tropical and subtropical urban trees in Florida, wood density did not affect branch loss or mortality (Duryea et al., 2007a). In addition to wood density, Duryea et al. (2007a,b)also evaluated Modulus of Rupture (MOR, a measure of wood strength) and Modulus of Elasticity (MOE, a measure of wood stiffness) in both coastal plain and tropical/subtropical species in managed urban settings. Mortality was lower in coastal plain species with greater MOE and MOR, though these characteristics were not related to branch failure. Species with greater MOE and MOR had lower mortality for one hurricane, but these factors were not important during a tropical cyclone with higher wind speeds (Duryea et al., 2007a). Trees with a greater MOR had a lower likelihood of Stem Damage following a typhoon in Sakai, Japan (Nakamura, 2020).

In rural studies, greater Wood Density (Figure 8) was often associated with less damage and mortality (Curran et al., 2008; Vandecar et al., 2011; Webb et al., 2014; Uriarte et al., 2019), though other studies observed a negative relationship or no relationship between Wood Density and damage (Bellingham et al., 1995; Van Bloem et al., 2006; Xu et al., 2008; Jimenez-Rodríguez et al., 2018; Paz et al., 2018). When wood density was not identified as a significant predictor, other factors such as size (Jimenez-Rodríguez et al., 2018) may have played a more important role in tree damage. Isolating single traits for selecting tropical cyclone resistant species can be challenged by the tendency of many traits to co-vary with each other. For example, Paz et al. (2018) observed crown shape (Crown:Stem Ratio) was correlated with Wood Density and that both features influenced tropical cyclone resistance. In their study, trees with dense wood tended to be slimmer with wider crowns and were more prone to stem or root failure. Uriarte et al. (2019) observed Wood Density was an important predictor of stem breakage for one tropical cyclone (Hurricane Maria, 2017, Saffir–Simpson Category 4) but not another (Hurricane Hugo, 1989, Saffir–Simpson Category 3). Other wood properties may also be more relevant to tropical cyclone resistance. For example, Xu et al. (2014) observed that wood fiber width and the ratio of fiber length to width were positively and negatively, respectively, associated with tree damage in a forest plantation, although wood density was not a significant predictor. Wood density is also correlated with successional status, where pioneer woody species tend to have lower wood density and a greater propensity for damage (Zimmerman et al., 1994; Canham et al., 2010). While trees with greater wood density appear more likely to resist tropical cyclone damage, this property should be considered in the context of multiple biotic and abiotic factors.

3.2.5. Extrinsic biological factors

In managed urban settings where trees may grow in an open environment or in close proximity to other trees (Grouped Trees, Figure 8), the types and proximity of trees in a neighborhood can influence tropical cyclone damage. Coastal plain and tropical/subtropical species in managed urban settings in Florida were less likely to die when they were growing in groups of five or more (Duryea et al., 2007a,b). Grouping was also associated with lower branch loss for tropical/subtropical species, but made no difference for coastal plain species (Duryea et al., 2007a,b). However, distance to the nearest standing tree was not an important predictor of root and stem failure in managed and unmanaged urban trees in Newfoundland, Canada (Wiersma et al., 2012). When assessing damage at the plot scale in managed urban settings, Landry et al. (2021) observed that plots with greater species diversity (Stand Composition) and a greater proportion of trees rated as having low wind resistance [as defined in Duryea et al. (2007b)] were more likely to be more damaged. In that study, the proportion of canopy cover within a plot was not a significant predictor of damage at the plot scale (Landry et al., 2021). Trees in a forest stand embedded within Kyoto, Japan, were less likely to be damaged if they were in an area with high Stand Density (Tabata et al., 2020). Notably, while forest fragmentation is a common feature of urban landscape (Doroski et al., 2022), it was not a predictor examined by urban studies.

