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Forest Reorganisation After Natural Disturbance: A Synthesis

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ABSTRACT

Aim: Natural disturbances are intensifying under global change, yet a global synthesis of their effects on forest structure and composition remains lacking. We aimed to assess the prevalence of structural versus compositional changes and to identify common post-disturbance reorganisation pathways across forest biomes.

Time Period: 1980–2023.

Location: Global.

Taxa Studied: Forest tree species.

Methods: We conducted a systematic literature review of 159 studies reporting pre- and post-disturbance forest structure and composition (i.e., mainly from fires, insect outbreaks and windthrow). We quantified structural and compositional changes by disturbance agent, biome, severity, study method and time since disturbance. We subsequently classified post-disturbance trajectories into four pathways: self-replacement, relay succession, novelty, and delayed regeneration.

Results: Most studies on post-disturbance forest development focused on temperate forests and fire, with structural change being more common than compositional change. Knowledge of post-disturbance trajectories is largely dominated by short-term studies, revealing a critical gap in understanding long-term post-disturbance trajectories. Self-replacement is common across biomes, suggesting that disturbances act as catalysts of change only under specific conditions. Relay succession is a prevalent post-disturbance development pathway in boreal forests, delayed regeneration in temperate broadleaved and mixed forests, and post-disturbance novelty occurs in temperate, Mediterranean and tropical regions.

Main Conclusions: As disturbances continue to change, the emerging novel disturbance regimes could alter prevailing reorganisation pathways. Understanding post-disturbance forest reorganisation is thus critical for forest management and conservation in an era of global change.

1 | Introduction

Global change is shifting natural disturbance regimes across all forested biomes (Seidl et al. 2017). In boreal forests, wildfires are becoming more frequent and intense due to warmer and drier conditions (Young et al. 2017), and increasing carbon

emissions to the atmosphere (Zhao et al. 2021). Temperate forests have experienced exceptional bark beetle outbreaks (Hlásny et al. 2021; Jaime et al. 2024) and extreme wildfire events in Mediterranean forests are causing important ecological and economic impacts (Bowman et al. 2017; Lecina-Diaz et al. 2023; Mohr et al. 2025). In tropical forests,

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post-hurricane conditions with abundant light and nutrients favour fast-growing species at the expense of higher overall forest vulnerability to drought (Smith-Martin et al. 2022). As disturbance regimes continue to change, the likelihood of the emergence of novel disturbance regimes increases (Turner and Seidl 2023), with the potential for severe impacts for the supply of ecosystem services (Lecina-Diaz, Senf, et al. 2024; Thom and Seidl 2016).

Natural disturbances can profoundly modify ecosystem structure and composition (Seidl and Turner 2022). Structural changes have been driven by the extensive die-off of tall trees (e.g., as a result of prolonged drought), ultimately favouring shorter trees (Stovall et al. 2019). Increasing disturbance frequency and intensity also result in younger and more open forests, altering the distribution of distinct successional stages on the landscape (McDowell et al. 2020). In addition, structural recovery (e.g., canopy closure, stem density) is generally faster than compositional recovery following major disturbances (Cerioni et al. 2024; Seidl et al. 2014), because early-successional species often dominate initially, filling space quickly, while the eventual replacement by late-successional, shade-tolerant species can take decades to centuries. In some ecosystems, disturbances can lead to pronounced species shifts, with post-disturbance tree communities dominated by disturbance-adapted deciduous species, rather than the conifer species that dominated prior to disturbance (Anoszko et al. 2022). An example for this pattern of structural recovery but changed composition is the large wave of tree mortality that affected Central Europe in the years 2019–2020, where post-disturbance shifts in forest composition were more prominent than structural changes, particularly due to the decline of the previously dominant conifer, Norway spruce (*Picea abies*) (Seidl et al. 2024). Similarly, in subalpine forests of the US Rocky Mountains, bark beetle outbreaks have caused shifts in forest structure and composition by reducing live tree size and increasing aspen (*Populus tremuloides*) dominance, a change that may persist for decades (Rodman et al. 2022). Although disturbances are powerful drivers of change in forest ecosystems, the extent to which they fundamentally alter forest structure and composition worldwide remains uncertain. Yet, understanding and quantifying these changes is crucial, as both these variables shape the trajectories of forest reorganisation after disturbances.

The reorganisation phase is a critical window for forest change (Seidl and Turner 2022). Following disturbance, a relatively short time window determines whether a system follows a development trajectory similar to the one before the disturbance or changes to a different one, leading to an altered ecosystem (Rocha et al. 2018; Seidl and Turner 2022). For example, after disturbance, a forest might shift from being dense and dominated by conifers with a closed canopy to a more open forest with fewer trees and mostly broadleaf species (Albrich, Rammer, and Seidl 2020). Understanding forest reorganisation is thus essential for anticipating and predicting forest changes, which is particularly important due to the long lifespan of trees compared to the time window of forest management and policy. Moreover, current environmental conditions (e.g., climate, CO₂ emissions) in many locations exceed the variation of the past several thousand years, representing an additional source of uncertainty for forest development (Beedlow et al. 2004; Case et al. 2021).

Despite its relevance, post-disturbance forest development pathways have only been evaluated under specific circumstances or study areas, and a global synthesis is lacking to date. Existing reviews and syntheses indicate that disturbances have profound effects on forest structure, function, and dynamics across ecosystems. For instance, tropical montane forests experience a range of disturbances, from small-scale landslides to cyclones and fires, which influence species composition and diversity in predictable patterns along environmental gradients (Crausbay and Martin 2016). Similarly, assessments of global novelty in ecosystems indicate that anthropogenic pressures, including human population growth and climate change, are already altering ecosystems, with further impacts expected by 2050 (Radeloff et al. 2015). Literature on forest conversion after fire in western North America highlights that post-disturbance trajectories can lead to the emergence of resprouting shrublands, early-successional or hardwood stands when current forest types fail to self-replace (Coop et al. 2020). A quantitative analysis of the literature from Canadian forests shows that recovery rates vary with disturbance type, forest biome, and ecozone, with most ecosystems reaching structural benchmarks such as canopy cover and tree height within 5–10 years post-disturbance (Bartels et al. 2016). These studies highlight both the spatial and temporal variability in forest recovery, but they do not provide a comprehensive, global synthesis of post-disturbance development pathways.

