frontiers in Forests and Global Change

TYPE Review
PUBLISHED 02 April 2026
DOI 10.3389/ffgc.2026.1746510

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OPEN ACCESS

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RECEIVED 14 November 2025
REVISED 02 March 2026
ACCEPTED 11 March 2026
PUBLISHED 02 April 2026

CITATION
Kuzee T, Locatelli T, Robinson S, Perks MP, Burgess PJ and Khouakhi A (2026) A review on the resilience of temperate forests to extreme precipitation and wind events. *Front. For. Glob. Change* 9:1746510. doi: 10.3389/ffgc.2026.1746510

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A review on the resilience of temperate forests to extreme precipitation and wind events

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Temperate forests which provide vital ecosystem functions through the provision of timber resources, carbon sequestration, and recreational value are increasingly affected by extreme weather events, with wind and precipitation extremes (drought and excessive rainfall) posing significant challenges to forest resilience. This review synthesizes current knowledge on the impacts of wind and precipitation extremes on temperate forests, focusing on compound disturbance interactions, vulnerability factors, and recovery processes through a systematic review of 248 sources. Research concentrated on single disturbances, with drought and wind most frequently studied. Moreover, there is a focus on short-term resistance and recovery, with limited evidence on reorientation (i.e., transition to a new ecosystem state). Furthermore, we assess recent advancements in disturbance modeling, remote sensing, and machine learning for detecting and forecasting damage from these events. The key observation is that remote sensing and disturbance models are rapidly growing areas of study, but they are skewed toward single disturbance types and are highly specific to particular ecosystems. Machine learning has reduced this specificity and allowed for more data integration in recent years, although small-scale disturbance detection in remote sensing remains challenging owing to data availability limitations. By integrating climate, ecological, and management perspectives, this review concludes that future research and practice must explicitly integrate compound events into multi-hazard models, supported by strengthened long-term (remote sensing) monitoring networks, and adopt adaptive silvicultural strategies. Improved monitoring and multi-hazard modeling will enhance early warning, attribution, and predictive capacity, thereby supporting risk-informed decision-making and the design of targeted adaptive management interventions. Such shifts are essential to sustain ecosystem services and enhance forest resilience under increasing climate extremes.

KEYWORDS
adaptive management, compound events, drought, forest resilience, modeling, remote sensing, waterlogging, windthrow

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1 Introduction

Temperate forests are becoming more vulnerable to impacts of increasingly frequent and severe extreme weather events under climate change (Van Den Hurk et al., 2023; Patacca et al., 2023; Ridder et al., 2020; Tew et al., 2024). Notable examples exist for European temperate forests, which in recent decades have experienced a higher incidence of extreme storms (Forzieri et al., 2020), droughts (Buras et al., 2020a; Gazol and Camarero, 2022), and floods (Patacca et al., 2023; Ridder et al., 2020) disrupting the structure and function of forest ecosystems, including ecosystem services (Barrere et al., 2023; Forest Research, 2024; Lecina-Diaz et al., 2024; Seidl et al., 2017; Vacek et al., 2023). Despite wind disturbances accounting for 40–50% of European forest damage (Patacca et al., 2023), the stochastic nature of windstorms means that wind risk has received limited attention (Albrich et al., 2020). Across Europe, exposure to frequent individual high-intensity wind events puts forests at significant risk (Manning et al., 2023; Mölter et al., 2016; Xu et al., 2024). While historically considered in isolation, single impact events are increasingly viewed as interconnected (Bastos et al., 2023; Kleinman et al., 2019; Zscheischler et al., 2020), and are referred to as compound events (CEs; Leonard et al., 2014; Raymond et al., 2020; Zscheischler et al., 2018; Zhang et al., 2021a).

In this context, forest resilience is a key concept, here defined as the capacity of an ecosystem to resist, recover, and reorient from disturbances (Bathiany et al., 2024; Holling, 1973; Yi and Jackson, 2021). Resilience can be further understood through two complementary perspectives: engineering resilience, which focuses on the speed and efficiency of returning to a pre-disturbance state, and ecological resilience, which refers to the capacity of the system to absorb disturbance impacts while potentially shifting to alternative (stable) states that can still sustain functionality (Albrich et al., 2020; Bathiany et al., 2024; Mori, 2016). Forest characteristics, such as species diversity, successional dynamics, and structural characteristics, strongly influence both engineering resilience (henceforth resistance and recovery) and ecological resilience (henceforth reorientation). Given the capacity of forest characteristics to moderate disturbance impacts, management plays a key role in determining forest resilience. Management practices including different thinning strategies (Chagnon et al., 2025; Meijers et al., 2025), stocking density (Meijers et al., 2025; Quine et al., 1995), species selection (Kleinman et al., 2019), and landscape design (e.g., edge management for wind; Gardiner and Stacey, 1996) can also influence forest stability by modifying forest exposure to, e.g., extreme drought or wind gusts (Finér et al., 2024; Vacek et al., 2023).

Provisioning services, such as timber, are directly impacted, for instance, by large windthrow events that result in substantial timber losses and disruptions to forest operations (Forest Research, 2024; Seidl and Blennow, 2012), thereby reducing timber value (Schwarzbauer and Rauch, 2013; Udali et al., 2021), and increasing management costs (Augustynczik et al., 2020; Bréda and Brunette, 2019; Kärhä et al., 2018). Regulating services, particularly carbon sequestration and water management are also at risk, as windthrow events lead to tree mortality, releasing stored carbon and reducing a forest's carbon sink potential (Kleinman et al., 2019; Seidl et al., 2017). Additionally, in regions such as the UK, increasing winter precipitation extremes exacerbate issues of waterlogging, threatening forests' capacity to buffer flooding (Lecina-Diaz et al., 2021; Simmonds et al., 2022). Cultural services, including recreation and aesthetic value, may be hindered by damaged landscapes and safety risks (Blennow and Persson, 2013). Supporting services, such as nutrient cycling, may also be disrupted when disturbances alter forest structure and soil microbial activity (Chen et al., 2025).

Modeling the impacts of extreme events provides a means to assess forest vulnerability, quantify climate change risks (i.e., changes in frequency, intensity, and spatial extent under different climate change scenarios), and inform adaptive management to maximize ecosystem services. Disturbance models such as ForestGALES have been developed to calculate risk metrics and for spatial simulations of windthrow dynamics (Hale et al., 2015; Locatelli et al., 2022; Seidl et al., 2012), while drought has also been analyzed using process-based approaches including iLand, 3-PG, and other growth models (Landsberg and Waring, 1997; Pretzsch et al., 2015; Seidl et al., 2012). Remote sensing has increasingly complemented these modeling approaches, offering near-real-time disturbance detection and long-term forest monitoring, with radar (e.g., Sentinel-1), optical (e.g., Sentinel-2), and LiDAR data shown to be particularly effective in detecting windthrow (Watt et al., 2025) and drought-induced canopy stress (Rao et al., 2019). Meanwhile, very-high-resolution and hyperspectral satellites are poised to become dominant future imagery resources. Nevertheless, integration between remote sensing and process-based models remains limited, and only a few studies capture the combined impacts of multiple stressors, despite CEs having produced more severe and less predictable consequences for forest ecosystems (Csilléry et al., 2017; Díaz-Yáñez et al., 2019).

Although a growing number of studies have begun to address the combined impacts of multiple stressors, synthesizing their findings remains challenging due to differences in scale, focus, and the way disturbance interactions are defined. Earlier reviews established key principles of forest resilience but largely examined single hazards or short-term processes (Albrich et al., 2020; Yi and Jackson, 2021), while later syntheses emphasized the increasing importance of disturbance interactions under a changing climate (Kleinman et al., 2019; Seidl et al., 2017). More recently, the CE framework has advanced understanding of concurrent and cascading extremes (Bastos et al., 2023; Zscheischler et al., 2018, 2020), highlighting the interconnected nature of climate drivers and ecosystem responses. Yet few studies have systematically linked compound precipitation and wind extremes to the broader dimensions of forest resilience.

This review aims to explore the individual and combined ecological and socio-economic impacts and perspectives of precipitation extremes including both deficits (drought) and overabundance (soil waterlogging) as well as wind-related disturbances (Figure 1). This review synthesizes current state-of-the-art knowledge primarily drawn from studies of temperate forests, guided by the following objectives:

1. To describe the changes in extreme precipitation and wind event trends and their impact on temperate forests through an individual and CE-focused framework.
2. To identify the characteristics of temperate forests and their management that determine: (i) their resistance, (ii) recovery,

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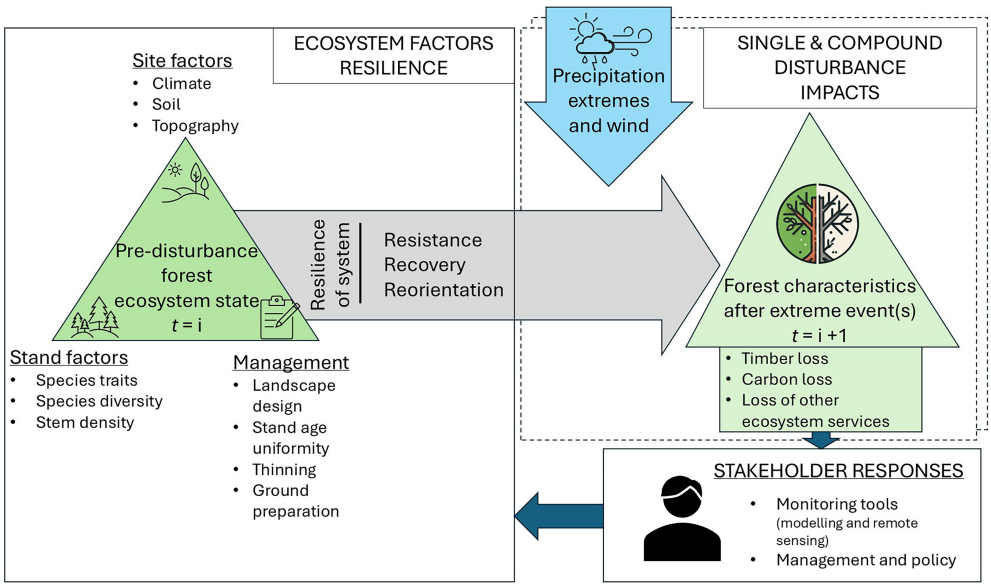

FIGURE 1
Conceptual framework illustrating forest ecosystem resilience to (compound) disturbances from precipitation extremes (i.e., drought and waterlogging) and extreme wind. Pre-disturbance forest ecosystem state (t = i) shape the system's resilience, which determines its capacity for resistance, recovery, and/or re-orientation (i.e., adaptation or transformation) after extreme events. These disturbances alter forest characteristics (i.e., at t = i + 1), resulting in impacts on ecosystem services. Stakeholder responses feed back into the system to inform decisions that influence future resilience and disturbance outcomes.

and (iii) reorientation in response to extreme precipitation and wind events.

3. To illustrate how remote sensing and modeling tools can support forest managers and researchers in enhancing the understanding of temperate forest resilience to extreme precipitation and wind events.

2 Methodology

2.1 Literature search strategy

We conducted a literature search to review individual and compound effects of extreme wind and precipitation events on temperate forests using Scopus and Google Scholar. The search was restricted largely to peer-reviewed articles, with some additional sources related to model descriptions from research institutions (e.g., UK Met Office; Sanderson et al., 2012) and governmental reports (e.g., UK Forestry Commission, EU; Forest Research, 2024; Gardiner et al., 2013). The timescale was left unrestricted to highlight the changing conceptualization and understanding of extreme events and their impacts on forest ecosystems.

2.2 Screening process

The search captured both single and compound extreme events, as well as the approaches to studying them (Figure 2). The searches targeted literature in the domains of forest ecology, remote sensing, disturbance modeling, and climate change impacts. The Boolean search strings were structured around three core thematic pillars: (1) compound and extreme events, (2) forest vulnerability and resilience, and (3) tools or frameworks for detection, modeling, and management of the impact of extreme events on forest resources.

From over 670 studies identified in the initial search, articles were screened in a two-stage process based on four inclusion criteria (Figure 2). First, titles, abstracts, and keywords were screened to exclude studies that were clearly outside the thematic scope (Appendix). Second, full-text screening was applied to assess whether studies' overall relevance to the review objectives, resulting in 248 studies retained for analysis.

Following eligibility screening, retained studies were classified according to four analytical criteria describing their contribution to understanding extreme events and forest resilience. These criteria were evaluated independently and were not applied sequentially:

1. Does the study synthesize or provide new insights into current research on extreme events and their impacts on forests?
2. Does the study explore how local factors are affected by extreme events?
3. Does the study identify vulnerability factors that modify forest resilience to extreme events?
4. Does the study explore current or future remote sensing or (machine learning) modeling techniques to analyze extreme events?

