



Carbon Emissions from Forest Disturbances Under Global Change

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Abstract

Purpose of Review Forests have a key role in global carbon dynamics, acting as both carbon sinks and sources. Yet, the intensification of global change-related natural and anthropogenic forest disturbances such as forest fires, deforestation, management practices, and biotic agents, among others, have the potential to compromise their carbon sink function. Here, we synthesize the current understanding of forest disturbances' impact on forest carbon dynamics under varying spatial, temporal, and ecological contexts globally. Thereby, our goal is to address ongoing uncertainties around the pattern, magnitude, persistence, and variability of carbon emissions linked to forest disturbances and to identify underrepresented regions, disturbance types, or forest ecosystems that remain understudied.

Recent Findings We present a synthesis of previous research from 2020 until early 2025. After screening 519 records, 90 studies were included for full synthesis following the PRISMA guidelines and PICOS framework. Data were extracted on forest type, carbon pool, disturbance type, geographic location, and study design. Recent studies have dominantly quantified carbon emissions from high-severity disturbances such as forest fires and deforestation. These disturbances have significant carbon impacts and have been amplifying under climate change. Furthermore, evidence from studies shows that compound disturbances often interact synergistically. However, the carbon impacts of low-intensity disturbances such as forest degradation, selective harvesting, or compound disturbances such as drought-fire interactions remain limited and fragmented. Moreover, the literature is biased toward aboveground pool estimates, with limited studies quantifying Total Ecosystem Carbon (TEC), as well as toward a remarkable underrepresentation of the Global South, with most research focused on areas and countries from the Global North.

Summary This review identifies key gaps in the literature, particularly regarding underrepresented geographic regions, compound disturbance effects, and the integration of multiple carbon pools in carbon estimates. We conclude by offering recommendations to address these gaps, aiming to improve carbon flux estimates and support adaptive forest management.

Keywords Forest disturbance · Carbon emission · Carbon dynamics · Climate change · Fire · Land use change

Introduction

Forest ecosystems cover approximately one-third of Earth's land surface and play a crucial role in the global carbon cycle through their dual function as carbon sinks and sources [1, 2]. Annually, the global forest sink is at 3.6 ± 0.4 Pg C yr⁻¹ in the 1990s and 2000s and 3.5 ± 0.4 Pg C yr⁻¹ in the 2010s, according to [3]. Estimated carbon stock changes of live woody biomass from 2000 to 2019 have shown that live biomass has removed $4.9\text{--}5.5$ Pg C yr⁻¹ from the atmosphere [4]. Despite their global importance as carbon sinks, forest ecosystems are increasingly threatened by both natural and anthropogenic disturbances that can alter their functioning. Though forests have been affected and shaped by

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these disturbances over time, the intensity, frequency, severity, and spatial extent of these disturbances has amplified under global change [5–7]. As an example, two-thirds of the global forest sink has been counteracted by tropical deforestation ($2.2 \pm 0.5 \text{ Pg C yr}^{-1}$ in 1990–2019) and further intensification of forest disturbance regimes [3]. Globally, gross emissions from disturbances account for $4.6 \pm 0.1 \text{ Pg C yr}^{-1}$ effectively reducing the net carbon sink of live biomass to just 0.2 to 0.9 Pg C yr^{-1} .

The intensification of human-driven disturbances can transform forests from a carbon sink to a source [8, 9]. For instance, the IPCC report [6] showed that land use changes caused about one-quarter of the global greenhouse gas emissions between 2007 and 2016. Land-use change, deforestation, and forest degradation in the tropics are estimated to have emitted approximately 1.4 Pg C yr^{-1} between 1990 and 2010 ($\sim 15\%$ of anthropogenic carbon emissions) [10] and 1.1 Pg C yr^{-1} ($\sim 10\%$ of total anthropogenic CO_2 emissions) between 2011 and 2020 [11, 12]. Another study [13] reported that the world's tropical forests represent a net carbon source, releasing $0.40 \pm 0.09 \text{ Pg C yr}^{-1}$, this net emission stemming from total carbon losses of $0.86 \pm 0.08 \text{ Pg C yr}^{-1}$ primarily due to deforestation and degradation or disturbance accounting for 68.9% of the total losses. On the other hand, more recent research found that tropical deforestation and degradation emit approximately $2.2 \pm 0.5 \text{ Pg C yr}^{-1}$, this being offset by forests regrowth, making tropical forests almost neutral to small net sink or source between (-0.1 and 0.6 Pg C yr^{-1} in 1990–2019), although this balance remains vulnerable to disturbance regime intensified by climate change [3].

In addition to human-driven disturbances, climate-induced disturbances are also intensifying, especially in temperate and boreal forests, leading to increased carbon emissions [5, 7]. In extratropical regions (i.e., temperate and boreal), fire-related carbon emissions increased by 60% globally between 2001 and 2023. This trend shows that climatic factors play a larger role in driving fires in extratropical areas, whereas human activities remain the dominant driver in tropical regions [14, 15]. These biome-specific patterns show that both the type of disturbances and the local context might affect forest carbon dynamics. Moreover, the feedback loops generated by these disturbances further reinforce climate change, consequently increasing the likelihood and severity of climate-induced disturbances [14, 16]. Moreover, the compounded effects of interacting forest disturbances (e.g., bark beetle outbreaks \times fire, fire \times deforestation) further complicate forest carbon dynamics, creating an increasingly complex and interdependent system in which disturbance regimes both respond to and drive climate change [7, 17–19]. These findings show how both human- and climate-induced disturbances affect forest

carbon dynamics, challenging the traditional focus on deforestation by revealing the often-overlooked contribution of other disturbances to long-term carbon loss.

However, the long-term carbon impacts of these disturbances remain debated. Some studies highlight forest resilience, showing that forest ecosystems can recover their carbon stocks and maintain overall carbon stability through post-disturbance regeneration (particularly following low-severity wildfires and low-impact harvesting), provided that the land use remains unchanged [20]. Nevertheless, growing evidence shows that the increasing frequency and severity of forest fires under climate change can surpass the recovery potential of forests, leading to long-term carbon losses and potentially shifting forests from carbon sinks to sources [21]. Similarly, the carbon impacts of forest degradation remain uncertain and are often underreported in national greenhouse gas inventories due to definitional ambiguity, inconsistent methodologies, and challenges in quantifying subtle but cumulative changes over time [22]. The impacts of forest management practices also raise contrasting viewpoints about carbon removal through harvesting and carbon sequestration through forest regeneration. There are studies that claim that the effects of management on forest regeneration allow the forest carbon stock and timber harvests to increase simultaneously [23]. Harvesting under sustainable forest management can provide climatic benefits by enabling the substitution of carbon-intensive products and allowing forest regrowth that captures back the released carbon [24–26]. However, other studies show that the removal of biomass from forests can cause carbon losses that may take a long time to recover, as recovery is heavily influenced by the type of silviculture, extent of the disturbances along with forest types and environmental conditions [18, 27, 28]. The expectation of complete regrowth holds a high degree of uncertainty, especially under global change, where disturbances have a significant role in forest carbon dynamics [7, 17, 29].

Building upon this context, this review aims to systematically assess and synthesize studies on carbon dynamics under different disturbances scenarios, published between 2020 and the beginning of 2025. We aim to clarify the carbon emission impacts of disturbances by synthesizing studies under varying spatial, temporal, and ecological contexts. By doing this, we address uncertainties surrounding the persistence, magnitude, and variability of carbon emissions linked to different types of natural and anthropogenic forest disturbances. The objectives of this review are threefold: (1) to identify which types of disturbances are most often assessed by forest carbon emission studies and how their impacts vary by forest biome, (2) to synthesise reported carbon emissions associated with forest disturbances and reveal prevailing patterns, (3) to highlight underrepresented

regions, disturbance types, or forest ecosystems where knowledge gaps persist and to make recommendations for future research and monitoring priorities. Ultimately, our goal is to establish an evidence-based scientific foundation to improve the global representation of disturbance-driven carbon fluxes while informing climate mitigation strategies.