This gap is particularly relevant given the recent trends of climate and disturbance change, which challenge forest resilience. For example, species such as black spruce (*Picea mariana*) may experience regeneration failure under shortened disturbance return intervals and adverse post-disturbance climatic conditions (Baltzer et al. 2021; Hoecker and Turner 2022; Stoddard et al. 2018). This is exemplified by the decline in post-fire tree seedling establishment in areas affected by drought, where the combination of shortened disturbance intervals and adverse climatic conditions hampered forest recovery (Hoecker et al. 2020). In some cases, regeneration may be abundant but the resulting species composition deviates from historical successional trajectories, leading to novel ecosystems (i.e., ecosystems with some degree of dissimilarity, measured in one or more dimensions relative to a reference baseline, see Radeloff et al. 2015; Turner and Seidl 2023). For instance, arid and semiarid forests in Arizona have shifted in dominance from coniferous obligate seeders to resprouting hardwoods and shrubs following fire (Poulos et al. 2021). Similarly, bark beetle outbreaks have reduced pine and spruce dominance while favouring non-host species such as fir and aspen (Rodman et al. 2022). In other cases, relay succession has been observed in temperate and boreal ecosystems, where light-demanding pioneer species initially establish and are gradually replaced by more shade-tolerant, late-successional species (Adámek et al. 2016; Lavoie and Sirois 1998). Alternatively, self-replacement trajectories, where post-fire species composition and structure resemble pre-fire conditions, have been reported in Mediterranean forests (Adámek et al. 2016; Viana-Soto et al. 2022). The finding that the capacity to retain structure and composition within the system's range of variability depends on disturbance history (Dollinger et al. 2024) adds additional complexity to post-disturbance forest dynamics. While a multitude of different

post-disturbance trajectories have been reported, a synthetic understanding of their occurrence remains missing. Are changes in structure or composition more common after disturbance? What are the differences between biomes and disturbance agents? And how prevalent are patterns such as relay succession and self-replacement?

Here, we aimed to synthesise knowledge of post-disturbance forest reorganisation and assess how strongly natural disturbances act as agents of change. Specifically, we addressed the following questions: (1) How prevalent is a change in forest composition and structure after natural disturbance? What is the influence of factors such as disturbance agent, severity, time since disturbance, biome and research methods? And (2) How prevalent are specific post-disturbance patterns such as self-replacement, relay succession, novelty and delayed regeneration in forests around the globe? We addressed these questions through a literature review, focusing on studies that provided data on pre- and post-disturbance forest structure and composition. We collected information on natural disturbance characteristics (e.g., disturbance agent, severity), study method, and ecological responses (e.g., time since disturbance, pre- and post-disturbance dominant species, indicator values of structure and composition) to identify patterns of forest change.

2 | Methods

2.1 | Surveying the Literature

We searched the literature for studies on pre- and post-disturbance forest structure or/and composition. The literature search was performed in *Scopus* and the cut-off date for the inclusion of publications was December 31, 2023 (i.e., 1980–2023 period). We included both the terms “disturbance”, defined as an abrupt event that results in the loss or transformation of live biomass, and “stress”, which represents a more continuous and persistent negative effect (Wohlgemuth et al. 2022). Considering both allowed us to capture a more complete picture of the processes influencing forest responses. In addition, we included specific disturbances (i.e., fire, insect, pathogen, wind, avalanche, snow, ice, storm, hurricane and drought) in our search. Although other disturbances are likely to be important (or even dominant) in specific ecological contexts (e.g., flooding and permafrost degradation in boreal forests), the ones we included are the most widespread forest disturbances globally (Jentsch and von Heßberg 2022). The search terms were applied to titles, abstracts, and keywords, and included common synonyms (Appendix S1). We excluded reviews and conference reviews to avoid double counting. Out of an initial pool of 3300 articles for which the title was screened, 943 proceeded to abstract review. From these, we selected 523 articles for a full screening, and we extracted information from a final set of 159 articles (Figure S1). From each of these studies, we collected information in several categories (1) Article information: authors, title, publication year, and DOI; (2) Location: continent, country, biome, and dominant forest type; (3) Extent and grain of the study: spatial and temporal extent, along with spatial grain; (4) Natural disturbance characteristics: year of disturbance, disturbance

agent, severity, size, frequency, the reference condition used to assess disturbance effects (pre-disturbance state, undisturbed reference, disturbed—*inferred from measurements taken after the disturbance* –, synthetic—*simulation of undisturbed condition*), study method (empirical, experimental, remote sensing, simulation), and whether the study included single or multiple post-disturbance time-steps (the latter being further classified as chronosequences or true time series); (5) Ecological responses: time since disturbance, pre- and post-disturbance dominant species, pre-disturbance structure or composition indicator values (both central tendency and variation), post-disturbance trend (increase, decrease, or no change), post-disturbance management (e.g., salvage logging, site preparation), and post-disturbance agent of change (e.g., seed predation, climate, wind). Note that severity classifications were taken from the definitions used in each study, as standardisation across disturbance types was not feasible. Fire severity was usually derived from remote sensing indices (e.g., NBR, dNBR, RdNBR) or field-based measures. For windthrow and insect outbreaks, severity was generally based on the extent of stand replacement or tree mortality (e.g., in percent basal area killed). All severity definitions are available in the database accompanying this publication (see Data and Code Availability Statement). We allowed multiple entries (henceforth referred to as observations) per study, for instance if a study examined more than one disturbance agent, time-frames or severity.