Because studies frequently addressed multiple research dimensions, criteria were applied non-exclusively, and individual

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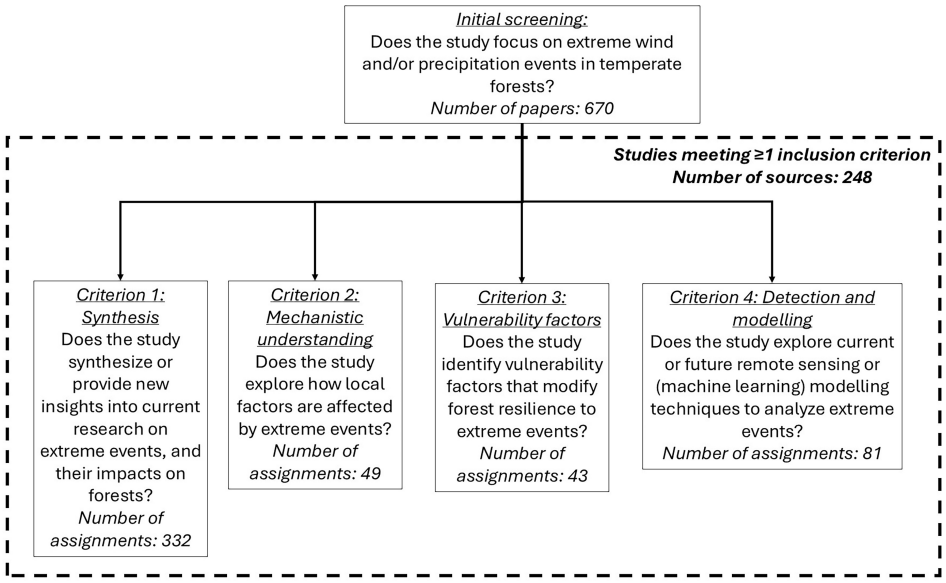

FIGURE 2
Decision tree diagram illustrating the journal article identification and screening workflow. See Appendix for the search strings. Studies were identified through database searches and additional snowballing (screening of reference lists of selected papers; n = 68). Following screening, 248 unique sources were retained for inclusion in the review. Retained studies were subsequently classified according to four analytical criteria describing their contribution to the review objectives. All screened studies were assessed against four inclusion criteria applied independently and non-sequentially, and studies could satisfy multiple criteria (criteria 2–4); therefore, category totals exceed the number of unique included studies. Numbers associated with each criterion represent non-exclusive classification assignments rather than additional or sequential inclusion steps.

studies could be assigned to more than one category. Reported counts therefore represent thematic classifications given the multifaceted nature of compound events, and totals across criteria exceed the number of retained studies shown in Figure 2. In particular, synthesis-oriented contributions (Criterion 1) were recorded at the level of thematic coverage, meaning that individual studies contributing synthesis insights (e.g., for various hazards or resilience aspects) across multiple extreme event contexts could generate multiple thematic assignments.

2.3 Extraction and evidence analysis

After applying these criteria, with the additional discovery of articles through snowballing (i.e., applying selection criteria to literature in references; n = 68) screened articles, 248 sources were included in the review, representing diverse methodologies, spatial scales, temporal contexts, and applications. The literature predominantly originates from European temperate forests (n = 137), but some research is also global (n = 59) or from Asia (n = 11) and North America (n = 15; Figure 3). The sources from temperate forests are focused on a mix of disturbance impacts and detection (through remote sensing), while literature from the tropics (n = 13) was used solely for the remote sensing application to detect disturbances in forests.

To evaluate the strength of evidence systematically, each study was categorized in a table by publication date, disturbance type, methodological approach (e.g., modeling, field study, remote sensing, review), sample size, and statistical treatment where applicable. We also recorded the type of signal reported (e.g., mortality, growth response, resilience metrics) and, where available, its quantitative strength. This allowed us to compare similar evidence metrics across studies on to one another and to identify where findings are robust, limited (including data types and metrics used), or inconsistent.

2.4 Structure of the review

The remaining part of this paper is divided into four sections: Section 3 examines the responses of forest resilience to weather extremes, including resistance, recovery, and re-orientation. Section 4 discusses the changing effect of extreme events on temperate forests. Section 5 examines developments in extreme event detection and modeling, while Section 6 identifies research gaps and suggests directions for future research.

3 Forest resilience

Forest resilience represents the capacity of a system to withstand, absorb, and adapt to disturbances, often prescribed through three dimensions: resistance, recovery, and reorientation (Fuller and Quine, 2016; Holling, 1973). Resistance refers to the ability of a forest to endure disturbance with minimal change; recovery describes the process through which a forest regains structure, function, or ecosystem services after disturbance; and

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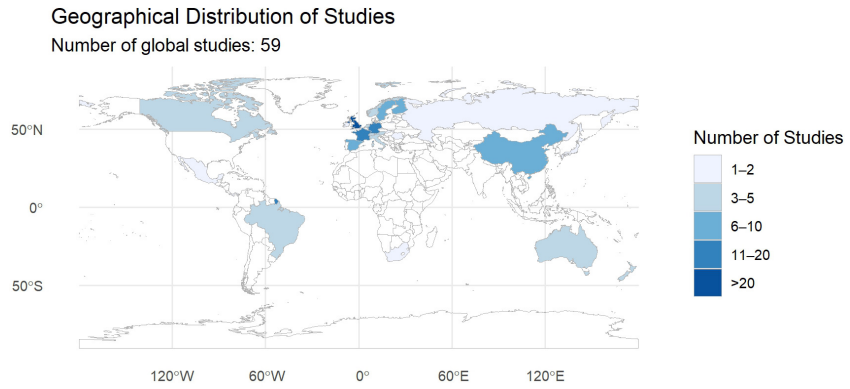

FIGURE 3
Map of the literature references, which displays the geographical distribution of studies on extreme wind and precipitation disturbances. Research is heavily concentrated in European temperate regions, with few studies in North America or Asia. The few studies in the tropics are focused solely on the use of remote sensing for disturbance detection, and so no inferences on the disturbance mechanisms are based on these sources. Additionally, a subset of studies was classified as "global" in scope (n = 59), highlighting broad-scale syntheses and modeling efforts; these are not attributed to individual countries and area therefore excluded from country-level totals. In addition, some studies span multiple countries, meaning country-level totals do not sum the total number of references (n = 248). The uneven geographical coverage suggests an important research gap, as (compound) extreme event dynamics may manifest differently in underrepresented regions.

reorientation captures long-term adjustments or shifts in ecosystem composition to a new state. The literature was categorized based on used metrics, which meant it was particularly challenging to classify disturbances studied as CEs, given that the term was not explicitly used in many studies, highlighting that the paradigm shift from individual disturbance to CEs is still underway. Nonetheless, literature was categorized as studying CEs where two or more interacting disturbances were investigated. The categorization indicates that studies addressing forest resilience are focused on resistance and recovery, whereas no articles on reorientation were found (Figure 4). This is likely due to reorientation transitions occurring over longer timescales and are thus harder to observe empirically or simulate within existing study frameworks. The imbalance between resistance-recovery and reorientation is particularly evident for CEs (~10 journal papers), where most research focuses on reviewing short-term resistance and recovery responses (e.g., immediately post-drought or bark beetle attack), neglecting long-term shifts in forest structure and function.

3.1 Site factors influencing forest vulnerability

Forest risk resulting from climate-driven disturbances is partially influenced by local site factors (i.e., soil, topography). It is important to clarify key terms (van Oijen, 2024): hazard denotes the probability of exposure to potentially damaging physical event (e.g., windstorms); vulnerability represents the susceptibility of a unit to be damaged (e.g., forest type or ecosystem services; (Calvin et al., 2023). Together, these components interact to determine the forest's overall risk (i.e., probability of hazard relative to the system's vulnerability; van Oijen, 2024). The site factors therefore affect the resistance, recovery, and reorientation of temperate forests similarly.

3.1.1 Soil characteristics

Soil type and soil properties collectively influence a forest's response to extreme events (Carminati and Javaux, 2020; Gardiner, 2021; Paterson and Mason, 1999) and is therefore key for forest managers when guiding establishment and management. Sandy soils, for instance, have low water retention capacities (Paterson and Mason, 1999; Défossez et al., 2021), while clay soils, quite common in e.g., the UK (UKSO, 2025), are prone to waterlogging (Paterson and Mason, 1999), where excess water impedes root aeration and compromises tree health (Konôpka et al., 2010; Scottish Forestry, 2021). Peaty soils (> 50 cm depth), prevalent in many upland forested areas, have a generally high-water table, but fluctuations in water table level can result in periods of excessive desiccation or saturation, both of which reduce tree (root) growth and stability (Armstrong et al., 1976; Konôpka et al., 2010). Good growth is expected on brown earth and cultivated gley soils, while calcareous soils require some interventions, and there is only minimal growth potential on skeletal and littoral soils (Scottish Forestry, 2021). Soil depth can impact the rooting capacity of vegetation and therefore stability (Yang et al., 2014, 2018). Mechanical cultivation practices (plowing, mounding, ripping) were once used to enhance rooting but are now restricted or discouraged in many countries to reduce soil erosion and carbon loss (in peaty soils; Friggens et al., 2020; European Commission, 2023), so silvicultural choices at establishment and restocking must balance production-oriented management with minimal soil disturbance (Forest Research, 2023; Scottish Forestry, 2021; Paterson and Mason, 1999).

3.1.2 Topography and exposure factors

Topography—including slope, elevation, and aspect—affects forest risk by influencing wind patterns and microclimate (Díaz-Yáñez et al., 2019; Forzieri et al., 2021). Higher-elevation and wind-exposed sites, common in UK commercial forestry (e.g., in Scotland), are more prone to windthrow (Forest Research, 2024;

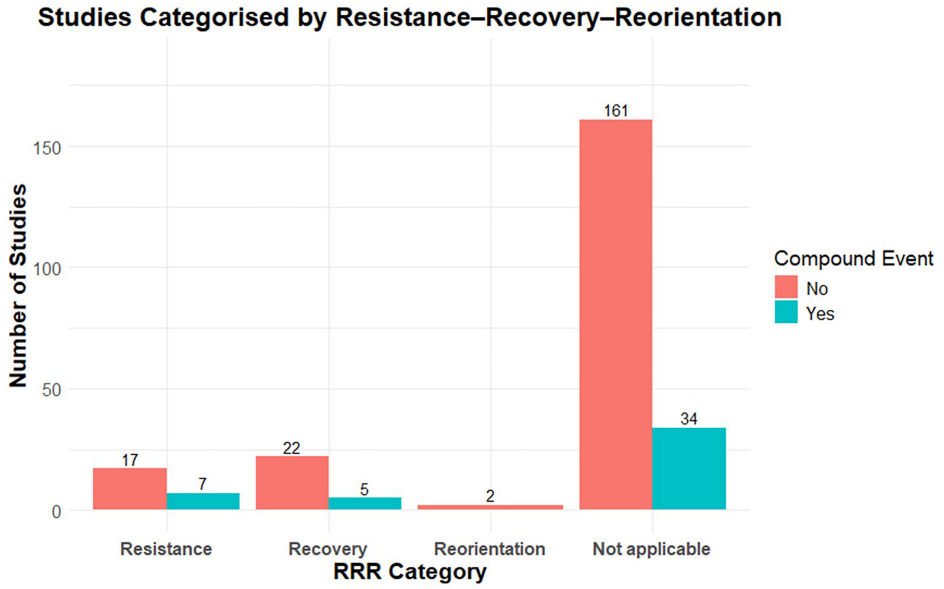

FIGURE 4
Literature referenced organized per resilience category (i.e., resistance, recovery, reorientation, or if not classifiable, not applicable). The sources are also separated by whether they studied single extreme or compound events.

Quine et al., 1995). Aspect also affects soil moisture and temperature, influencing tree growth and form, and therefore vulnerability to wind damage (Primicia et al., 2015).

Forest edges are especially vulnerable due to increased wind turbulence and the lack of shelter (Gardiner, 2021), while additionally being more at risk to drought (Sturm et al., 2025). Trees newly exposed by harvesting or windthrow are at heightened risk, often lacking structural adaptations, and forming so-called "brown edges" with the canopy concentrated at the top of the tree (Ní Dhubháin and Farrelly, 2018; Poëtte et al., 2017). However, wind-exposed trees can adapt over time through a process known as thigmomorphogenesis (Dlouhá et al., 2025; Telewski and Jaffe, 1986). Management can reduce topography-related risk via site-specific windbreaks, buffer zones, and contour planting (Gardiner and Stacey, 1996; Paterson and Mason, 1999).

3.1.3 Climate and microclimate

Tied to topography, local climate conditions, including temperature and precipitation regimes, play a pivotal role in shaping forest vulnerability to extreme events by modifying growth conditions and overall tree fitness. Wind acts not only as a disturbance, but also as a developmental force that influences tree morphology and biomechanics (Brunet et al., 2013; Gardiner et al., 2016; Telewski and Jaffe, 1986). Persistent wind exposure reduces height growth while promoting thicker stems, greater stem taper, and stronger root systems, collectively increasing mechanical stability (Stokes et al., 1995; Telewski and Jaffe, 1986). Adaptive responses such as buttressing (i.e., local thickening of the stem base; Nicoll and Ray, 1996), asymmetric root radial development toward the stressor stimuli (Nicoll et al., 2019), and the formation of (tension or compression) reaction wood allows trees to compensate for imbalances in their posture or support. However, these adaptations develop gradually following a period of temporary stability loss, as is the case for internal trees when edge trees are removed (Nicoll and Ray, 1996; Quine and Gardiner, 2007). Crown asymmetry can streamline trees in the direction of dominant winds—reducing drag, yet it can also increase drag from wind from unusual directions (Telewski and Jaffe, 1986; Watt et al., 2005), as seen recently in the case of Storm Arwen in the UK in 2021 (Forest Research, 2022). Microclimatic conditions vary significantly across a small scale. This can be due to the topography, with sheltered valleys receiving partial protection from the wind, but also potentially trapping cold air (Fortuin et al., 2021).