The presence of woody vines (lianas) can also increase the likelihood of tree failure during a tropical cyclone (Allen et al., 1997), at least in temperate bottomland forests. Researchers in tropical settings such as Queensland, Australia and Panama, while not focused on tropical cyclone damage per se, have also observed an association between increased treefall and woody vine abundance (Webb, 1958; Putz, 1984). While the excess weight of woody vines likely reduces the ability of trees to withstand wind damage, Putz (1984) points out that vines can also be a symptom of other problems with a tree rather than the sole cause of failure. Woody vine prevalence, especially of non-native species, tends to increase following disturbance by tropical cyclones (Horvitz et al., 1998), and tends to be greater along forest edges (Camarero, 2019). Consequently, the impact of woody vines on tree stability warrants further investigation in urban settings where fragmentation is common and creates many forest edges.

One topic mentioned by Everham and Brokaw (1996) that was only indirectly assessed by one study in our review was the effect of pathogens and pests on the susceptibility of tree damage by hurricanes. Nelson et al. (2022) analyzed the association of cankers (an infected wound on a tree) and rotted wood with hurricane damage in Florida, though they observed no significant effect. Other studies have reported anecdotal associations between defects related to wood decay and hurricane damage (Trousdell, 1955; Thompson, 1983).

3.3. Abiotic factors

Infrastructure such as buildings, pavement, and utilities in the urban environment create growing conditions that can increase or decrease tropical cyclone damage to trees. Nearby infrastructure such as buildings which could have been a source of Wind Protection (Figure 8) did not affect the amount of damage in plots of managed urban trees in Florida (Landry et al., 2021). Similarly, Nelson et al. (2022) did not observe an impact on damage by windbreaks, defined as the proportion of building and canopy cover within a 10 m radius of the target tree. Tropical/subtropical species in managed urban settings in Florida were less likely to have branch failure when growing in larger Rooting Spaces (defined as greater than 7 m^2), though Rooting Space had no significant effect on survival (Duryea et al., 2007a). Rooting Space was not evaluated in the companion study about coastal plain species in urban Florida (Duryea et al., 2007b). Managed urban trees in Florida growing underneath Utility Lines were less likely to be severely damaged following a tropical cyclone (Klein et al., 2020). Researchers in rural forests have studied a range of soil characteristics in the context of tree damage (e.g., Isamoto and Takamiya, 1992; Xi et al., 2008; Sato et al., 2009; Ni et al., 2021). In the studies we surveyed it was uncommon for soil characteristics to be significant predictors of damage, though interestingly Rutledge et al. (2021) observed an interacting effect on damage between soil drainage class and species.

Over large scales, increasing Wind Speed appears to be associated with increased damage to urban trees (Francis and Gillespie, 1993; Duryea et al., 2007b). At the city scale, tree mortality increased with increasing Wind Speed across eight tropical cyclones that impacted Florida (Duryea et al., 2007b). Francis and Gillespie (1993) also observed a positive relationship between Wind Speed and all types of tree damage aggregated across multiple Caribbean sites impacted by the same storm. These authors also observed a curvilinear relationship between branch damage, gust speed, and DBH, with damage peaking at Wind Speeds of approximately 260 km/h, but no relationship between root or branch failure and Wind Speed. However, within a single tropical cyclone in Florida, Wind Speed was not a significant predictor of managed urban tree damage (Landry et al., 2021).

3.4. Management factors

Several species of trees (excluding palms) pruned prior to a tropical cyclone were less likely to die than unpruned trees (Pruning, Figure 8; Duryea et al., 2007a). Klein et al. (2020) observed that urban trees under Utility Lines were less likely to be damaged during tropical cyclones, likely because they had been pruned for utility clearance. Moreover, while not directly related to urban management, sociodemographic factors were hypothesized to influence tropical cyclone damage through indirect effects on managed urban tree canopy distribution and condition in Florida (Landry et al., 2021). The authors observed that higher proportions of African American and Hispanic populations were associated with lower frequencies of tree damage and that these communities also tended to have fewer trees. Plots with higher median population age were also associated with less tree damage, although conversely, these plots were associated with more trees.