We first removed observations for which salvage logging was reported directly after disturbance, as we aimed to characterise the disturbance effect in the absence of management. However, we acknowledge that past land-use practices may still influence forest responses through legacy effects. Subsequently, we followed a two-step analysis approach. First, we assessed how prevalent changes in forest structure and composition are, and whether they differ by disturbance agent, biome (classified using Olson et al. (2001)), study method, and time since disturbance. To that end, we used descriptive classifications such as frequency categories. Second, we focused on specific development pathways and quantified their prevalence. These pathways are self-replacement, relay succession, delayed regeneration and novelty. Self-replacement was defined as cases in which the dominant species (either as defined by the authors or inferred by us based on available density or basal area information) before and after disturbance remained the same. In cases with co-dominant species, an observation was classified as self-replacement if at least one of the pre-disturbance dominant species remained dominant after disturbance. The patterns of relay succession and novelty were distinguished based on shade tolerance, which serves as an ecologically meaningful and parsimonious indicator for separating these pathways from other patterns of post-disturbance reorganisation (Seidl et al. 2024). After a disturbance, shade-intolerant species dominate open sites in the relay succession pathway. As the forest develops, shade-tolerant species gradually increase, eventually outcompeting shade-intolerant species (Clements 1916). If, however, a disturbance is followed immediately by the dominance of a species that is even more shade-tolerant than the pre-disturbance species, it suggests the original species is unlikely to recover dominance (hence referred to this trajectory as novelty). We characterised the

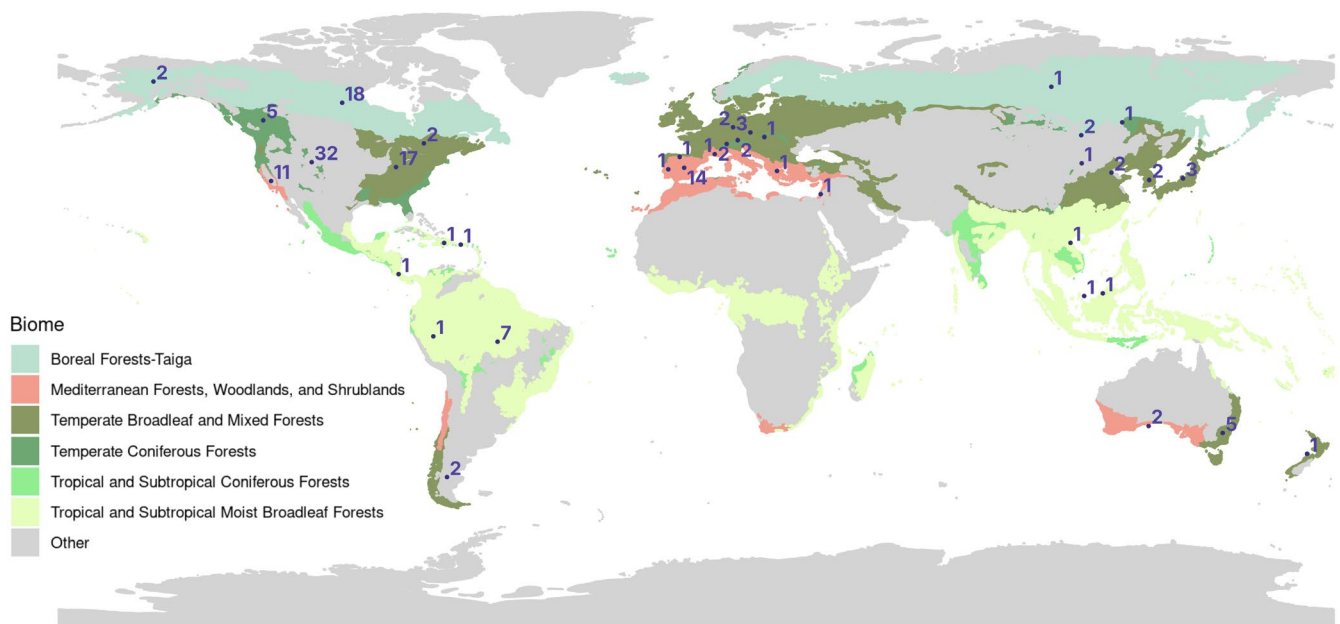


FIGURE 1 | Number of studies of post-disturbance forest reorganisation (including pre-disturbance data) by biome and country. Note that the point does not indicate the exact location but the country and biome centroid location.

dominant pre- and post-disturbance species using shade tolerance metrics from Niinemets and Valladares (2006), ranging from 0 (high light demand) to 5 (maximum shade tolerance). Among all cases that were not self-replacing, an observation was classified as relay succession if the dominant species after disturbance was less shade-tolerant than the pre-disturbance dominant species. If the post-disturbance dominant species was more shade-tolerant, we classified the case as an indication of novelty. When multiple dominant species were present before or after disturbance, we calculated the average shade tolerance for each state. The fourth pathway was delayed regeneration. Delayed regeneration occurs when regeneration density remains below 50 stems per hectare more than 10 years after disturbance, indicating prolonged recovery times (Hansen et al. 2018; Rammer et al. 2021). This pattern could also be the precursor to long-term regeneration failure and potential regime shifts (Kiel et al. 2025). To ensure the robust identification of these post-disturbance pathways, we excluded studies with data collected less than 5 years after disturbance for all reorganisation pathways except delayed regeneration, thereby focusing our analyses on multi-year trends in forest reorganisation (Seidl and Turner 2022). The final database included 4385 observations from 159 studies and was used to assess the prevalence of changes in forest structure and composition (question 1). A subset of 243 observations was then used to analyse specific forest reorganisation pathways (question 2).

3 | Results

3.1 | Prevalence of Change in Forest Structure and Composition

Most studies analysing forest structure and composition before and after disturbance have been conducted in the Northern Hemisphere (88% vs. 12% in the Southern Hemisphere, Figure 1)

with most in North America (57%, Figure 1). Changes in forest structure following disturbance are more prevalent in the literature than changes in composition (Figure 2a). Specifically, studies reporting the effects of disturbance on forest structure are most common (41%), followed by those reporting changes in both structure and composition (35%), and those focusing only on composition (24%). Structural changes are also the most commonly studied response across all forested biomes (Figure S4) and disturbance agents (Figure 3). The highest share of studies on post-disturbance forest development was conducted in temperate coniferous, broadleaf and mixed forest (54%), followed by Mediterranean (17%) and boreal forests (15%). Only 27 observations (13%) from the 201 observations analysed were from tropical forests. Some studies contributed more than one observation if they included multiple biomes or reported changes in different metrics (structure, composition, or both), which explains why the total number of observations exceeds the number of distinct studies. Fire is the disturbance agent most frequently analysed (67%), followed by windthrows (16%) and insect-outbreaks (14%) (Figure 3).