3.2 Resistance

Forest resistance plays a critical role in limiting the impact of a hazard and is closely linked to vulnerability through stand factors, which uniquely affects recovery and reorientation as well (Yi and Jackson, 2021). Resistance reflects adaptive capacity of a species or stand to a hazard, depending on when a threshold (e.g., critical wind speed) is exceeded (Holling, 1973; van Oijen, 2024).

3.2.1 Tree and stand factors

Stand structure can be modified through management, particularly through changes to species composition and structural diversity (e.g., canopy layers and canopy cover.; Figure 5; Barrere et al., 2023; Poorter et al., 2024). Management interventions such as different selective thinning interventions (i.e., low, crown, intermediate, line thinning, etc.), harvesting, or species selection offer pathways to influence gradual forest development changes

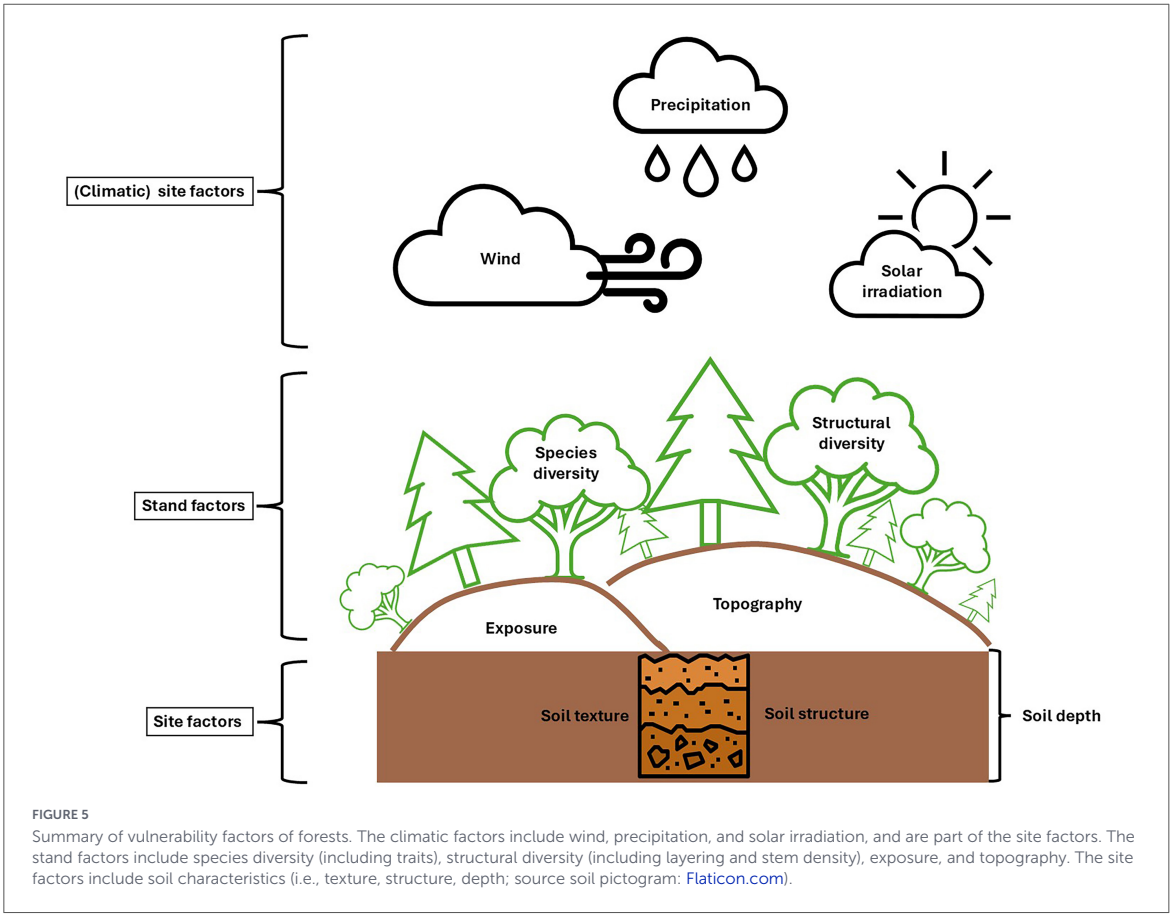

FIGURE 5
Summary of vulnerability factors of forests. The climatic factors include wind, precipitation, and solar irradiation, and are part of the site factors. The stand factors include species diversity (including traits), structural diversity (including layering and stem density), exposure, and topography. The site factors include soil characteristics (i.e., texture, structure, depth; source soil pictogram: Flaticon.com).

and, consequently, vulnerability to disturbances (Broadmeadow, 2002; Kerr and Haufe, 2011).

3.2.1.1 Species composition and diversity

Mixed-species forests generally exhibit greater resistance to extreme events compared to monocultures, due in part to the diversity of functional traits such as rooting depth (Table 1), canopy architecture, and drought tolerance (Cardoso et al., 2025; Hao et al., 2025; Niinemets and Valladares, 2006). This functional complementarity can buffer the system against stress by distributing resource uptake across time and space (Zuppinger-Dingley et al., 2014). However, there is evidence that certain mixtures do not increase resistance to events such as spring droughts (Ovenden et al., 2022).

In contrast, monocultures grown on suboptimal soils are more vulnerable due to their structural and functional homogeneity (Cardoso et al., 2025; Paterson and Mason, 1999). Uniform rooting depths mean that trees draw water and nutrients from the same soil layers, intensifying drought stress (Finér et al., 2024), and increasing vulnerability to uprooting because of the smaller and finite space available for root anchorage. The lack of genetic and species diversity in monoculture forests also reduces their adaptive capacity, making these forests more prone to secondary disturbances such as pest outbreaks or fungal infections (Knutzen et al., 2023; Rouault et al., 2006).

While strong evidence for root stratification exists in tropical systems (Schwendenmann et al., 2015), its role in temperate forests is still emerging and may be most pronounced in mixtures of conifers and broadleaves. For instance Wambsganss et al. (2021), found that species mixing in European forests increased the length of absorptive fine roots, suggesting a shift in belowground foraging strategy rather than clear vertical separation. These findings highlight the importance of species diversity not only above ground but also in root system architecture, reinforcing its importance in enhancing forest resilience under climate stress.

3.2.1.2 Structural characteristics

The structural attributes of forest stands (e.g., age distribution, density, and canopy layering) influence extreme event impacts. Structurally uniform stands distribute wind loads evenly due to reduced canopy roughness, but are prone to cascading failures during strong storms (Quine et al., 1995). In contrast, uneven-aged stands, with varied canopy layers and structural diversity, are more resilient as they dissipate wind energy effectively and support recovery through diverse microhabitats (Finér et al., 2024; Mason, 2002; Zuppinger-Dingley et al., 2014); in Central Europe, a modeling study showed that disturbed forest stock decreased by as much as 50% in diverse stands (Dobor et al., 2020b).

TABLE 1 Summary of rooting and water uptake patterns depending on species composition.

Species	Stand context	Root/water uptake pattern	References
Beech	Mixed with spruce	Deepened, intensified roots, greater deep-water uptake	(Schume et al., 2004)
Spruce	Mixed with beech	More shallow roots, reduced water uptake	(Schume et al., 2004)
Red maple	Mixed species	Variable uptake depth depending on neighbors	(Sobota et al., 2025)
Red maple	Monoculture	Fixed rooting depth, less plasticity	(Sobota et al., 2025)

Stand density further modulates vulnerability: high density can exacerbate competition for resources during droughts and reduce overall water availability through increased canopy interception (Lloret and Kitzberger, 2018; Schume et al., 2004). For example, *Picea abies* (L.) H. Karst. forests in Romania suggests that high-density stands exhibit stronger climate-growth dependencies, particularly in response to precipitation variability (i.e., droughts; Primicia et al., 2015). For wind disturbances, denser stands can reduce wind penetration and provide mutual crown support (Pukkala et al., 2016), but often produce tall, slender trees that heighten individual and stand-level vulnerability (Wonn and O'hara, 2001). In contrast, lower-density stands promote stronger taper and deeper rooting, improving mechanical stability yet exposing maladapted trees to greater wind stress (Morimoto et al., 2021).

Some structural management practices, e.g., (early) thinning and selective harvesting, can enhance stand wind resistance (Broadmeadow, 2002; Ní Dhubháin and Farrelly, 2018). Nicoll et al. (2019) found that thinning increased radial growth in spruce and altered biomass allocation patterns toward root and lower stem development. In a modeling study in Germany, after height and species, removals—including selective thinning—explained up to 20% of storm damage (Albrecht et al., 2012), which is likely due to thinning promoting structural growth and stem development. However, it is well known that thinning temporarily destabilizes the canopy, increasing wind exposure and turbulence for about 2–10-years (Brunet et al., 2013). The spatial arrangement of trees within a stand also influences vulnerability, offering opportunities for tailored management approaches based on the local topography and management costs (Broadmeadow, 2002; Gardiner and Stacey, 1996).

3.2.2 Compounding event risks

When assessing risk, understanding vulnerability thresholds—and the interactions between thresholds of different disturbance agents—is essential (Holling, 1973; van Oijen, 2024). For example, when high stand density coincides with poor drainage or drought-stricken soils and extreme wind events, the resulting damage can exceed the sum of the individual stressors (Temperli et al., 2013). Compound risk interaction can result in non-linear responses, where small increases in hazard can trigger disproportionate impacts once a threshold is crossed. Thresholds are not fixed, varying depending on species traits, site conditions, stand structure, and regional climate regimes. For instance, shallow-rooted trees on compacted or poorly drained soils may experience a tipping point in wind resistance at much lower wind speeds compared to deep-rooted individuals of the same tree species on well-drained sites (Morimoto et al., 2021; Nicoll et al., 2006). Likewise, recurrent exposure to sub-lethal levels of stress—such as from drought or waterlogging—can lower resistance over time, making systems more sensitive to future hazard exposure (Coutts and Philipson, 1977; Nisbet et al., 1989; van Oijen, 2024). However, this depends entirely on the type of hazard, with recurrent wind disturbance, for instance, promoting adaptive growth (Nicoll and Ray, 1996; Quine et al., 1995), which could change the interaction with other hazards.

3.3 Recovery

Recovery from forest disturbances relies on a complex interplay of site and stand factors (including management objectives) (Bastos et al., 2023; Kleinman et al., 2019), influencing the trajectory, scale, rate of recovery, and their combined effects determine a forest's ability to regain ecological functionality (Fuller and Quine, 2016; Gann et al., 2019; Holling, 1973).

3.3.1 Species diversity

Higher species diversity in forests can increase the capacity for recovery after disturbance due to the larger variety of traits. For instance, the creation of canopy gaps can allow the regeneration of shade-tolerant species thereby increasing species and/or structural richness (Smart et al., 2014). Forests with intact seed banks, a developed understory, or nearby undisturbed areas, providing seed resources for natural regeneration, may recover more effectively (Camarero et al., 2021; Poorter et al., 2024). In cases where such a diverse seed bank is absent due to the long-term presence of monocultural production forest, planting may be required (Poorter et al., 2024). Structural complexity (i.e., variation in tree height, age, and density) further aids recovery by offering diverse microhabitats and niches (Holling, 1973). This is also relevant in production forests, in which advanced regeneration of the understory can be the primary path of recovery, as in advanced shelterwood and Continuous Cover Forestry (CCF) systems (Taeroe et al., 2019). The benefits of each management system must be weighed against potential trade-offs, which might include reduced timber yield or carbon sequestration in some mixed-species stands—where higher species diversity may not always align with production-focused objectives (Häyhä and Franzese, 2014), although some evidence exists of overyielding in mixed-species stands (Leslie and Short, 2025).

3.3.2 Adaptive management

Management practices can also enhance forest recovery (Dobor et al., 2020b; Lecina-Diaz et al., 2021; Vacek et al., 2023). In wind-damaged forests, timely and careful salvage logging can reduce the risk of potentially catastrophic pest outbreaks (Dobor et al., 2020a; Stadelmann et al., 2013) and create open spaces for

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regeneration (Gardiner et al., 2013). However, it may potentially increase future windthrow risk due to increased edge exposure (Gardiner and Stacey, 1996) and reduced mutual sheltering among remaining trees (Locatelli et al., 2016; Schelhaas et al., 2007; Figure 6). Similarly, thinning operations and drainage maintenance have been proposed as effective strategies to mitigate future impacts of windthrow and waterlogging, and thus improve recovery rates (Finér et al., 2024; Ní Dhubháin and Farrelly, 2018). However, site drainage operations have fallen out of favor or been banned in peaty soils recently due to the potential impacts that would result in increased greenhouse gas emissions from the soil (Friggens et al., 2020).

3.4 Reorientation

Reorientation following forest disturbances refers to the long-term ecological shifts and adaptations that occur as forests establish new structural, compositional, and functional configurations in response to altered environmental conditions (Fuller and Quine, 2016). Unlike recovery, which implies a return toward pre-disturbance conditions, reorientation reflects the gradual emergence of new trajectories (Holling, 1973; Poorter et al., 2024), further influenced by external drivers, such as climate change, land use policy, and socio-economic demands (Brèteau-Amores et al., 2023; Tew et al., 2024).

