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Review

Unearthing Current Knowledge Gaps in Our Understanding of Tree Stability: Review and Bibliometric Analysis

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Abstract: Forest preservation and management are paramount for sustainable mitigation of climate change, timber production, and the economy. However, the potential of trees and forests to provide these benefits to the ecosystem is hampered by natural phenomena such as windthrow and anthropogenic activities. The aim of the current research was to undertake a critical thematic review (from 1983 to 2023) informed by a bibliometric analysis of existing literature on tree stability. The results revealed an increase in tree stability research between 2019 and 2022, with the USA, France, and Italy leading in research output, while Scotland and England notably demonstrated high research influence despite fewer publications. A keyword analysis showed that tree stability can be divided into four themes: tree species, architecture, anchorage, and environmental factors. Prominent studies on tree stability have focused on root anchorage. However, more recently, there has been a growing emphasis on urban forestry and disease-induced tree damage, underscoring a shift towards climate change and diversity research. It was concluded that considerable knowledge gaps still exist; that greater geographic diversification of research is needed and should include tropical and sub-tropical regions; that research relating to a wider range of soil types (and textures) should be conducted; and that a greater emphasis on large-scale physical modelling is required. Data and knowledge produced from these areas will improve our collective understanding of tree stability and therefore help decision makers and practitioners manage forestry resources in a more sustainable way into the future.

Keywords: forest; tree architecture; anchorage; soil; models

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Citation: Ekeoma, E.C.; Sterling, M.; Metje, N.; Spink, J.; Farrelly, N.; Fenton, O. Unearthing Current Knowledge Gaps in Our Understanding of Tree Stability: Review and Bibliometric Analysis. *Forests* **2024**, *15*, 513. https://doi.org/10.3390/f15030513

Academic Editor: Francisco Bruno Navarro Reyes

Received: 27 January 2024
Revised: 4 March 2024
Accepted: 5 March 2024
Published: 9 March 2024

1. Introduction

Trees contribute positively to the environment by reducing air pollution [1], soil conservation and protection against erosion [2], water regulation [3], and carbon (C) sequestration [4]. With respect to C sequestration, between 1990 and 2005, European forests annually absorbed ~100 tera-grams of C, which is equivalent to ~10% of the European fossil-fuel emissions during this period [5]. Hence, forest preservation and management are paramount for sustainable mitigation of climate change, timber production, and the economy. However, the potential of trees and forests to provide these benefits to the ecosystem is hampered by natural phenomena (e.g., windthrow, debris flow, and soil liquefaction) and anthropogenic activities (e.g., deforestation and poor forest management). For instance, over 50% of all forest damage in Europe is caused by extreme wind events [6] that are classified as catastrophic or endemic [7]. Catastrophic windthrow occurs due to storms of extreme intensity (e.g., maximum gust speeds > 22 m s^{-1}) [8], while endemic windthrow tends to be observed in some countries every year [7]. Savill [9] noted that endemic windthrow has the tendency to spread rapidly, which can limit the management options available to foresters and ultimately result in the clearcutting of the affected area. The failure of trees due to catastrophic winds can lead to considerable financial losses, infrastructure damage, major injuries, and fatalities in a small number of cases. Figure 1A shows the volume of timber damaged due to some selected major windstorms that occurred across Europe from 1990 to 2018. The Lothar and Martin storm which impacted Europe in 1999 resulted in the largest timber losses (240 million m^3) [8], equivalent to 95.4% and 43.0% of the annual harvest of the most affected countries and Europe, respectively (Figure 1B,C), and the death of ~137 people [10]. From 1995 to 2007, there were a total of 407 fatalities attributed to wind-related tree failure in the United States of America (USA) [11].

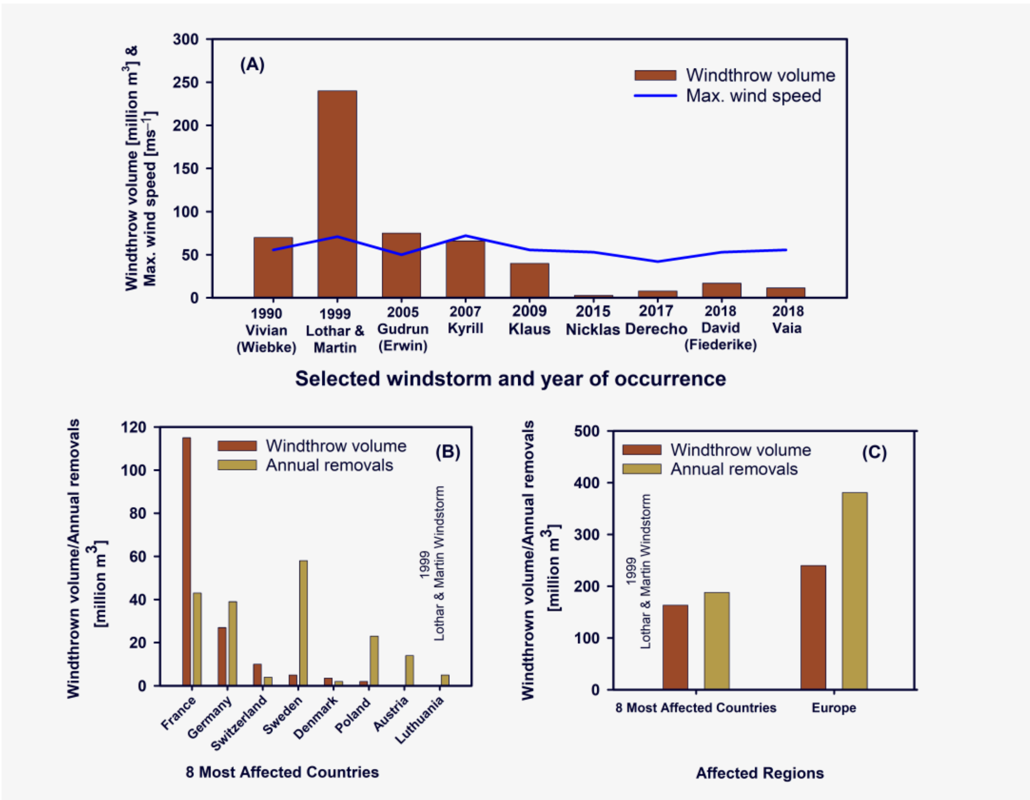

Figure 1. Volume of timber loss due to severe windstorms. (**A**): The timber loss from selected European windstorms [12–15]. (**B**): Comparison of the timber loss due to the 1999 Lothar and Martin windstorm with the 1998 annual timber removal in the countries most affected by the storm. (**C**): Comparison of the effects of the 1999 Lothar and Martin windstorm in the 8 most affected countries with the combined effect in Europe [8,16].

Globally, due to the heightened importance of trees to the global ecosystem especially with a changing climate, studies on the stability of trees are beginning to gain more relevance [17–19]. Although the tree failure mechanism has been widely researched, predicting tree failure is challenging due to the variability in tree characteristics, which depend on factors such as species [20], tree architecture and biomechanics [21,22], age [23], climate [24], soil characteristics [25,26], pests or diseases, and silvicultural practices [27]. These different factors make it a challenge to precisely predict when, and under what circumstances, trees blow over. To address knowledge gaps related to the determination of tree stability, several research approaches have been developed. These include tree-pulling tests [28,29], real-time monitoring of trees using advanced sensor technologies, and the use of advanced mechanistic [30] and statistical models [31]. Biomechanical testing of trees is mainly destructive and is challenging due to measurement precision and species variability [28]. Hence, there is no universally applicable testing protocol. Also, real-time monitoring requires a substantial investment, and most of the models are largely sensitive to geographical locations [31]. Hence, to enhance our understanding of tree stability and prediction accuracy, a holistic interdisciplinary approach may be more appropriate.

Forests are a key part of national climate mitigation strategies, and tree planting is a major part of government strategies to reduce carbon; as such, there has been an increase in the incentive to encourage tree planting across the globe. For example, the European Union biodiversity strategy includes planting three billion trees by 2030 [32], whilst the USA plans to plant over a billion trees in the next decade [33]. To effectively increase forest coverage, it is imperative to ensure that these forests are managed sustainably and safeguarded against heightened disturbances. Protection of forests from windblow necessitates a comprehensive understanding of the factors influencing tree stability and information that can be used to assess the level of risk to existing forests, which can be assisted by the development of predictive models that can be used to minimise the risk of windthrow or understand the factors that may influence its occurrence. Many studies have examined the factors associated with windthrow and tree stability [25,34–36]; however, an up-to-date bibliometric analysis on the subject is lacking. Global climate change projections indicate a probable rise in the frequency of winter storms, which is expected to lead to increased occurrences of wind-induced tree failure in forest plantations. Considering the importance of forest expansion and its contribution to climate change goals, it is an appropriate time to undertake a systematic review of the literature on the subject. To obtain an unbiased view (or at least to ensure that the degree of bias is minimised), a bibliometric analysis has been used to inform this review.

A bibliometric analysis is a quantitative and qualitative assessment of various aspects of scholarly publications in which to assess their citation frequencies, quality and impact, authors/institutional collaborations [37], and the degree of interaction between different elements of research questions. The visual presentation of this information is key for the rapid assessment and identification of the strength, present state, and research gaps in different research domains [38]. Recently, bibliometric analysis has been used to review forest C sequestration [39], and forest genetics [40] within the forestry research area.

The aim of the current research was to undertake a critical thematic review of tree stability informed by a bibliometric analysis of existing literature. Related to this aim were four objectives: (i) to provide a comprehensive understanding of the existing state of knowledge on tree stability, (ii) to identify the most influential articles, authors, and journals in this field, (iii) to examine thematic evolution of literature over time, and (iv) to identify the emerging trends and probable directions for future studies. This paper is organised as follows: Section 2 outlines the approach used to obtain the relevant data and briefly discusses the software used in the bibliometric analysis, whilst Section 3 contains the results and visualisation of the bibliometric analysis including the identification of the key themes. Section 4 presents a critical discussion of the emerging themes. Finally, Section 5 summarises the main findings and restates the areas where additional research is required.

2. Method

2.1. Data Collection

A structured literature review and bibliometric analysis were performed following the stepwise approach shown in Figure 2 as recommended by Zupic and Cater [41]. The Web of Science Core Collection (WoSCC) database was initially used to obtain articles/research papers relevant to the study. The WoSCC database was chosen due to its comprehensive coverage, meticulous indexing, and inclusion of high-quality, peer reviewed scholarly publications. It is noted that this particular database has been used successfully for other aspects of forestry research [39].

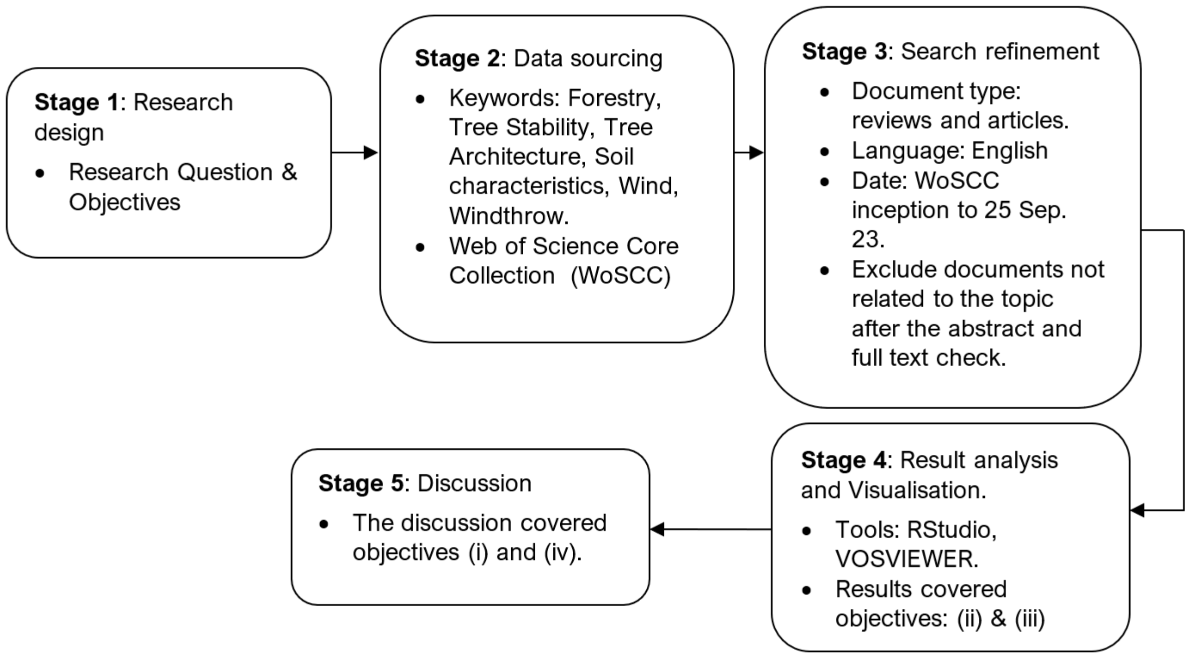

Figure 2. Methodological framework used during the literature review and bibliometric analysis (WOSCC stands for Web of Science Core Collection; VOSVIEWER and RStudio are software packages used for visualisation of the bibliometric data).

In order to undertake the bibliometric analysis, keywords were required to define the search. The keywords chosen for the current purpose were assembled in the following search string: ("Tree Stability" OR "Tree Failure" AND Tree Architecture) OR ("Tree Stability" OR "Tree Failure" AND Soil Characteristics) OR ("Tree Stability" OR "Tree Failure" AND Silvicultural Practices) OR (Modelling "Tree Stability") OR ("Tree Stability" OR "Tree Failure" AND Winds) OR ("Tree Stability" OR "Tree Failure" AND Forestry) OR ("Tree Stability" AND Windthrow).

To refine the search results, the document type was set to "reviews" and "articles", and the language was limited to English to ensure the comprehensibility of the retrieved articles. However, there was no restriction on the date of the publication, as the search included articles from the inception of WoSCC (1900) to 25 September 2023. It is acknowledged that a degree of bias is introduced when specifying the search string and refining the results. Whilst this is inevitable, the above search string was considered to be sufficiently broad to capture a variety of outputs across several research fields, whilst also sufficiently focused to fulfil the aim of the research. Put simply, had these steps not been undertaken, then it would have proved impossible to effectively use bibliometric analysis.

The initial search yielded 317 publications. However, only articles that discussed tree stability (irrespective of the methods or scope) were included in the study. Hence, after a detailed review of the title and abstracts, 2 duplicates and 59 publications were removed because they were not related to the field of study. Following a detailed review of all the papers, a further 22 articles were removed because they were not related to tree stability and, hence, were deemed to be inappropriate for the current study. Thus, 234 articles published between 1983 and 2023 formed the basis of the current research and were exported in plain text format to enable a detailed bibliometric analysis.