Materials and Methods

Search Strategy

This systematic review was conducted following the guidelines of the Preferred Reporting Items for Systematic Reviews and Meta-analysis statement (PRISMA) [30] (Fig. 1). The literature search was conducted using two major databases (Scopus and Web of Science), which provide structured, advanced, and replicable search capabilities, making them appropriate for systematic synthesis under PRISMA guidelines. The search strategy was developed around four thematic categories: “carbon metrics”, “forest disturbances”, “global change”, and “forest ecosystem”. Keywords and synonyms were then identified under each theme and combined with Boolean operators (AND, OR) as shown in Table 1. To ensure consistency and sensitivity across databases, syntax was tailored to each database accordingly: TITLE-ABS-KEY was used for Scopus, and Topic (TS) for Web of Science. In addition, through a citation network analysis, relevant articles that were not obtained by the bibliographic search were included. The publication date was restricted from January 1, 2020, to March 15, 2025.

The literature search was limited to 2020 to 2025 to capture recent advances while complementing earlier review findings that covered pre-2020, also keeping search results tractable given the vast volume of forest disturbance-related research on carbon emissions published over the last decades. Although the included studies publication window was mostly limited to the last 5 years, many studies analysed long-term datasets. Following the execution of the search, all retrieved records were exported to the Covidence tool, which was used to manage the systematic review process: (1) management of the search results, (2) title and abstract screening, (3) full text review, and (4) data extraction.

Eligibility Criteria

After exporting and removing duplicates, studies were screened for relevance using the PICOS (Population, Intervention, Comparator, Outcome, Study Design) framework [31–33] (Fig. 1). The criteria were structured

as follows: Population (P) forest ecosystems; Intervention (I) forest disturbances; Comparator (C) not applicable; Outcome (O) carbon impacts; Study Design (S) empirical and analytical studies, including observational, experimental, modelling, and remote sensing approaches are included (Table 2). Screening was conducted in two stages: (1) title and abstract review and screening, and (2) full-text review for studies that met initial inclusion criteria or required further assessment. Studies that did not meet the PICOS criteria were excluded. Additional inclusion criteria included: (i) primary research articles and relevant reviews; (ii) written in English; and (iii) published from 2020 onwards. Based on these predefined inclusion and exclusion criteria, 90 studies that met all criteria underwent full text review and data extraction for the final synthesis.

Data Extraction

Data extraction was conducted systematically using predefined attributes to capture both descriptive and quantitative results. Relevant articles were reviewed manually using spreadsheets and Covidence (<https://www.covidence.org/>) simultaneously. For each study, the following information related to forest disturbances and carbon-related outcomes was recorded: authors, title, year of publication, source, document type, country, biome, disturbance type, carbon pool and metric reported, methodology, study design used, and spatial and temporal scales.

Synthesis Methods

We used a mixed-methods synthesis approach to organize and report the findings. First, all included studies were grouped by disturbance type (e.g., fire, deforestation, drought) and biome (tropical, temperate, boreal) to allow for thematic comparison. Data were extracted into structured matrices capturing carbon metrics (e.g., aboveground carbon (AGC) loss, soil organic carbon (SOC) loss, total emissions), and spatial and temporal dimensions, among others. Quantitative findings were synthesized using a descriptive narrative, summarizing emission ranges and biome-specific patterns where applicable. The qualitative synthesis examined cross-study patterns, disturbance-specific trends, and temporal dynamics of carbon flux. Special attention was given to understudied carbon pools (e.g., SOC, peat carbon) and to the identification of delayed or compound disturbance effects to identify gaps in the literature. Due to heterogeneity in study designs, carbon metrics, and spatial-temporal scales, a meta-analysis was not feasible.

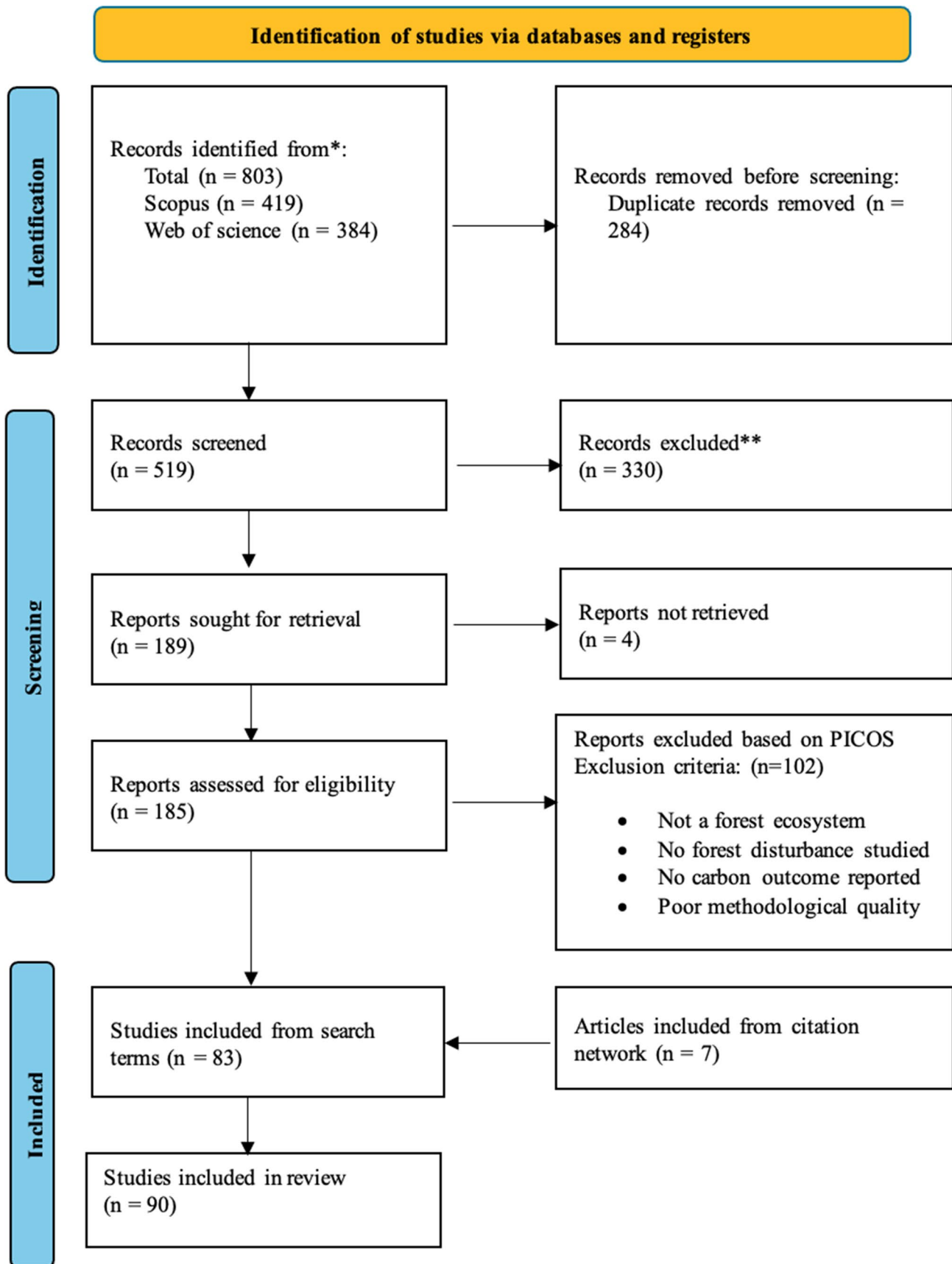


Fig. 1 PRISMA flowchart showing the study selection process [30]

Table 1 Keywords and syntax used for the literature search conducted within this study

No	Theme	Search query
1	Carbon metrics	TITLE (“carbon emission*” OR “GHG emission*” OR “forest carbon emission*” OR “CO2 emission*” OR “carbon release*” OR “carbon dynamics*” OR “carbon loss*” OR “carbon cycle*” OR “biomass change*” OR “carbon stock*” OR “carbon pool*” OR “carbon flux”*)
2	Forest disturbances	TITLE-ABS-KEY (“forest disturbance*” OR “deforestation” OR “forest degradation” OR “forest management” OR “silviculture” OR “forest migration” OR “forest fire*” OR “wildfire*” OR “pest*” OR “drought” OR “storm”*)
3	Global change	TITLE-ABS-KEY (“land use change*” OR “climate change” OR “global change”*)
4	Forest ecosystem	TITLE-ABS-KEY (“forest”*)

Table 2 Criteria used for relevance assessment of selected papers according to the PICOS (i.e., Population, Intervention, Comparator, Outcome, study Design) framework

Component	Definition	Criteria
Population	Forest ecosystem	Global forest (tropical, boreal, temperate)
Intervention	Forest disturbances	Both natural and anthropogenic forest disturbances
Comparator	Not applicable	No comparator criteria are needed for inclusion.
Outcome	Carbon related effects	Studies must report an emission, change, loss, or release of carbon resulting from forest disturbances.
Study design	Empirical and analytical	Peer-reviewed articles, modelling, remote sensing, and reviews. Excluded non-peer-reviewed works (e.g., book chapters, editorials).