A lack of management and regular care may also increase tree susceptibility to damage. Trees in managed urban landscapes in South Carolina and Georgia (USA) were more likely to have whole tree or branch failure if they had dead branches, deep planting depth, severe stem girdling roots, and wounds prior to a tropical cyclone (Management History, Figure 8; Koeser et al., 2020). Additionally, the authors found that trees identified by a risk assessment process as having an "imminent" Failure Likelihood Rating were associated with high failure rates following a tropical cyclone. Similarly, Nelson et al. (2022) observed urban trees in Tampa, Florida, with greater likelihood ratings were more likely to be damaged during tropical cyclones.

4. Discussion

4.1. State of urban cyclone research

Contrary to our initial hypothesis, the collection of urban studies represented a narrower range of factors, although several factors examined were unique to urban settings. The narrower range of urban factors may reflect the speed at which urban studies need to be conducted in response to rapid cleanup activities, possibly limiting data collection options. Additionally, rural studies were more likely to assess variables at multiple scales (e.g., the individual tree, stand, and larger region), which increased the number of potential factors studied in rural forests compared to urban studies focused on tree-level attributes. On average, urban data collection occurred about one month after the tropical cyclone while rural data collection occurred usually seven months post-cyclone. The urban studies tended to focus on characteristics of individual trees and occasionally their immediate surroundings (e.g., rooting space) which reflects how trees are managed both by public and private stakeholders in the built environment as well as the prioritization of safety (Hauer and Johnson, 2003; Miller et al., 2015). In contrast, the goal of many studies examining rural damage was to understand the role of tropical cyclones in a broader ecological context (e.g., Harcombe et al., 2009). Consequently, they considered factors that operate across larger scales (e.g., topography, Eppinga and Pucko, 2018) or connect to other ecological processes (e.g., shade tolerance, Boucher et al., 2005). Since urban forests are complex socio-ecological systems, tropical cyclone tree research in these settings could benefit from the examination of broader factors that influence tree management, similar to approaches used by Landry et al. (2021). Unfortunately, the studies in our review used a wide range of statistical methods, which would complicate the application of meta-analysis approaches to this dataset.

Studies assessing the factors that impact tropical cyclone damage to urban trees are limited in geographic scope, conducted primarily in tropical climates and North America, considering that tropical cyclones impact multiple continents and biomes across the world. The bias toward research in tropical or subtropical biomes likely reflects the greater frequency with which these regions experience tropical cyclones. While some studies project greater poleward migration of tropical cyclones under future climate change scenarios, there is a high degree of uncertainty around these models; Knutson et al. (2020) expressed low confidence in such predictions. Using a model based on historic tropical cyclone data and the distribution of urban forest cover in the continental United States, Cole et al. (2021) identified urban forests in the southeastern and northeastern United States, places with temperate and cold climates, as locations at risk from tropical cyclone damage. Additionally, in northern latitudes where tropical cyclones are less frequent, tree species are less likely to have evolved resistance to such disturbances (Wiersma et al., 2012). This phenomenon has also been observed in tree response to ice storms, as tree ecotypes growing in regions with little to no ice storm loading undergo greater damage when subjected to ice loading (Hauer et al., 2006). Consequently, caution is needed when extrapolating observations of tropical cyclone tree damage beyond regions frequently impacted by tropical cyclones. The work of Cole et al. (2021) emphasizes a need to study urban forests and tropical cyclones beyond tropical regions.