2.2. Analysis and Visualisation

A bibliometric analysis primarily relies on two factors, i.e., the number of scientific productions (which serves as an indicator of research productivity) and their received citations (which is used as a proxy for their scientific significance) [42]. Whilst these two factors form a core approach, it is appreciated that the quality of a publication cannot be simply reduced to a handful of metrics. Thus, the current research adopted a comprehensive approach, encompassing both bibliometric analysis and an in-depth exploration of thematic trends.

The bibliometric analysis was performed using the Biblioshiny app in Rstudio (Version 4.3.1, Posit PBC, Naples, Italy) [43] and VOSviewer (Version 1.6.18, Leiden, The Netherlands) [44]. VOSviewer and Biblioshiny are both web-based applications and easily accessible. They visualise and analyse bibliometric data, facilitating the exploration of research networks, identifying key trends, and gaining insights into the relationships between authors, keywords, and publications in any given field of study [44]. Previous studies have shown that network plots can examine collaborative relationships among researchers [45,46]. Consequently, in this study, the VOSviewer application was used to generate the visual representation of networks depicting the interconnections between authors, keywords, and citations. The nodes in these networks represent authors, keywords, or publications, while the links signify collaborative ties, co-occurrences of the keywords, or citation relationships [44].

To gain a holistic understanding of both the impact and distribution of research in this field, we used Biblioshiny to conduct an in-depth analysis of the influence of leading research journals through a combination of source impact assessment and Bradford's law [47]. The source impact was evaluated using various indices, including the h-index (which considers the number of publications and citations), the g-index (emphasising highly cited publications), total citations (for overall impact assessment), number of publications (for productivity evaluation), and publication starting year (for assessing longevity in the field) [48]. These indices collectively provide a comprehensive evaluation of a source's impact, considering both the quality and quantity of their work overtime. As noted, Bradford's law was used to elucidate the distribution pattern of the articles across the journals [47]. This law emphasises that a small number of sources in a particular field are responsible for the majority of published literature, while the rest of the published literature is distributed across numerous sources, each contributing only a few articles. Here, the journals are classified into three zones in the following proportion $1:n:n^2$, where 'n' is the number of publications. Zone 1 represents the sources with the most significant contributions to the field, Zone 2 comprises a broader set of journals with moderate impact, and Zone 3 encompasses the majority of journals with relatively fewer published articles [47]. Biblioshiny was also used to obtain the general statistical data and perform a thematic evolution analysis and three-field analysis, which show the interconnection between the journals, keywords, and countries [43]. The key themes obtained from the bibliometric analysis are discussed below, and research gaps are identified.

3. Results

3.1. Descriptive Statistics

Figure 3 shows the variations in annual publications and total citations between 1983 and 2023. Whilst the number of annual publications does not appear to follow a defined pattern, it is observed that there is a gradual increase in the annual citations. A notable increase in both metrics occurred between 2019 and 2022, indicating a period of heightened research activity and impact.

Table 1 highlights the top 10 countries with the most research output and citations. The USA, France, and Italy are the top three contributors in terms of research output with 43, 23, and 21 publications, respectively. However, the number of publications alone does not necessarily indicate the quality or influence of the research. Citations play a crucial role in assessing the impact and significance of research [48]. For example, France and Scotland demonstrated that even with fewer publications, their work can have a substantial influence on the academic community. In terms of citations, Europe accounted for more than 70% of the research (Table 1). Aside from the presence of renowned research institutions across Europe, there have been several windstorms (up to 130) in Europe since 1950 which may have affected the number of publications [49].

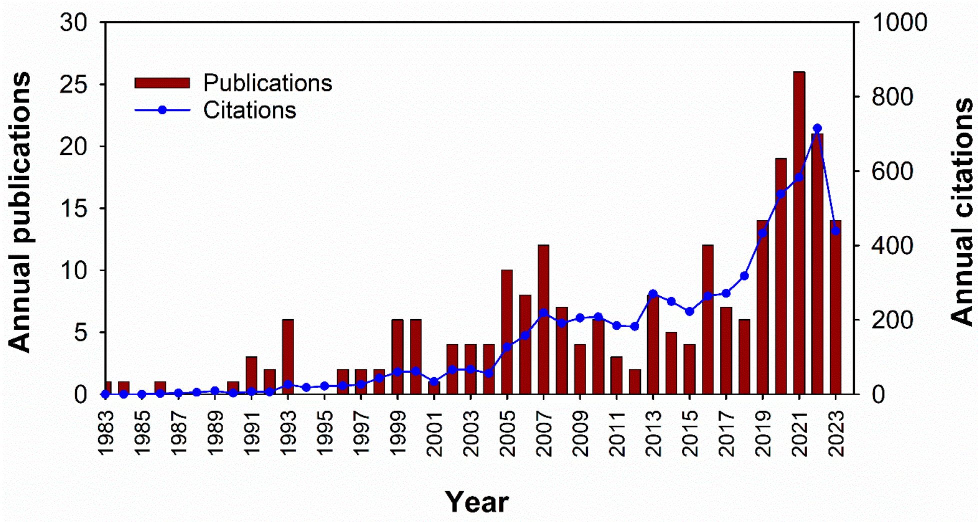

Figure 3. The trend of annual publication and citations in tree stability research.

Table 1. Top 10 most prolific countries in tree stability research ranked by their publications. The number of citations and the ratio of citations to publications are included to aid in understanding the influence of the publications.

Country	Publications	Citations	Citation/Publications
USA	43	792	18.4
France	23	1474	64.1
Italy	21	260	12.4
China	19	236	12.4
Scotland	17	1273	74.9
Singapore	14	115	8.2
Canada	13	254	19.5
England	11	744	67.6
Czech Republic	11	40	3.6
Germany	10	165	16.5

Table 2 shows the organisations with the highest research output in tree stability. In contrast to Table 1, institutions from Scotland, England, Canada, and Germany do not make the list, suggesting that none of the institutions from these countries had up to six publications in this area. The list is dominated by institutions in the USA (the University of Massachusetts and the University of Florida), France (INRAE and the University of Bordeaux), and Singapore (Nanyang Technology University and National PK Board). Interestingly, despite Finland and Latvia not ranking among the top 10 countries, their institutions have secured spots in the top 10 for tree stability research. The leading 10 affiliations contributed 90 articles, which constituted ~38% of the entire publication count (234) and ~62% of the overall citations (9177).

Table 2. Top 10 most prolific institutions in tree stability research ranked based on the number of publications, country, and number of citations.

Institutions	Country	Publications	Citations
University Massachusetts	USA	14	181
National Research Institute for Agriculture, Food, and the Environment (INRAE)	France	12	1031
Nanyang Technology University (NTU)	Singapore	12	107
National PK Board	Singapore	11	99
University Bordeaux 1	France	10	623
University Florida	USA	9	63
Mendel University Brno	Czech Republic	7	16
University Joensuu	Finland	7	216
Latvian State Forest Research Institute (SILAVA)	Latvia	6	164
University of Georgia	USA	5	92

3.2. Most Influential Sources

Table 3 illustrates the journals where most of the related research has been published and illustrates the large range of journals that publish research on this topic. However, Table 4 shows that most of the articles appear in four journals, namely, Forest Ecology and Management (EISSN: 1872-7042), Forests (EISSN 1999-4907), Urban Forest & Urban Greening (EISSN 1618-8667), and Forestry (EISSN 1464-3626), which emerge as core sources (Zone 1; Table 4). These journals represent less than 5% of the total journals based on WOS but contain over 34% of the published articles in this field (Table 4). In contrast, journals in Zone 2 and Zone 3 represent 21% and 75%, respectively, of the total journals, but each contain 33% of the articles. This observation underscores the impact of the aforementioned journals in shaping research discourse within this domain.

Table 3. Top 10 prolific journals in tree stability research ranked based on their number of publications (NP). The impact of the publications was assessed using the following factors: h-index, g-index, total citations (TC), and publication starting year (PY start).

Source	NP	h-Index	g-Index	TC	Rank	PY Start
Forest Ecology and Management	22	14	22	610	1	1992
Forests	22	6	9	109	2	2014
Urban Forestry & Urban Greening	21	8	13	197	3	2009
Forestry	15	11	15	819	4	1986
Plant and Soil	11	11	11	884	5	1983
Trees Structure and Function	10	8	10	256	6	1990
Canadian Journal of Forest Research-Revue Canadienne De Recherche Forestiere	8	8	8	207	7	1993
Journal of Experiment Botany	6	6	6	379	8	1991
American Journal of Botany	4	4	4	373	9	2002
Tree Physiology	4	4	4	405	10	1996

Table 4. Zone-wise categorisation of the journals following Bradford's law.

Zone	Number of Journals (92)	Journal Percentage (%)	Total Articles (234)	Article Percentage (%)
Zone 1	4	4.3	80	34.2
Zone 2	19	20.7	77	32.9
Zone 3	69	75	77	32.9

3.3. Most Influential Articles

The most influential articles on tree stability were identified through citation analysis. The citation index is an indicator of the impact of a research paper within a domain [50]. It helps track the evolution of key ideas and technologies, which ultimately drives advancements in the field. The five most cited articles in the tree stability-related literature are presented in Table 5 and shown visually in Figure 4. Four out of five of the most cited publications belong to a single cluster (i.e., Coutts [28], Gardiner et al. [35], Nicoll and Ray [51], and Coutts [52]) and all align with the red cluster in Figure 4. These studies mainly evaluated the impact of anchorage on tree stability. The review by Gardiner et al. [35] has the largest number of citations per year compared to the other studies. This could be attributed to its comprehensive synthesis of existing knowledge in the field (at the time of publication), serving as a valuable reference for researchers and thus continually contributing to the discourse on tree stability. Cluster 2 (Green) contains articles that mainly focused on wind damage in forest ecosystems. Research within this cluster includes the resistance of trees to overturning in various conditions [53], the effects of species and size on stability [54], and the dynamics of tree failure during wind events. Cluster 3 (Blue) contains papers that centred around tree stability and risk assessment. Articles in this cluster are associated with assessing and predicting tree stability within forest stands. Topics include modelling windthrow risk [55,56], the impact of silvicultural practices on tree stability [27] and the use of machine learning and decision support systems to evaluate and manage tree hazards in both forested and urban environments [57]. Finally, Cluster 4 (Yellow) contains articles that focus on the dynamic behaviour and mechanical properties of trees. It includes studies on tree swaying and dynamic amplification [58,59], natural frequencies of trees [60], and the effect of various factors, such as pruning and splits, on tree behaviour. Research in this cluster aims to understand the physical characteristics that contribute to tree stability and resilience to wind and other dynamic loads.

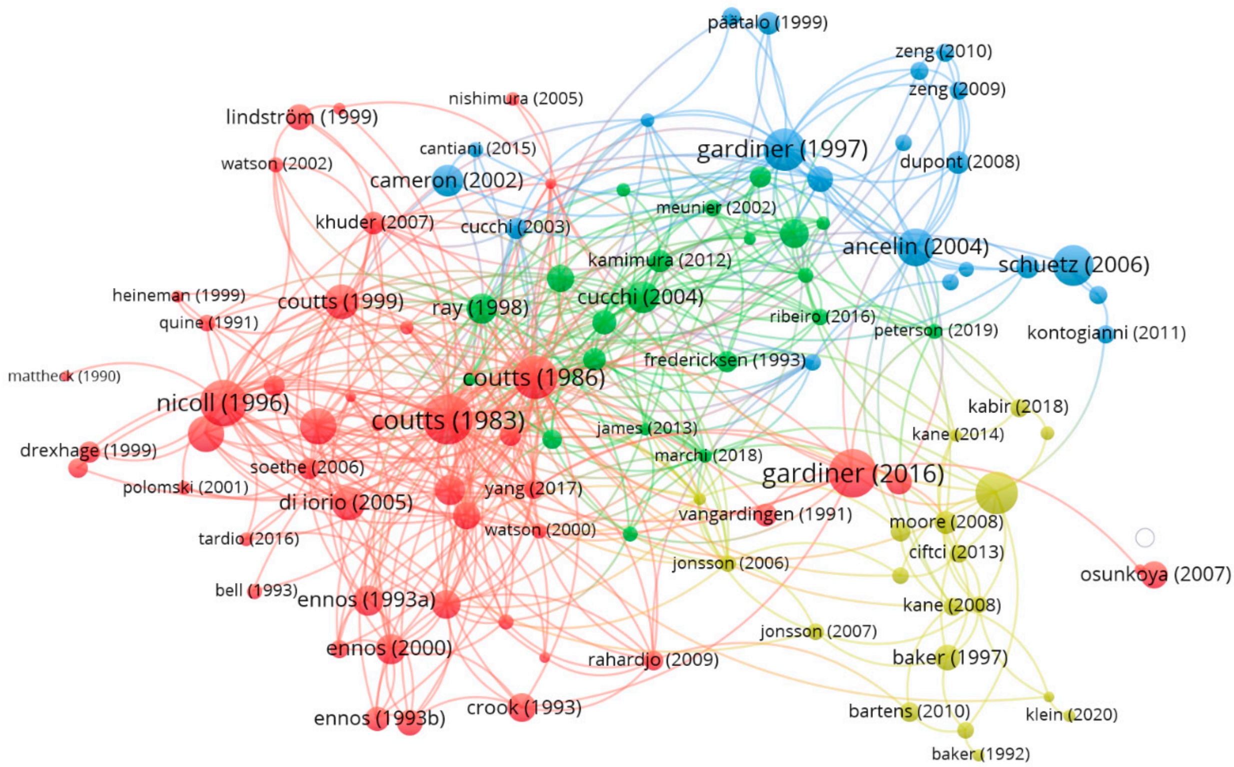

Figure 4. Citation analysis map showing the interrelationship between papers focused around four main themes. Articles with a minimum of 10 citations are included in the network. Also, the nodes are based on the strength of the citations, while the links represent the relationship between articles. (Red [19,21,23,28,35,51,52,62–78], Green [10,26,79–84], Blue [27,56,85–92], and Yellow [58–60,93–99] examined root systems and tree stability, wind damage and forest ecosystem, tree stability assessment and forest management, and tree dynamics and mechanical properties, respectively).

Table 5. Top five most cited articles in tree stability research. Abbreviation used: TC = total citations, C/Y = citations per year.

Author(s)	Title	Source	Year	TC	C/Y
Coutts [28]	Root architecture and tree stability	Plant and Soil	1983	275	6.9
Gardiner et al. [35]	Review: Wind impact on plant growth, mechanics, and damage	Plant Science	2016	256	36.4
Nicoll and Ray [51]	Adaptive growth of tree root systems in response to wind action and site conditions	Tree Physiology	1996	240	8.9
Coutts [52]	Components of tree stability in Sitka	Forestry	1986	201	5.4
Gardiner et al. [61]	Field and wind tunnel assessments of the implications of respacing and thinning for tree stability	Forestry	1997	189	7.3

3.4. Co-Authorship Analysis—Country

Figure 5 highlights the international collaborations among authors. The nodes show the strength of the links each country has with the others. The clusters represent countries with more collaborations among themselves. Overall, the USA, China, England, Spain, and France are the top five countries with international co-authors. Only authors from 10 out of the 52 countries represented in this study had no co-authors from other countries. These countries are mostly classified as developing countries (Brunei, Costa Rica, Indonesia, Malaysia, Thailand, and Turkey) [100], apart from Hungary, Russia, Poland, and Slovakia. The low international collaboration could be attributed to low funding, language barriers, and low research outputs.