3.4.1 Climate

Adequate rainfall and temperatures at a landscape level can accelerate seedling establishment and tree growth compared to drought or extreme weather situations (Gazol and Camarero, 2022). Similarly, favorable microclimatic conditions following windthrow events, such as gap creation, can facilitate rapid regeneration (Smart et al., 2014). However, gap formation introduces a risk of increased evapotranspiration due to soil exposure, increasing temperature variability and evapotranspiration (Camarero et al., 2021; Finér et al., 2024). As a result, shade-tolerant, moisture-demanding species may experience increased stress and reduced seedling survival rates, while light-demanding species may benefit from these conditions (see Niinemets and Valladares, 2006).

3.4.2 Proactive management

Proactive management plays a central role in shaping forest reorientation by anticipating disturbances and guiding ecosystems toward more resilient trajectories, embracing change and uncertainty by using climate-adapted species, structural diversification, and spatial planning.

The importance of genetic diversity is evidenced by varying responses of provenances of the same species (Buras et al., 2020b; Finér et al., 2024). This is because over the entire suitability range of a species, certain genotypes are more adapted to local environmental conditions due to genetic differentiation. For instance, in the Netherlands, provenance testing on 2-year-old oaks found that certain provenances had a higher drought tolerance (Buras et al., 2020b). However, recent research in Britain found that growth and survival differences in provenances of several 6-year-old trees were not significant, suggesting that provenance effects may be context- or age-dependent (Ovenden et al., 2024).

More generally, species choice and stand mixtures can be modified, while delivering against forest management objectives. In production forests, species can be favored that are more tolerant to precipitation extremes (Niinemets and Valladares, 2006), though extreme conditions can still negatively affect tolerant species (Brunner et al., 2015). Meanwhile, more biodiversity-focused forests can be managed under resilient systems like CCF, accounting for potential lower productivity (Gustafsson et al., 2020; Pukkala et al., 2016). However, adoption of CCF in Europe has been slow due to poor institutional and logistical support (e.g., larger log sawmills); (Ireland, 2006), and silvicultural understanding of transforming stands (Hertog et al., 2022; Mason et al., 2022). Intensively managed production forests will likely remain monospecific due to the operational (including e.g., wind risk) and economic constraints (Mason et al., 2022). In such contexts, the potential for natural diversification is low, with recovery prioritizing restocking or artificial regeneration (Everham and Brokaw, 1996; Poorter et al., 2024; Scottish Forestry, 2024). The UK Forestry Standard acknowledges this tension by promoting species and structural diversity at the landscape level (Forest Research, 2023). This raises questions about how CEs might affect a mosaic landscape: multiple stand types may respond differently, and regrowth may hinge on landscape-level planning to buffer risk and maintain continuity of multiple functions.

4 Effects of extreme events on temperate forest

The effects of extreme events, such as precipitation and wind disturbances, on temperate forests are numerous and are mediated by the ecosystem vulnerability (Seidl et al., 2017; Smith et al., 2009; Yi and Jackson, 2021). Precipitation extremes primarily impact hydrological processes and tree physiology (Finér et al., 2024), with cascading effects on water and nutrient acquisition (Armstrong et al., 1976; Finér et al., 2024), and soil property modifications (Défossez et al., 2021; Nisbet et al., 1989). In contrast, wind disturbances often directly affect trees through mechanical stress, resulting in breakage or uprooting (Mitchell, 2013; Ulanova, 2000). In turn, they create canopy and stand gaps (Gardiner, 2021; Ulanova, 2000) and shift stand-level microclimatic conditions (Xenakis et al., 2021). Stand-level disturbance responses are affected by stand density, structural complexity, exposure (Cucchi et al., 2005; Mason, 2002), and species composition, all of which is modulated by management (Albrecht et al., 2012; Cucchi et al., 2005; Mitchell, 2013). Despite the interconnected nature of these drivers, many empirical studies remain selective in how they link them (Figure 7). For instance, remote sensing studies frequently focus on single hazards (e.g., wind extremes), connecting directly to ecosystem impacts (e.g., biomass loss), without fully considering the other processes such as climate change influencing hazard frequency or predisposing forests to structural damage. This gap is reflected in the literature: while ecosystem impacts are most frequently addressed ($n = 125$), the numbers drop for the key earlier and intermediate stages, including structural damage ($n = 61$), physiological impairment ($n = 45$), and management factors



FIGURE 6
Illustration of effects of forest edge vulnerability to extreme wind. Picture on the left highlights the creation of "brown edges" in Harwood Forest, Northumberland, United Kingdom: The canopy is limited to the upper portion of the tree due to limiting light conditions during tree development, whereafter the tree is exposed due to felling or windthrow of neighboring trees. This practice is known to increase the risk of windthrow in these new edges. Picture on the right shows a schematic representation of the two types of edges (Source pictograms: Vecteezy.com).

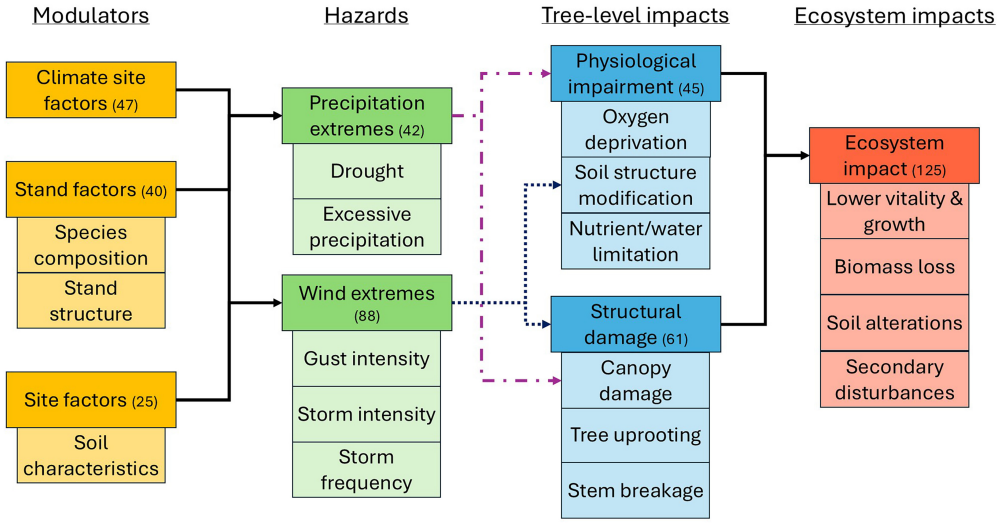

FIGURE 7
Flow diagram of the pathways of impact for drought, excessive precipitation, and wind extremes. This scales down from large-scale modulators (yellow), through hazards (green), tree-level impacts (blue), and the ecosystem impacts (red). Colored arrows highlight the connection between drivers and local hazards for precipitation extremes (purple arrows) and wind extremes (blue). The numbers listed in the main element boxes reflects the number of consulted relevant literature references. Inspired by Zscheischler et al. (2020).

(n = 51). Therefore, it is essential to understand the individual effects of each stage on both individual hazards, as discussed below first, and then the compounding effects.

4.1 Drought and excessive precipitation

Precipitation extremes (i.e., prolonged droughts and excessive precipitation) can negatively impact forest growth on a large spatial scale (Broadmeadow, 2002), through hydraulic function (Sanderson et al., 2012; Xenakis et al., 2021; Zhang et al., 2021a), soil attributes (Camarero et al., 2021), and physiological stress on trees (Camarero et al., 2021; Zhang et al., 2021a; Figure 8).

4.1.1 Drought

Prolonged drought can lead to reduced growth and physiological damage in temperate forests (Vacek et al., 2023; Wolf and Paul-Limoges, 2023; Fischer and Neuwirth, 2013). A prolonged drought in 2018 across Europe (Buras et al., 2020a;

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Xenakis et al., 2021) led to major growth reductions, particularly among species that are more vulnerable to dry conditions and young trees, including, for example, *P. abies* and multiple oak species in Europe (Candotti et al., 2022; Gazol and Camarero, 2022). In addition, the effects of drought were exacerbated by higher-than-average temperatures which further increased tree desiccation (Hajek et al., 2022). Following these extreme drought conditions, surviving trees were weakened and became more susceptible to bark beetle infestations (Knutzen et al., 2023). Drought affects trees through two critical interlinked physiological mechanisms (Figure 8): hydraulic failure and carbon starvation (Hajek et al., 2022; McDowell et al., 2008), modulated by vapor pressure deficit (VPD; i.e., difference between moisture holding capacity and actual moisture content of the air).

4.1.1.1 Hydraulic failure

Hydraulic failure occurs when sudden prolonged drought reduces water availability to the extent that trees can no longer maintain adequate water transport through their xylem tissues (Martínez-Vilalta et al., 2002; McDowell et al., 2008). As soil moisture declines while the water demand remains or increases, the water potential in the leaves and stems becomes more severely negative. Trees will attempt to minimize water stress through stomatal closure (Carminati and Javaux, 2020). While this response conserves water, it also limits gas exchange, reducing photosynthesis and overall growth (Schönbeck et al., 2022). Under extreme conditions, sustained tension in the xylem can lead to cavitation and the formation of embolisms, disrupting water flow and causing hydraulic conductivity to collapse. This can result in symptoms such as leaf wilting, premature defoliation (Schuldt et al., 2020), and branch or root dieback (Finér et al., 2024), potentially leading to mortality.

During the 2018 European drought, widespread hydraulic stress was observed across several species (Buras et al., 2020a). In particular, *Picea abies* showed marked growth decline and increased crown defoliation in Central Europe, particularly in sites with shallow soils that restricted rooting depth (Vacek et al., 2023).

4.1.1.2 Carbon starvation

Carbon starvation is a key physiological mechanism associated with drought. Trees close their stomata to reduce water loss, limiting carbon dioxide uptake, reducing photosynthetic rates and, over time, depleting non-structural carbohydrate (NSC) reserves (Wolf and Paul-Limoges, 2023). If drought persists, trees may become carbon-limited—unable to maintain basic metabolic functions, repair tissue, or mount effective defenses against pests and pathogens (Hartmann et al., 2018; Temperli et al., 2013).

While carbon starvation is difficult to measure directly, several studies have documented its effects through carbohydrate reserves reductions. For instance, in a *P. sylvestris* forest in northeastern Spain, (Galiano et al., 2011) found that trees exhibiting severe defoliation after the 2004–2005 drought also showed a significant depletion of NSC in stem tissues. These individuals experienced lower radial growth and higher post-drought mortality. Broadly, it has been shown that sustained carbon limitation is due to suppressed photosynthesis, increased respiratory demand, and the allocation of remaining carbohydrates to defense or osmoregulation (Hartmann et al., 2018).

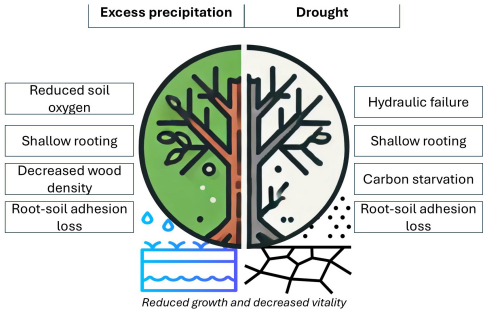

FIGURE 8
Mechanisms affected by excessive precipitation (waterlogging) and drought. Waterlogging reduces soil oxygen, leading to shallow rooting, decreased wood density, and weakened root-soil adhesion, thereby impairing growth and decreasing tree vitality. Drought increases water shortages, also resulting in shallow rooting, but with increased wood density. Ultimately, drought also leads to reduced tree growth and vitality (source pictogram: Flaticon.com).

During the 2018 European drought, *P. sylvestris* and several oak species [*Quercus robur* L. and *petraea* (Matt.) Liebl.] in managed forests showed signs of reduced photosynthesis and energy reserve depletion (Schwenke et al., 2024; Vacek et al., 2023). In parts of southern and eastern Europe, weakened trees, frequently in monocultures, were subsequently attacked by bark beetles (*Ips typographus*) and died (Candotti et al., 2022). While definitive attribution to carbon starvation is difficult, these patterns highlight how prolonged drought, sometimes combined with biotic agents, can tip vulnerable trees to mortality.

4.1.1.3 Vapor pressure deficit exacerbation

The effects of hydraulic failure and carbon starvation are further intensified by rising VPD during spring and summer droughts, such as during the 2018 drought (Hartmann et al., 2018). This increase in VPD is driven by high temperatures and low relative humidity, reflecting the atmosphere's drying power and thus accelerating water loss through evapotranspiration (Tijerín-Triviño et al., 2025; Xenakis et al., 2021). While it is difficult to isolate the specific contribution of VPD to tree mortality, elevated VPD is recognized as an amplifier of drought stress (Novick et al., 2016; Sturm et al., 2025). For instance, forests in Central Europe showed how increased VPD amplified stress in species like *P. abies* (Vacek et al., 2023), leading to cascading impacts through reduced hydraulic efficiency and heightened vulnerability to pests.

However, Schönbeck et al. (2022) showed that elevated VPD alone, under otherwise well-watered conditions, reduced stem hydraulic conductivity and induced osmotic stress in temperate tree species. Their experimental work demonstrated that beech (*Fagus sylvatica* L.) was especially vulnerable to high VPD, exhibiting reduced stomatal control and limited hydraulic plasticity compared to more drought-tolerant species like *Quercus ilex* L.