Most studies are conducted within the first 10 years after disturbance. There is a sharp decline in research on structure, composition, and their combined effects beyond 20 years post-disturbance (Figure 2a). In terms of study methods, empirical field studies are most prevalent, followed by remote sensing studies and those combining multiple methods (Figure 2b). Among remote sensing studies, Landsat and LiDAR were the sensors most commonly used, with Landsat often applied to quantify fire severity. Simulation studies primarily employed population or demographic models, while experimental studies were few and typically involved field-based disturbance manipulations (Figure S9). While studies using true time-series dominate across all time since disturbance categories, single-point-in-time studies are frequently conducted shortly after disturbance (<10 years) (Figure 2c). Over time, studies analyzing structural changes have increased more strongly

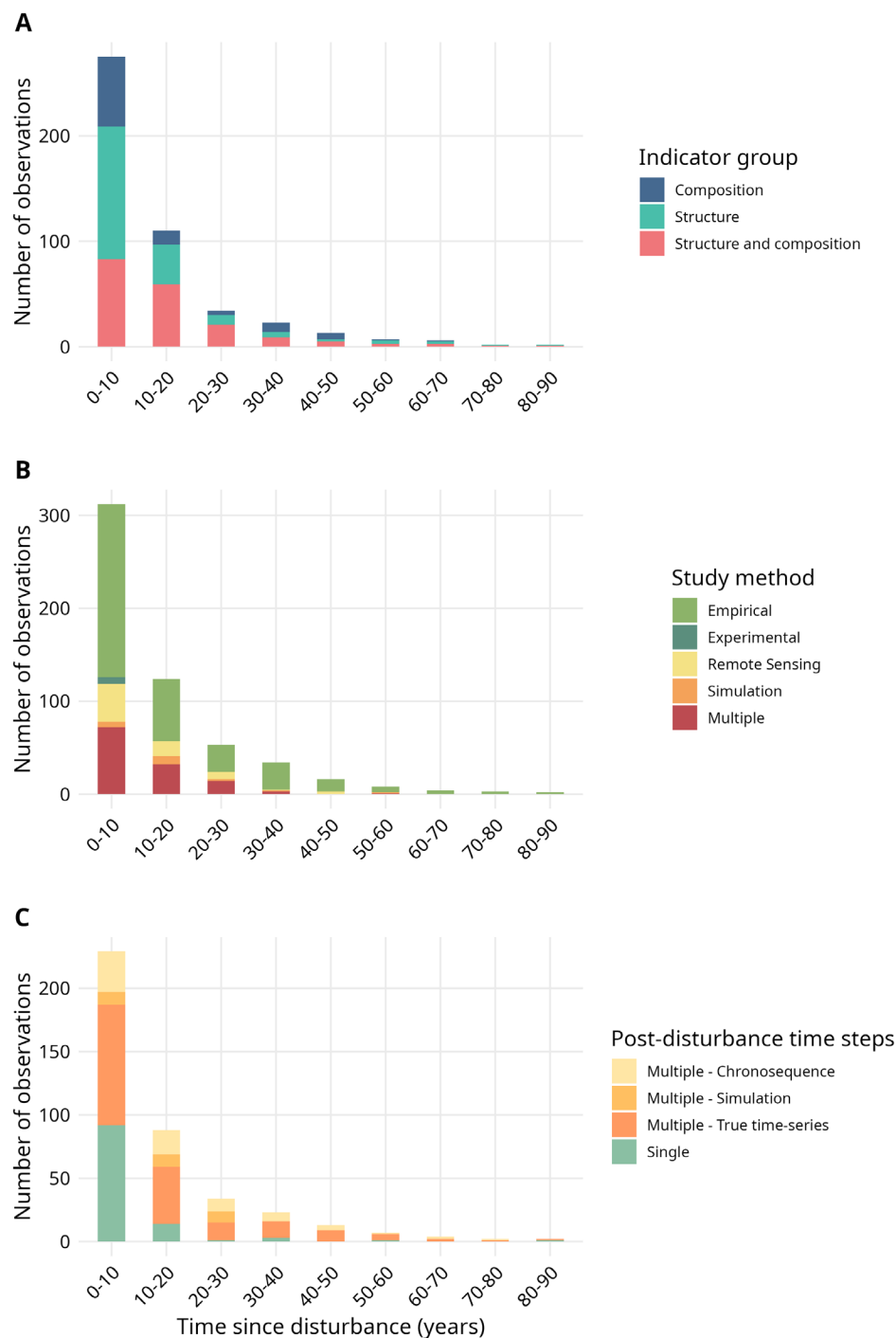


FIGURE 2 | Number of observations over time since disturbance (years), grouped by indicator group (A); study method (B); and post-disturbance time steps analysed (C).

than those focusing on composition or both dimensions (Figure S3).

3.2 | Prevalence of Forest Reorganisation Pathways Across the World's Forest Biomes

Self-replacement is the most common pathway reported in the literature (53%), followed by relay succession (27%), novelty (12%) and delayed regeneration (8%) (Table S1). At the level of individual biomes, self-replacement is the most common

development pathway across biomes, except in the boreal biome, where relay succession dominates. Delayed regeneration is prevalent in temperate broadleaved and mixed forests, but is less prominent in boreal forests and temperate coniferous forests. Novelty occurs primarily in temperate forests and, to a lesser extent, in Mediterranean, tropical and subtropical moist broadleaved forests (Figure 4).