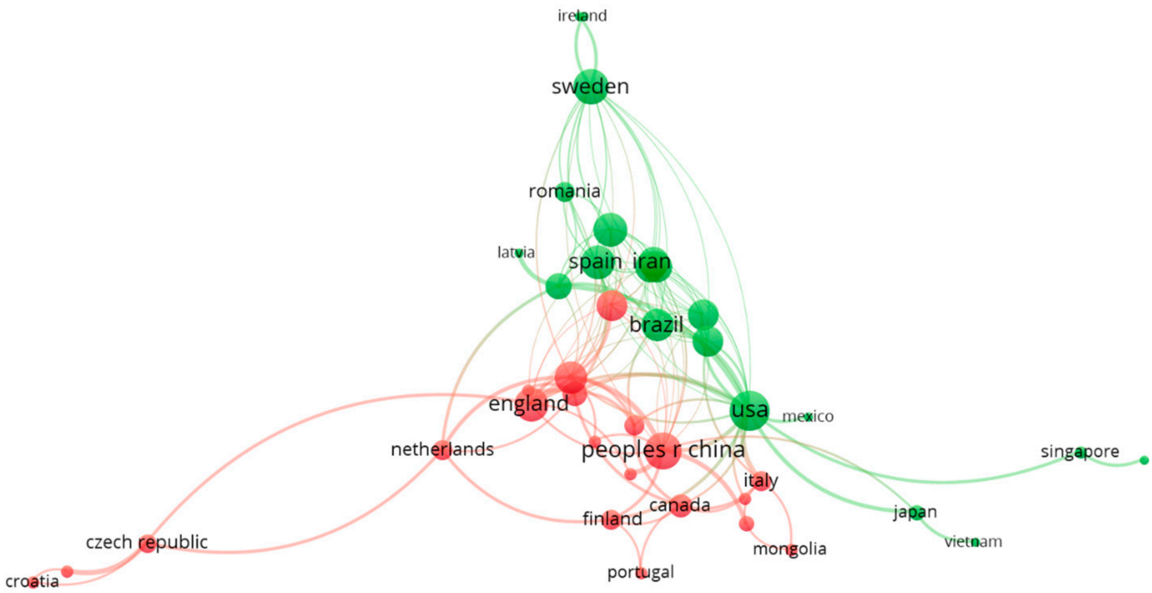

Figure 5. Co-authorship by country. Nodes represent the strength of links the countries have, while the green and red colours represent clusters of countries with more collaborations among themselves. Only countries with a minimum of 5 articles were included in the network.

3.5. Co-Citations Analysis

Co-citation is a bibliometric concept that refers to the occurrence of two or more publications being cited together by a third document [101]. Co-citation analysis of references is a valuable tool for understanding the structure and development of a research domain [102]. This shows the similarities between the research topics of different authors who may not be actively collaborating [103]. The nodes correspond to the strength of the co-citation connections, while the multiple lines extending from each node indicate how frequently the authors are co-cited. The co-citation analysis showed two distinct clusters (green and red) (Figure 6). The first cluster consisted of pioneering studies on tree anchorage (e.g., Coutts, [28,52], Crook and Ennos [29], and Fraser et al. [104]). To understand tree anchorage, most of these studies performed tree-pulling tests (e.g., Crook and Ennos [29] and Nicoll and Ray [51]), although a small number relate to numerical modelling (e.g., Dupuy et al. [105,106] and Fourcaud et al. [17]) to generate the empirical relationships between tree morphology, root anchorage, and tree stability. The second cluster (green) consisted of pioneering studies focused on wind risk modelling (e.g., Petty and Worrell [107], Petty and Swain [108], and Gardiner et al. [61]). While some of the studies performed wind tunnel experiments [61,107], others developed mechanistic models (e.g., GALES and HWIND) to predict tree failure using empirical data from tree-pulling experiments or climate data [109] or using a static approach [85].

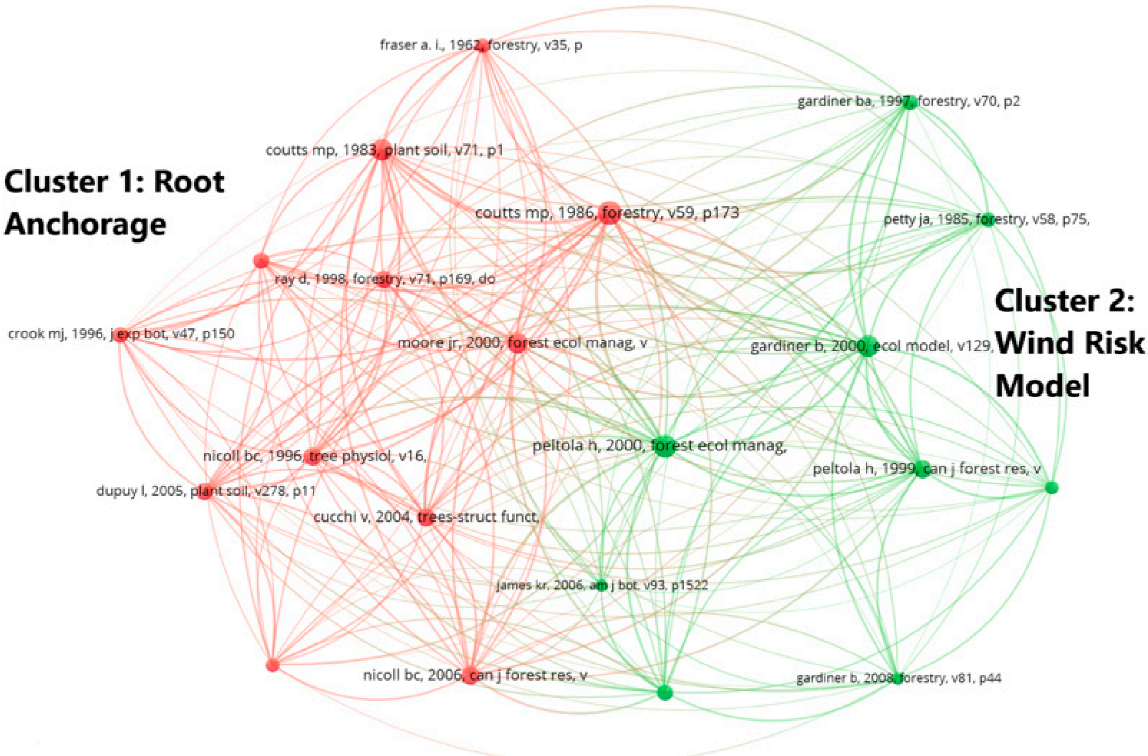

Figure 6. Co-citation analysis network with 10+ keywords per cluster (keywords occur a minimum of 5 times). The distinct clusters were identified as follows: Cluster 1 (root anchorage) represented with red nodes and links [28,29,51,52,79,80,104,106,110,111] and Cluster 2 (wind risk model) represented with green nodes and links [30,61,108,109,112–114].

3.6. Research Themes

Keyword co-occurrence analysis was conducted on selected papers to identify the most used terms, facilitating the identification of key themes (Figure 7). Only keywords which occurred at least five times were included in the network. The nodes represent the keywords, and their proximity reflects their relatedness [115]. To determine the key themes, resolution of the keyword clusters was set as a minimum of 10 words per cluster in VOSviewer, and the strength of the links was normalised using the fractionalisation method [44]. Following this, two distinct clusters were identified (Figure 7). The first cluster (red) contained 57 keywords that mainly focussed on factors controlling tree stability (e.g., root anchorage, tree morphology, soil properties, and wind), tree response to wind (growth pattern), and models for predicting tree stability. The first cluster also mainly focussed on rural trees, with Sitka spruce, Norway spruce, Scot pine, Picea sitchensis, lodgepole pine, and Douglas-fir being the common tree species in this cluster. However, the second cluster (green) containing 21 keywords mainly focussed on urban forestry with sub-themes such as tree damage (decay) due to disease and tree risk assessment. The chronology overlay of the co-occurrence highlights the evolution of the keywords (Figure 8). Figure 8 shows that recently, research efforts have been focused on urban forestry and tree failure due to decay (disease) [116]. Climate change and diversity are two sub-themes driving recent studies on the stability of rural forests [117,118].

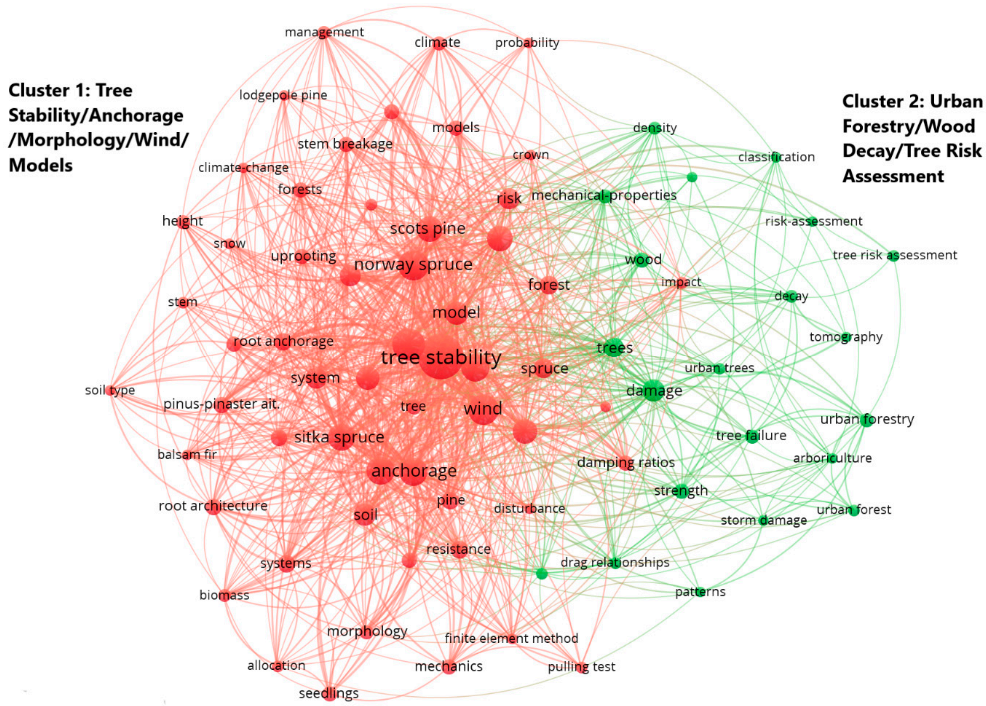

Figure 7. Network illustrating keyword co-occurrences between 1983 and 2023. The red lines and nodes represent the first cluster, which focuses on tree stability/anchorage/morphology/wind/models, while the green lines and nodes represent the second cluster, which focuses on urban forestry/wood decay/tree risk assessment.

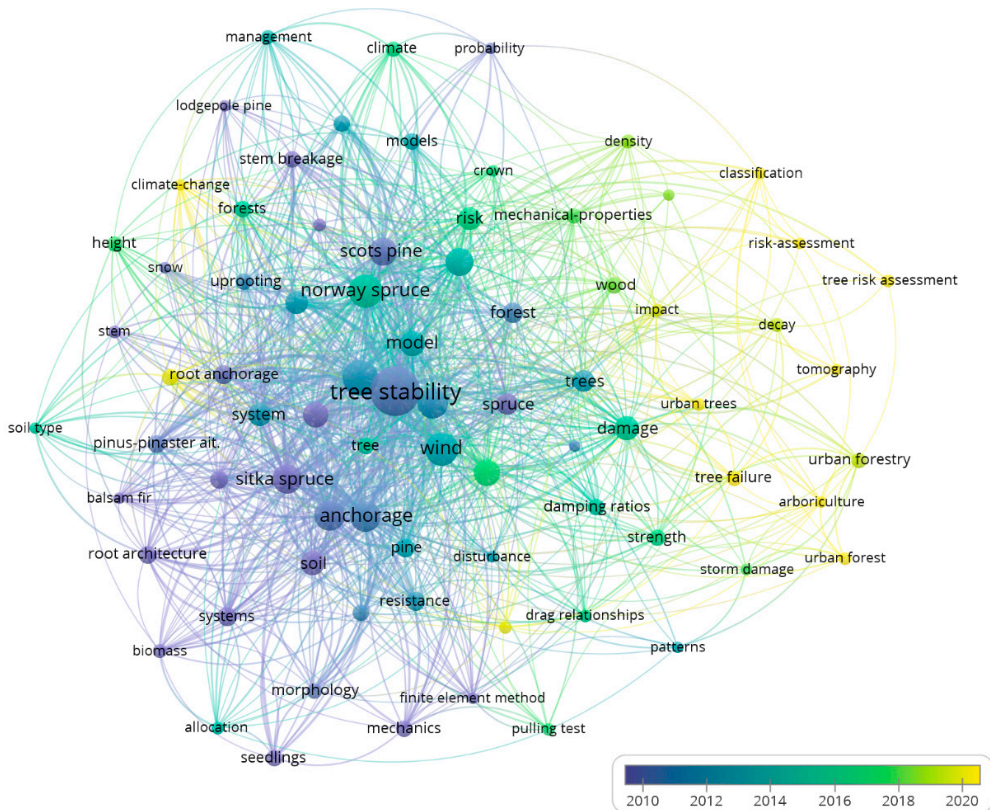

Figure 8. Clustering of publications using keyword co-occurrence by year of publication. The different colours and legend show the yearly evolution of the keywords.

4. Discussion

4.1. Implications of Bibliometric Analysis

The results of the bibliometric analysis provide information on publication trends, influential sources, international collaborations, co-citations, and research themes. Such combined information gives a clearer picture of global research trends pertaining to tree anchorage over time. For example, a notable surge in both annual publications and citations occurred between 2019 and 2022 (Figure 1). This could be attributed to growing concerns about the impact of climate change and extreme weather events on tree stability. However, the overall number of publications remained relatively low, averaging less than 30 per year (with the proviso that the search was limited to papers published in English). Presently, about 20% of the countries with at least one publication in tree stability do not have international co-authors. The USA, China, England, Spain, and France are the top nations with international co-authors. Strengthening international partnerships can contribute to a more holistic and inclusive approach, accelerating advancements in tree stability research to address the challenges posed by climate change. The most influential articles were focused on root anchorage, while most of the prolific institutions in terms of research output and citations were from the USA, France, and Singapore. Forest Ecology and Management, Forests, Urban Forestry & Urban Greening, Forestry, and Plant and Soil are the top journals in the field, with over 36% of published articles. Recent research efforts have been directed towards urban forestry, tree failure due to decay, climate change, and biodiversity, indicating the evolving landscape of tree stability research. These results show the intellectual structure of tree stability research and can serve as valuable guidance for researchers in strategizing their future studies and collaborations.