4.1.2 Waterlogging

Waterlogging lacks a strict definition, as this depends on the forest, soil characteristics, and site history. Generally, waterlogging occurs when water is at soil saturation level for extended periods of

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time (i.e., several days to weeks), resulting in reduced tree vitality through hypoxia, root decay, nutrient deficiency and increased secondary disturbance risks (Coutts and Philipson, 1977; Finér et al., 2024; Sanderson and Armstrong, 1978; Figure 8).

4.1.2.1 Oxygen deprivation

Waterlogged soils are typically oxygen depleted, leading to an anaerobic environment that directly impairs root metabolism. The resulting hypoxia restricts root respiration and energy production, which in turn limits water and nutrient uptake (Coutts and Philipson, 1987; Finér et al., 2024; Konôpka et al., 2010). Prolonged hypoxic conditions lead to phytotoxic conditions due to the buildup of toxic substances (e.g., aldehydes, ethanol, methane; Finér et al., 2024; Sanderson and Armstrong, 1978). The phytotoxic state reduces energy available for water and nutrient uptake, weakening the tree further, while also leading to fine root dieback.

4.1.2.2 Rooting depth impairment

Waterlogged conditions constrain rooting depth, producing shallow, dense root mats of fine roots that aid nutrient uptake but provide limited anchorage (Coutts and Philipson, 1987; Freschet et al., 2021; Smith et al., 1987; Yang et al., 2014). Under saturated or weak soils, these mats can share wind loading, but also act as shear planes, increasing the risk of uprooting—especially under high wind loads (Coutts, 1983; Smith et al., 1987). Waterlogging can disproportionally affect species with shallow root systems in shallow soils or those prone to saturation or with hardpans (Défossez et al., 2021; Morimoto et al., 2021; Yang et al., 2018). For example, excessive rainfall in the UK in the winter of 2013–2014 led to high soil saturation, which when combined with high winds, led to substantial damage (Armstrong et al., 1976; MET Office, 2014).

While UK-grown *P. sitchensis* is often associated with shallow rooting, this is largely a consequence of site conditions (Armstrong et al., 1976). In the UK, plantation forests are frequently established on suboptimal sites—such as upland peats, gleys, or areas with compacted layers or hardpans—due to the (agricultural) land-use prioritization (Bateman et al., 2013). Historical intensive site preparation practices to remedy lower soil quality such as plowing, fertilization, and drainage, (Nicoll and Ray, 1996; Paterson and Mason, 1999), are now less common to reduce soil carbon losses.

4.1.2.3 Mechanical tree destabilization

As a secondary consequence of root impairment and saturated soil conditions, tree mechanical stability is often reduced. Excessive soil moisture can reduce the shear strength of the soil, particularly in fine-textured or organic soils, making it less able to resist lateral forces (Armstrong et al., 1976; Moore, 2014). In extreme cases, such as in poorly drained gleys or peats, quasi-liquefaction may occur, when soils lose cohesion and show mechanical behaviors more akin to those of liquid mediums (Ray and Nicoll, 1998). Additionally, near-destructive wind can weaken root-soil connections through a process known as "pumping," where repeated wind stress leads to progressive loosening of the soil-root matrix (Ray and Nicoll, 1998). The impact of water saturation largely depends on the soil type, but the timing of events is also important, as root growth can re-occur during drier periods, reducing the likelihood and impact of pumping.

4.2 Extreme wind

Windthrow—the uprooting or breakage of trees due to high winds (Gardiner, 2021) —has been the most damaging form of forest disturbances in Europe over the last 75 years (Patacca et al., 2023). Windthrow can reduce timber production and carbon sequestration (Lecina-Diaz et al., 2024; Monge and McDonald, 2020), and trigger cascading effects to soil composition (Gardiner, 2021; Ulanova, 2000), microclimate (Leslie et al., 2024; Ulanova, 2000), and biodiversity (Smart et al., 2014). Socio-economic impacts include destabilizing timber markets with large quantities of low-grade salvage wood, lowering prices, disrupting planning (Hanewinkel and Peyron, 2013; Schwarzbauer and Rauch, 2013; Udali et al., 2021), and raising costs of salvage, replanting, and pest control to manage bark beetle outbreaks (Kärhä et al., 2018; Temperli et al., 2013). In regions reliant on forestry, such disturbances can also affect employment, supply chains, and community wellbeing (Blennow and Persson, 2013).

Severe damage occurs after sequential storms, or when wind blows from atypical directions. For example, Storm Gudrun (2005) caused widespread damage in southern Sweden, and 2 years later Storm Per caused heavy losses despite weaker winds, likely due to weakened stands by Gudrun (Valinger and Fridman, 2011) Alexandersson and Edquist, 2007, as cited in Öhrn et al., 2018). In the UK, Storm Arwen (2021) caused extensive forest damage in Scotland (Manning et al., 2023), which was largely attributed to the atypical wind direction (North–Northeast), similar to the 1953 storm (Lines, 1954), for which trees were not acclimated. Similar vulnerability to less common wind directions was also seen during, for instance, Cyclone Gabrielle in New Zealand (Watt et al., 2025).

Forest structure strongly mediates windthrow risk. Even-aged plantations form uniform canopies that generate coherent eddies and contain trees with similar failure thresholds (Brunet et al., 2013; Mason, 2002). Such homogeneity, often the product of management for high timber yield and form, increases vulnerability, though narrow spacing can also reduce wind penetration and shield interior trees (Dupont and Brunet, 2008). This creates a trade-off: dense stands buffer inner trees but produce tall, slender forms that make failure more likely when suddenly exposed due to thinning or a strong windthrow event. Crown traits also matter: dense crowns increase drag and torque (Peltola, 2006; Petty and Swain, 1985), making newly exposed trees prone to uprooting or snapping (Gardiner, 2021; Ní Dhubháin and Farrelly, 2018), while porous stands encourage gradual acclimation, stronger roots, and stem flexibility (Gardiner et al., 2016; Telewski and Jaffe, 1986). The severe windthrow of *P. abies* during Gudrun reflected these vulnerabilities—tall uniform, low-porosity stands with abrupt edges were most damaged (Seidl and Blennow, 2012; Valinger and Fridman, 2011).

4.2.1 Stem breakage

Stem breakage occurs when wind loading exceeds tree trunk mechanical strength (Peltola, 2006), influenced by tree and stand characteristics and also pre-existing structural weaknesses (Figure 9; Zscheischler et al., 2020). Trees with a high height-to-diameter ratio—often a product of silvicultural practices—are particularly vulnerable to stem breakage (Díaz-Yáñez et al., 2019; Locatelli et al., 2017; Ní Dhubháin and Farrelly, 2018). For example,

unthinned or late-thinned production forest stands of *P. abies* and *P. sitchensis* are affected due to their tall, slender profile and dense crowns (Mason, 2002). Previous damage (e.g., due to drought-induced cavitation) can also lead to weak point creation exploited by strong winds (Csilléry et al., 2017; Vacek et al., 2023). Species can also differ in resistance: *P. sylvestris* is generally less prone to breakage than *P. abies* (Peltola et al., 2000). Stand age and tree density add complexity (Cucchi et al., 2005; Forzieri et al., 2021): older trees may be brittle but also thicker—thereby increasing the second moment of area of the stem (i.e., mechanical property that enhances resistance to bending and reduces stem breakage risk; (Wood, 1995), while dense, low-porosity stands (i.e., proportion of open space in canopy and between tree stems, thereby governing stand airflow; (Gardiner, 2021; Mitchell, 2013) can shield interior trees yet limit their mechanical acclimation through stem thickening and root biomass allocation (Dlouhá et al., 2025; Ní Dhubháin and Farrelly, 2018).

4.2.2 Uprooting

Uprooting happens when the bending moment on the tree caused by the cumulative effect of both wind loading and gravity exceeds the resistive moment provided by roots, soil, and stem weight (Figure 9). Sandy or waterlogged soils with low shear strength increase risk (Défossez et al., 2021), while clay or loam offer stronger anchorage (Gardiner, 2021). Shallow soils, common on steep slopes and along ridges, further raise vulnerability (Morimoto et al., 2021). Root architecture modifies this interaction: species with a tendency to develop dominant taproots but weak lateral systems may be especially at risk on poorly drained soil (Mitchell, 2000), as shown for *Abies sachalinensis* (F. Schmidt) in Japan (Morimoto et al., 2021).

4.3 Interactions of windthrow and precipitation extremes

Precipitation extremes can interact with extreme wind events resulting in interaction effects from multiple hazards. The physiological and mechanical stresses induced by prior drought or waterlogging reduces a tree's resistance to extreme wind, increasing the likelihood of uprooting or stem breakage. The spatial and temporal overlap of these drivers intensifies the risk of damage depending on forest characteristics (e.g., soil conditions, forest exposure, species composition).

4.3.1 Compound impacts of drought and wind disturbances

Permanent dry conditions can alter belowground carbon allocation, with trees favoring exploratory fine root growth (Nisbet et al., 1989; Ray and Nicoll, 1998) at the expense of structural coarse roots (Freschet et al., 2021). While this enhances water foraging, it reduces mechanical anchorage. Fine roots also decompose more rapidly under sudden extreme drought stress, further undermining tree stability (Finér et al., 2024).

Soil type mediates drought impacts on tree anchorage. Dry sandy soils lose cohesion and offer limited grip for roots (Défossez et al., 2021; Yang et al., 2014), while mineral soils exposed to repeated drought and rewetting cycles may crack, disrupting root-soil contact (Gimbel et al., 2016). Although such cracking can create new pathways for root expansion over time, it may also compromise structural integrity when a wind event occurs soon after the soil cracking has occurred.

Species differences further shape vulnerability. Gymnosperms are generally more prone to windthrow than angiosperms, although this pattern is often confounded by planting practices, with conifers commonly established on marginal soils such as peaty gleys or dry sands (Gardiner, 2021). It is likely that the retainment of foliage by gymnosperms during the stormier winter season may also factor into this pattern (Gardiner et al., 2010).

Stem breakage may become more likely under drought due to insufficient water and nutrients to sustain wood production and maintain strength (Csilléry et al., 2017; Ulanova, 2000). Chronic drought can reduce radial growth and impair hydraulic conductivity (Gazol and Camarero, 2022; Schönbeck et al., 2022; Xenakis et al., 2020), potentially increasing vulnerability to mechanical failure. For instance, in drought-prone pine plantations in Spain, windthrow damage has been linked to preceding dry years, suggesting that drought may predispose stands to wind disturbance (Camarero et al., 2021). However, confounding this relationship, *P. sylvestris*—despite showing drought-induced growth reductions—often exhibits lower cavitation risk and is commonly planted on dry sandy soils due to its drought tolerance (Niinemets and Valladares, 2006). By forming a deep tap- and sinker root system in these dry sandy soils, *P. sylvestris* may also confer anchorage benefits that reduce the likelihood of uprooting under wind loading (Mickovski and Ennos, 2002).

4.3.2 Compound impacts of waterlogging and wind disturbances

There are known feedback loops between waterlogging and windthrow, as soil saturation can weaken root-soil anchorage by reducing shear strength (Défossez et al., 2021; Kamimura et al., 2012) and inducing root dieback (Finér et al., 2024; Sanderson and Armstrong, 1978). For instance, Csilléry et al. (2017) attributed severe windthrow in the Western Alps and Jura Mountains to a sequence of excessive rainfall followed by strong winds. Experimental manipulations have confirmed this (Défossez et al., 2021) used winching tests and simulations on *P. pinaster* in sandy soils and found that anchorage resistance dropped by up to 40% when soils reached full saturation as the capillarity-driven suction declined. Similarly, Kamimura et al. (2012) conducted tree-pulling experiments on *Chamaecyparis obtuse* (Siebold and Zucc.) Endl. under different irrigation treatments. They found that water added beneath the root plate initially improved resistance (i.e., soil-root plate weight increased), but over time significantly reduced tree stability by lowering soil stiffness and the maximum turning moment (Cannon et al., 2024) also found that heavy rainfall can temporarily enhance root anchorage in sandy soil by increasing the root-soil plate weight and friction between roots and surrounding soil particles. These findings suggest that rapid wetting may, in some cases, improve short-term resistance to uprooting, depending on tree species, rooting morphology, and soil characteristics (Kamimura et al., 2012; Morimoto et al., 2021).