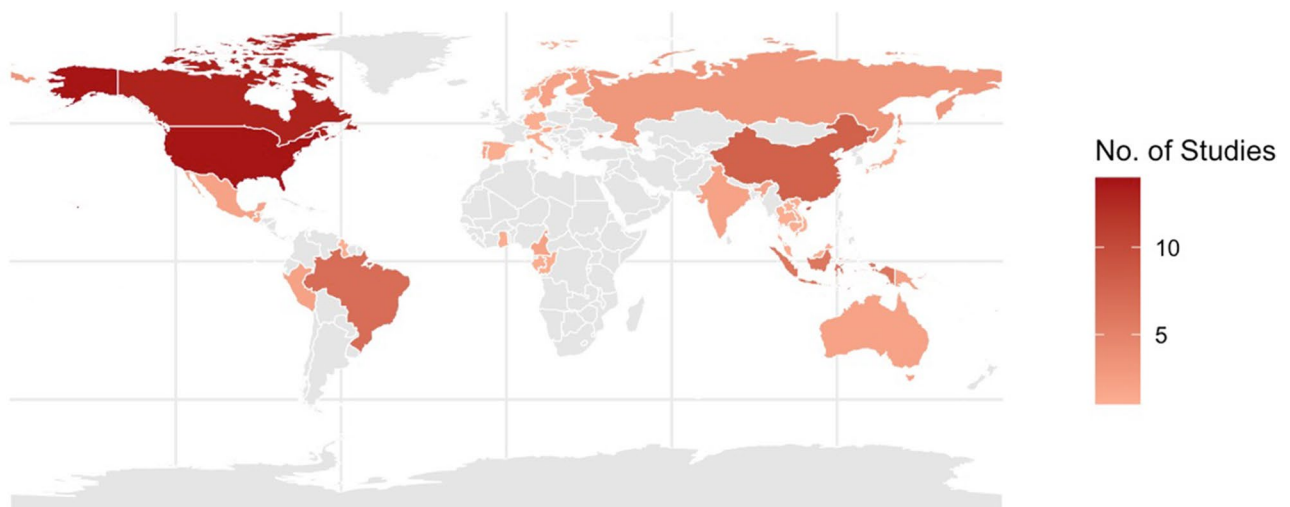
Characterization of Reviewed Research

The included studies represent a broad but uneven geographical distribution (Fig. 2). Out of the 90 studies, 68 focused on specific countries, even though some studies were conducted in multiple countries. The remaining 22 studies covered broader spatial scales, including 15 at a global scale and 7 eco-regional or continental studies. Most of the country-specific studies were concentrated in North America. The United States, Canada, and China together accounted for more than half of nationally focused studies. Brazil and

Indonesia were the most represented countries among those hosting extensive tropical forests. Conversely, forests in Europe, Africa, parts of Asia, and parts of Oceania remain largely understudied. Despite this uneven distribution across countries, all three major forest biomes were quite evenly represented in the considered literature, with the tropical, temperate and boreal forest biomes being represented in 44, 40 and 28 studies, respectively.

In terms of spatial scales, the reviewed studies varied from local to global focus, with a balanced distribution across scales (Fig. 3). Forest fire-related studies were dominated

Geographic Distribution of Included Studies



Countries in grey had no studies.

Fig. 2 Geographic distribution of included studies

Distribution of Spatial Scales Across Studies

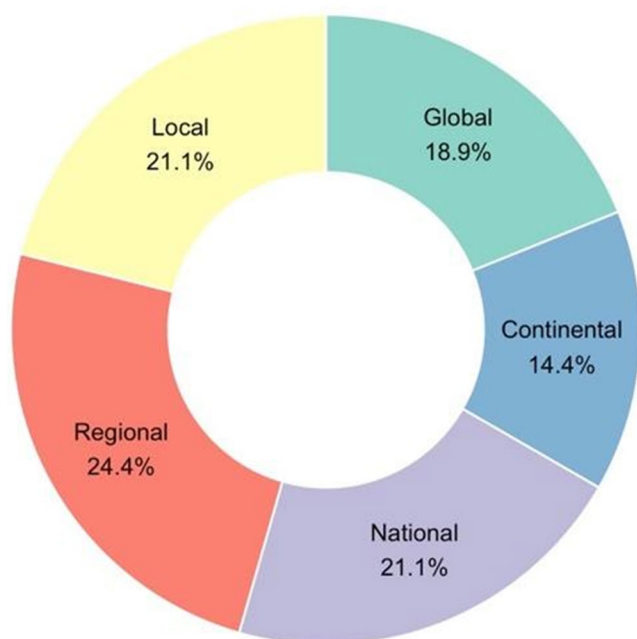


Fig. 3 Spatial scale across studies. Local: site/landscape-level; Regional: subnational or multi-site within one country; National: country scale; Continental: multiple countries within a continent; Global: worldwide coverage

by national and regional scales ($n=10$ each), while deforestation studies covered a broader range of scales. In contrast, studies on disturbances such as harvesting, windthrow, biotic factors and drought focused on smaller scales, with few global-scale studies represented.

When categorised by forest disturbances, forest fires emerged as the most frequently studied disturbance, followed by deforestation. Forest fires were more prevalent in boreal and temperate regions, whereas research in tropical forests tended to focus on deforestation and degradation (Fig. 4). Only a small number of studies addressed other types of disturbances.

In this review carbon pools are defined as follows: AGC refers to living aboveground biomass, SOC refers to organic carbon contained in soil profile, BGC refers to roots or belowground biomass, and TEC is the sum of all the carbon pools. The review also revealed an uneven representation of measured carbon pools (Fig. 5). Most studies, regardless of disturbance type, focused mainly on AGC and SOC measurements, with limited attention to belowground carbon (BGC) and detrital carbon pools (Fig. 5). Only 8 studies measured TEC, while another 7 did not specify the carbon pool measured, mostly those examining carbon fluxes.

Carbon Emissions from Forest Disturbances Under Global Change

Forest disturbances, both human- and climate-induced, have substantial impacts on forest carbon dynamics, as shown across the reviewed studies. Human footprint expansion led to 20 Pg C of AGC loss between 2010 and 2018 globally, with tropical and subtropical biomes undergoing the most severe losses, especially in the Global South [34]. Global forest carbon sink was stable at 3.5 Pg C yr⁻¹ from 1990s to 2010s. However, this stability is offset due to intensifying disturbances such as degradation and deforestation. After accounting for disturbance-related emissions, the global forest carbon sink progressively weakened during the 2000s and 2010s [3]. For instance, in the Amazon forest 6.3 Pg C were lost to disturbances between 1996 and 2017, with a net loss of ~5 Pg C representing 2% of global carbon emissions [35]. Deforestation and degradation in the tropics remain high with a recent increasing trend in some regions. It is estimated that gross AGC emissions from deforestation was 10,521 Tg C and degradation 2,916 Tg C between 1984 and 2018 [36]. The following section provides a disturbance-specific assessment of forest carbon impacts, while quantitative carbon responses to disturbances are summarized in Table 3.