4.2. Review on Tree Stability

This section reviews the established knowledge gaps influencing tree stability, as highlighted in Figure 8 (Cluster 1). To provide a structured understanding of these factors, the keywords (57) within Cluster 1 were grouped into five overarching themes: tree species, architecture, anchorage, models, and environmental factors (Figure 9). All the themes also appeared as keywords except for "tree species" and "environmental factors". Each theme encompasses a set of keywords that shed light on the diverse elements contributing to tree stability. The number of times the keywords occur is represented in brackets (Figure 9). The first theme explores the role of tree species and how their distinct characteristics impact their resilience to windthrow. The theme 'Architecture' discusses how elements such as tree height, diameter at breast height (DBH), crown characteristics, and spacing affect tree stability. The 'Anchorage' theme discusses the significance of root systems and their architecture on the stability of trees. The theme 'Model' focuses on the various models (i.e., numerical, mechanistic, and advanced statistical) used to predict tree stability and their applicability in various environmental contexts. Finally, the 'Environmental Factors' theme discusses environmental factors controlling tree stability (e.g., windstorm, climate change, and soil properties). The identified themes (species, architecture, anchorage, models, and environmental factors) were further grouped into two key sections, namely, Factors Controlling Tree Stability, which contains species, architecture, anchorage, and environmental factors, and Predicting Tree Stability, which contains numerical, mechanistic, and statistical models.

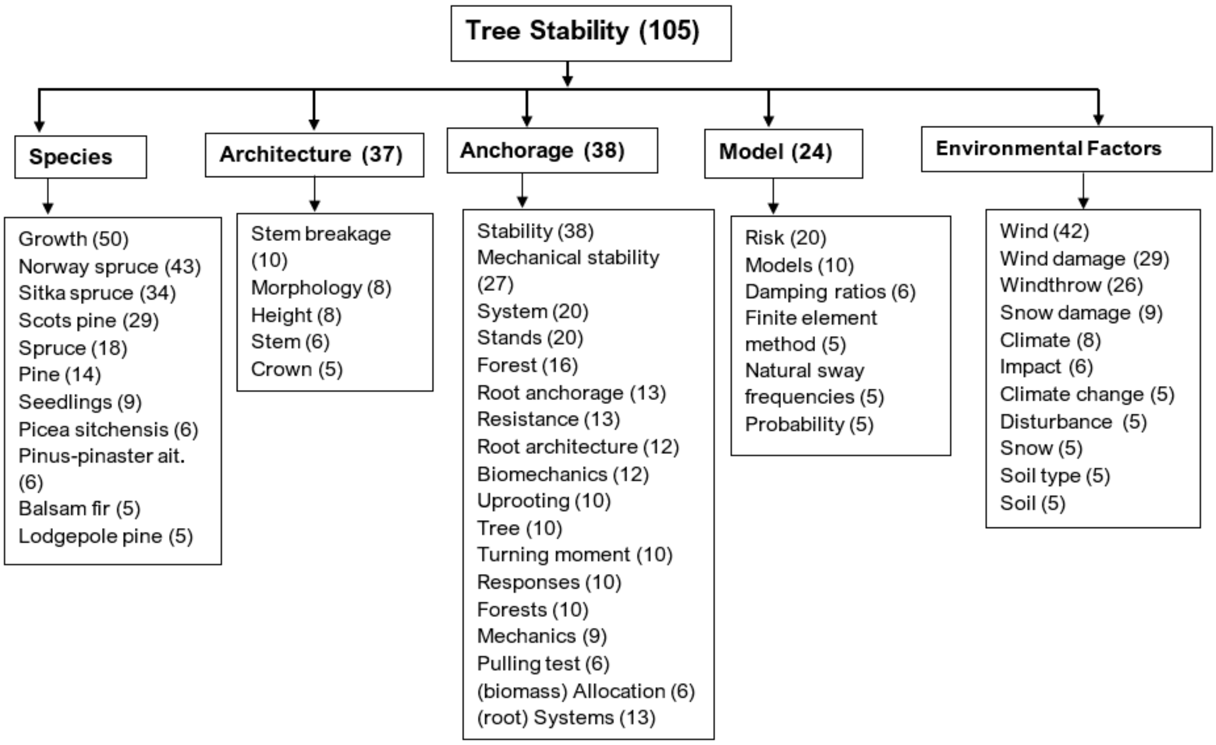

Figure 9. Grouping of the keywords into themes with the occurrence count in brackets. The themes of species and environmental factors did not appear as keywords in the occurrence analysis but served as representative themes for the keywords.

4.3. Factors Controlling Tree Stability

4.3.1. Tree Species

The type of tree species can significantly influence their susceptibility to windthrow [119]. However, there is a dearth of studies that have compared the susceptibility of different tree species to windthrow. The keyword analysis (Figure 9) showed that most of the tree species examined are conifers, e.g., Norway spruce, Sitka spruce, Scots pine, Picea sitchensis, Pinus pinaster, Balsam fir, and Lodgepole pine. This suggests that conifers are less stable compared to broadleaves. The keyword Norway spruce appeared 43 times, suggesting that this species was studied more and is potentially less stable than other species. However, this may also be a reflection of the fact that Norway spruce is one of the most important species in European forests. Conifers (gymnosperms) are characterised by needle-like or scale-like leaves and bear cones, whereas broadleaves (hardwood), have broad, flat leaves, and typically have wider trunks and more extensive roots systems [120], which could make them less susceptible to windthrow. However, this is often complicated by other considerations such as the location where the trees are planted since specific species are typically chosen for planting in areas that are more exposed and have poorer soil conditions for root development [8]. Again, coniferous forests often has denser canopies and retain their foliage year-round, which increases the drag and likelihood of windthrow especially in winter when broadleaved species are leafless [121].

4.3.2. Architecture: Morphology, Tree Height, Diameter, and Crown Characteristics

The diameter at breast height (DBH) [122], crown characteristics [93], and spacing contribute significantly to tree stability. For example, mechanistic models for predicting tree stability have established that both resistance to stem breakage and tree uprooting are directly proportional to DBH^3 [30,55,112]. This implies that the larger the tree is (the greater the value of DBH since this parameter is also related to tree age, which is in turn related to tree height), the greater the resistance to stem and root failure. However, taller trees tend to have a lower critical wind speed for windthrow compared to shorter trees [123]. This is because they have lower natural frequency compared to shorter trees [58,60]. Hence, the forest stand can become more prone to damage as the tree height increases [124]. Conversely, Landry et al. [125] reported that tree height did not significantly affect the prediction of damage in urban forests affected by tropical cyclones in Florida. Competition is a significant factor that affects the balance of allometric relationships between tree height and diameter [126]. Intense competition among neighbouring trees forces them to prioritise height over diameter growth to compete for sunlight, resulting in larger height-to-diameter ratios in more competitive stands. This has been confirmed for different species of Chinese fir, Engelmann spruce [126,127], Betula pendula Roth and B. pubescens Ehrh [128], Norway spruce [129], and Sitka spruce [21]. Aside from tree diameter and height, the crown characteristics are important, as they affect the projected area that the wind 'sees' [130] and the tree dynamic response, and therefore control the wind loading on the tree [86,113]. Specifically, the shape, density, and overall configuration of the tree crown affect how it interacts with wind, altering its resistance and susceptibility to wind-induced force, which is known as streamlining [124]. Hence, a tree with increased streamlining has less chance of windthrow. The streamlining effect is more pronounced in open-grown or urban trees than in forest trees because they face more steady wind flows compared to forest trees, which are loaded by canopy-scale gusts [131]. An understanding of the temporal variation of tree diameter and height due to management practices and forest structure is critical for ensuring tree stability.

4.3.3. Root Anchorage

Recent advancements in plant biomechanics have highlighted the significant role of plant geometry (i.e., both aerial and below ground) in determining its mechanical strength and stability. Some of the studies have contended that root architecture rather than the mechanical properties of the wood material has a greater influence on the response of a plant to wind [132,133]. Also, Yang et al. [134] noted that tree root morphology contributes more to tree stability during windstorms than soil properties and root biomechanics. A proper characterisation of plant roots is crucial because it can enable the prediction of potential variations in root architecture due to environmental conditions and determines root capability to anchor plants [135]. Plant roots can be classified based on their developmental origins (i.e., tap roots, lateral roots, basal roots, and short-borne roots) or diameter class (fine, medium, and large roots) [136]. Tap roots are defined as a central root that grows straight downward from the seed, while lateral roots are secondary roots that branch off from the primary root or another lateral root, growing horizontally and diagonally; the basal root proceeds from the hypocotyls, and the short-borne root proceeds from the stem [136]. Tree root architecture is classified based on the type of roots that dominate the tree. Here, tree root architecture can be divided into three systems, namely, the tap-root system (dominated by the taproot), the heart-root system (dominated by basal and lateral roots), and the plate-root system (dominated by lateral and vertical sinker roots) [137]. Research by Crook and Ennos [29] in waterlogged soils showed that larch trees have roots that are vertically orientated and thus have a more efficient anchorage system than Sitka spruce trees with a plate-root system. Generally, the heart-root system is assumed to provide greater resistance to wind loading followed by the tap-root system and the plate-root system [105]. The anchorage capacity of the plate-root system is decreased due to the lack of deep vertical roots [105]. Typically, young trees possess a dominant vertical tap root and several smaller lateral roots but, as the tree grows older, the lateral roots tend to grow larger, while the tap root may stop growing altogether [137]. The tap root therefore has a greater influence on the stability of younger trees than older trees, and its importance is controlled by its dimension in proportion to the size of the aerial part of the tree [23,29,134,138].

Root architecture may evolve because of the plasticity genetics of the species [62]. Here, the morphology of the roots of the same species may differ as the tree tries to adapt to the environmental constraints such as the growth medium (i.e., the physical, chemical, and biological characteristics of the soil) [138,139] and anthropogenic action (e.g., soil compaction) [140]. For example, the proliferation of the primary taproot may cease if it encounters a hard soil layer or is unable to access water, leading to the formation of numerous secondary roots near the primary root [138]. These factors affect not only the morphology of the roots but their mechanical properties. According to Likitlersuang et al. [139], the tensile strength of roots grown in non-soil media (e.g., hydroponic, rice husk ash) differs significantly from that of roots grown in natural soil. Cucchi et al. [80] reported that *P. pinaster* trees at the forest edge had larger windward roots compared to trees in the middle. Hence, the windward roots have a greater contribution to tree anchorage than the leeward roots. [29,105,134] reported that for larch trees, the windward lateral and the taproot contributed 75% to its anchorage, whereas the leeward contributed 25%. However, the latter is known to break only after the maximum anchorage moment is exceeded [29], which potentially calls into question if the relative contributions from the windward and leeward roots are correct. During a windstorm, trees can fail by uprooting, trunk breakage, crown, or branch failure. There is a dearth of studies on the correlation between tree roots and trunk biomechanics (e.g., Young's modulus and tensile strength), root age, root volume, varying wind intensities, and tree stability.

One challenge that can be identified in terms of determining tree anchorage is that the techniques involved tend to be destructive [105]. Given the variability that can exist between trees and their associated soil conditions, it is not possible (at present) to accurately evaluate how the stability of an individual tree (or groups of trees) can vary throughout its (their) life.

4.3.4. Environmental Factors

Windthrow: Wind, Climate Change, Snow

Windthrow occurs when the force of the wind on the canopy of a tree, leveraged against the stem, surpasses the tree's resistance to bending or uprooting [141]. Recurrent extreme winds, the intensity of weather events, topography, climate change, and regional climate patterns are the major abiotic factors causing windthrow [142]. According to the Beaufort scale, extreme winds are categorised into three groups based on their intensities: gales (17–24 ms^{-1}), storms (25–33 ms^{-1}), and hurricanes (>33 ms^{-1}) [141]. In mid-latitude temperate zones, extra-tropical cyclones, which develop over the oceans, are a major source of recurrent gale and storm force winds, causing substantial damage to forests, particularly in coastal regions [143]. These cyclones are associated with counter-clockwise rotation in the Northern Hemisphere and often bring strong winds accompanied by considerable rainfall [144]. Convective storms can develop on hot and humid days [145], creating intense localised updrafts and downdrafts, leading to strong winds and causing windthrow [146]. Derechos are fast-moving lines of severe thunderstorms that generate straight-line winds, damaging trees and forests over significant distances. Non-synoptic storms such as tornadoes and thunderstorm downbursts occur at different scales and can produce high wind speeds resulting in significant localised treefall [147].

The severity of forest damage during extreme wind events primarily depends on its exposure, duration of the wind, maximum sustained wind speed, gustiness (turbulence levels), and precipitation [97,148]. Klein et al. [97] found that across eight different hurricanes, the survivability of sixteen tree species declined as the wind speed increased. Irrespective of other factors (e.g., soil type), sustained wind speeds of 25–29 ms^{-1} are sufficient to cause considerable damage to the forest [149]. However, studies suggest that the gust speed is the most critical factor, as trees tend to fail under the influence of gusts rather than mean wind speeds [150]. The identification and prediction of tree failure patterns is complicated, since the local wind speed, influenced by factors such as engineered structures, surface cover and topography can deviate from the average wind speed recorded at the meteorological stations.

Soil Strength

The likelihood of tree failure due to abiotic factors especially windstorms depends on not only the tree species (Figure 9) or morphology but also the soil characteristics (e.g., soil shear strength, pore water pressure, particle size distribution, etc.) [19,25,26]. Rahardjo et al. [19] reported that the tree anchorage failure modes (e.g., shear or slippage) are controlled by the soil characteristics. In their numerical model, the stability of the trees improved when the granite chips were mixed with the topsoil, making the soil coarser. During windstorms, soil failure reduces the tree anchorage, which in turn reduces the maximum bending moment the tree can withstand. This may enhance the degree of tree sway [151], which has the potential to increase the applied loading if the tree is swaying at or close to its natural frequency [98].

To potentially complicate matters further, it has been observed that during dynamic tree-pulling tests, there can be a build-up of pore water pressure beneath the roots, which in turn can result in the liquefaction of the soil and subsequent collapse of the tree [151]. For instance, Li et al. [152] reported that the lean of Eugenia Grandis under wind drag increased by 0.7% and 16.5% due to the increase in the constant modulus of the soil from 5 MPa to 20 MPa, respectively, resulting from changes in the matric suction. Therefore, the anchorage failure can be associated purely with the soil and not the breakage of roots.