Self-replacement generally declines with increasing disturbance severity, and less than 50% of the observations after high-severity disturbances self-replace (Figure 5a). The

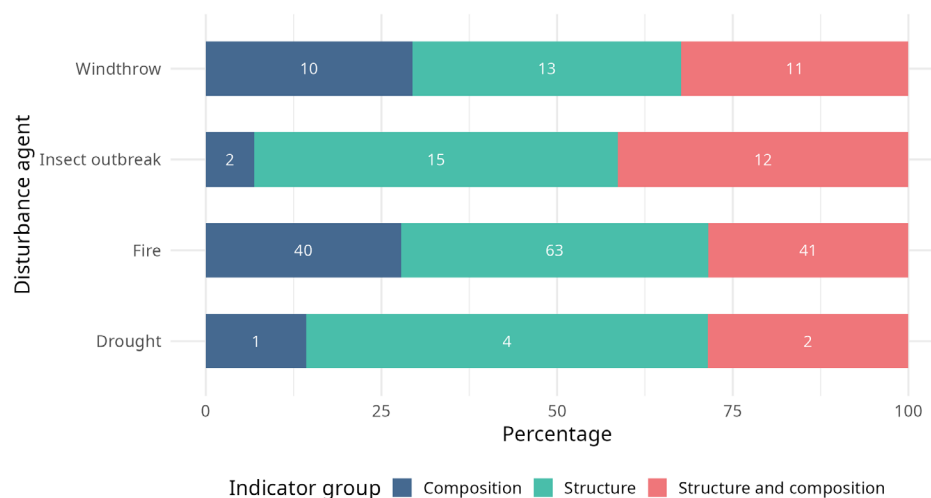


FIGURE 3 | Percentage of observations of the impact of disturbances on forest structure, composition or both by disturbance agent (windthrow, insect outbreaks, fire or drought). Absolute numbers of observations are given in the respective segments of the bars.

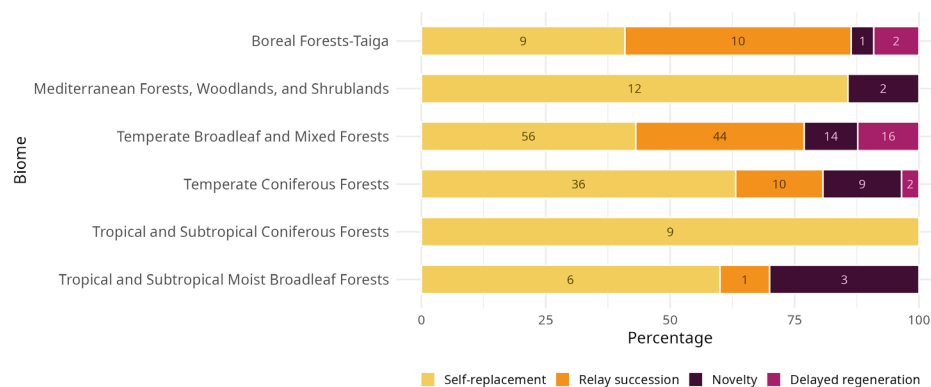


FIGURE 4 | Post-disturbance trajectories of forest development by biome. The coloured segments indicate the proportion of observations following different reorganisation pathways after disturbance (yellow for self-replacement, orange for relay succession, dark purple for novelty, and purple for delayed regeneration). Numbers within each segment show the absolute number of observations per reorganisation pathway and biome.

genera with high levels of self-replacement and high number of observations are *Pinus* and *Abies*. These genera are predominantly reported in North America, but several observations also come from Europe, Asia, and other regions, reflecting their wide geographic distribution and relevance for post-disturbance forest dynamics (Figure S10). *Pinus* has a high self-replacement rate (77%), followed by *Populus* (69%), *Pseudotsuga* (55%), *Abies* (45%), and *Picea* (39%). *Acer* and *Protium* have a 100% self-replacement rate, but only occur in a low number of observations (Figure 5b). The most common changes from pre- to post-disturbance in relay succession pathways are from *Abies* to *Populus* or *Quercus* and from *Picea* to *Quercus*. In contrast, *Abies* dominates as the post-disturbance genus in the novelty pathway (Figure S8).

4 | Discussion

4.1 | Current Knowledge on Disturbance Effects on Forest Structure and Composition

Despite a large number of studies of post-disturbance forest structure and composition, relatively few studies include pre-disturbance data or other reference conditions to assess

disturbance-induced change. In fact, many studies had to be excluded from our analysis because they did not report reference conditions, i.e., information on pre-disturbance structure and composition or the development of a similar undisturbed stand. This is perhaps not surprising, as disturbance events are stochastic, and pre-disturbance data may only be available opportunistically. Furthermore, it may only be possible to reconstruct pre-fire structure and composition in the first few years post-disturbance (Turner et al. 2019). The lack of reference conditions limits current understanding of post-disturbance reorganisation, since assessing changes requires comparison to a reference state. In climate science, counterfactuals (e.g., hypothetical scenarios representing system behaviour in the absence of anthropogenic forcing) are pivotal to attributing observed changes to specific drivers (Mengel et al. 2021). Similarly, in forest ecology, reference conditions are important counterfactuals, offering baselines to discern the magnitude and direction of disturbance-induced changes (Sales et al. 2022; Thompson and Carriger 2023). The recognition of distinct long-term vegetation trajectories dates back to early work in ecological succession (Cowles 1899; Clements 1916; Gleason 1926), underpinning the importance of reconstructing pre-disturbance states or identifying comparable undisturbed areas as key to understanding forest responses to disturbance.