Forest Fires

Forest fires are one of the major disturbances affecting forest carbon dynamics worldwide. Across the reviewed studies, wildfires consistently caused significant AGC losses, with several studies also reporting substantial belowground impacts, especially in high-latitude and peatland forest ecosystems [37–39]. For example, in terms of direct carbon emissions, forest fires in tropical dry forests (TDFs) globally cause the emission of 259.6 Tg C yr⁻¹ on average, with notable spatial variation across regions such as Mexico and Central America [40]. Another study in North America (USA and Canada) estimated that boreal forest fires burned approximately 2.9 Mha annually, releasing 79 Tg C yr⁻¹ [41]. Wildfires are rapidly expanding in boreal forests. Although they typically account for about 10% of global forest fire CO₂ emissions, boreal fires contributed 23% (0.5 billion t C) in 2021, the highest level recorded since 2000 [42]. A study from southern Europe also estimated emissions from major wildfire events in Portugal, highlighting substantial releases of greenhouse gases, such emissions being greater than Portuguese anthropogenic emissions over the entire year 2017 [43]. In the same vein [44], analysed satellite observations of large wildfires in southwestern Europe, showing significant fire-driven greenhouse gas fluxes at regional

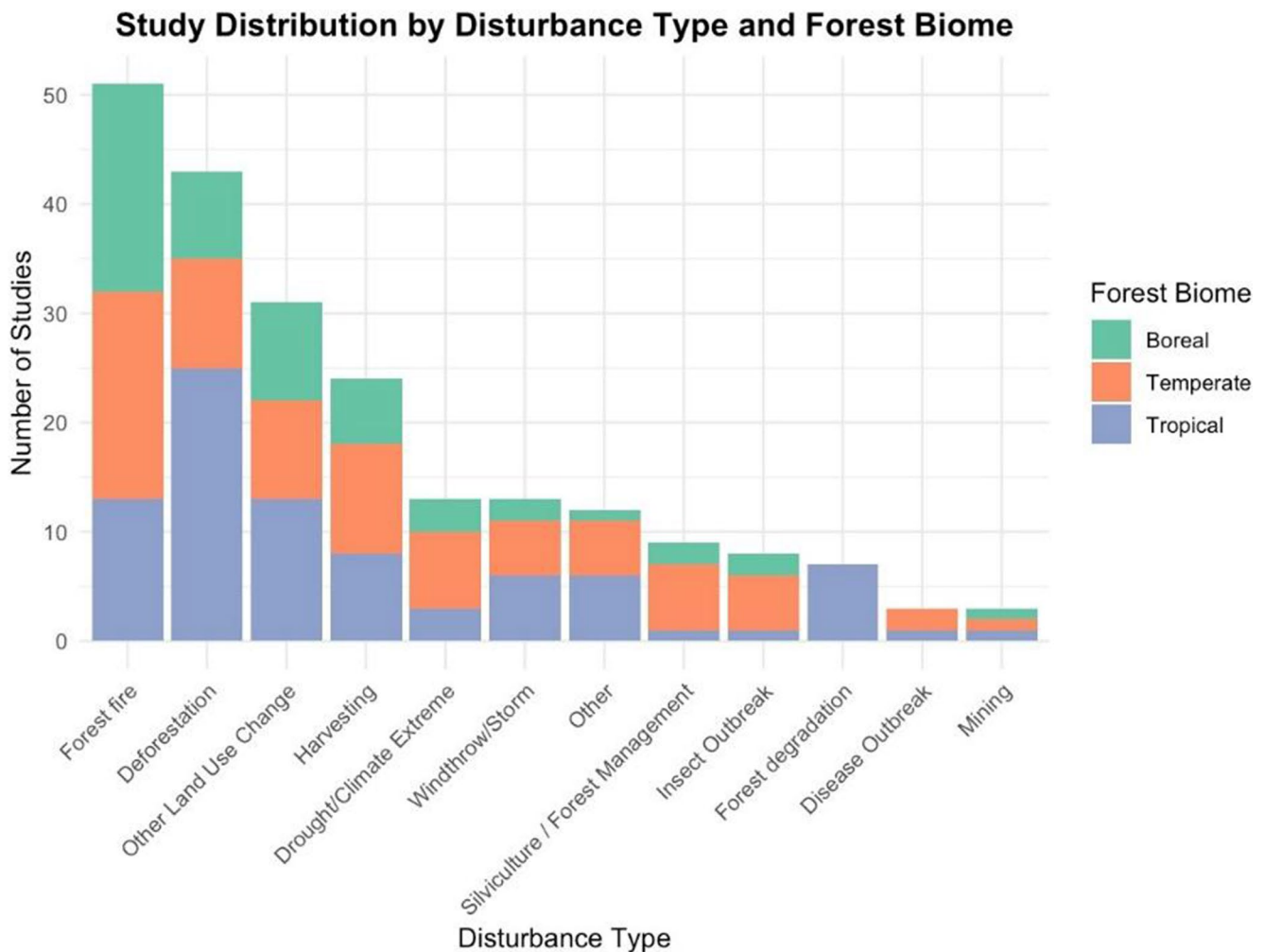


Fig. 4 Study frequency by forest biome (colors) and disturbance type. “Other” includes less frequent or uncertain reported disturbances such as changing rainfall patterns, fragmentation & edge effects, landslides, shifting cultivation, forest migration, and permafrost thaw

scales. Together, these studies show that severe fire events in European ecosystems can contribute notably to atmospheric carbon dynamics. Prescribed fires have also been reported to result in carbon emissions [45], for instance, in the U.S. temperate hardwood forests, where repeated low-intensity prescribed fires were found to cause a 53% reduction in SOC [46]. However, this does not explicitly account for avoided emissions resulting from fire hazard mitigation as a result of prescribed burning. Nonetheless, over the long term, prescribed fire may enhance SOC retention by shifting carbon into slower-cycling pools.

Beyond direct AGC impacts, forest fires significantly affect BGC pools [47, 48]. Although most studies reported AGC as the primary source of immediate carbon emissions following forest fires, in certain ecosystems where data were available, SOC losses were higher in quantity and more persistent, especially in organic-rich soils. For example [41], showed that 90% of carbon emissions from the forest fires were from belowground (organic soil), and that these were

heavily influenced by burn depth and fire severity. A high-resolution case study in Russia assessing carbon losses from forest-peat fires found that soil carbon losses (mean 98 t C ha⁻¹) were approximately 50% larger than tree biomass losses (58.8 t C ha⁻¹) [49]. In the boreal forests of north-west Canada, wildfires caused immediate carbon emissions from the humus layer and delayed emissions from mineral soils. In forested permafrost areas, soils emitted three times more CO₂ than non-permafrost areas, highlighting their heightened and long-term vulnerability to carbon loss [50]. These belowground losses were hardly offset by post-fire regrowth and caused long-term carbon losses. Similarly, carbon recovery in boreal forests after wildfire, which can cause 60% TEC losses, takes up to 50–100 years due to the delayed releases from decomposition [42]. These findings show that while AGC losses are immediate and more visible, BGC dynamics, especially in peat-rich and permafrost regions, represent a greater and long-lasting source of carbon emissions. Geographic trends revealed contrasting