The resistance of the soil to shearing can vary considerably depending on its properties. For example, research has shown varying failure mechanisms in trees depending on whether they are grown in clay or sandy soils. In clay soils with consistent shear strength, the failure mechanism has been found to be symmetrical; however, the failure mechanism is asymmetrical in sandy soils because the shear strength depends mainly on the overburden pressure [105]. A numerical model by Rahardjo et al. [19] suggested that replacing 80% of topsoil with granite chips led to an increase in the shear strength of the soil and could increase the resistance of the tree to pulling out by 15%–20%. They opined that the improvement in soil properties is more significant if the tree fails due to the shear failure of the soil. There are no experimental data to validate the result by Rahardjo et al. [19]; also, replacing the topsoil may not be practicable for large forests.

Soil Water Content

Previous studies have shown that the soil water content affects root anchorage in the soil [25,26,34,35,52,79,119,152,153]. Ray and Nicoll [79] investigated the effect of varying water tables on the development of the root plate and stability of Sitka spruce trees. The study results concluded that trees grown in soils with a shallow water table (0.3 m) had smaller and shallower root plates compared to those grown in soils with a deeper water table (0.6 m). They concluded that trees located in soils with a shallow water table have less resistance to being uprooted compared to trees growing in areas with a deeper water table. The result obtained by Ray and Nicoll [79] aligns with that of Kamimura et al. [26] who studied the stability of 30-year-old hinoki trees under typhoon-like soil conditions by subjecting them to different irrigation treatments. However, Kamimura et al. [26] noted that a decreased moisture content in the soil-root plate zone tends to increase tree stability, while increased moisture content of the soil below the root plate tends to decrease tree stability. The major limitation of both studies is that they did not provide robust statistical evidence or an empirical relationship between the soil mechanical strength and the stability of the trees. A recent study by Défossez et al. [25] suggested that the anchorage of Pinus pinaster does not decrease considerably with increasing moisture content in a sandy soil until the soil is fully saturated. Their result differs from that of Rahardjo et al. [19] and Rahardjo et al. [36] who reported that root resistance reduces significantly with wetting; however, while the study by Défossez et al. [25] was performed on a sandy soil, Rahardjo et al. [19] used a clay soil. The contrasting results highlight the need for nuanced laboratory and field assessments considering the interplay between soil type and moisture regime in affecting tree stability. A physical model where the different root architectures are represented with synthetic materials would be helpful in this regard.

4.4. Predicting Tree Stability

4.4.1. Numerical Models

Due to the advancements in plant architecture digitisation and numerical analysis techniques, several numerical simulations have been performed to improve the understanding of tree anchorage mechanisms without destructive testing of the tree [17,19,105,154–157]. The aforementioned researchers investigated the deformation of the root-soil composite due to the lateral loading of the tree using a finite element method. With the numerical approach, a comparison between the theoretical anchorage capabilities of various types of roots (e.g., tap, heart, plate-like, or herringbone root systems) can be assessed in different soil types (e.g., clay and sandy soils). However, only Dupuy et al. [17,19,105,154–157] performed the numerical simulation using a real root architecture, while the other studies simplified the root architecture as a root-soil plate [17,105,106,155]. By modelling the roots as a root-plate, most of the numerical models assume the diameter of the roots as uniform and the strength contribution of the roots is taken as summative even though the roots may break progressively during shear [19,155,156].

Some of the numerical models either neglect the friction between the root-soil system [19,156] or model the root-soil interaction as rigid [154]. The assumption of rigid root-soil interactions is based on the observation that roots are still embedded in a mass of soil even after uprooting [154]; however, this might not be always the case, especially for trees grown in less cohesive soils. Surface-to-surface interaction is important in numerical modelling because it could affect the accuracy and reliability of the simulations. For instance, in a pile foundation, 15%–50% variation in the resistance can result from the roughness of the interface between the pile and soil [158]. The results obtained by Dupuy et al. [154] show that soil cohesion is more critical for the tree uproot resistance than the mechanical properties of the roots. However, when a cohesive soil was used for the numerical simulation, Dupuy et al. [154] predicted an uproot resistance of the tree that overestimated field measurements by 70%, whereas with a frictional soil, the model underestimated the uproot resistance by 20%. This demonstrates that further studies are required to improve the accuracy of the numerical simulations for the prediction of tree stability.

Apart from the evaluation of the influence of the plant root architecture on tree stability, Rahardjo et al. [19] investigated the effect of improved soil properties on the stability of trees using SIGMA/W (Geo-Slope International Ltd., Calgary, AB, Canada), a finite element-based software, and static analysis (limit equilibrium method). The result from the numerical analysis suggested that the shear strength of the soil contributes more to the tree's stability than the root architecture, although the outcome was not validated with a field or laboratory experiment. Conversely, a recent numerical study by Rahardjo et al. [156] argued that the stability of trees is not dependent on soil strength. Choosing appropriate elements for modelling is crucial in finite element analysis because it directly affects the accuracy and reliability of the analysis. Further investigation is required to ascertain the best element to be used in modelling plant roots and trunks. Most of the numerical models do not consider the contribution of the fine roots and the crown of the trees [17,154,155]. However, a study by Rahardjo et al. [156] showed that when the tree is pulled sideways, the crown has a higher lateral displacement as compared to the stem of the tree. Therefore, the crown can exert an additional overturning moment on the root system. Some of the numerical simulations have not been validated by experimental data [105] thus providing less confidence in the results.

4.4.2. Mechanistic Models

Most of the existing mechanistic models for predicting tree stability apart from Saunderson et al. [159] are based on either the HWIND or GALES models [30,55,109,113]. Saunderson et al. [159] developed a dynamic mathematical model to predict the stability of Sitka spruce in high winds. Their model features a vertical tapered cantilever representing the tree trunk with specified stiffness and mass distributions. The canopy is depicted as a cylindrical body with varying density at the top of the trunk. Wind loading is represented by a spatially constant distribution on the upper canopy with realistic spectral properties. Damping of the tree's oscillations is exclusively due to aerodynamic factors. The complex fourth-order differential equations resulting from this model are solved using numerical methods. The model is then used to predict transfer functions that relate tree displacement spectra to wind spectra. The results from their study demonstrated good agreement with experimental spectra in predicting the natural frequency of trees.

The models based on the GALES or HWIND models calculate the probability of windthrow in the forests using the following steps: (i) determination of the above-canopy critical wind speed (CWS) that is needed to overturn trees or cause breakage of the trees and (ii) assessment of the local wind patterns and determining the likelihood of wind speeds at the level occurring at the specific geographic location where the trees are situated. For the GALES model, the CWS required to break or overturn the trees is calculated using Equations (1) and (2), respectively [109].

$$\text{CWS}_{\text{break}} = \frac{1}{kD}\left[\frac{\pi MOR \times DBH^3}{32\rho G(d-1.3)}\right]^{\frac{1}{2}}\left[\frac{f_{knot}}{f_{edge}f_{CW}}\right]^{\frac{1}{2}}\ln\left(\frac{h-d}{z_0}\right) \quad (1)$$

where k is the Von Karman's constant given as 0.4, D (m) is the mean spacing of the trees, MOR is the stem moment of resistance, DBH (m) is the diameter at breast height (typically measured 1.3 above ground level), ρ $\left(\text{kg m}^{-3}\right)$ is the air density, d (m) is the zero-plane displacement, G is a gust factor, f_{knot} accounts for the strength reduction due to knots, f_{edge} is the tree position concerning the forest edge, f_{CW} is the additional load due to crown weight, h (m) is the mean height of the trees, and z_0 is the aero-dynamic roughness.

$$\text{CWS}_{\text{over}} = \frac{1}{kD}\left[\frac{C_{\text{reg}}SW}{\rho Gd}\right]^{\frac{1}{2}}\left[\frac{1}{f_{edge}f_{CW}}\right]^{\frac{1}{2}}\ln\left(\frac{h-d}{z_0}\right) \quad (2)$$

C_{reg} is a regression constant that accounts for the soil and rooting depth, and SW (kg) is the weight of the stem. The HWIND model calculates the total mean wind-induced force ($F(z)$) acting on a tree at height 'z' using Equation (3):

$$\text{F}_1(z) = \frac{1}{2}C_d\rho u(z)^2[z]^2\text{A}(z) \quad (3)$$

where C_d is the drag coefficient, $u\left(\text{ms}^{-1}\right)$ is the mean wind speed at height 'z', and A is the streamlined projected area (m^2) of the stem and crown. The next step in mechanistic modelling involves forecasting the likelihood of the CWS being surpassed using climate parameters [30]. This prediction relies on estimating the local wind climate, which varies depending on terrain complexity. Weibull parameters and the wind atlas analysis program (WAsP) and an airflow model are used to estimate the peak return period of the peak wind for flat and hilly terrains, respectively [160,161]. Alternatively, mechanistic models can be linked to empirically derived systems such as the Detailed Aspect Method of Scoring (DAMS) to accurately predict local Weibull parameters. For more complex terrain and wind climates, Weibull parameters can be determined through high-resolution numerical simulations based on weather forecast data. These parameters, combined with CWS information, are vital for building wind risk management tools for forestry assessments. More details on the mechanistic models can be found in the review by Gardiner et al. [30].

4.4.3. Advanced Statistical Models

Artificial Intelligence (AI) has emerged as an important tool in contemporary environmental science, with its applications increasingly evident in various research areas [162]. Since its introduction in forestry by Kourtz [163], AI has been applied in several aspects of forestry, including the prediction of forest fires [164], height of trees, forest classifications [165], and forest inventory [166]. However, the use of AI for modelling wind risk has received limited consideration [31,167–170]. Among several AI approaches, only artificial neural network (ANN), random forest (FR), and support vector machine (SVM) have been used for the investigation of tree susceptibility to failure. Hanewinkel et al. [168] and Jahani and Saffariha [170] employed a feed forward (multi-layer perception) neural network to predict wind risk. The multi-layer perception (MLP) neural network consists of multiple layers of interconnected nodes, or "neurons" [171]. MLP is a multi-layer version of feed-forward neural network with unidirectional input layers (i.e., without loops or cycles), traversing through hidden layers, and culminating in the output layer (Figure 10). Backpropagation is used to calculate the gradient of the loss function with respect to the weights. These gradients guide weight updates to minimise the error. The difference between the MLP and radial basis function neural network (RBFNN) is that the hidden neuron in the latter is activated using a Gaussian function [170]. Conversely, random forest is an ensemble machine learning method that combines multiple decision trees to make more robust and accurate predictions by averaging their outputs or using a voting mechanism.

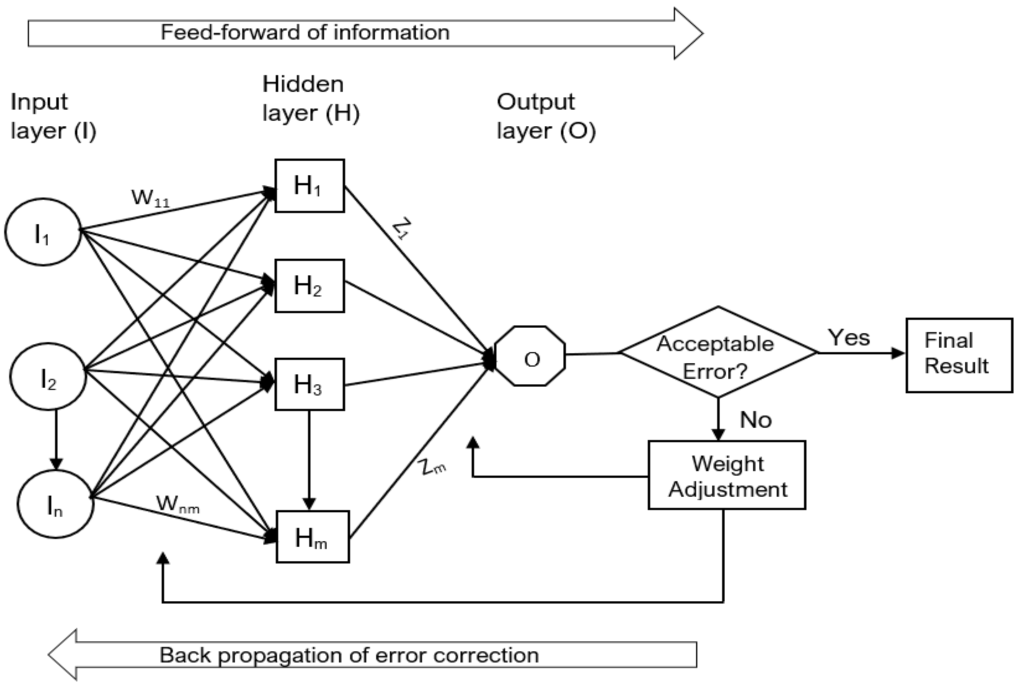

Figure 10. Typical architecture of the multi-layer perception (MLP) neural network.

Hart et al. [169] compared the effectiveness of artificial neural networks, a random forest (RF) analysis, and logistic regression (LOG) for predicting wind damage to individual trees within forested environments, with a specific focus on maritime pine forests. Their result shows that the RF model had a better accuracy (72.5%) compared to the ANN model (68.7%) and LOG (67%). This is similar to the accuracy range (71.9%–72.4%) obtained by Kamimura et al. [172] for LOG and NN models; however, it differed from Hanewinkel et al. [168] and Hanewinkel et al. [167], which showed that ANN predictions had greater accuracy compared to LOG models. Also, Jahani and Saffariha [170] reported that MLP (a type of ANN) achieved an accuracy of 97.7% in identifying wind-susceptible trees outperforming RBFNN (94%) and SVM (97%). However, Jahani and Saffariha [31] showed that the SVM model had a greater accuracy with 97.5% in predicting the stability of urban trees (*Platanus orientalis*) compared to RBFNN (87.9%) and MLP (94%). This heightens the impact of the geographical context on the ability of the models to predict the susceptibility of trees to windthrow. According to Hart et al. [169], the accuracies of the LOG and ANN models were found to be relatively sensitive to the exclusion of individual variables, particularly those related to site characteristics such as soil type, hydrological conditions, and ecological regions. In contrast, the RF model displayed remarkable insensitivity to the removal of individual variables and showed improved accuracy or discrimination when tree-specific parameters were removed [169]. This implies that the properties of the stand characteristics and vulnerable edges due to recently clear-felled trees had a greater contribution to the tree stability compared to the individual tree characteristics [169,172,173]. However, Jahani and Saffariha [170] demonstrated that both the tree and stand characteristics play the same role in the MLP model. Here, the stand characteristics (mean tree height and density) and tree properties (crown diameter and height) correlate negatively and positively with the trees susceptible to windthrow, respectively. One of the limitations of the study by Jahani and Saffariha [170] is that factors such as tree diversity, soil type, and forest edge were not included in the model. The applicability of these models to other forest types or regions may be limited due to the variations in environmental conditions, species composition, and forest management practices.

Finally, it is important to note the limitations of this study. This study focused solely on literature sourced from Web of Science-indexed journals, excluding grey literature and articles in non-indexed journals. Consequently, there could be an underestimation of journals from non-English-speaking countries, the number of citations, and collaborations. For future research, it would be valuable to consider a comparative analysis of articles published in different databases, including both indexed and non-indexed sources.