A key contributing mechanism is soil "pumping," where heavy precipitation infiltrates and saturates the root-soil interface, and

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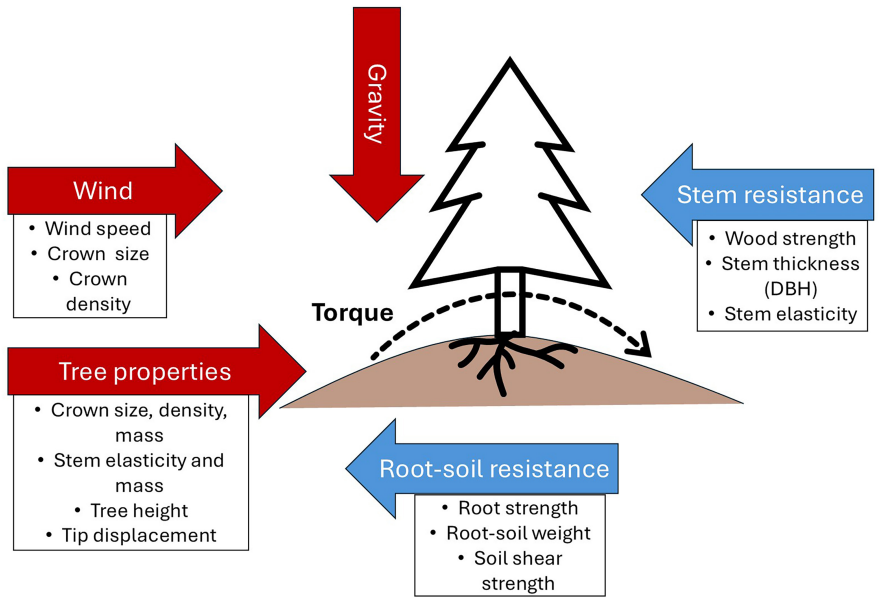

FIGURE 9
Conceptual model of individual tree stability under wind loading, illustrating the balance between applied (red) and resistive forces (green). Applied forces generate torque that can lead to tree failure when resistive forces are insufficient. Applied forces depend on external factors such as wind speed and internal tree properties, including crown and stem properties size, and tree height and tip displacement. Resistance is provided by mechanical properties of the stem and root-soil system. When stem resistance is exceeded, failure occurs primarily through stem breakage; whereas when root-soil resistance is exceeded, failure occurs through uprooting. The dominant failure mode therefore reflects the relative strength and elasticity of stem tissues versus root anchorage and soil cohesion. Inspired by Peltola (2006).

cyclic swaying under wind loads forces water deeper into micro-gaps, progressively breaking root-soil adhesion (Ray and Nicoll, 1998). This effect is likely amplified on edges and ridges due to both higher wind exposure and shallower, less cohesive soils (Morimoto et al., 2021). Consequently, high moisture levels reduce soil cohesion and shear strength, leading to a marked decline in the resistive moment of the root-soil system and greater wind damage.

4.3.3 Projected trends in precipitation and wind extremes

Global climate models consistently predict an intensification of extreme events, with events becoming longer, more frequent, and more intense across many regions (Calvin et al., 2023; Forestry Commission, 2022). Climate warming is closely linked to an increased prevalence of drought during the summer (Calvin et al., 2023; Van Oijen et al., 2014), as higher temperatures enhance evapotranspiration (Doshi et al., 2023), and reduced soil moisture availability (Xenakis et al., 2021). Drought projections exhibit regional disparities (Ridder et al., 2020; Seidl et al., 2017), with some areas expected to experience more frequent and intense droughts, while others may see shifts in seasonality rather than overall frequency (Table 2). These changes will depend on factors such as precipitation regimes (Calvin et al., 2023), soil characteristics (Buras et al., 2020b), and land-atmosphere feedback mechanisms (Zhang et al., 2021a), making localized assessments critical for understanding future risks.

Precipitation extremes are also projected to become more intense due to a warmer atmosphere's increased capacity to hold moisture (Min et al., 2011). This can lead to heightened risks of waterlogging (Finér et al., 2024). In Europe, this increased precipitation will be primarily concentrated in the winter, whereas summers will see more intense but less frequent rainfall (Calvin et al., 2023).

Windstorm patterns are also expected to shift under future climate scenarios, though projections remain complex and regionally dependent). Changes in windstorm activity across the North Atlantic Ocean (NAO), for example, are influenced by large-scale atmospheric patterns and blocking, such as the NAO and the behavior of the jet stream, both of which are subject to considerable variability and complex interactions with climate change (Kautz et al., 2022; Xu et al., 2024). Some models suggest a strengthening of storms over Central and Western Europe, with potential consequences for European forests (Haarsma et al., 2013; Mölter et al., 2016).

The increase in all these extreme events is also likely to lead to an increase in CEs (Ridder et al., 2020; Zscheischler et al., 2018). The interplay between atmospheric and oceanic processes introduces additional uncertainty into extreme event projections. This shift is mirrored in the literature: while early disturbance studies primarily focused on wind impacts, more recent decades show a diversification toward drought, extreme precipitation, and multiple interacting drivers. The growth in CE studies after 2010, from 4 to 40 cited sources, in particular reflects a broader recognition of the need to examine disturbance interactions rather than isolated hazards, consistent with emerging climate projections (Calvin et al., 2023; Zscheischler et al., 2018).

TABLE 2 Overview of projected European trends of extreme events (i.e., drought, extreme precipitation, extreme wind) under climate change and impacts on forests.

Extreme event	Trends	Drivers	Forest impacts	Confidence in projections (Global/Europe; Calvin et al. 2023)
Drought	More frequent, longer, and intense (Seidl et al., 2017)	Higher temperatures, increased evapotranspiration (Hajek et al., 2022; McDowell et al., 2008)	Reduced soil moisture, tree vitality, lower resilience (Gazol and Camarero, 2022)	Medium/high (especially in Southern and Western Europe; Calvin et al., 2023; Gazol and Camarero, 2022)
Extreme precipitation	More intense rainfall events, especially in winter (Gardiner et al., 2010	Warmer atmosphere holds more moisture (Min et al., 2011	Increased risk of soil saturation, waterlogging (Zhang et al., 2021a)	High/likely (Northern and Central Europe; Calvin et al., 2023); (Gardiner et al., 2010)
Extreme wind	Possible increase in frequency and severity (Haarsma et al., 2013)	Changes in baroclinicity, jet stream variability (Xu et al., 2024)	Increased windthrow, altered forest and soil structure (Camarero et al., 2021)	Low/medium (no consistent signal for Europe; (Calvin et al., 2023; Haarsma et al., 2013)
Compound event	Increasing frequency of interaction (Zscheischler et al., 2018)	Combination of multiple drivers (Raymond et al., 2020; Zscheischler et al., 2020)	Amplified forest disturbances, higher mortality (Csilléry et al., 2017; Zscheischler et al., 2018)	High/high (especially Mediterranean Europe; (Manning et al., 2024; Zscheischler et al., 2018)

The scale of the projections heavily influences confidence in projections. For instance, extreme wind projections are relatively uncertain at large scales; however, in the United Kingdom, it is expected that more extreme winds will occur in the future (Manning et al., 2023).

5 Tools to manage extreme precipitation and wind events in forests

Sustainable forest management can be defined as the process of making informed decisions and balancing resources to achieve and maintain economic production, social values, and biodiversity objectives in the present and the future across local, national, and global levels (Forest Research, 2023). While many management principles are well-established based on ecological knowledge (e.g., increasing species diversity for greater resilience), it is still essential to have the right tools to generate and test new knowledge by monitoring and simulating different silvicultural approaches. The three key elements required to improve decision making to increase forest resilience understanding in the face of extreme precipitation and wind events include the ability to (i) detect disturbances, (ii) monitor impacts, and (iii) model disturbance impacts.

5.1 Detection of disturbances

Remote sensing is one of the most widely used tools for detecting forest disturbances, particularly those caused by extreme precipitation and wind. Though limitations are present for each remote sensing data source (e.g., atmospheric interference, data availability, and temporal vs. spatial resolution balancing), remote sensing enables accurate, cost-effective, and repeatable data collection over large spatial scales, making it especially useful for forest resilience planning and disturbance monitoring (Bathiany et al., 2024; Lechner et al., 2020; Wegler and Kuenzer, 2024).

5.1.1 Satellite-based remote sensing

Large-scale remote sensing can leverage freely available, open satellite data, including MODIS, Landsat, and Sentinel-1 and -2 to provide consistent, long-term coverage at regional to global scales (Table 3). Data from these satellites are commonly used for detecting forest disturbances (Forzieri et al., 2020; Radeloff et al., 2019).

MODIS offers near-daily revisit rates and products like the normalized difference vegetation index (NDVI) and enhanced vegetation index (EVI) (Radeloff et al., 2019), but the relatively coarse spatial resolution (~250–1,000 m) can limit the precision needed for site- or stand-specific assessments (Wegler and Kuenzer, 2024). MODIS can be used to determine Dynamic Habitat Indices (DHI), which capture variation in NDVI, gross primary productivity (GPP), and leaf-area index (LAI). These metrics have recently been calculated globally at a 1-km scale (Radeloff et al., 2019). MODIS has been used to detect disturbances induced by waterlogging in Siberia, but it was not able to capture small-scale tree mortality (Nagano et al., 2022).

Landsat satellites offer a much higher spatial resolution (~30 m) dating back to 1972, making them very valuable for long-term trend analyses (Marques et al., 2024; Wegler and Kuenzer, 2024). The trade-off, however, is a lower revisit frequency of 16 days (Wegler and Kuenzer, 2024).

Sentinel-2 combines a 10 m spatial resolution with a 5-day revisit cycle (Freitas et al., 2024), enabling effective detection of canopy damage, as demonstrated in studies of windthrow across Europe (Candotti et al., 2022). For instance, a large windthrown area affected on the Italy-Austria border was correctly assigned as windthrown and bark beetle damaged (89% accuracy; Candotti et al., 2022. In a separate study focused solely on insect-induced dieback, maximum detection accuracy was lower (71%; Recchia et al., 2025).

More recently, commercial very-high-resolution satellites have become available, including PlanetScope (PlanetScope - Earth Online, 2025), Worldview (WorldView-3 – Earth Online, 2025), and a hyperspectral satellite Pixxel (Pixxel, 2025), with sub-meter resolution and near-real-time monitoring capabilities. For example, Kislov and Korznikov (2020) found a 94% windthrow accuracy using a combination of WorldView-3 and Pleiades 1A/B. Hyperspectral satellites in particular can be beneficial due to their greater range of spectral bands compared to very-high-resolution satellites (Pixxel, 2025). These systems can detect small-scale disturbances (i.e., individual tree to stand-level) and offer opportunities for species-level assessments (Deigele et al., 2020; Yan et al., 2021). Despite the current commercial costs associated

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TABLE 3 Overview of satellite sensors applicable to forest disturbance monitoring.

Satellite sensor	Spatial resolution	Temporal resolution	Applications	Limitations
MODIS (e.g., Radeloff et al., 2019)	250 m - 1 km	Daily [Terra (terrestrial) and Aqua (hydrological)]	Forest cover monitoring, vegetation indices, land use/land cover change, environmental monitoring	Coarse spatial resolution; cloud cover; limited spectral bands
Landsat (e.g., Marques et al., 2024; Wegler and Kuenzer, 2024)	30 m (multispectral), 15 m (panchromatic)	16 Days (Landsat 8/9)	Land use/land cover change, forest disturbances, land degradation, forest health monitoring	Long revisit time; cloud cover
Sentinel-1 (SAR; e.g., (Kacic et al., 2025; Rüetschi et al., 2019)	10 m [Interferometric Wide (IW; wide area, high resolution burst acquisitions) mode]	6 Days (Sentinel-1A and 1B/1C)	Detection of windthrow, monitoring deforestation, forest structure, soil moisture, mapping floods	Sensitivity to forest type and structure, complex data interpretation
Sentinel-2 (e.g., (Freitas et al., 2024)	10 m (visible, Near Infrared), 20 m (Short-wave Infrared), 60 m (thermal)	5 Days (Sentinel-2A and -2B)	Vegetation mapping, land cover change, crop monitoring, forest health, disaster monitoring	Cloud cover, saturation due to high reflectance surfaces, restricted by sensor design for some forest types
Very-high-resolution satellites (e.g., PlanetScope - Earth Online, 2025; WorldView-3 – Earth Online, 2025)	30 cm - 1 m	Varies (daily to several days)	High-resolution forest mapping, detailed forest structure, urban planning, agriculture, disaster response	Expensive (commercial); limited coverage; high data processing requirements
Hyperspectral satellites (Pixxel, 2025)	5 m	Daily	High-resolution and multi-spectral band forest mapping, agriculture, (energy) infrastructure,	Expensive (commercial); high data processing requirements; limited temporal scope

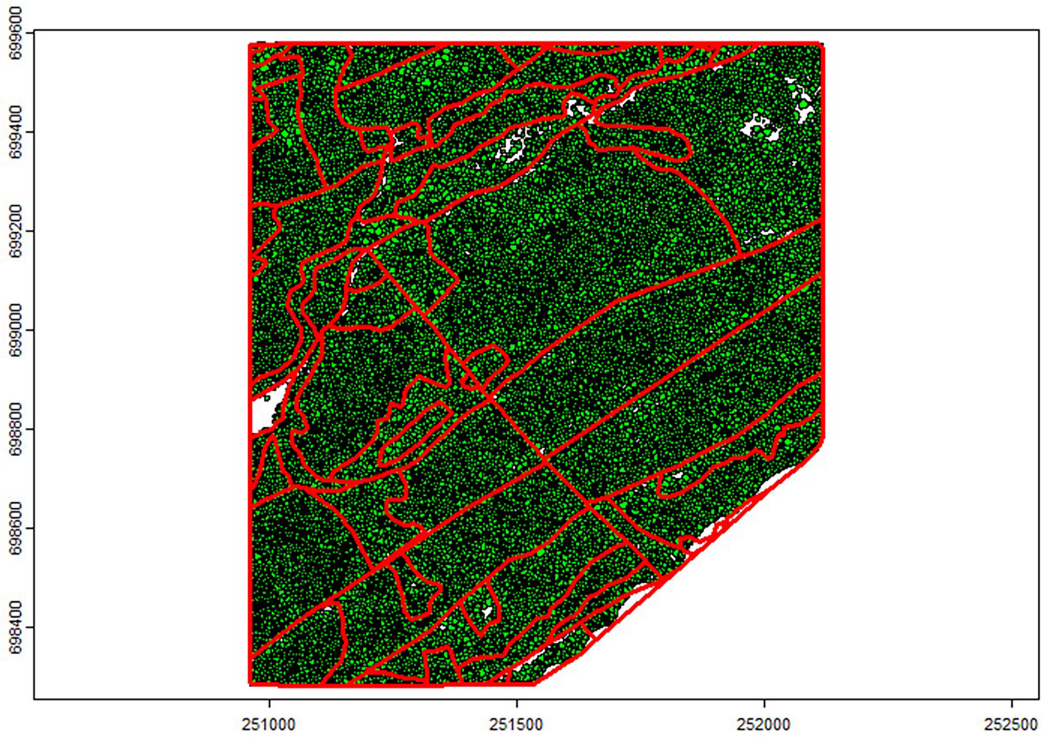

FIGURE 10
Forest gaps (white) visible in LiDAR data measured in Queen Elizabeth Forest Park, Scotland. Segmented individual tree canopies can serve as accurate inputs for (the individual tree method of) ForestGALES (Locatelli, 2024). Stands borders are highlighted in red, while the green area are the detected trees.

with very-high resolution and hyperspectral satellites (Deigele et al., 2020), hyperspectral data has already been used to detect bark beetle induced mortality with an 84–96% accuracy (Fassnacht et al., 2014).