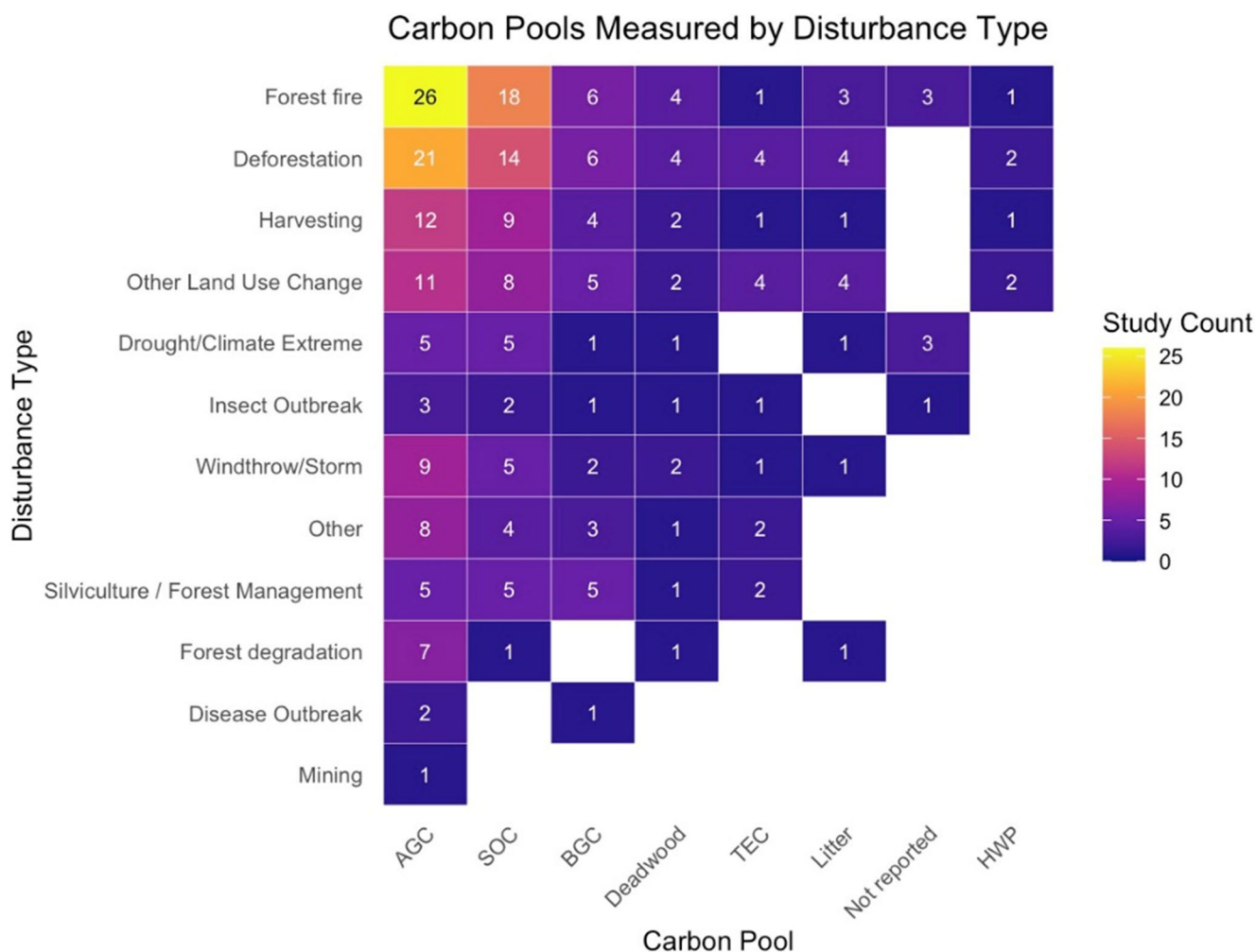


Fig. 5 Carbon pools measured by disturbance type (AGC: above-ground carbon; SOC: soil organic carbon; BGC: belowground carbon; TEC: total ecosystem carbon; HWP: harvested wood products).

“Other” includes less frequent or uncertain reported disturbances such as changing rainfall patterns, fragmentation & edge effects, landslides, shifting cultivation, forest migration, and permafrost thaw

fire emission trajectories. For example, in mainland China, a study showed that CO₂ and CH₄ emissions declined by 48.4% and 88.9% after fire respectively, compared to the 1990s [51], and forest fire carbon emissions were regionally distinct and linked to forest type [51, 52]. In contrast, boreal fire emissions have significantly increased, with a notable upward trend of ~ 5 Tg C yr⁻¹ from 2008 to 2022, driven by warming temperatures, longer fire seasons, and increasing fire weather index (FWI) conditions [53]. Overall, wildfires are immediate and severe sources of forest carbon loss and have potential impacts on deep soil and persistent carbon impacts under climate change.

Forest Degradation and Deforestation

Deforestation and forest degradation are the major drivers of forest carbon emissions globally, though the reported impacts in previous research differ in severity, spatial

patterns, and recovery trajectories. Across the reviewed studies, these disturbances were reported to have caused significant forest and carbon loss especially in tropical and mountain regions [84–87]. Although global tropical deforested and degraded old-growth forests are nearly carbon neutral, wet tropical forests were a net carbon source (0.07 Pg C yr⁻¹) due to deforestation (0.04 Pg C yr⁻¹) and agriculture expansion (0.03 Pg C yr⁻¹) between 2010 and 2019 [88]. On the other hand, previous research also reported a moderate net AGC sink of 0.21 ± 0.06 Pg C yr⁻¹ throughout the global tropics from 2010 to 2020 as a result of a gross carbon loss of - 1.79 Pg C yr⁻¹ offset by a gain of 2.01 ± 0.06 Pg C yr⁻¹ [89]. Global deforestation for agriculture and settlements caused 12.3 Gt C from 2010 to 2018 (mostly in the tropics) [90]. These findings show the significant role of tropical forests in global carbon dynamics, highlighting the need to focus on land-use change in these high-emission regions.

Table 3 Main quantitative impacts of forest disturbances on carbon stocks across disturbance types and biomes reported in the literature

Disturbance Type(s)	Forest Biome	Carbon Pools Measured	Spatial Scale	Temporal Scale	Quantitative Value(s)	Studies
Deforestation	Temperate	SOC	Local	1-year post-deforestation	20.1% increase (0–100 cm)	(Wang et al., 2022) [54]
	Tropical	TEC	Local	up to 120 years post-deforestation	35% to 85% decrease	(Grieco et al., 2024) [55]
	Boreal	SOC	Regional	~0–100 years (quasi-chrono sequence)	On average, permafrost-affected forest soils lost: 15.6±21.3% to cropland 23.0±13.0% to grassland	(Peplau et al., 2022) [56]
	Tropical	AGC	National	2010–2019	27% of gross loss of 4.45 Pg C	(Qin et al., 2021) [57]
	Tropical	AGC	National scale	2003–2015	Avoided emissions: 4.6 t CO ₂ -eq ha ⁻¹ (Petén) 2.15 t CO ₂ -eq ha ⁻¹ (Acre)	(Alejo et al., 2022) [58]
	Tropical	AGC, SOC, Deadwood	Continental	2001–2017	Net annual emissions: 72.9±6.2 Tg C yr ⁻¹ With delayed emissions: 102.8±8.6 Tg C yr ⁻¹	(Tang et al., 2021) [59]
	Temperate	AGC	Regional	2000–2017 (18 years)	Across six states: Mean AGB change: 0.38±5.73 Mg C ha ⁻¹ 3.4% of forest inventory plots deforested	(Fitts et al., 2021) [60]
Drought/Climate Extreme	Tropical	AGC, BGC, TEC	Local	15 months post-disturbance	TECS loss: -270.5 Mg C ha ⁻¹ (-14.6%) AGC: -49.4% BGC: -61.2% Emissions: 992.8 Mg CO _{2e} ha ⁻¹	(Gomes et al., 2021) [61]
	Temperate	SOC	Local	5 years (2014–2019)	+2.7 kgm ⁻² (<i>P. abies</i>), +1.1 kgm ⁻² (<i>F. sylvatica</i>)	(Brunn et al., 2023) [62]
Drought/Climate Extreme + Forest management degradation	Boreal	Not specified	Local	1997–2021 (focus: 2018–2021)	Offset 8–92% of climate-driven C gains	(Wu et al., 2024) [63]
	Tropical	AGC	Bio geographical Amazon	2010–2020	Disturbance = 192 T g C yr ⁻¹ Old-growth sink = 333±195 Tg C yr ⁻¹ Net = 141±195 T g C yr ⁻¹	(Rosan et al., 2024) [64]
	Tropical	AGC	National	2010–2019	73% of gross loss of 4.45 Pg C	(Qin et al., 2021) [57]
Forest fire	Temperate	AGC, SOC	Local	2010 fire event	AGC loss: 58.8 t C/ha SOC loss: 98 t C/ha (mean) or 92 t C/ha (median); Total CO ₂ emissions ~650 t CO ₂ /ha	(Sirin et al., 2021) [49]
	Boreal	AGC, BGC, SOC	Regional	Single event focus (2015 fires), with legacy	Avg. emission: 3.3±1.1 kg C/m ² to 14.2 kg C/m ² Total emission: 36.3±15.0 Tg C	(Dieleman et al., 2020) [65]
	Boreal	Not specified	National	2023	647 Tg C (range 570–727 Tg C); 15 million ha burned	(Byrne et al., 2024) [66]
Insect Outbreak	Temperate	Not specified	Regional	2020–2022 (3 years)	Deciduous forest: GPP by -35% Mixed forest: GPP by -23% Carbon loss: 21.1–21.4 million t C	(Hussain et al., 2024) [67]
	Temperate	TEC	Local	1997–2100 (104-year simulation under RCP4.5 and RCP8.5)	C at 80–95% salvage Total stock loss: ~405–419 t C ha ⁻¹	(Dobor et al., 2020) [68]