5. Conclusions

This study presents the first bibliometric analysis of tree stability-related literature. The key factors, research themes, and research gaps in the literature were identified and discussed. The analysis performed here serves to establish a baseline for the state of knowledge on the topic and, thus, identifies gaps in the knowledge, which serve to establish future research directions. The following conclusions can be drawn from this research:

i. The systematic literature review has provided interesting insights into research on tree windthrow and anchorage. It has demonstrated that most of the research published is constrained to a small number of countries in Europe or the USA with the majority published in four journals, i.e., Forest Ecology & Management, Forests, Urban Forestry & Urban Greening, and Forestry. Most of the research has been undertaken in temperate climates. Future studies could consider the effect of climate change factors such as severe windstorm on tree stability in other climates, e.g., tropical and sub-tropical climate regions.

ii. The bibliometric analysis indicated that there are five themes (species, architecture, anchorage, models, and environmental factors) that reoccur in the publications. There is a noticeable increase in the use of artificial intelligence and machine learning since 2019, although it is reasonable to note that their application to windthrow is still in its infancy. Most of the models used are notably sensitive to the exclusion of specific variables, particularly those associated with site characteristics.

iii. The most dominating factors influencing windthrow are the architecture of the tree and soil characteristics. The shape, density, and overall configuration of the tree crown affects how it interacts with wind, altering its resistance and susceptibility to wind-induced forces. Also, an understanding of the temporal variation of tree diameter and height due to management practices and forest structure is critical for ensuring tree stability.

iv. Although the type and strength characteristics of the soil are recognised as a factor contributing to tree stability, there is a lack of robust data relating to the stability of different species of trees with respect to soil types and characteristics. Observations suggest that trees fail sometimes not as a result of root or stem damage but the failure of the soil. Further work is required in this area to gain a true understanding of windthrow.

v. Most research has been conducted on different species of the conifer family. These appear to be more susceptible to windthrow, as they do not shed their leaves during the winter when the most severe storms occur.

vi. Existing windthrow models tend not to account for the temporal variation between the occurrence of stem and root damage during failure. As such, whether this is an important issue remains an unresolved question.
vii. While physical tests have been undertaken (e.g., tree-pulling tests), recent advances in sensing technologies (e.g., optical fibres) potentially could provide enhanced insights into the root-soil behaviour.

Funding: This research was funded by Teagasc Walsh Scholarship Programme (Ref: 2022006) and the APC was funded by the University of Birmingham.

Acknowledgments: The authors would like to thank the Teagasc Walsh Scholarship Programme (Ref: 2022006) and the University of Birmingham for their support in making this research possible.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Nowak, D.J.; Greenfield, E.J. US Urban Forest Statistics, Values, and Projections. *J. For.* **2018**, *116*, 164–177. [CrossRef]
2. Ganasri, B.P.; Ramesh, H. Assessment of soil erosion by RUSLE model using remote sensing and GIS—A case study of Nethravathi Basin. *Geosci. Front.* **2016**, *7*, 953–961. [CrossRef]
3. Carvalho-Santos, C.; Honrado, J.P.; Hein, L. Hydrological services and the role of forests: Conceptualization and indicator-based analysis with an illustration at a regional scale. *Ecol. Complex.* **2014**, *20*, 69–80. [CrossRef]
4. Domkea, G.M.; Oswaltb, S.N.; Waltersa, B.F.; Morinc, R.S. Tree planting has the potential to increase carbon sequestration capacity of forests in the United States. *Proc. Natl. Acad. Sci. USA* **2020**, *117*, 24649–24651. [CrossRef] [PubMed]
5. Bellassen, V.; Luyssaert, S. Carbon sequestration: Managing forests in uncertain times. *Nature* **2014**, *506*, 153–155. [CrossRef] [PubMed]
6. Schelhaas, M.J.; Nabuurs, G.J.; Schuck, A. Natural disturbances in the European forests in the 19th and 20th centuries. *Glob. Chang. Biol.* **2003**, *9*, 1620–1633. [CrossRef]
7. Dhubháin, Á.N.; Farrelly, N. Understanding and managing windthrow. In *COFORD Connects*; Department of Agriculture, Food and the Marine: Dublin, Ireland, 2018.
8. Suhuck, A.; Schelhaas, M. Storm damage in Europe—An overview. In *Living with Storm Damage to Forests*; Gardiner, B., Schuck, A., Schelhaas, M.J., Orazio, C., Blennow, K., Nicoll, B., Eds.; European Forest Institute Joensuu: Joensuu, Finland, 2013; Volume 3, pp. 15–23.
9. Savill, P.S. Silviculture in windy climates. *For. Abstr.* **1983**, *44*, 473–488.
10. James, K.; Hallam, C.; Spencer, C. Measuring tilt of tree structural root zones under static and wind loading. *Agric. For. Meteorol.* **2013**, *168*, 160–167. [CrossRef]
11. Schmidlin, T.W. Human fatalities from wind-related tree failures in the United States, 1995–2007. *Nat. Hazards* **2009**, *50*, 13–25. [CrossRef]
12. Extreme Wind Storms (XWS) Catalogue. Available online: http://www.europeanwindstorms.org/cgi-bin/storms/storms.cgi?storm1=Xynthia (accessed on 20 February 2024).
13. Motta, R.; Ascoli, D.; Corona, P.; Marchetti, M.; Vacchiano, G. Selvicoltura e schianti da vento. Il caso della "tempesta Vaia". *For.—Riv. Selvic. Ecol. For.* **2018**, *15*, 94–98. [CrossRef]
14. Biggest Windthrow Volumes. Available online: https://www.timber-online.net/blog/biggest-windthrow-volumes.html (accessed on 29 February 2024).
15. Sanginés de Cárcer, P.; Mederski, P.S.; Magagnotti, N.; Spinelli, R.; Engler, B.; Seidl, R.; Eriksson, A.; Eggers, J.; Bont, L.G.; Schweier, J. The Management Response to Wind Disturbances in European Forests. *Curr. For. Rep.* **2021**, *7*, 167–180. [CrossRef]
16. Storms of December 1999 fell 165 millions m3 of timber: Equivalent of 6 months harvest in three days. Available online: https://unece.org/fileadmin/DAM/timber/storm/00-2-e.htm (accessed on 5 December 2023).
17. Fourcaud, T.; Ji, J.-N.; Zhang, Z.-Q.; Stokes, A. Understanding the impact of root morphology on overturning mechanisms: A modelling approach. *Ann. Bot.* **2008**, *101*, 1267–1280. [CrossRef] [PubMed]
18. Nicoll, B.C.; Achim, A.; Mochan, S.; Gardiner, B.A. Does steep terrain influence tree stability? A field investigation. *Can. J. For. Res.* **2005**, *35*, 2360–2367. [CrossRef]
19. Rahardjo, H.; Harnas, F.; Leong, E.; Tan, P.; Fong, Y.; Sim, E. Tree stability in an improved soil to withstand wind loading. *Urban For. Urban Green.* **2009**, *8*, 237–247. [CrossRef]
20. Gilman, E.F.; Masters, F.J. Effect of tree size, root pruning, and production method on root growth and lateral stability of Quercus virginiana. *J. Arboric.* **2010**, *36*, 281. [CrossRef]
21. Coutts, M.; Nielsen, C.; Nicoll, B. The development of symmetry, rigidity and anchorage in the structural root system of conifers. *Plant Soil* **1999**, *217*, 1–15. [CrossRef]
22. Stokes, A. Responses of Young Trees to Wind: Effects on Root Architecture and Anchorage Strength. Ph.D. Thesis, University of York, York, UK, 1994.

23. Khuder, H.; Stokes, A.; Danjon, F.; Gouskou, K.; Lagane, F. Is it possible to manipulate root anchorage in young trees? *Plant Soil* **2007**, *294*, 87–102. [CrossRef]
24. Jiao, L.; Jiang, Y.; Zhang, W.; Wang, M.; Wang, S.; Liu, X. Assessing the stability of radial growth responses to climate change by two dominant conifer trees species in the Tianshan Mountains, northwest China. *For. Ecol. Manag.* **2019**, *433*, 667–677. [CrossRef]
25. Défossez, P.; Veylon, G.; Yang, M.; Bonnefond, J.-M.; Garrigou, D.; Trichet, P.; Danjon, F. Impact of soil water content on the overturning resistance of young Pinus Pinaster in sandy soil. *For. Ecol. Manag.* **2021**, *480*, 118614. [CrossRef]
26. Kamimura, K.; Kitagawa, K.; Saito, S.; Mizunaga, H. Root anchorage of hinoki (*Chamaecyparis obtuse* (Sieb. Et Zucc.) Endl.) under the combined loading of wind and rapidly supplied water on soil: Analyses based on tree-pulling experiments. *Eur. J. For. Res.* **2012**, *131*, 219–227. [CrossRef]
27. Cameron, A.D. Importance of early selective thinning in the development of long-term stand stability and improved log quality: A review. *Forestry* **2002**, *75*, 25–35. [CrossRef]
28. Coutts, M. Root architecture and tree stability. In *Tree Root Systems and Their Mycorrhizas*; Springer: Dordrecht, The Netherlands, 1983; pp. 171–188.
29. Crook, M.; Ennos, A. Mechanical differences between free-standing and supported wheat plants, *Triticum aestivum* L. *Ann. Bot.* **1996**, *77*, 197–202. [CrossRef]
30. Gardiner, B.; Byrne, K.; Hale, S.; Kamimura, K.; Mitchell, S.J.; Peltola, H.; Ruel, J.-C. A review of mechanistic modelling of wind damage risk to forests. *Forestry* **2008**, *81*, 447–463. [CrossRef]
31. Jahani, A.; Saffariha, M. Tree failure prediction model (TFPM): Machine learning techniques comparison in failure hazard assessment of *Platanus orientalis* in urban forestry. *Nat. Hazards* **2022**, *110*, 881–898. [CrossRef]
32. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee, and the Committee of the Regions: Eu Biodiversity Strategy for 2030. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0380 (accessed on 12 November 2023).
33. USDA. Biden-Harris Administration Announces Plans for Reforestation, Climate Adaptation, Including New Resources from Bipartisan In-Frastructure Law. Available online: https://www.usda.gov/media/press-releases/2022/07/25/biden-harris-administration-announces-plans-reforestation-climate (accessed on 12 November 2023).
34. Ennos, A. The mechanics of root anchorage. *Adv. Bot. Res.* **2000**, *33*, 133–157. [CrossRef]
35. Gardiner, B.; Berry, P.; Moulia, B. Wind impacts on plant growth, mechanics and damage. *Plant Sci.* **2016**, *245*, 94–118. [CrossRef] [PubMed]
36. Rahardjo, H.; Amalia, N.; Choon, L.E.; Harnas, F.R.; Tieng, L.T.; King, F.Y. Flux boundary measurements for the study of tree stability. *Landsc. Ecol. Eng.* **2017**, *13*, 81–92. [CrossRef]
37. Merigó, J.M.; Cancino, C.A.; Coronado, F.; Urbano, D. Academic research in innovation: A country analysis. *Scientometrics* **2016**, *108*, 559–593. [CrossRef]
38. Keathley-Herring, H.; Van Aken, E.; Gonzalez-Aleu, F.; Deschamps, F.; Letens, G.; Orlandini, P.C. Assessing the maturity of a research area: Bibliometric review and proposed framework. *Scientometrics* **2016**, *109*, 927–951. [CrossRef]
39. Huang, L.; Zhou, M.; Lv, J.; Chen, K. Trends in global research in forest carbon sequestration: A bibliometric analysis. *J. Clean. Prod.* **2020**, *252*, 119908. [CrossRef]
40. Fady, B.; Esposito, E.; Abulaila, K.; Aleksic, J.M.; Alia, R.; Alizoti, P.; Apostol, E.-N.; Aravanopoulos, P.; Ballian, D.; Kharrat, M.B.D. Forest genetics research in the Mediterranean Basin: Bibliometric analysis, knowledge gaps, and perspectives. *Curr. For. Rep.* **2022**, *8*, 277–298. [CrossRef]
41. Zupic, I.; Čater, T. Bibliometric methods in management and organization. *Organ. Res. Methods* **2015**, *18*, 429–472. [CrossRef]
42. Moed, H.F. Citation analysis of scientific journals and journal impact measures. *Curr. Sci.* **2005**, *89*, 1990–1996.
43. Aria, M.; Cuccurullo, C. Bibliometrix: An R-tool for comprehensive science mapping analysis. *J. Informetr.* **2017**, *11*, 959–975. [CrossRef]
44. van Eck, N.J.; Waltman, L. Software survey: VOSviewer, a computer program for bibliometric mapping. *Scientometrics* **2010**, *84*, 523–538. [CrossRef] [PubMed]
45. Peters, H.P.F.; Vanraan, A.F.J. Structuring scientific activities by co-author analysis—An exercise on a university-faculty level. *Scientometrics* **1991**, *20*, 235–255. [CrossRef]
46. White, H.D.; McCain, K.W. Visualizing a discipline: An author co-citation analysis of information science, 1972-1995. *J. Am. Soc. Inf. Sci.* **1998**, *49*, 327–355. [CrossRef]
47. Bradford, S.C. Sources of information on specific subjects (Reprinted from Engineering an Illustrated Weekly Journal, VOL 137, PG 85–86, 1934). *J. Inf. Sci.* **1985**, *10*, 176–180.
48. Aksnes, D.W.; Langfeldt, L.; Wouters, P. Citations, Citation Indicators, and Research Quality: An Overview of Basic Concepts and Theories. *Sage Open* **2019**, *9*, 2158244019829575. [CrossRef]
49. Chirici, G.; Bottalico, F.; Giannetti, F.; Del Perugia, B.; Travaglini, D.; Nocentini, S.; Kutchartt, E.; Marchi, E.; Foderi, C.; Fioravanti, M.; et al. Assessing forest windthrow damage using single-date, post-event airborne laser scanning data. *Forestry* **2018**, *91*, 27–37. [CrossRef]
50. Rüdiger, M.S.; Antons, D.; Salge, T.O. The explanatory power of citations: A new approach to unpacking impact in science. *Scientometrics* **2021**, *126*, 9779–9809. [CrossRef]