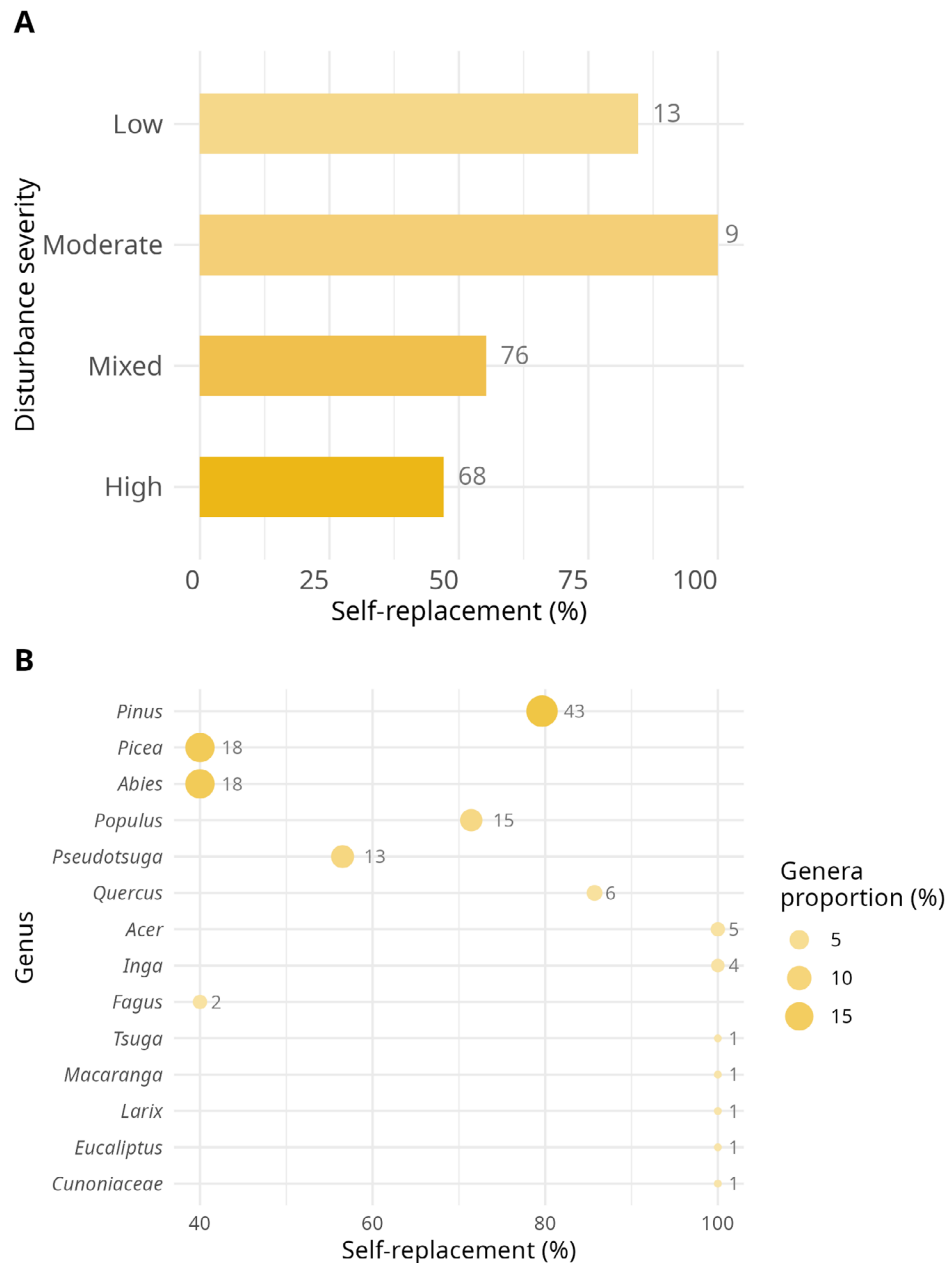


FIGURE 5 | Self-replacement as a function of disturbance severity (A) and genus (B). In panel A, the numbers at the right of the bars indicate the number of observations in each severity category. In panel B, circle size represents the sample size, i.e., the percentage of observations within each genus that are self-replacing, relative to the total number of observations for all genera. The number close to each circle indicates the absolute number of observations with self-replacement for each genus.

The focus of post-disturbance studies on forest structure over composition is likely at least partly the result of the rise of remote sensing to study forest dynamics (Figure S3). Remote sensing techniques are commonly deployed for detecting structural changes (Matasci et al. 2018; Lin et al. 2023), while assessing compositional shifts from remote sensing remains more challenging (but see Danneyrolles et al. (2020); White et al. (2023)). We argue that focusing solely on structure while neglecting composition (because one is easier to monitor than the other) may mask critical transformations in forests. A similar structure before and after disturbance (e.g., in terms of canopy cover or tree height) may be taken to indicate resilience, but shifts in species composition could indicate a fundamentally altered system, with different system properties that alter ecosystem

functions and services (Johnstone et al. 2016; Lecina-Diaz, Martinez-Vilalta, et al. 2024; Mack et al. 2021). A comprehensive assessment of forest change, incorporating both structure and composition, is therefore essential for accurately understanding ecosystem dynamics and resilience (Thom et al. 2019; Turner et al. 2020). Consequently, more studies integrating across both aspects are needed to capture the full range of forest responses to disturbances and improve predictions of ecosystem trajectories in a changing climate.

We found a considerable imbalance in the current literature on disturbance effects in terms of geography and methodology. First, the available literature is heterogeneously distributed over biomes and disturbance agents, with most studies addressing