4.2. Future research directions

Studying tropical cyclone damage to urban trees is challenging due to the opportunistic nature of such research, though experimental biomechanical work can play an important role in addressing specific questions on the topic (e.g., Gilman et al., 2008). Many studies on tropical cyclone projects have taken place in long-term research sites that were serendipitously affected by tropical cyclones. Long-term research sites in rural tropical areas have provided many study opportunities, though they were not originally designed to study tropical cyclones (e.g., Luquillo Experimental Forest, Uriarte et al., 2019). Similarly, municipal urban tree inventories are a valuable resource for tropical cyclone research (e.g., Landry et al., 2021). Furthermore, although most trees occur on private lands (Miller et al., 2015), the tree inventories of most communities (> 90%) are not located on private property (Hauer and Peterson, 2016; Ma et al., 2021). Based on our review, we propose researchers focus on the following seven topics in future studies: (1) precipitation, (2) root architecture, anchorage, and interactions with site and soil conditions, (3) pruning, (4) the interaction of factors affecting damage resistance and recovery, (5) pest and pathogens, (6) patterns of damage at multiple scales and their impacts on ecosystem service provisions across all land areas, and (7) a comprehensive rating system for species.

Assessing the impacts of weather variables requires large-scale sampling to capture sufficient variation in factors such as wind speed and precipitation. Xi et al. (2008) analyzed a statewide dataset of rural forest damage observations to test the impacts of wind and rainfall following Hurricane Fran in North Carolina and observed an increase in damage with higher rainfall and wind speed. Francis and Gillespie (1993) and Duryea et al. (2007a,b) used a similar approach to assess the impacts of wind speed on urban forest damage. However, precipitation has not been evaluated in urban settings despite its ability to impact forest damage (Xi et al., 2008). Experimental studies have demonstrated that wet soils can affect root anchorage and increase the likelihood of root plate failure (Kamimura et al., 2012). The topic of tropical cyclone and tree damage is particularly important considering that future climate change projections predict with moderately high confidence that tropical cyclone precipitation rates will increase (Knutson et al., 2020).

Precipitation is not a factor urban forest managers can control. However, while examining forests in northern Japan, Morimoto et al. (2021) demonstrated that precipitation can interact with stand species composition to influence damage. They hypothesized that this relationship could in part be driven by differences in root architecture among species, with species having dense networks of lateral roots exhibiting greater resistance to uprooting. Root architecture is driven both by genetics within a species or genus and by environmental conditions (Akinnifesi et al., 2004). It is also necessary to examine the interactions between root architecture and soil or site characteristics which are unique to the urban environment, such as engineered soils and planting spaces confined by pavement. Johnson et al. (2019) observed that sidewalk replacement activities and boulevard widening influence tree failure during storms with high winds in Minnesota, US. In their recommendations for choosing urban tree species to plant in tropical cyclone prone cities, Zhang et al. (2021) advocate for considering root growth characteristics in addition to above-ground qualities.

Tree above-ground architecture was only the focus of one set of urban tropical cyclone studies (Duryea et al., 2007a,b) and is also an infrequent subject in the rural literature. The crown shape of trees in tropical forests was studied both by Paz et al. (2018) and Webb et al. (2014) who observed that trees with greater crown width to trunk diameter ratios were more likely to be uprooted or have broken stems. The dynamic properties of tree crowns are also important as the ability of branches and leaves to deform in response to wind can enhance wind resistance (Gardiner, 2021). In the city of San Juan, Puerto Rico, Francis (2000) observed that resistance to branch flexing was positively associated with defoliation, but was not a significant predictor of stem failure. Above-ground architecture is a particularly relevant research subject in urban forestry since crown characteristics can be manipulated to a greater extent in highly managed landscapes.

Despite pruning being a widespread management practice used in urban tree planting environments (Ma et al., 2021), pruning was not well documented in the urban studies identified by our literature review. Additionally, pruning is not a topic investigated in rural forests since the practice is less commonly implemented in these settings. Contrary to observations by Duryea et al. (2007a) and Klein et al. (2020) that pruned urban trees were more likely to survive a tropical cyclone, Kane (2008) did not find an association between evidence of pruning and damage following a severe windstorm in a campground. This discrepancy could be explained by differences in setting – open grown urban trees compared to forest trees – and differences in pruning techniques. In an experimental study, Gilman et al. (2008) observed that crown pruning techniques affected the extent of live oak (*Quercus virginiana*) trunk bending in response to hurricane force winds. These results suggest trees with crown reduction or thinning are less likely to fail during extreme winds. One potential hindrance to evaluating pruning as a predictor of damage resistance is the lack of a standardized evaluation approach to quantify the extent of a tree's pruning history and type of pruning. For example, "lion's tailing" is a practice of removing interior branches resulting in more foliage at the exterior of the canopy and changing the biomechanics of damping wind forces (Smiley and Kane 2006). Future research could focus on refining guidance by tree age, species or location to help urban forestry programs prioritize pruning activities when budgets are limited. Additionally, pruning practices may vary among countries and cultures, necessitating pruning research across multiple countries.