Table 3 (continued)

Disturbance Type(s)	Forest Biome	Carbon Pools Measured	Spatial Scale	Temporal Scale	Quantitative Value(s)	Studies
Forest Management	Temperate	TEC	Local	5 years post-treatment (2017–2022)	Control: 207.6 ± 8.6 Mg C/ha; Partial cut: 189.2 ± 11.8 Mg C/ha (−8.9%) Clear-cut: 107.4 ± 8.2 Mg C/ha (−48.3%)	(Ola et al., 2024) [69]
	Boreal	AGC, BGC, SOC, Deadwood	Regional	2010–2110 (100 years)	Partial cutting by 5 t C ha ^{−1} yr ^{−1} Clearcutting loss by ~10 t C ha ^{−1} yr ^{−1}	(Ameray et al., 2024) [70]
	Temperate	AGC, BGC, SOC	National	2010–2150	Carbon stock: BAU=307 Mt, CSC=452 Mt (+47%), SRC=223 Mt (−27%); Salvage logging: Vs. BAU CSC=−14%, SRC=−32%	(Ledermann et al., 2022) [71]
Windthrow/ Storm	Temperate	AGC	Regional	2001–2007	Hardwood 74.5 t C/ha; Mixed stands 17.8 t C/ha Up to 121.6 t C/ha young tall trees	(Alam et al., 2024) [72]
	Tropical	AGC, Deadwood, SOC	Local	1985–2018; focus on post-2004	Total=427–3,599 Mg C depending on scenario	(Peneva-Reed et al., 2021) [73]
	Temperate	AGC	Regional	Simulated over 100 years; modelled for 2020 conditions	121 million t CO ₂ e (baseline), 182 million t CO ₂ e (8% wind increase), 250 million t CO ₂ e (16% increase);	(Tumber-Dávila et al., 2024) [74]
Multiple Disturbances	Boreal, Temperate, Tropical	AGC, SOC	Global	1961–2020	Average net emission of 1.2 Pg C year ^{−1} .	(Qin et al., 2024) [75]
	Boreal, Temperate, Tropical	TEC	Global	2001–2019	gross emissions (8.1 ± 2.5 Gt CO ₂ e yr ^{−1})	(Harris et al., 2021) [76]
	Boreal, Temperate, Tropical	SOC	Global	1983–2022 (with observations up to ≥40 years post-disturbance)	SOC loss average: 7.2 ± 1.3 Mg/ha (−25.7%); Wildfire: −11.0 ± 2.4 Mg/ha Harvesting: −6.3 ± 1.8 Mg/ha Windstorm: −8.6 ± 4.1 Mg/ha Insect: −2.0 ± 3.6 Mg/ha	(Mayer et al., 2024) [77]
	Boreal, Temperate, Tropical	AGC, SOC, Litter	Continental	2000–2019	Fire: 0.28–0.35 Pg C yr ^{−1} In drought years net C source: −0.02 ± 0.46 Pg C yr ^{−1}	(Murray-Tortarolo et al., 2022) [78]
	Boreal, Temperate, Tropical	AGC, BGC	Global	1990–2020 (30-year period)	Cumulative net C emissions from forest area loss: ~0.74 Gt C total (0.03 Gt C yr ^{−1}) 4.9 Gt C without harvest change. 0.63 Gt C without burnt area change	(Noë et al., 2021) [79]
	Temperate	AGC	Regional	2009–2018	Average fire emissions: 59.95 Tg CO ₂ e/yr Harvest: 49.88 Tg CO ₂ e/yr Clear-cutting emits 2–8× more C per area than fire	(Bartowitz et al., 2022) [80]
	Temperate	AGC, BGC	National	2000–2050 (50 years)	Wildfires reduce carbon stocks by up to 33% Schoolbook management, final carbon stock projected at −20.7% (B2)	(Adame et al., 2020) [81]
	Tropical	AGC, BGC	Local	Up to 25 years post-disturbance	Undisturbed C stock: 182–2,730 Mg C ha ^{−1} Aquaculture conversion=−85% biomass, −60% soil C Harvesting=−75% biomass C, no soil C loss	(Sasmito et al., 2020) [82]
	Tropical	AGC, BGC	Global	Up to 2100	−3.4 Pg CO ₂ loss under high sea-level rise with coastal squeeze	(Alongi, 2022) [83]

Topics such as embodied deforestation and extractive land-use activities like mining remain understudied, despite their significant contribution to global forest carbon emissions. For example, a study that analysed transboundary impacts of embodied deforestation (2000–2020) found that palm oil consumption in Europe caused emissions of up to 445 kg CO₂ capita⁻¹ yr⁻¹, primarily in Southeast Asia [91]. Globally, mining-induced forest loss between 2000 and 2019 resulted in cumulative emissions of ~ 490,525 Gg CO₂, with Indonesia, Brazil, and Canada being the largest contributors [92]. These findings highlight that forest carbon loss is not only driven by local land-use practices but also by cross-boundary trade and natural resource extraction. Both embodied deforestation and mining expansion directly cause forest cover loss and lead to carbon emissions from forest ecosystems.

In addition to immediate AGC loss, both forest degradation and deforestation are associated with SOC loss, too [93–95]. Research conducted in Brazil showed that native vegetation deforestation for agriculture through conventional tillage resulted in a progressive loss (1%–26%) in SOC stocks over time, although the impacts differ across Brazilian regions [96]. A study from India found that converting forest land to cultivated land led to a 21% loss in TEC and 41.2% loss in SOC. Collectively, these studies highlight that agricultural practices, such as deforestation for cropland and subsequent soil tillage, can alter carbon fluxes by increasing SOC losses and reducing overall carbon storage capacity. Similarly to trends observed in fire-affected permafrost regions, a study in Canada's discontinuous permafrost zone found that converting boreal forest to agricultural land led to long-term soil carbon losses of up to 41 Mg C ha⁻¹, while non-permafrost soils showed no significant loss [56]. These results consistently demonstrate that soil carbon losses occur following land conversion and are strongly influenced by biome type, tillage intensity, and soil properties.

Geographically, forest degradation was studied exclusively in tropical regions, while deforestation studies covered a broader spatial range. However, emerging trends show that degradation may surpass deforestation in long-term carbon impacts [35, 57, 97]. For example, in the Brazilian Amazon, forest degradation is predicted to account for up to 47% of gross carbon emissions by 2050, surpassing deforestation as the dominant source, with emissions ranging from 1.3 to 24 Gt CO₂ [98]. In recent years, the area of forest degradation in the Brazilian Amazon has been higher than the area affected by deforestation [98]. These studies show that, although deforestation has broader biome coverage and immediate AGC impacts, degradation may cause more long-term carbon losses over time in tropical regions.

Forest Management-Related Disturbances: Silviculture and Harvesting

Forest management-related disturbances, such as harvesting, silviculture, and post-disturbance interventions, represent a distinct category of forest carbon drivers. Harvesting aims primarily at tree removal for resource extraction, whereas silviculture is a broader management approach also focused on achieving long-term forest ecological objectives, which may include harvesting. Unlike natural disturbances, these anthropogenic activities are intended to achieve specific management goals and can either reduce or enhance forest carbon stocks depending on the context and goals. For example, research conducted in Austria measured and compared the effect of three forest management scenarios on carbon stocks: business-as-usual (BAU), shortened rotation cycles (SRC), and changes in species composition (CSC). The findings showed that SRC reduced salvage logging by 32% but resulted in a 27% decrease in carbon stock compared to BAU, while the CSC increased carbon stocks by 47% and reduced salvage logging by 14% [71]. Similarly, in Mediterranean beech forests, species mixtures and low-intensity management enhanced long-term carbon stock and sink, whereas high-intensity harvesting led to substantial carbon loss, especially in monospecific beech stands [99].