disturbances in temperate forests, focusing on wildfires. This is in line with studies highlighting the global and dominant role of wildfire over other disturbances (Seidl et al. 2017; Thom and Seidl 2016). However, a publication bias towards the Global North (and mainly the temperate biome (Skopec et al. 2020)), amplified by language barriers (Konno et al. 2020), may have contributed to lower data availability from other biomes such as the tropics. In tropical regions, human-induced disturbances such as logging, land-use change, and forest fragmentation are more common than natural disturbances like wildfires (Pyles et al. 2022) these human disturbances were not included in our analysis. Our focus was on the most common natural disturbance agents (fire, wind, and insects), but other disturbances such as flooding, landslides, and permafrost degradation can be dominant in specific ecosystems. Additionally, even when focusing on natural disturbances, past and ongoing human land-use practices (e.g., logging, land conversion, altered fire regimes) can leave persistent legacy effects that influence both the magnitude of disturbance and subsequent forest reorganisation pathways (Cagliero et al. 2022; McMichael 2021). Second, a major limitation of current understanding of disturbance effects relates to the long-term consequences of forest disturbances, as evidenced by the paucity of studies extending beyond 20 years post-disturbance. This limits the ability to assess long-term implications and to quantify the length of the reorganisation period in forest ecosystems (Seidl and Turner 2022). Most studies assess disturbance effects within a decade of disturbance, which is often too short to distinguish typical successional dynamics from regime shifts (Kiel and Turner 2022). For instance, a study in the European Central Alps found that initial post-fire recruitment favoured transient pioneer species over the species dominating the stand pre-fire and that a lasting shift in species composition could only be confirmed over longer time scales (Moser et al. 2010). Similarly, research spanning more than three decades after the 1988 fires in Yellowstone National Park (Wyoming, USA) demonstrated how longer time series are essential to detect dynamics in sparse recovery trajectories. In a subset of the area that burned in 1988 and was characterised as recovering only sparsely after 34 years (approximately 16% of the total area), nearly half of the sampled plots transitioned to non-forest systems, while the remaining plots followed slow forest recovery trajectories (Kiel et al. 2025). Empirical studies are the dominant methodology to study post-disturbance development, and they tend to prioritise short-term observations. Simulation models can fill this gap by projecting long-term ecological trajectories and assessing forest development under different disturbance regimes (Albrich, Rammer, Turner, et al. 2020; Bugmann et al. 2019). Surprisingly, we found that true time-series studies are more common than chronosequences or simulations. Chronosequences or space-for-time substitutions have several limitations such as lacking rigorous controls for other influencing factors such as non-constant climate, management actions or variables related to topography and soil type (Kashian et al. 2005; Kreyling 2025). True time series of repeated measurements of the same plots offer valuable insights into forest recovery processes, and can be complemented by other approaches such as experiments aimed at understanding mechanisms, and simulations aimed at exploring a wider range of conditions and extrapolating in space and time. By integrating simulation approaches into disturbance research, potential effects of global change on post-disturbance forest development can be

addressed more explicitly (Maréchaux et al. 2021). Experiments could be employed to better understand the underlying processes of certain post-disturbance forest trajectories (García-Forner et al. 2016; Mejstřík et al. 2024). We found a low level of experimental evidence on post-disturbance forest development, despite experiments being the gold standard for science. This likely reflects the inherent challenges in using experimental approaches to study large-scale, infrequent, and stochastic disturbances (but see e.g., Müller et al. (2023)). Additionally, studies focusing on specific mechanisms via experimentation may be published independently from observational data documenting forest conditions before and after disturbance—the basis of our inclusion in the current study—and thus were not captured by our analysis. Overall, we argue that different methodological approaches and their individual strengths should be combined towards a better overall understanding of complex ecological phenomena such as disturbances (Cavender-Bares et al. 2022).

4.2 | Towards a Global Understanding of Post-Disturbance Forest Reorganisation Pathways

Variation in the prevalence of self-replacement among species and with disturbance severity likely reflects several underlying mechanisms. This includes neighbourhood effects (proximity of seed sources of the same species) as well as founder effects (propagules of the previously dominating species occupying niches before other species can establish), which manifest in advance regeneration (Zeppenfeld et al. 2015; Seidl et al. 2024). These processes are particularly prominent in trailing edge populations, i.e., the ones at the warm limits of a species' distribution range (Margalef-Marrase et al. 2022). In addition, diversity of species with different regeneration strategies (e.g., resprouting and obligate seeders that are serotinous or not) can also strongly influence reorganisation pathways (Ramiadantsoa et al. 2023). The genus *Pinus* had the highest self-replacement rate (77%) in our analysis, which may reflect its adaptation to disturbances, with many fire-adapted traits and frequently high drought tolerance (Lamont et al. 2020; Lloret et al. 2022). A second genus with high self-replacement and the ability to colonise recently disturbed areas was *Populus* (69%), which also has many traits adapted to disturbance such as a high capacity to recolonise disturbed areas, fast growth rate, low shade tolerance, effective long-distance seed dispersal, and ability to resprout (Hansen et al. 2016). Self-replacement rates declined with increasing disturbance severity. More severe disturbances are more likely to eliminate pre-existing seedlings and saplings and result in greater mortality of mature trees, limiting the availability of on-site seed sources (Duivenvoorden et al. 2024). Severe disturbances can also create conditions such as increasing light availability and more extreme microclimatic conditions that favour early successional species, which can—at least temporarily—dominate disturbed sites (Anoszko et al. 2022). Furthermore, these high severity disturbances can alter soil properties, nutrient cycling, and water availability, potentially creating an environment less suitable for the regeneration of the species dominating prior to disturbance (Szwagrzyk et al. 2021; McGinn et al. 2023). Interestingly, despite the low sample size, self-replacement was also the most common pathway reported in the literature for tropical forests. This aligns with studies showing that tropical forests experience small-scale gap

dynamics and localised natural disturbances, which promote turnover without altering forest composition, thus facilitating self-replacement (Acil et al. 2024; Hunter et al. 2015). Moreover, the high structural complexity and functional diversity of tropical forests, shaped by warm and humid climates, favour species than can rapidly regenerate in canopy gaps, stabilising forest composition (Ehbrecht et al. 2021). This differs from other ecosystems where more severe disturbances lead to species turnover or (temporary) shifts in tree species after disturbance, such as relay succession.

Relay succession was prevalent in temperate broadleaf and mixed forests and, to a lesser extent, in boreal forests. The temperate zone is where the concept was first conceived and has been extensively researched (Christensen 2014; Pulsford et al. 2016). Unlike temperate coniferous forests, where relay succession is the least common pathway, broadleaved and mixed forest species contribute to high soil nutrient availability due to fast leaf litter decomposition, facilitating the establishment of early-successional species (Desie et al. 2023). Additionally, broadleaved and mixed temperate forests contain a wider range of species with different shade tolerance and longevity, which is the prerequisite for sequential replacement of species in post-disturbance forest development (Borderieux et al. 2021; Hanberry 2019).