51. Nicoll, B.C.; Ray, D. Adaptive growth of tree root systems in response to wind action and site conditions. *Tree Physiol.* **1996**, *16*, 891–898. [CrossRef]
52. Coutts, M.P. Components of tree stability in Sitka Spruce on peaty gley soil. *Forestry* **1986**, *59*, 173–197. [CrossRef]
53. Marchi, L.; Costa, M.; Grigolato, S.; Lingua, E. Overturning resistance of large diameter Norway spruce (*Picea abies* (L.) Karst) on sloped conditions. *For. Ecol. Manag.* **2022**, *524*, 120531. [CrossRef]
54. Byrne, K.E.; Mitchell, S.J. Overturning resistance of western redcedar and western hemlock in mixed-species stands in coastal British Columbia. *Can. J. For. Res.-Rev. Can. Rech. For.* **2007**, *37*, 931–939. [CrossRef]
55. Cucchi, V.; Meredieu, C.; Stokes, A.; de Coligny, F.; Suarez, J.; Gardiner, B.A. Modelling the windthrow risk for simulated forest stands of Maritime pine (*Pinus pinaster* Ait.). *For. Ecol. Manag.* **2005**, *213*, 184–196. [CrossRef]
56. Zeng, H.C.; Garcia-Gonzalo, J.; Peltola, H.; Kellomäki, S. The effects of forest structure on the risk of wind damage at a landscape level in a boreal forest ecosystem. *Ann. For. Sci.* **2010**, *67*, 111. [CrossRef]
57. Mickovski, S.B.; Stokes, A.; van Beek, L. A decision support tool for windthrow hazard assessment and prevention. *For. Ecol. Manag.* **2005**, *216*, 64–76. [CrossRef]
58. Baker, C.J. Measurements of the natural frequencies of trees. *J. Exp. Bot.* **1997**, *48*, 1125–1132. [CrossRef]
59. Ciftci, C.; Brena, S.F.; Kane, B.; Arwade, S.R. The effect of crown architecture on dynamic amplification factor of an open-grown sugar maple (*Acer saccharum* L.). *Trees-Struct. Funct.* **2013**, *27*, 1175–1189. [CrossRef]
60. Baker, C.J.; Bell, H.J. The aerodynamics of urban trees. *J. Wind Eng. Ind. Aerodyn.* **1992**, *44*, 2655–2666. [CrossRef]
61. Gardiner, B.A.; Stacey, G.R.; Belcher, R.E.; Wood, C.J. Field and wind tunnel assessments of the implications of respacing and thinning for tree stability. *Forestry* **1997**, *70*, 233–252. [CrossRef]
62. Yang, M.; Défossez, P.; Danjon, F.; Dupont, S.; Fourcaud, T. Which root architectural elements contribute the best to anchorage of *Pinus* species? Insights from in silico experiments. *Plant Soil* **2017**, *411*, 275–291. [CrossRef]
63. Bell, D.T.; Vandermoezel, P.G.; Bennett, I.J.; McComb, J.A.; Wilkins, C.F.; Marshall, S.C.B.; Morgan, A.L. Comparisons of growth of Eucalyptus-camaldulensis from seeds and tissue-culture-root, shoot and leaf morphology of 9-month-old plants grown in deep sand and sand over clay. *For. Ecol. Manag.* **1993**, *57*, 125–139. [CrossRef]
64. Crook, M.J.; Ennos, A.R. The Mechanics of Root Lodging in Winter-Wheat, *Triticum aestivum* L. *J. Exp. Bot.* **1993**, *44*, 1219–1224. [CrossRef]
65. Di Iorio, A.; Lasserre, B.; Scippa, G.S.; Chiatante, D. Root system architecture of *Quercus pubescens* trees growing on different sloping conditions. *Ann. Bot.* **2005**, *95*, 351–361. [CrossRef] [PubMed]
66. Drexhage, M.; Chauvière, M.; Colin, F.; Nielsen, C.N.N. Development of structural root architecture and allometry of *Quercus petraea*. *Can. J. For. Res.* **1999**, *29*, 600–608. [CrossRef]
67. Ennos, A.R. The scaling of root anchorage. *J. Theor. Biol.* **1993**, *161*, 61–75. [CrossRef]
68. Ennos, A.R.; Crook, M.J.; Grimshaw, C. A Comparative Study of the Anchorage Systems of Himalayan Balsam (*Impatiens glandulifera*) and Mature Sunflower (*Helianthus annuus*). *J. Exp. Bot.* **1993**, *44*, 133–146. [CrossRef]
69. Heineman, J.L.; Bedford, L.; Sword, D. Root system development of 12-year-old white spruce (*Picea glauca* (Moench) Voss) on a mounded subhygric-mesic site in northern interior British Columbia. *For. Ecol. Manag.* **1999**, *123*, 167–177. [CrossRef]
70. Lindström, A.; Rune, G. Root deformation in plantations of container-grown Scots pine trees:: Effects on root growth, tree stability and stem straightness. *Plant Soil* **1999**, *217*, 29–37. [CrossRef]
71. Mattheck, C.; Bethge, K. Wind breakage of trees initiated by root delamination. *Trees-Struct. Funct.* **1990**, *4*, 225–227. [CrossRef]
72. Nishimura, T.B. Tree characteristics related to stem breakage of *Picea glehnii* and *Abies sachalinensis*. *For. Ecol. Manag.* **2005**, *215*, 295–306. [CrossRef]
73. Osunkoya, O.O.; Omar-Ali, K.; Amit, N.; Dayan, J.; Daud, D.S.; Sheng, T.K. Comparative height-crown allometry and mechanical design in 22 tree species of Kuala Belalong rainforest, Brunei, Borneo. *Am. J. Bot.* **2007**, *94*, 1951–1962. [CrossRef]
74. Polomski, J.; Kuhn, N. Root habitus and wind stability of trees. *Forstwiss. Centralbl.* **2001**, *120*, 303–317. [CrossRef]
75. Soethe, N.; Lehmann, J.; Engels, C. Root morphology and anchorage of six native tree species from a tropical montane forest and an elfin forest in Ecuador. *Plant Soil* **2006**, *279*, 173–185. [CrossRef]
76. Tardío, G.; González-Ollauri, A.; Mickovski, S.B. A non-invasive preferential root distribution analysis methodology from a slope stability approach. *Ecol. Eng.* **2016**, *97*, 46–57. [CrossRef]
77. Watson, A. Wind-induced forces in the near-surface lateral roots of radiata pine. *For. Ecol. Manag.* **2000**, *135*, 133–142. [CrossRef]
78. Watson, A.J.; Tombleson, J.D. Toppling in juvenile pines: A comparison of the root system characteristics of direct-sown seedlings, and bare-root seedlings and cuttings. *Plant Soil* **2002**, *239*, 187–196. [CrossRef]
79. Ray, D.; Nicoll, B.C. The effect of soil water-table depth on root-plate development and stability of Sitka spruce. *Forestry* **1998**, *71*, 169–182. [CrossRef]
80. Cucchi, V.; Meredieu, C.; Stokes, A.; Berthier, S.; Bert, D.; Najar, M.; Denis, A.; Lastennet, R. Root anchorage of inner and edge trees in stands of Maritime pine (*Pinus pinaster* Ait.) growing in different podzolic soil conditions. *Trees-Struct. Funct.* **2004**, *18*, 460–466. [CrossRef]
81. Meunier, S.; Ruel, J.C.; Laflamme, G.; Achim, A. Comparative resistance of white spruce and balsam fir to overturning. *Can. J. For. Res.-Rev. Can. Rech. For.* **2002**, *32*, 642–652. [CrossRef]
82. Fredericksen, T.S.; Hedden, R.L.; Williams, S.A. Testing Loblolly-Pine wind firmness with simulated wind stress. *Can. J. For. Res.-Rev. Can. Rech. For.* **1993**, *23*, 1760–1765. [CrossRef]

83. Ribeiro, G.; Chambers, J.Q.; Peterson, C.J.; Trumbore, S.E.; Marra, D.M.; Wirth, C.; Cannon, J.B.; Négron-Juárez, R.I.; Lima, A.J.N.; de Paula, E.; et al. Mechanical vulnerability and resistance to snapping and uprooting for Central Amazon tree species. *For. Ecol. Manag.* **2016**, *380*, 1–10. [CrossRef]
84. Peterson, C.J.; Ribeiro, G.; Negrón-Juárez, R.; Marra, D.M.; Chambers, J.Q.; Higuchi, N.; Lima, A.; Cannon, J.B. Critical wind speeds suggest wind could be an important disturbance agent in Amazonian forests. *Forestry* **2019**, *92*, 444–459. [CrossRef]
85. Ancelin, P.; Courbaud, B.; Fourcaud, T. Development of an individual tree-based mechanical model to predict wind damage within forest stands. *For. Ecol. Manag.* **2004**, *203*, 101–121. [CrossRef]
86. Päätalo, M.L.; Peltola, H.; Kellomäki, S. Modelling the risk of snow damage to forests under short-term snow loading. *For. Ecol. Manag.* **1999**, *116*, 51–70. [CrossRef]
87. Apostolov, A.; Oke, J.; Suttle, R.; Arwade, S.; Kane, B. Predicting tree failure likelihood for utility risk mitigation via a convolutional neural network. *Sustain. Resil. Infrastruct.* **2023**, *8*, 572–588. [CrossRef]
88. Cantiani, P.; Chiavetta, U. Estimating the mechanical stability of *Pinus nigra* Arn. using an alternative approach across several plantations in central Italy. *iForest* **2015**, *8*, 846–852. [CrossRef]
89. Dupont, S.; Brunet, Y. Impact of forest edge shape on tree stability: A large-eddy simulation study. *Forestry* **2008**, *81*, 299–315. [CrossRef]
90. Kontogianni, A.; Tsitsoni, T.; Goudelis, G. An index based on silvicultural knowledge for tree stability assessment and improved ecological function in urban ecosystems. *Ecol. Eng.* **2011**, *37*, 914–919. [CrossRef]
91. Schütz, J.P.; Götz, M.; Schmid, W.; Mandallaz, D. Vulnerability of spruce (*Picea abies*) and beech (*Fagus sylvatica*) forest stands to storms and consequences for silviculture. *Eur. J. For. Res.* **2006**, *125*, 291–302. [CrossRef]
92. Zeng, H.C.; Peltola, H.; Väisänen, H.; Kellomäki, S. The effects of fragmentation on the susceptibility of a boreal forest ecosystem to wind damage. *For. Ecol. Manag.* **2009**, *257*, 1165–1173. [CrossRef]
93. Kane, B.; Modarres-Sadeghi, Y.; James, K.R.; Reiland, M. Effects of crown structure on the sway characteristics of large decurrent trees. *Trees-Struct. Funct.* **2014**, *28*, 151–159. [CrossRef]
94. Kabir, E.; Guikema, S.; Kane, B. Statistical modeling of tree failures during storms. *Reliab. Eng. Syst. Saf.* **2018**, *177*, 68–79. [CrossRef]
95. Moore, J.R.; Maguire, D.A. Simulating the dynamic behavior of Douglas-fir trees under applied loads by the finite element method. *Tree Physiol.* **2008**, *28*, 75–83. [CrossRef]
96. Bartens, J.; Wiseman, P.E.; Smiley, E.T. Stability of landscape trees in engineered and conventional urban soil mixes. *Urban For. Urban Green.* **2010**, *9*, 333–338. [CrossRef]
97. 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* **2020**, *11*, 485. [CrossRef]
98. Jonsson, M.J.; Foetzki, A.; Kalberer, M.; Lundstro, T.; Ammann, W.; Stöckli, V. Natural frequencies and damping ratios of Norway spruce (*Picea abies* (L.) Karst) growing on subalpine forested slopes. *Trees-Struct. Funct.* **2007**, *21*, 541–548. [CrossRef]
99. Jonsson, M.J.; Foetzki, A.; Kalberer, M.; Lundström, T.; Ammann, W.; Stöckli, V. Root-soil rotation stiffness of Norway spruce (*Picea abies* (L.) Karst) growing on subalpine forested slopes. *Plant Soil* **2006**, *285*, 267–277. [CrossRef]
100. GOV.UK. Countries Defined as Developing by the OECD. Available online: https://www.gov.uk/government/publications/countries-defined-as-developing-by-the-oecd (accessed on 12 November 2023).
101. Small, H. Co-citation in the scientific literature: A new measure of the relationship between two documents. *J. Am. Soc. Inf. Sci.* **1973**, *24*, 265–269. [CrossRef]
102. Galletta, S.; Mazzu, S.; Naciti, V. A bibliometric analysis of ESG performance in the banking industry: From the current status to future directions. *Res. Int. Bus. Financ.* **2022**, *62*, 101684. [CrossRef]
103. Paltrinieri, A.; Hassan, M.K.; Bahoo, S.; Khan, A. A bibliometric review of sukuk literature. *Int. Rev. Econ. Financ.* **2023**, *86*, 897–918. [CrossRef]
104. Fraser, A.I. The soil and roots as factors in tree stability. *Forestry* **1962**, *34*, 117–127. [CrossRef]
105. Dupuy, L.; Fourcaud, T.; Stokes, A. A numerical investigation into factors affecting the anchorage of roots in tension. *Eur. J. Soil Sci.* **2005**, *56*, 319–327. [CrossRef]
106. Dupuy, L.; Fourcaud, T.; Stokes, A. A numerical investigation into the influence of soil type and root architecture on tree anchorage. *Plant Soil* **2005**, *278*, 119–134. [CrossRef]
107. Petty, J.A.; Worrell, R. Stability of coniferous tree stems in relation to damage by snow. *Forestry* **1981**, *54*, 115–128. [CrossRef]
108. Petty, J.A.; Swain, C. Factors influencing stem breakage of conifers in high winds. *Forestry* **1985**, *58*, 75–84. [CrossRef]
109. Gardiner, B.; Peltola, H.; Kellomäki, S. Comparison of two models for predicting the critical wind speeds required to damage coniferous trees. *Ecol. Model.* **2000**, *129*, 1–23. [CrossRef]
110. Moore, J.; Quine, C.P. A comparison of the relative risk of wind damage to planted forests in Border Forest Park, Great Britain, and the Central North Island, New Zealand. *For. Ecol. Manag.* **2000**, *135*, 345–353. [CrossRef]
111. Nicoll, B.C.; Berthier, S.; Achim, A.; Gouskou, K.; Danjon, F.; van Beek, L.P.H. The architecture of *Picea sitchensis* structural root systems on horizontal and sloping terrain. *Trees-Struct. Funct.* **2006**, *20*, 701–712. [CrossRef]
112. 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. *For. Ecol. Manag.* **2000**, *135*, 143–153. [CrossRef]