Factors that influence tropical cyclone damage to urban trees should also be studied in the context of tree and forest recovery following a disaster, similar to some studies in rural contexts (e.g., Vandermeer et al., 1990; Saito, 2002; Franklin et al., 2004). In the urban context, over 50% of municipal survey respondents in the United States identified "replacement after disaster" as a potential benefit of large-scale tree planting initiatives (Eisenman et al., 2021). Yet, the planning and planting of new trees in managed urban environments and the regrowth and recruitment of new trees in unmanaged urban natural forests is understudied. Urban tree recovery, including restoring damaged trees, after tropical cyclones has been studied in managed settings in China (Zhou and Dong, 2018; Jin et al., 2019). In the United States, recovery research has primarily focused on cleanup activities associated with debris and tree removal (Escobedo et al., 2009; Thompson et al., 2011). These studies highlight regional differences in approaches to urban tree management after a disaster, again highlighting the need for research across geographic settings.

Pest and pathogen impacts on tree susceptibility to hurricane damage is another important subject for study that remains understudied. Termites warrant particular attention in tropical and subtropical settings where their abundance in urban areas has increased with the loss of natural habitat and the introduction of non-native species (Osbrink et al., 1999; Fontes and Milano, 2002). Following Hurricane George in Louisiana, USA, most hurricane damaged park trees showed evidence of termites (Osbrink et al., 1999). Pest and pathogen impacts on tree susceptibility to hurricane damage was a sparsely studied topic when Everham and Brokaw (1996) completed their wind resistance literature and it remains understudied despite continued introductions of non-native species (Seebens et al., 2017).

Another important avenue for research is connecting patterns of tropical cyclone urban tree damage across multiple spatial and temporal scales, following similar recommendations for research that have been made for rural habitats (e.g., López-Marrero et al., 2019; Lin et al., 2020; Heartsill-Scalley and López-Marrero, 2021). Some rural studies demonstrate how tree damage can be assessed at multiple scales by collecting tree level data across wide geographic areas (e.g., Xi et al., 2008) or by combining tree level observations with remote sensing data (e.g., Oswalt and Oswalt, 2008). Our review focused on studies that assessed damage at the scale of individual trees through the collection of ground-based data. However, many of the ecosystem services which are highly valued by municipalities, such as air pollution mitigation and stormwater management, scale with the extent of tree canopy (Nowak et al., 2008); more trees are needed to provide meaningful benefit quantities. Additionally, long-term tracking of tropical cyclone impacts is needed since most data studies focus data collection on the period immediately following the tropical cyclone. It is possible that tree condition may continue to deteriorate in the years following a storm (Walker, 1995), and that people may remove additional trees that are perceived to be potential hazards should another storm strike. Consequently, future urban tree tropical cyclone research would benefit from data collection at multiple scales to help us better connect factors that influence tree resistance to tropical cyclones and the ecosystem services the entire urban forest can provide.

Although wind resistance ratings for tree species were developed by Everham and Brokaw (1996), Bellingham et al. (1995), and Duryea et al. (2007a,b), these systems are limited to those species observed in wind damage studies and lack a method for applying ratings to species not included in their studies. For example, out of the 107 tree and palm species identified as preferred species for replanting the City of Tampa, Florida's urban forest, 44 of these species lack a wind resistance rating. There is a need for a more comprehensive and repeatable approach to classifying the tropical cyclone resistance of tree species, especially those that may rare or underutilized in urban landscapes.