When forests deviate from self-replacement or relay succession pathways, they may undergo delayed regeneration or change into novel ecosystems with distinctly different species composition. Delayed regeneration was particularly relevant in the temperate and boreal biomes, where forests require extended periods to recover (Stevens-Rumann et al. 2022). Recent observations revealed that boreal forests are experiencing delayed regeneration and rapid vegetation changes in response to global change, despite their adaptations to wildfire (Boucher et al. 2020; Hayes and Buma 2021). In these forests, drought in the years following a disturbance can impede seedling establishment, further delaying regeneration and altering forest structure over long time periods (Whitman et al. 2019). Importantly, delayed regeneration can act as an early warning sign of potential regeneration failure. If recovery does not occur within 20–30 years post-disturbance it may indicate an impending regime shift towards non-forest states (Stevens-Rumann et al. 2022). We note, however, that we used a rather narrow time window of 10 years to identify delayed regeneration, and that tree regeneration can take several decades to establish, particularly in harsh environments like boreal and mountain ecosystems (Kuuluvainen and Aakala 2011). This underlines that while longer time-series are needed to confirm whether our data—synthesised from the literature—signal regeneration failure, simulation studies may provide additional insights in this regard, as they are able to anticipate the impacts of ongoing environmental changes. For instance, a study on temperate mountain forests of Greater Yellowstone points towards widespread regeneration failure of the currently prevailing forest types under future scenarios of fire and climate. Using simulations extending to 2100, projections suggest that between 28% and 59% of current forest types could fail to self-replace (Knowlton et al. 2025; Rammer et al. 2021). Moreover, novel ecosystems may emerge due to regeneration failure or when shifts in the competitiveness of species lead to divergence from previous patterns (such as relay succession). We found

evidence for novel post-disturbance forest development in temperate and, to a lower extent, Mediterranean and tropical forests. The increasing frequency of severe and short-interval fires, exacerbated by compound drought-fire disturbances, has, for instance, led to significant changes in species dominance in different parts in the world, with resprouters gaining a competitive advantage over obligate seeders (Arroyo-Vargas et al. 2024; Batllori et al. 2019; Bowd et al. 2023).

Overall, our findings suggest that increasing forest disturbances will promote the emergence of novel forest ecosystems in an era of global change. These novel ecosystems, such as resprouting shrublands or early-successional hardwood stands (Coop et al. 2020) can alter land-atmosphere interactions. For example, lower-canopy or shrub-dominated systems often have different albedo, evapotranspiration rates, and hydrological behaviour compared to closed, mature forests. Consequently, failure to regenerate historical forest types could change regional energy fluxes, water cycling, and carbon dynamics, with implications for vegetation-climate feedbacks and ecosystem services. Regenerating forests are a major component of the global carbon sink (Pugh et al. 2019), and post-disturbance regeneration can enhance gross primary productivity in various regions, including California (Hemes et al. 2023) and boreal North America (Kim et al. 2024). We note, however, that the geographic imbalance of our data makes a global assessment of these effects difficult based on available literature, which is also evident when considering genera and reorganisation pathways (Figures S10 and S11). Most observations across all four pathways come from temperate conifer genera such as *Pinus*, *Abies*, *Picea*, *Populus*, and *Pseudotsuga*, with the majority originating from North America and a few European and East Asian countries. In contrast, tropical and Southern Hemisphere genera are represented by very few studies, limiting our ability to generalise reorganisation patterns beyond the temperate biome. As a result, currently available evidence primarily reflects disturbance responses in temperate conifer forests, while patterns in tropical, subtropical, and other underrepresented biomes remain largely unknown.

5 | Conclusions

Our analysis of the current state of knowledge on post-disturbance reorganisation available in the scientific literature revealed that forest structural changes have been more frequently studied than compositional ones, and that long-term assessments (beyond 10 years post-disturbance) remain scarce. Previous research has primarily focused on temperate forests and fire, highlighting the need for more studies in tropical forests and on other disturbance agents. Self-replacement is the most common development pathway, suggesting that evidence for altered development trajectories remains limited, potentially reflecting the large body of research on temperate ecosystems and the selection criteria of our analysis. Rates of self-replacement decline with increasing disturbance severity (from 100% after low severity disturbance to 40% after high-severity disturbance), underscoring the need for more studies focusing on high-severity disturbances that strongly modulate environmental conditions and promote changes in species composition. Shifts in composition and structure can have profound implications for forest ecosystem functioning, biodiversity, and

the supply of ecosystem services. Robust studies that consider pre- and post-disturbance forest characteristics across a wider array of biomes and disturbances are needed to support forest management and conservation in the face of global change. The variability in post-disturbance reorganisation pathways has broad implications for Earth system modelling, as it influences carbon storage trajectories and land-atmosphere-water interactions that are often simplified in large-scale models (Fisher et al. 2018). This variability may be also relevant for SDG 13 (Climate Action) and SDG 15 (Life on Land) (<https://sdgs.un.org/goals>), highlighting which forests are more vulnerable or resilient to disturbances. Additionally, understanding these pathways can guide implementation of the 30×30 biodiversity targets (<https://www.cbd.int/gbf/targets>) by identifying areas where protection or restoration is most likely to maintain or enhance ecosystem resilience.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data and code are available in the following link: <https://zenodo.org/records/15792226>.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Appendix S1:** Search string in Scopus by TITLE-ABS-KEY. **Appendix S2:** Supplementary tables and figures. **Table S1:** Number of observations and percentage of each post-disturbance pathway. **Figure S1:** PRISMA diagram of the literature review. **Figure S2:** Percentage (and *n*) of observations of structure, composition or both. **Figure S3:** Number of observations by publication year. **Figure S4:** Percentage of observations by biome. **Figure S5:** Post-disturbance trajectories of forest development by disturbance year, agent and severity. **Figure S6:** Self-replacement percentage by species. **Figure S7:** Shade tolerance of the dominant species before and after disturbance. **Figure S8:** Changes in dominant species from pre- to post-disturbance states. **Figure S9:** Details on the methodologies used for remote sensing and simulation studies. **Figure S10:** Dominant genus per country and reorganisation pattern. **Figure S11:** Dominant genus per biome and reorganisation pattern.