5.1.2 LiDAR and UAV-based remote sensing

LiDAR (Light Detection And Ranging) has emerged as a valuable tool for understanding the structural impacts of extreme events on forests. Airborne LiDAR systems can generate highly detailed 3D maps of canopy structure, tree heights, and biomass, making them particularly useful for assessing changes in forest cover caused by e.g., windthrow effects (Suarez et al., 2008; Figure 10). However, the reliance on clear skies during data collection (to account for lighting differences; (Wegler and Kuenzer, 2024) and the high cost of airborne LiDAR to cover a large geographical area can limit its application (Ørka and Hauglin, 2016).

Complementing aircraft LiDAR, Unmanned Aerial Vehicles (UAVs) can be equipped with multispectral or thermal sensors, offering more flexible and extremely high-resolution alternative for local studies (Ørka and Hauglin, 2016). Drones can capture ultra-high-resolution images, allowing for detailed assessments of wind damage or other extreme events in heterogeneous forests (Chen et al., 2024).

5.1.3 Multi-sensor approaches

Multi-sensor approaches combine the strengths of various remote sensing technologies to provide a more holistic understanding of forest disturbances. For example, optical sensors, e.g., Sentinel-2, can capture (spectral) changes in NDVI and NDMI), which correlate index decreases with wind damage or forest attribute changes (Kuzu et al., 2024; Piragnolo et al., 2021). Radar-based sensors, such as Sentinel-1, complement optical systems by providing canopy-penetrating and weather-independent data, enabling consistent monitoring even during cloudy or rainy conditions (Rüetschi et al., 2019).

Emerging technologies, such as hyperspectral sensors and CubeSats (Freitas et al., 2024; Pixxel, 2025; Wegler and Kuenzer, 2024), offer exciting possibilities for multi-sensor integration. CubeSats, with their daily revisit rates, enable near-real-time monitoring of rapidly changing conditions Wegler and Kuenzer (2024). As these technologies become more accessible, their integration into operational forest management systems has the potential to revolutionize how extreme events will be detected in the future.

5.2 Machine learning for disturbance detection

Machine learning (ML) has emerged as a powerful tool to analyze remote sensing data and (automatically) monitor forests. ML has shown remarkable accuracy in identifying patterns and anomalies in vegetation indices (Table 4), including random forests (RF) (Garamszegi et al., 2022), support vector machines (SVM) (Yan et al., 2021), and deep learning such as convolutional neural networks (CNN) (Brodrick et al., 2019).

For instance, CNN can analyze high-resolution imagery from drones or satellites to classify areas affected by windthrow with a 94% accuracy (Kislov and Korznikov, 2020). The authors used a U-Net-like CNN that uses algorithms for the precise segmentation of satellite imagery. The high accuracy is because neural networks, have the significant advantage of being able to operate on a limited dataset that is transformed through several operations (e.g., cropping, rotating; Brodrick et al., 2019). Meanwhile, RF models have been moderately successfully (66% accuracy) used to detect drought-driven mortality in California using (passive) microwave-based water content data (Rao et al., 2019).

By training models on historical disturbance data, researchers can develop algorithms that identify impacts of extreme events, potentially through automated workflows (Garamszegi et al., 2022; Hamdi et al., 2019). For instance, changes in NDMI and NDVI captured by Sentinel-2 can be negatively correlated with storm severity in a RF model, enabling rapid identification of affected areas (Piragnolo et al., 2021). However, the accuracy of these models depends on the availability and quality of training datasets, which remains a challenge in many regions and fields (Kattenborn et al., 2021).

5.2.1 Emerging algorithms and techniques

The future of ML in forest monitoring lies in the development of hybrid models that combine statistical and (dynamic) process-based disturbance models and remote sensing (Wegler and Kuenzer, 2024). As CEs become more common, the next generation of approaches will rely increasingly on artificial intelligence and deep learning techniques capable of integrating multiple data modalities and temporal dynamics. These systems could integrate data from satellites, drones, and ground-based sensors to provide comprehensive insights into forest health and responses to disturbances (Zweifel et al., 2023). For example, hybrid models could calculate the likelihood of storms and wind based on weather patterns (Manning et al., 2023; Mölter et al., 2016) and site-specific vulnerability factors from disturbance models (Locatelli et al., 2022), such as tree age and soil type, with remote sensing derived data (e.g., canopy closure, tree height) adding more accuracy to their predictions (Suarez et al., 2008).

Additionally, to help shift from individual extreme events (i.e., drought, windthrow; Hamdi et al., 2019) to CEs, recent advances in remote sensing will be critical, including foundation and self-supervised models, which learn generalizable spatial-temporal representations from vast unlabeled imagery. Vision foundation models (Tian et al., 2025) and self-supervised pretraining frameworks such as MoCoTP (Bourcier et al., 2022) have shown strong transferability and label efficiency, enabling accurate monitoring with limited annotated data. Parallel progress in temporal and multimodal learning is further enhancing forest disturbance monitoring. Deep temporal architectures (e.g., Siamese networks, temporal CNNs, Transformers; Kattenborn et al., 2021; Meng et al., 2024; Zhang et al., 2024) capture both short-term disturbance signals and long-term recovery, while multisensory fusion of optical, radar, and LiDAR data distinguishes structural from physiological impacts (Mihai et al., 2025; Zhang et al., 2025). Generative diffusion approaches such as RESTORE-DiT extend this potential by reconstructing cloud-contaminated or

TABLE 4 Summary of machine learning approaches used in detecting disturbances, either through modeling (**Wegler and Kuenzer, 2024**; **Garamszegi et al., 2022**) or remote sensing (**Candotti et al., 2022**; **Deigele et al., 2020**; **Einzmann et al., 2017**; **Hamdi et al., 2019**; **McInerney et al., 2016**).

Machine learning approach	Accuracy (%)	References
Simple linear methods (e.g., regression)	77–88	(Einzmann et al., 2017; Garamszegi et al., 2022; McInerney et al., 2016; Wegler and Kuenzer, 2024)
Support vector machine	75–85	(Candotti et al., 2022; Einzmann et al., 2017; Garamszegi et al., 2022; Hamdi et al., 2019; McInerney et al., 2016; Wegler and Kuenzer, 2024)
Random forest	72–93	(Candotti et al., 2022; Einzmann et al., 2017; Hamdi et al., 2019; Wegler and Kuenzer, 2024)
Convolutional neural network	83–95	(Candotti et al., 2022; Deigele et al., 2020; Hamdi et al., 2019)

incomplete time series, offering pathways for modeling disturbance and recovery under CEs (Shu et al., 2025).

5.3 Approaches for quantifying extreme weather events in forests

Various modeling techniques assess the occurrence and impacts of extreme events in forests. These approaches range from empirical probability models to process-based simulations (Locatelli et al., 2022; Manning et al., 2024), some of which integrate ML algorithms (Hart et al., 2019). Each method has its strengths and limitations, necessitating an integrated approach for improved accuracy and applicability.

5.3.1 Statistical models

Empirical and statistical models rely on historical and field inventory data to estimate the probability and severity of extreme events (Manning et al., 2024). These models often employ regression techniques, logistic models, and some limited ML approaches to quantify relationships between environmental factors and disturbance likelihood (Garamszegi et al., 2022). For instance, logistic regression models have been used to relate general weather trends to biomass loss following a disturbance (Anand et al., 2024). Generalized Linear Models (GLMs) and Boosted Regression Trees (BRTs) have been applied to assess the risk of wind-related damage under varying climate conditions (Díaz-Yáñez et al., 2019; Lloret and Kitzberger, 2018). These models have shown mixed simple relational results, reiterating known correlations between increased damage, wind speeds, tree height, and increased exposure. A notable example of the application of Generalized Linear Mixed Models (GLMMs) and Classification and Regression Trees (CART) to long-term forest inventory data in south-western Germany highlighted the significant role of tree species, stand height, and silvicultural interventions (e.g., thinning history) in influencing storm vulnerability (Albrecht et al., 2012). Lastly, another widely used statistical approach involves return period analysis (Zhang et al., 2021b), which estimate the frequency of extreme events, such as storms, based on past occurrences and impacts (Manning et al., 2023, 2024).

5.3.2 Process-based mechanistic models

Process-based mechanistic models simulate the physical and biological mechanisms that determine the response of trees and forests with regards to the impact of forest disturbances (Hale et al., 2015; Seidl et al., 2014). For instance, many (hybrid-mechanistic) wind disturbance models use similar data (i.e., stand, tree, soil, and climate variables) to calculate the probability of wind damage. ForestGALES is one of the most widely adopted process-based wind risk models, developed initially for conifer plantations in the UK and subsequently developed and successfully applied in several other countries and forest types (Byrne and Mitchell, 2013; Cucchi et al., 2005; Locatelli et al., 2016), with various inputs (e.g., remote sensing; Suarez et al., 2008) and growth models (Byrne and Mitchell, 2013). The latest version of the model allows for complete customization providing additional flexibility to simulate forest management and climatic conditions, working at both the stand and tree level (Locatelli et al., 2022). Through its integration in iLand, an ecosystem-scale temporal simulation model, ForestGALES has also been used to simulate the impact of windthrow and insect outbreaks (Dobor et al., 2020b).

Other process-based wind disturbance models have been developed, including HWIND and FOREOLE (Ancelin et al., 2004; Peltola et al., 1999), which share similar mechanistic foundations with ForestGALES, but differ in their assumptions, spatial applications, and handing of tree resistance and wind loading. HWIND, developed to assess windthrow risk particularly at the stand edge, similarly calculates wind loading from drag coefficients and vertical crown frontal area profile, but unlike ForestGALES, it determines resistance to uprooting based on root-soil plate mass (Gardiner et al., 2000). It simulates breakage or uprooting when the applied bending moment exceeds structural resistance of the tree. HWIND has been in operational contexts such as modeling tropical cyclone damage within a windthrow decision support system for insurance payout assessments (Moody's, 2024). In contrast, FOREOLE assesses the risk to individual trees within a stand, which HWIND and the initial versions of ForestGALES were not designed for, accounting for heterogeneity in tree structure and wind exposure (Ancelin et al., 2004). FOREOLE uses a more detailed numerical description of tree architecture and applies wind and self-weight loads at multiple points along the stem, unlike ForestGALES and HWIND (i.e., they assume uniform stress along the stem). The design of each model determines its applicability depending on the question (e.g., interior or forest edge, assumption of uniform or varying stem stress), highlighting the need to consider model architecture when utilizing process-based models (Peltola, 2006).

5.3.3 Process-based model limitations

Process-based models are designed to represent the underlying physical mechanisms of wind damage and can be parameterized to the local forest and site conditions to increase reliability

and confidence in projections. For example, ForestGALES was initially developed for the UK conditions and has been regionally adapted—such as by adjusting parameters for tree wind response in countries like Canada and Germany—to accurately reflect global variability (Byrne and Mitchell, 2013; Locatelli et al., 2017; Stadelmann et al., 2025).

Additionally, current mechanistic models operate by estimating, for instance, wind risk and impact based on parameterized relationships (Locatelli et al., 2022), rather than dynamically simulating the evolving physiological and structural responses of forest stands to wind exposure—such as altered canopy structure following initial damage events. Some attempts have been made to bridge this gap, including ecosystem-level models like iLand (Seidl et al., 2012; Seidl et al., 2014), that attempts to dynamically incorporate growth responses feedbacks following a disturbance. Nonetheless, the reliability of model outputs continues to hinge on the accurate calibration of key parameters (Stadelmann et al., 2025), which despite being constrained by limited empirical data and varying across forest types, can effectively be accommodated by flexible models like ForestGALES, demonstrating its robustness and broad applicability (Costa et al., 2023; Cucchi et al., 2005; Locatelli et al., 2016).