Silvicultural thinning, when applied moderately, can increase SOC stocks in managed forests, especially in low-humidity regions and over long recovery periods. A meta-analysis conducted across China showed that forest thinning increased SOC stocks in planted forests by 7.2%, with mid-intensity thinning (35–55%) in stand basal area resulting in the greatest increase (+ 16.1%) compared to non-thinned controls. The positive effect of the thinning became statistically significant after five years [100]. These findings highlight how thinning intensity, site climatic conditions, and recovery period can strongly influence carbon impact. However, intense thinning may disturb soil processes and result in SOC loss.

Harvesting also shows a similar pattern to thinning. A study based on long-term simulations in eastern Canadian boreal forests showed that clearcutting substantially reduces TEC stocks. However, partial cutting that keeps canopy cover and forest structural integrity, seemed to lead to stable net ecosystem productivity (NEP) over time [70]. Likewise, in Douglas-fir forests of British Columbia, harvesting intensity was identified as the dominant driver of future carbon stock trajectories, with clearcutting reducing ecosystem carbon by up to 36% [101]. These findings together show that forest management practices are not inherently carbon-negative or carbon-positive but are determined by the local

context, including silvicultural treatments types and intensity, ecological conditions, and long-term carbon recovery dynamics. While moderate interventions such as selective thinning, variable retention harvest and compositional adjustments have been shown to increase soil carbon and reduce disturbance risk, more intensive treatments such as clearcutting and shortened rotations can result in consistent and long-term carbon losses.

Drought

Drought is a critical climate-induced disturbance with variable effects on forest carbon dynamics depending on forest type, seasonality, legacy effects, and interaction with other disturbances. For example, in subtropical forests of China, a severe summer drought in 2022 led to different carbon responses in evergreen and deciduous forests. Indeed, the first impact on NEP varied according to forest type, with evergreen forests showing stronger resistance, while deciduous forests experienced sharper NEP reductions [102]. Likewise, a synthesis of North American forests found that late-summer droughts in deciduous forests reduced NEP by up to $6 \text{ g C m}^{-2}\text{day}^{-1}$, mainly due to decreased gross ecosystem productivity (GEP), while evergreen forests remained stable due to simultaneous declines in both GEP and respiration [103]. A study comparing drought impacts on carbon fluxes in Norway spruce forests under different site conditions in the Czech Republic, found that drought entailed stronger reductions in GPP (− 14%) and NEP (− 38%) under drier site conditions compared to more humid areas, suggesting that site-specific differences modulate ecosystem responses and carbon fluxes under changing climatic conditions, with higher vulnerability in drier regions [104]. There is also emerging evidence showing forest resilience to drought over time, as reported for the Amazonian rainforest based on a long-term experimental drought research that reveals that tropical forest can structurally adjust and stabilise after prolonged drought stress, even though the initial impact of drought disturbance entails substantial carbon loss before recovery [105].

Contrary to the previous finding highlighting that drought reduces carbon sinks, experimental drought treatments in a mature temperate forest showed an over 80% increase in SOC in the top 0–5 cm soil layer under spruce. This increase was attributed to enhanced organic matter stabilization and carbon reallocation belowground [62]. These findings emphasize that while drought may reduce ecosystem-level carbon uptake, BGC sequestration can improve, depending on species composition and soil depth, revealing the dual effect of drought.

Windthrow and Storms

Hurricanes and extreme wind events represent powerful disturbances that significantly impact forest carbon dynamics, primarily through canopy damage and long-term carbon emission legacies. In New England's (USA) temperate forests, a simulation study estimated that a single severe hurricane can result in the loss of 121–250 million t CO₂e of AGC, which are released through decomposition over a 100-year period [74]. In the tropical forests of Puerto Rico, a modelling study found that an increased hurricane frequency reduced AGC by up to 59%, doubling the forest carbon source potential of the forest. Soil carbon gains from accumulated debris were insufficient to compensate for the substantial AGC losses over the period [106].

Moreover, there is also evidence that forest structure, disturbance intensity, and local conditions determine the magnitude of carbon impacts associated with these disturbances. For instance, in Florida's Perdido Bay watershed, Hurricane Ivan caused a decrease of 74.5 and 17.8 metric tons/ha of AGC in hardwood and mixed plots, respectively. AGC in young (< 25 years) taller trees (>15 m) decreased by 121.6 metric tons/ha of carbon immediately after the hurricane, showing that both physiographic features and tree characteristics contribute to carbon impacts [72]. These results underscore that wind events may not immediately cause carbon emissions like wildfires, but they are accompanied with long-term and delayed emissions through decomposition pathways that are underrepresented in carbon accounting. Moreover, the variation in carbon loss across forest types shows that both the regional context and forest type play a crucial role in determining the impact.

Biotic Disturbances: Insect and Disease Outbreaks

Biotic disturbances such as insect defoliators, bark beetles, and invasive pathogens are among the forest disturbances that are also intensifying under climate change. These agents may disturb tree physiology, induce widespread mortality, and cause both immediate carbon loss and long-term changes in ecosystem carbon trajectory. Previous research shows that these disturbances are spatially heterogeneous but consistently have negative impacts on forest carbon stocks. For example, in North America's Great Lakes region, a 2021 spongy moth (*Lymantria dispar*) outbreak caused a 35% and 23% GPP decline in deciduous and mixed forests, respectively, resulting in an estimated carbon loss of ~ 21 Mt C. However, conifer forests showed stable productivity, emphasizing the importance of species composition in disturbance resilience [67]. Climate change can result in a two/three-fold increase in bark

beetles (*Dendroctonus spp.*) disturbances throughout the 21st century. It has been estimated that removing >95% of disturbed trees can effectively buffer the effect of disturbances, dampening bark beetle infestations and increasing live tree carbon. Although salvage interventions reduced beetle-related mortality, they led to an increase in wind damage and lower TEC based on the salvaged percentage, showing the compound disturbance trade-offs influencing long-term carbon dynamics [68].

Disease outbreaks, such as the pine wood nematode, also pose significant carbon risks. For example, in East Asia, China's forest carbon stocks at risk from pine wood nematode increased from 87 million to 99 million t C, with the affected habitat expanding by 116,000 km² and especially affecting Masson and black pine forests in the southeast (as opposed to white pine and larch) [107]. Notably, no studies on disturbances driven by fungi were identified through the search criteria, showing a gap in the literature and the need for also accounting for pathogen-driven carbon dynamics in future research. Together, these studies show that biotic disturbances are among the major and increasing threats to forest carbon under global change. Their carbon impacts are determined by species susceptibility, disturbance interaction (e.g., salvage logging), and regional climate.

Compound Disturbance Effects

Multiple disturbances, such as drought, wildfire, harvesting, pests, or storms, can simultaneously or subsequently occur and may have a compounding effect. The interaction between disturbances is observed to have amplified carbon loss and impact on forest resilience [60, 108, 109]. For example, in Finland's boreal forests, a combination of severe summer drought in 2018 and subsequent thinning in 2019–2020 shifted the ecosystem from a carbon sink to a temporary carbon source, offsetting up to 92% of modelled climate-driven carbon gains during 2018–2021 [63]. In Canada's eastern boreal forest, long-term simulations revealed that the combined impacts of harvesting and spruce budworm (*Choristoneura fumiferana*) outbreaks can shift the forest into a net carbon source [70]. Similarly, in the Northern Rockies of Idaho, modelling showed that interacting disturbances under climate change had amplified effects. Fire-harvest scenarios resulted in greater cumulative annual burned area and carbon emissions compared to fire-only scenarios, especially on private lands where harvesting was more intensive [110]. Australia's 2019–2020 megafires, driven by the compounding effects of drought and repeated extreme fire events, released an estimated 0.67 Pg CO₂ [21], potentially shifting temperate *Eucalyptus* forests into long-term carbon sources.