113. Peltola, H.; Kellomäki, S.; Väisänen, H.; Ikonen, V.P. A mechanistic model for assessing the risk of wind and snow damage to single trees and stands of Scots pine, Norway spruce, and birch. *Can. J. For. Res.-Rev. Can. Rech. For.* **1999**, *29*, 647–661. [CrossRef]
114. James, K.R.; Haritos, N.; Ades, P.K. Mechanical stability of trees under dynamic loads. *Am. J. Bot.* **2006**, *93*, 1522–1530. [CrossRef] [PubMed]
115. Laudano, M.C.; Marzi, G.; Caputo, A. A decade of the international journal of entrepreneurship and small business: A bibliometric analysis. *Int. J. Entrep. Small Bus.* **2018**, *33*, 289–314. [CrossRef]
116. Cristini, V.; Nop, P.; Zlámal, J.; Vand, M.H.; Šeda, V.; Tippner, J. *Fomes fomentarius* and *F. inzengae*—A Comparison of Their Decay Patterns on Beech Wood. *Microorganisms* **2023**, *11*, 679. [CrossRef]
117. Tian, D.; Jiang, L.; Wang, J. The influence of climate, soil physicochemical properties and tree size inequality on tree slenderness in mixed forests of Northeastern China. *For. Ecol. Manag.* **2023**, *529*, 120719. [CrossRef]
118. Wang, J.; Wang, Y.; Tian, D.; Wang, W.; Jiang, L. Modeling response of tree slenderness to climate, soil, diversity, and competition in natural secondary forests. *For. Ecol. Manag.* **2023**, *545*, 121253. [CrossRef]
119. Gardiner, B.; Blennow, K.; Carnus, J.; Fleischer, P.; Ingemarson, F.; Landmann, G.; Lindner, M.; Marzano, M.; Nicoll, B.; Orazio, C.; et al. *Destructive Storms in European Forests: Past and Forthcoming Impacts*; European Forest Institute: Joensuu, Finland, 2010.
120. Valinger, E.; Fridman, J. Factors affecting the probability of windthrow at stand level as a result of Gudrun winter storm in southern Sweden. *For. Ecol. Manag.* **2011**, *262*, 398–403. [CrossRef]
121. Hanewinkel, M.; Cullmann, D.A.; Schelhaas, M.J.; Nabuurs, G.J.; Zimmermann, N.E. Climate change may cause severe loss in the economic value of European forest land. *Nat. Clim. Chang.* **2013**, *3*, 203–207. [CrossRef]
122. Locatelli, T.; Tarantola, S.; Gardiner, B.; Patenaude, G. Variance-based sensitivity analysis of a wind risk model—Model behaviour and lessons for forest modelling. *Environ. Model. Softw.* **2017**, *87*, 84–109. [CrossRef]
123. Locatelli, T.; Gardiner, B.; Tarantola, S.; Nicoll, B.; Bonnefond, J.M.; Garrigou, D.; Kamimura, K.; Patenaude, G. Modelling wind risk to *Eucalyptus globulus* (Labill.) stands. *For. Ecol. Manag.* **2016**, *365*, 159–173. [CrossRef]
124. Quine, C.P.; Gardiner, B.A.; Moore, J. Wind disturbance in forests: The process of wind created gaps, tree overturning, and stem breakage. In *Plant Disturbance Ecology*, 2nd ed.; Johnson, E.A., Miyanishi, K., Eds.; Academic Press: San Diego, CA, USA, 2021; pp. 117–184. [CrossRef]
125. Landry, S.M.; Koeser, A.K.; Kane, B.; Hilbert, D.R.; McLean, D.C.; Andreu, M.; Staudhammer, C.L. Urban forest response to Hurricane Irma: The role of landscape characteristics and sociodemographic context. *Urban For. Urban Green.* **2021**, *61*, 127093. [CrossRef]
126. Liu, S.; Liu, Y.; Wu, L.; Yi, X.; Sun, H. Examining the interactive effects of neighborhood characteristics and environmental conditions on height-to-diameter ratio of Chinese fir based on random forest. *For. Ecol. Manag.* **2023**, *544*, 121189. [CrossRef]
127. Liu, S.; Liu, Y.; Xia, R.L. Using random forest to disentangle the effects of environmental conditions on height-to-diameter ratio of Engelmann spruce. *New For.* **2023**. [CrossRef]
128. Kitenberga, M.; Snepsts, G.; Vuguls, J.; Elferts, D.; Jaunslaviete, I.; Jansons, A. Tree- and stand-scale factors shape the probability of wind damage to birch in hemiboreal forests. *Silva Fenn.* **2021**, *55*, 10483. [CrossRef]
129. Vasilescu, M.M.; Teresneu, C.C.; Dinulica, F. A rapid method for estimating the median diameter of the stem profile of Norway spruce (*Picea abies* Karst) trees. *iForest* **2017**, *10*, 328–333. [CrossRef]
130. Raupach, M.R. Simplified expressions for vegetation roughness length and zero-plane displacement as functions of canopy height and area index. *Bound.-Layer Meteorol.* **1994**, *71*, 211–216. [CrossRef]
131. Hale, S.E.; Gardiner, B.A.; Wellpott, A.; Nicoll, B.C.; Achim, A. Wind loading of trees: Influence of tree size and competition. *Eur. J. For. Res.* **2012**, *131*, 203–217. [CrossRef]
132. Sellier, D.; Brunet, Y.; Fourcaud, T. A numerical model of tree aerodynamic response to a turbulent airflow. *Forestry* **2008**, *81*, 279–297. [CrossRef]
133. Sellier, D.; Fourcaud, T. Crown structure and wood properties: Influence on tree sway and response to high winds. *Am. J. Bot.* **2009**, *96*, 885–896. [CrossRef]
134. Yang, M.; Défossez, P.; Danjon, F.; Fourcaud, T. Analyzing key factors of roots and soil contributing to tree anchorage of *Pinus* species. *Trees-Struct. Funct.* **2018**, *32*, 703–712. [CrossRef]
135. Bodner, G.; Leitner, D.; Nakhforoosh, A.; Sobotik, M.; Moder, K.; Kaul, H.P. A statistical approach to root system classification. *Front. For. Glob. Chang.* **2013**, *4*, 292. [CrossRef] [PubMed]
136. Zobel, R.W.; Waisel, Y. A plant root system architectural taxonomy: A framework for root nomenclature. *Plant Biosyst.* **2010**, *144*, 507–512. [CrossRef]
137. Stokes, A.; Mattheck, C. Variation of wood strength in tree roots. *J. Exp. Bot.* **1996**, *47*, 693–699. [CrossRef]
138. Danjon, F.; Fourcaud, T.; Bert, D. Root architecture and wind-firmness of mature *Pinus pinaster*. *New Phytol.* **2005**, *168*, 387–400. [CrossRef] [PubMed]
139. Likitlersuang, S.; Phan, T.N.; Boldrin, D.; Leung, A.K. Influence of growth media on the biomechanical properties of the fibrous roots of two contrasting vetiver grass species. *Ecol. Eng.* **2022**, *178*, 106574. [CrossRef]
140. Correa, J.; Postma, J.A.; Watt, M.; Wojciechowski, T. Soil compaction and the architectural plasticity of root systems. *J. Exp. Bot.* **2019**, *70*, 6019–6034. [CrossRef] [PubMed]
141. Mitchell, S.J. Wind as a natural disturbance agent in forests: A synthesis. *Forestry* **2013**, *86*, 147–157. [CrossRef]

142. Quine, C. Assessing the risk of wind damage to forests: Practice and pitfalls. In *Wind and Trees*; Coutts, M.P., Grace, J., Eds.; Cambridge University Press: Cambridge, UK, 1995; pp. 379–403.
143. Salisbury, A.B.; Koeser, A.K.; Andreu, M.G.; Chen, Y.J.; Freeman, Z.; Miesbauer, J.W.; Herrera-Montes, A.; Kua, C.S.; Nukina, R.H.; Rockwell, C.A.; et al. Predictors of tropical cyclone-induced urban tree failure: An international scoping review. *Front. For. Glob. Chang.* **2023**, *6*, 1168495. [CrossRef]
144. Zehnder, J.A. Tropical Cyclone. Available online: https://www.britannica.com/science/tropical-cyclone (accessed on 29 February 2024).
145. Nunes, A.M.P.; Dias, M.; Anselmo, E.M.; Morales, C. Severe Convection Features in the Amazon Basin: A TRMM-Based 15 Year Evaluation. *Front. For. Glob. Chang.* **2016**, *4*, 37. [CrossRef]
146. Feng, Y.L.; Negrón-Juárez, R.I.; Romps, D.M.; Chambers, J.Q. Amazon windthrow disturbances are likely to increase with storm frequency under global warming. *Nat. Commun.* **2023**, *14*, 101. [CrossRef]
147. Mansour, M.A.; Rhee, D.M.; Newson, T.; Peterson, C.; Lombardo, F.T. Estimating wind damage in forested areas due to tornadoes. *Forests* **2021**, *12*, 17. [CrossRef]
148. Pasztor, F.; Matulla, C.; Zuvela-Aloise, M.; Rammer, W.; Lexer, M.J. Developing predictive models of wind damage in Austrian forests. *Ann. For. Sci.* **2015**, *72*, 289–301. [CrossRef]
149. Savill, P.; Evans, J.; Auclair, D.; Falck, J. *Plantation silviculture in Europe*; Oxford University Press: Oxford, UK, 1997. [CrossRef]
150. Brunet, K. Airflow over forest. In *Living with Storm Damage to Forest. What Science Can Tell Us*; Gardiner, B., Schuck, A., Schelhaas, M.J., Orazio, C., Blennow, K., Nicoll, B., Eds.; European Forest Institute: Joensuu, Finland, 2013; Volume 3, pp. 25–30.
151. Teagasc. Reducing Windthrow Losses in Farm Forestry. Available online: https://www.teagasc.ie/crops/forestry/research/reducing-windthrow-losses-in-farm-forestry/ (accessed on 12 November 2023).
152. Li, Y.Y.; Rahardjo, H.; Irvine, K.N. Effect of weather conditions on leans of one Eugenia Grandis tree in Singapore. *Urban For. Urban Green.* **2019**, *43*, 126375. [CrossRef]
153. Fan, C.C.; Su, C.F. Effect of soil moisture content on the deformation behaviour of root-reinforced soils subjected to shear. *Plant Soil* **2009**, *324*, 57–69. [CrossRef]
154. Dupuy, L.X.; Fourcaud, T.; Lac, P.; Stokes, A. A generic 3d finite element model of tree anchorage integrating soil mechanics and real root system architecture. *Am. J. Bot.* **2007**, *94*, 1506–1514. [CrossRef]
155. Kim, Y.; Rahardjo, H.; Tsen-Tieng, D.L. Stability analysis of laterally loaded trees based on tree-root-soil interaction. *Urban For. Urban Green.* **2020**, *49*, 126639. [CrossRef]
156. Rahardjo, H.; Satyanaga, A.; Leong, E.C.; Santoso, V.A.; Ng, Y.S. Performance of an instrumented slope covered with shrubs and deep-rooted grass. *Soils Found.* **2014**, *54*, 417–425. [CrossRef]
157. Yang, M.; Défossez, P.; Danjon, F.; Fourcaud, T. Tree stability under wind: Simulating uprooting with root breakage using a finite element method. *Ann. Bot.* **2014**, *114*, 695–709. [CrossRef] [PubMed]
158. Chen, C.Y.; Martin, G.R. Soil-structure interaction for landslide stabilizing piles. *Comput. Geotech.* **2002**, *29*, 363–386. [CrossRef]
159. Saunderson, S.E.T.; England, A.H.; Baker, C.J. A dynamic model of the behaviour of sitka spruce in high winds. *J. Theor. Biol.* **1999**, *200*, 249–259. [CrossRef]
160. Mitchell, S.J.; Lanquaye-Opoku, N.; Modzelewski, H.; Shen, Y.; Stull, R.; Jackson, P.; Murphy, B.; Ruel, J.C. Comparison of wind speeds obtained using numerical weather prediction models and topographic exposure indices for predicting windthrow in mountainous terrain. *For. Ecol. Manag.* **2008**, *254*, 193–204. [CrossRef]
161. Kamimura, K.; Gardiner, B.; Kato, A.; Hiroshima, T.; Shiraishi, N. Developing a decision support approach to reduce wind damage risk: A case study on sugi (*Cryptomeria japonica* (L.f.) D.Don) forests in Japan. *Forestry* **2008**, *81*, 429–445. [CrossRef]
162. Chen, S.H.; Jakeman, A.J.; Norton, J.P. Artificial Intelligence techniques: An introduction to their use for modelling environmental systems. *Math. Comput. Simul.* **2008**, *78*, 379–400. [CrossRef]
163. Kourtz, P. Artificial-intelligence—A new tool for forest management. *Can. J. For. Res.-Rev. Can. Rech. For.* **1990**, *20*, 428–437. [CrossRef]
164. Lagerquist, R.; Flannigan, M.D.; Wang, X.L.; Marshall, G.A. Automated prediction of extreme fire weather from synoptic patterns in northern Alberta, Canada. *Can. J. For. Res.* **2017**, *47*, 1175–1183. [CrossRef]
165. Haq, M.A.; Rahaman, G.; Baral, P.; Ghosh, A. Deep Learning Based Supervised Image Classification Using UAV Images for Forest Areas Classification. *J. Indian Soc. Remote Sens.* **2021**, *49*, 601–606. [CrossRef]
166. Hao, Y.S.; Widagdo, F.R.A.; Liu, X.; Quan, Y.; Liu, Z.G.; Dong, L.H.; Li, F.R. Estimation and calibration of stem diameter distribution using UAV laser scanning data: A case study for larch (*Larix olgensis*) forests in Northeast China. *Remote Sens. Environ.* **2022**, *268*, 112769. [CrossRef]
167. Hanewinkel, M. Neural networks for assessing the risk of windthrow on the forest division level: A case study in southwest Germany. *Eur. J. For. Res.* **2005**, *124*, 243–249. [CrossRef]
168. Hanewinkel, M.; Zhou, W.C.; Schill, C. A neural network approach to identify forest stands susceptible to wind damage. *For. Ecol. Manag.* **2004**, *196*, 227–243. [CrossRef]
169. Hart, E.; Sim, K.; Kamimura, K.; Meredieu, C.; Guyon, D.; Gardiner, B. Use of machine learning techniques to model wind damage to forests. *Agric. For. Meteorol.* **2019**, *265*, 16–29. [CrossRef]
170. Jahani, A.; Saffariha, M. Modeling of trees failure under windstorm in harvested Hyrcanian forests using machine learning techniques. *Sci. Rep.* **2021**, *11*, 1124. [CrossRef] [PubMed]

171. Montesinos López, O.A.; Montesinos López, A.; Crossa, J. Fundamentals of Artificial Neural Networks and Deep Learning. In *Multivariate Statistical Machine Learning Methods for Genomic Prediction*; Montesinos López, O.A., Montesinos López, A., Crossa, J., Eds.; Springer International Publishing: Cham, Switzerland, 2022; pp. 379–425. [CrossRef]
172. Kamimura, K.; Gardiner, B.; Dupont, S.; Guyon, D.; Meredieu, C. Mechanistic and statistical approaches to predicting wind damage to individual maritime pine (*Pinus pinaster*) trees in forests. *Can. J. For. Res.* **2016**, *46*, 88–100. [CrossRef]
173. Dupont, S.; Défossez, P.; Bonnefond, J.M.; Irvine, M.R.; Garrigou, D. How stand tree motion impacts wind dynamics during windstorms. *Agric. For. Meteorol.* **2018**, *262*, 42–58. [CrossRef]