4.3. Management implications

The results of this literature review highlight several aspects of trees and tropical cyclones that can be managed by arborists, urban foresters, planners, landscape architects, and other tree care professionals to increase the resiliency of urban forests. They fit into a broader suite of mitigation efforts such as emergency planning and education (Escobedo et al., 2020). Prior to tree planting, species selection, site assessment, and planting location selection can improve the wind resistance of urban forests. For trees already growing in the urban forest, risk assessment practices and pruning can help to identify and mitigate potential tree failure (Koeser et al., 2016).

Knowledge about the tropical cyclone resistance of different tree species can be used to inform both new tree plantings and risk assessments. Multiple urban and rural studies have observed differences in tropical cyclone resistance among species (e.g., Doyle et al., 1995; Francis, 2000), emphasizing the importance of considering tropical cyclone resistant species and traits in regions prone to such extreme weather. Resistant species can be prioritized for planting areas in high-risk locations within urban areas such as near streets or buildings. Granted, selecting species for particular traits can affect taxonomic tree diversity in urban forests (Jenerette et al., 2016), so care should be taken to utilize the full range of a city's potential tree species whenever possible in lower risk locations to support regional tree diversity (Ma et al., 2021). Additionally, many damage-prone species can nevertheless resprout or regenerate via seeds after a tropical cyclone (Boucher et al., 1994; Bellingham et al., 1995). Research from tropical and sub-tropical forests could inform the identification of species with resprouting capabilities that could be appropriate for naturalized urban areas (Zimmerman et al., 1994; Bellingham et al., 1995; Curran et al., 2008).

Managers can also use species tropical cyclone resistance ratings to identify trees within their municipal inventories that may be at higher risk for damage. Conducting regular risk assessments, particularly in areas where the consequences of tree failure would be greatest, can help to identify and mitigate potential damage caused by tree failure during tropical cyclones (Koeser et al., 2020; Nelson et al., 2022). During risk assessments, in addition to the identification of species, visual characteristics requiring attention include dead branches, other dead wood, decay, severe stem girdling roots, buried root flare, and wounds, all associated with tropical cyclone tree damage (Koeser et al., 2020; Nelson et al., 2022). While municipal forestry budgets can be limited and split among many management activities (Hauer and Peterson, 2016), species with low resistance to tropical cyclone damage can be prioritized for risk assessment (Pokorny et al., 2003).

Pruning low wind resistance trees identified by inventories and risk assessments can be part of a proactive approach to urban tree risk management (Pokorny et al., 2003). As described in the future research section, few observational studies of pruning and tropical cyclone damage have been conducted, although work from Florida by Duryea et al. (2007a) and Klein et al. (2020) suggests pruning can confer potential reductions in tropical cyclone-related tree failure. Observations about trees damaged in ice storms suggest that regular pruning contributed to the reduction of urban tree failure in Illinois (Hauer et al., 1993), while biomechanical studies suggest that pruning practices which reduce the leaf area of the crown reduce wind drag on trees (Kane, 2017). Other studies in less intense windstorms have not reported a reduction in tree failures associated with pruning (Luley et al., 2002; Kane, 2008), which suggests that the type and extent of pruning, tree species, and setting likely play important roles in the efficacy of pruning for reducing tropical cyclone damage.