These studies together show that compound disturbances exert more intense and long-term effects on forest carbon dynamics than single disturbances. They have the potential to reduce NEP and delay recovery. The interactions also generate feedback loops, such as drought enhancing fire risk or harvest increasing wind susceptibility, that further worsens the carbon integrity of forest ecosystems, according to the research analysed in this review.

Knowledge Gaps and Future Directions

Uneven Geographical Distribution

The current literature on the effect of forest disturbances on carbon emissions reveals a clear geographical imbalance, with most studies concentrated in the Global North, particularly the United States, Canada, and China. Conversely, critical carbon-rich regions in the Global South, such as tropical Africa and Insular Southeast Asia, remain significantly underrepresented. This uneven representation is also evident for carbon-rich ecosystems such as mangroves and peatlands. These ecosystems are less represented in the literature compared to other forest ecosystems and, given their relevance for carbon stocks and high vulnerability to disturbance, this also represents an important gap deserving future research efforts. This spatial disparity undermines drawing general and robust assessments of carbon dynamics at the global scale, as key forest ecosystems facing intense disturbance pressures are insufficiently studied.

Although certain tropical regions like the Amazon Basin and Southeast Asia are well represented in research on deforestation and degradation, reflecting the dominance of land-use change disturbances within this context [1, 90, 111], regions such as Central Africa are largely understudied. In contrast, wildfires, harvesting, and biotic disturbances are more frequently studied in temperate and boreal regions, where such events are becoming increasingly relevant due to rising temperatures and longer fire seasons [14, 41, 112, 113]. For instance, in forests of Canada, the USA, and Australia, both mean and maximum fire sizes have increased by 65–450% over recent decades, with related emissions rising accordingly [113]. Overall, these patterns suggest that research is often geographically clustered in regions with stronger research infrastructure, potentially overlooking disturbance impacts in ecologically critical but under-resourced areas. Such biases, risk skewing carbon flux models and hinder comprehensive understanding of forest carbon dynamics under global change.

Low-Intensity Disturbances Underrepresented

There is strong evidence that high-severity, high-visibility disturbances, particularly wildfires and deforestation, drive substantial carbon losses. Wildfires consistently caused short-term AGC losses across multiple biomes, with emissions closely tied to fire severity [15, 21, 114–116]. Deforestation, especially in tropical regions, was also well-represented in the literature, with studies quantifying large-scale carbon fluxes from AGC and, to a lesser extent, SOC [90, 111, 117]. These two disturbance types form a robust core of the evidence base, supported by diverse methodologies including field measurements, satellite data, and process-based modelling. However, this focus has come at the expense of lower-intensity and longer-term disturbances, such as selective harvesting, prescribed burning, and forest degradation, which remain understudied despite their cumulative carbon impacts. These disturbances often involve subtle changes over extended timescales, making them harder to detect and quantify. For instance, in forested tropical peatland, degradation or selective logging may lead to sustained SOC losses, yet few studies have examined these effects in depth [98, 118]. Similarly, silvicultural practices like thinning, variable retention harvest, and species management are widespread but lack consistent assessment of their long-term carbon outcomes [71, 101]. In a world facing increasing fire activity, there is still no clear understanding of how carbon removal through strategic fuel management and pyrosilvicultural treatments (e.g., variable retention harvesting, prescribed burning) is offset by avoided fire emissions at the landscape level due to wildfire severity mitigation, this representing a gap in knowledge worth of further research. In summary, the carbon impacts of such lower-profile disturbances remain fragmented, underestimated, and context-specific, limiting the ability to draw broad, generalizable conclusions.

Uneven Representation of Carbon Pools

A key limitation identified in the literature is the uneven representation of different carbon pools, particularly SOC, across forest disturbance studies. While AGC loss is commonly measured, deep SOC fluxes, mineral-associated carbon, and other belowground pools remain underexplored. This is especially critical given that, in certain ecosystems, such as peatlands and permafrost-affected boreal forests, SOC losses can exceed AGC emissions [49, 50]. However, the number of studies capturing these belowground dynamics is limited, leaving substantial uncertainty in our understanding of the full carbon impact of disturbances, especially in carbon-dense or vulnerable soils.

Short Temporal Scope

In addition to geographical constraints in carbon pool measurement, there is also inconsistency in temporal scales among the reviewed literature. While most studies quantify immediate emissions following disturbance, few account for delayed fluxes from decomposition, regrowth, or microbial activity. Long-term SOC losses following deforestation, for example, are rarely measured, and the carbon uptake potential of post-disturbance regrowth is often overlooked. This short temporal scope hampers the ability to assess full disturbance-recovery cycles and complicates modelling efforts that aim to predict net carbon change under evolving climate scenarios.

Compound Disturbances

An important but often overlooked limitation identified in this review is the limited understanding of compound disturbances, i.e., interactions between multiple disturbance types such as drought-fire or harvest-pathogen events. Evidence suggests these interactions frequently amplify carbon losses, often exceeding the sum of their individual effects. For instance, in boreal forests, drought preceding harvest shifted ecosystems from carbon sinks to sources [63]. However, the effects of such interactions are highly variable and context-dependent, influenced by forest type, disturbance sequence, and ecosystem resilience. One study found that 71% of compound disturbance effects were amplifying, while 16.2% showed dampening effects, highlighting the complexity of these interactions [5]. This variability makes broad generalizations difficult and underscores the need for more ecosystem-specific research. Despite their increasing relevance under climate change, compound disturbances remain understudied, partly due to the methodological challenges of detecting overlapping disturbances and attributing their cumulative carbon impacts.

Strengths and Limitations of the Review

This systematic review offers a comprehensive synthesis of forest disturbances and their carbon impacts across global forest biomes. Key strengths include the identification of major disturbance types and their spatial patterns, quantitative assessments of associated carbon emissions, and the identification of underrepresented regions and disturbance drivers. By incorporating both natural and anthropogenic disturbances, as well as compound events like drought-fire interactions, the review provides broad thematic and spatial coverage. This makes it valuable for further research, policymaking, and carbon accounting efforts. However, several limitations should be noted. As outlined in Sect. 5.1–5.3 and

5.5, the literature is skewed toward Global North studies, dominated by high-severity disturbances, and uneven carbon pools coverage, while often overlooking cumulative, gradual, and lagged processes, including compound interactions. This affects the synthesis effort by disproportionately reflecting certain disturbance dynamics, possibly underestimating both low-intensity and compound disturbances, especially in underrepresented areas of the world. Furthermore, methodological heterogeneity and differences among Measuring, Reporting, Verification (MRV) systems applied across studies further constraining cross-comparability among previous research, a thorough meta-analysis was not feasible. The review included only English-language peer-reviewed studies and excluded grey literature, potentially omitting important regional insights.

Conclusions

This review synthesizes current knowledge on carbon impacts of forest disturbances across the globe, such knowledge remaining considerably uneven, with an emphasis on AGC, high-severity disturbances (notably forest fires and deforestation), and areas and ecosystems from the Global North. These imbalances constrain to some extent the comprehensiveness and generalizability of current knowledge. Another critical gap is the limited integration of compound disturbances such as drought-fire and harvest-pathogen interactions into carbon modelling and risk assessments. Our synthesis shows these interactions can significantly amplify emissions and alter recovery, yet they are seldom reflected in current models or national inventories. This review points out that these limitations can result in underestimation of emissions and in overestimation of forest recovery in global carbon models. To improve the accuracy, robustness, and generalizability of global carbon assessments, requires coordinated strategies. Strengthening international research collaborations can help ensure more balanced geographic representation, while building scientific capacity in underrepresented regions would improve local data availability and reduce reliance on extrapolation from other areas and ecosystems. Promoting standardized methodologies and reporting formats across studies would also enhance comparability and enable robust global syntheses. At the same time, future research should prioritize long-term disturbance effects, BGC responses, underrepresented regions and compounding interactions. Together, these strategies may strengthen the evidence, improve reliability of global carbon estimates, better inform climate mitigation policies, and enhance the role of forests as nature-based solutions in the face of global change to guide effective policymaking.

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Declarations

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