5.4 Integration of disturbance and growth models

Forest growth models simulate tree and stand development over time, considering carbon allocation, water balance, and competition (Landsberg and Waring, 1997; Pretzsch et al., 2015; Seidl et al., 2012). The field of forest growth modeling is expansive and well-developed, and has therefore been much reviewed in the past (Porté and Bartelink, 2002; Pretzsch et al., 2015). As such, only one frequently employed growth model will be highlighted for its potential to be integrated with a disturbance model.

3PG (Physiological Principles Predicting Growth) incorporates environmental variables to project biomass accumulation and productivity (Landsberg and Waring, 1997). The base model focuses on single species, in a relatively homogeneous stand with simple management interventions (i.e., thinning); however, more recent advancements have attempted to include more complex hydrological and soil nutrient cycles (Almeida and Sands, 2016; Xenakis et al., 2008), as well as focusing on mixed-species systems (Forrester et al., 2021), and introducing modifications for disturbances (e.g., drought; Forrester and Tang, 2015). The 3PG model has been adapted to model specific processes based on empirically measured responses. As 3PG provides outputs of biomass allocation to various compartments (roots, foliage, stem), they are primed to be integrated into risk assessment models of disturbances (Dlouhá et al., 2025).

5.4.1 Model parameterization and validation of growth and CE models

The successful integration of models for CE evaluation requires parameterization and validation using diverse data sources (van Oijen, 2024). Remote sensing offers valuable inputs for model calibration: LiDAR-derived canopy height and vertical structure, also from other remote sensing sources (Kuzu et al., 2024), inform allometric scaling and mechanical stability (Suarez et al., 2008); multispectral indices of vegetation health (e.g., NDVI, EVI) reflect canopy health and productivity proxies (Paluba et al., 2025); and radar data enables the detection of storm-induced structural damage, including windthrow patterns (Dalponte et al., 2023; Rüetschi et al., 2019). Complementing this, field measurements remain essential for model calibration and ecological realism that remote sensing is unable to capture (Valinger and Fridman, 2011). Metrics such as diameter-at-breast-height (DBH), tree height, stem taper, and root depth contribute to estimating tree stability, carbon allocation, and species-specific growth parameters in models (Landsberg and Waring, 1997; Locatelli et al., 2022). Dendrochronological data in particular can be used to reconstruct growth trajectories before and after disturbance events, offering empirical constraints on modeled recovery dynamics (Camarero et al., 2021; Primicia et al., 2015). In particular, long-term forest monitoring plots provide critical data on mortality rates, species turnover, and regeneration success (Chen et al., 2025; Smart et al., 2014).

6 Synthesis

This review consolidates current knowledge and shows that climate change is increasing the frequency and intensity of extreme events affecting temperate forests, and that considering their interactions as CEs is essential to understand amplified, often non-linear impacts on forest structure, function, and resilience (Calvin et al., 2023; Patacca et al., 2023). Traditionally, extreme events have been studied in isolation (Konôpka et al., 2010; Marchi et al., 2024; Xenakis et al., 2021); however, recent research underscores the need to consider their interactions, especially in the context of compound events (Zscheischler et al., 2018). When these extreme events are combined as CEs, they can increase forest damage (Csilléry et al., 2017; Défossez et al., 2021; Kleinman et al., 2019), which requires moving beyond climate science definitions, emphasizing the ecological and environmental interactions that shape forest disturbances (Bastos et al., 2023). By incorporating perspectives on how precipitation and wind extremes interact with forest ecosystems, this review provides a comprehensive understanding of disturbance dynamics and their implications for forest management and future research, to underpin assessment of CEs by complex integrated (process-based) models with remote sensing and ML (Brodrick et al., 2019; Hart et al., 2019; Wegler and Kuenzer, 2024).

6.1 Long-term monitoring and data gaps

While advances in remote sensing and ML have significantly improved the detection and modeling of extreme event-induced disturbances (Brodrick et al., 2019; Wegler and Kuenzer, 2024), long-term forest monitoring remains a critical challenge with several gaps and challenges. Many studies focus on immediate post-disturbance assessments (Rüetschi et al., 2019), yet understanding the full impact of extreme events requires continuous observations over extended periods (Smart et al., 2014).

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6.1.1 Inconsistencies in long-term datasets

One primary limitation is the inconsistency in long-term datasets, particularly for high-resolution monitoring. While Landsat provides a rich historical archive dating back to the 1970s (Wegler and Kuenzer, 2024), newer (very-)high-resolution platform, such as Sentinel-2 or commercial satellites (e.g., PlanetScope, WorldView-3), have only been operational for a decade or less (PlanetScope - Earth Online, 2025.; WorldView-3 – Earth Online, 2025; Freitas et al., 2024). This restricts the ability to conduct long-term comparative analyses at finer spatial scales, though this limitation will be reduced over time, depending on the costs development to obtain such (commercial) data (Ørka and Hauglin, 2016).

Secondly, the limited availability of (accessible) ground-truth data for validating remote sensing and ML models is another concern in forest disturbance monitoring. In particular, the origin of observed canopy or crown disturbances is often ambiguous in satellite data, as similar spectral or structural signals may result from natural disturbances or forest management activities (Wu et al., 2025). Many disturbance events, particularly those affecting below-canopy processes, are difficult to capture from spaceborne sensors alone, though newer satellites are reducing this limitation (Ma et al., 2023). Still, despite being resource-intensive and infrequent, field-based surveys remain necessary to confirm satellite observations (Yan et al., 2021). Efforts to integrate citizen science initiatives, and automated sensor networks, and Internet-of-Things (IoT) systems could help bridge this gap by providing supplementary ground-based observations (Singh et al., 2022; Zweifel et al., 2023).

6.1.2 Temporal resolution constraints

Temporal resolution also poses challenges for detecting subtle or slow-developing disturbances. While high-frequency satellite data can capture rapid changes without confounding impacts of other disturbances (Einzmann et al., 2017; Rüetschi et al., 2019), such as storm-induced windthrow, detecting long-term trends in forest resilience—including shifts in species composition or gradual declines in biomass—requires consistent, high-quality observations spanning over decades (Smart et al., 2014). Many existing satellite missions are limited in their operational lifespan, necessitating continued investment in long-term remote sensing programs.

Future efforts should thus also improve the integration of multi-source datasets for enhanced long-term monitoring (Einzmann et al., 2017; International Tree Mortality Network, 2025). Hybrid approaches that combine optical, radar, LiDAR, and *in situ* IoT data will be crucial for tracking forest resilience over time. Additionally, there is a need for standardized protocols in data collection, processing, and sharing to ensure that long-term datasets remain comparable and accessible for research and management applications.

6.2 Future research

Despite advancements in understanding forest disturbances, several avenues for future research remain. The definition of CEs within forest ecosystems is driven by meteorological perspectives emphasizing statistical dependencies between extreme weather variables (Kautz et al., 2022; Manning et al., 2024). However, future research should integrate ecological definitions of CEs, as they consider the interactions with forest physiology, structure, and function over time (Bastos et al., 2023; Kleinman et al., 2019).

The long-term ecological responses of CEs are also not well understood. While some studies have examined immediate post-disturbance impacts (McInerney et al., 2016), little is known about how forests recover over longer timescales (Poorter et al., 2024). Research should investigate how feedback loops, lag effects, and cumulative stress influence tree mortality, regeneration patterns, and overall forest resilience (Csilléry et al., 2017; Raymond et al., 2020).

Existing forest disturbance models, such as ForestGALES for windthrow, are primarily designed to assess risks from single events (Nicoll et al., 2015; Van Oijen et al., 2014), and growth models often focus on simple forest structures (i.e., single species, homogenous structure; Landsberg and Waring, 1997). This limits their applicability for CEs. To address this gap, integrating remote sensing, process-based growth models and (wind) risk models offers a pathway for model projection enhancement. Such integration enables dynamic feedbacks—where structural and physiological changes in forest biomass influence both growth trajectories and disturbance susceptibility—and allows the inclusion of pre-disturbance stress indicators (Hartmann et al., 2018; Suarez et al., 2008). Embedding detailed silvicultural strategies (e.g., thinning regime, and species mixtures and vulnerability) within these models can support adaptive management under increasing climatic uncertainty (Vacek et al., 2023).

Critically, future modeling frameworks should be explicitly designed as decision-support tools (Gardiner et al., 2010; Ray et al., 2019), enabling forest managers to explore alternative management scenarios (e.g., species diversification, structural complexity enhancement, rotation length adjustment, and spatial risk zoning) and evaluate their potential effectiveness in reducing vulnerability to compound disturbances (Vacek et al., 2023). This would allow quantitative assessment of trade-offs between productivity, stability, and resilience, thereby linking scientific advances directly to operational forest planning.

Recent advances in remote sensing, including multisensory integration, have improved the ability to detect windthrow and drought impacts (Bathiany et al., 2024; Suarez et al., 2008). Further refinement is needed to accurately distinguish between single and compound disturbances at different spatio-temporal scales. Research should also explore ML and high-resolution monitoring techniques to enhance detection capabilities and inform early-warning systems and models.

7 Conclusion

Overall, this review underscores the need for a paradigm shift to include CEs in extreme weather event research. This is because on their own these extremes create major damage, but combined, often result in even more significant impacts. By integrating CEs and remote sensing into models, they can be enhanced and provide insights for management to adequately address the changing

risks can be improved. Ultimately, a more holistic approach that integrates environmental interactions and ecological feedbacks is essential to mitigating risks and enhancing forest resilience in the future. To operationalize this shift, we propose a holistic framework that integrates continuous multi-sensor monitoring, process-based modeling, and adaptive forest management. This framework links early detection of pre-disturbance stress and post-disturbance impacts with scenario-based risk modeling and targeted silvicultural interventions, enabling a transition from reactive disturbance response to anticipatory, resilience-oriented forest planning.

Author contributions

TK: Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization, Visualization, Investigation, Validation. TL: Writing – review & editing, Conceptualization, Supervision. SR: Supervision, Conceptualization, Writing – review & editing. MP: Conceptualization, Writing – review & editing, Supervision. PB: Visualization, Writing – review & editing, Conceptualization, Supervision. AK: Supervision, Writing – review & editing, Funding acquisition, Conceptualization.

Funding

The author(s) declared that financial support was received for this work and/or its publication. This research was funded by the Natural Environment Research Council (NERC) sponsored by Central England NERC Training Alliance (CENTA2) Doctoral Training Partnership (grant no. NE/S007350/1).

Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Appendix

The following search strings were developed to systematically identify relevant literature on the intersection of compound events (such as drought, windstorm, and extreme precipitation) and their impacts on forest resilience, disturbance, and management. These search strings were designed to capture a broad range of studies across multiple databases, ensuring comprehensive coverage of the topic.

The search strings were structured using Boolean operators (AND, OR, Title-Abstract-Key words [TAK]) to combine key terms (Figure A1).

Search strings:
1. TAK ("compound events" OR "compound extremes" OR "extreme events") AND TAK ("forest resilience" OR "forest disturbances" OR "tree mortality" OR "forest vulnerability") AND TAK ("drought" OR "windstorm" OR "precipitation" OR "storm impacts" OR "waterlogging")
2. TAK ("remote sensing" OR "satellite monitoring" OR "Earth observation") AND TAK ("forest disturbance" OR "windthrow" OR "drought impacts" OR "storm damage") AND TAK ("LiDAR" OR "Sentinel-2" OR "Sentinel-1" OR "multispectral" OR "SAR" OR "machine learning")
3. TAK ("forest management" OR "forest resilience" OR "carbon sequestration" OR "biodiversity") AND TAK ("climate change" OR "wind disturbance" OR "drought resilience" OR "storm resilience") AND TAK ("forest structure" OR "species diversity" OR "ecosystem services" OR "forest margins")
4. TAK ("compound event typology" OR "framework for compound events" OR "multivariate extremes") AND TAK ("forest vulnerability" OR "forest disturbance" OR "climate change impacts") AND TAK ("risk assessment" OR "hazard modelling" OR "climate scenarios")
5. TAK ("drought" AND "windstorm") AND TAK ("forest mortality" OR "tree mortality" OR "ecosystem impact")
6. TAK ("extreme precipitation" OR "waterlogging" OR "drought") AND TAK ("soil saturation" OR "hydrological stress") AND TAK ("tree mortality" OR "forest resilience" OR "wind damage")
7. TAK ("windthrow risk model" OR "forest wind risk model" OR "wind damage model") OR TAK ("mechanical stability of trees" AND "wind resistance" AND uprooting)
8. TAK ("ForestGALES" OR “wind risk model”) AND TAK ("3-PG" OR "forest growth model" OR "tree growth model" OR "climate scenarios")
9. TAK ("species diversity" AND "forest recovery") AND TAK ("extreme event" OR "extreme disturbance") AND TAK (wind OR drought OR waterlogging)
10. TAK ("extreme disturbances" OR "extreme events") AND TAK ("temperate forests" OR "European forests") AND TAK ("historical trends" OR "long-term changes")

FIGURE A1
Overview of the search strings. The initial screening was based upon a set of 10 search strings in Scopus and Google Scholar. Articles were screened based relevant words in titles, abstracts and keywords, abbreviated to TAK, followed by full-text screening based on predefined inclusion criteria.