The ability of other trees and buildings to serve as windbreaks and reduce tropical cyclone damage to trees is unclear from the literature as differing methodologies make it difficult to draw comparisons between urban studies (Duryea et al., 2007a; Wiersma et al., 2012; Landry et al., 2021; Nelson et al., 2022). Duryea et al. (2007a) is the only study to provide explicit recommendations of tree planting locations based on observational data. Their recommendations included planting trees in clusters (groups of five or more not in a row) and in larger soil volumes. In a study of windstorms in Minnesota, USA, Johnson et al. (2019) observed that after construction activities, root failure was less likely in urban street or boulevard trees within larger planting volumes, though this effect was not observed in trees not exposed to construction. Modeling tools that predict damage to trees based on simulations of windflow in urban terrain could be used to identify locations where trees can be more or less exposed to high winds, though these models require multiple data streams and are computationally intensive (e.g., Giachetti et al., 2021; Gu et al., 2021). Given the uncertainty about the potential role buildings and other trees play in serving as windbreaks, managers are probably better served to identify tree planting locations based on more well-established criteria such as available soil volume and above-ground space (Day et al., 2010) in addition to local knowledge and observations of previous tropical cyclone damage.

Similar to other urban forestry activities, knowledge of tree resistance to tropical cyclones must be paired with community support and funding to effectively incorporate tropical cyclone preparation into urban forest management programs (Hauer and Peterson, 2016). In Canada, Konijnendijk et al. (2021) observed that collaboration with emergency management departments was one characteristic that helped urban forest programs respond to short term disasters. They also found that up-to-date inventories and management plans also facilitated disaster response and recovery. Unfortunately, tropical cyclone damage to trees can be a major source of concern for community members and alter perceptions about the urban forest (Wyman et al., 2012). While it is critical to understand tropical cyclone impacts on urban trees, such knowledge can only effectively be applied by considering the broader social context of the urban forest.

4.4. Study limitations

While we aimed to be thorough in our scoping review, there are nevertheless some limitations with our approach. Limiting our studies based on the presence of statistical analysis means that we did not document qualitative observations of factors that could predict tropical cyclone wind resistance, which can provide useful insights and directions for future research. It is possible that some relevant data were missed through our exclusion of government and non-governmental organization (NGO) reports. Though our criteria to only include studies which performed a statistical analysis on the relationship between wind resistance factors and damage likely would have excluded many non-peer-reviewed reports. Our focus on ground-based measurements resulted in the exclusion of studies using aerial surveys and modeling. These are other valuable approaches for studying tropical cyclone damage to trees, however we chose to focus on a data collection method that best matches the ways many urban forests are currently inventoried and managed.

5. Conclusion

Tropical cyclones occur every year around the world. The intent of this paper was to identify factors associated with how trees respond to these storms, with a primary focus on urban locations. Understanding these factors and developing strategies is required to increase tree and forest resiliency to tropical cyclones, which is especially salient in the context of climate change both increasing the severity of tropical cyclones and being a source of other stressors such as drought on urban forests. The application of management strategies within an urban location is likely more straightforward by selecting tree species, designing planting locations with greater soil volume, encouraging tree planting in groups, and pruning trees. Regardless of location and management intensity, tree damage from a partial to whole tree failure leads to costs associated with response and recovery. Findings from this literature review also provide steps to prevent, mitigate, and prepare for these intense storms. For example, while not a primary focus of this paper, after a tropical storm occurs, a response and recovery phase is required to immediately implement actions that return a built environment to pre-storm conditions. This literature review identified several predictors of tree resistance to winds during a tropical storm that can be used to mitigate future tree damage through the management strategies we identified. Future research directions are provided to fill the gaps identified through this study and provide a basis for data collection using a standardized methodology.

Author contributions

ABS: conceptualization, methodology, formal analysis, investigation, data curation, writing - original draft, writing - review and editing, visualization, supervision, project administration. AKK: conceptualization, methodology, investigation, writing - original draft, writing - review and editing, supervision, project administration, funding acquisition. RJH: conceptualization, methodology, investigation, data curation, writing - original draft, writing - review and editing, supervision, project administration. MA: conceptualization, funding acquisition. YC: investigation, writing - review and editing. ZF: investigation. JWM: writing - review and editing. AHM: investigation, writing - review and editing. CK: investigation, writing - review and editing. RHN: investigation. CAR - Investigation, writing - review and editing. SS: investigation, writing - review and editing. HT: investigation. BW: investigation, resources.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/ffgc.2023.1168495/full#supplementary-material

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