European Journal of Forest Research (2026) 145:69
https://doi.org/10.1007/s10342-026-01915-4

REVIEW

# Scoping review of climate-smart forestry for carbon sequestration in boreal and temperate forests

**Roberto Tognetti**[1] · **Chiara Torresan**[2]

Received: 10 October 2025 / Revised: 19 April 2026 / Accepted: 22 April 2026

## Abstract

Afforestation, reforestation, conservation, and restoration represent nature-based solutions (NBS) for carbon sequestration. These forest management options, aimed at advancing global targets outlined in international agreements, may limit the provision of specific ecosystem services and generate trade-offs, posing notable challenges for silviculture. In this context, we conducted a scoping review to collect and map evidence from studies evaluating management strategies for establishing, preserving, and restoring forest carbon sinks within a climate-smart framework in boreal and temperate ecoregions. We gathered data on forest types, the scale and duration of the analysis, carbon sequestration estimation methods, carbon pool types, disturbances, synergies and trade-offs. Our search, covering the period 1990–2025, revealed an increase in peer-reviewed research on afforestation, reforestation, conservation, and restoration outcomes since 2012, with occasional declines (e.g., 2014–2015 and 2019) indicating fluctuations in research intensity. Most of the studies were conducted in Europe (49%), North America (39%), and Asia (12%). Aboveground biomass and soil were the most frequently assessed carbon pools, with most studies employing wood or soil sampling and modelling approaches (e.g., the Gap-type forest ecosystem model, Yasso07 model, Forest Vegetation Simulator model) to estimate carbon sequestration. Our analysis revealed a critical gap in comprehensive assessments of synergies and trade-offs between climate-smart and conventional land management practices, particularly regarding their carbon sequestration potential and the effectiveness of climate-smart strategies in mitigating risks to forest carbon capture and storage functions. Additionally, uncertainty in climate projections limits the ability to optimise benefits and minimise trade-offs through silvicultural strategies. This scoping review highlights a scarcity of studies that explicitly address trade-offs among management strategies and goals. Greater empirical evidence, cross-sectoral integration (e.g., forestry and agriculture), and concurrent consideration of climate impacts and market dynamics are needed.

**Keywords** Carbon forestry · Carbon farming · Environmental disturbance · Forest ecology · Nature-based solutions

## Introduction

### Climate-smart forestry as a strategy for enhancing carbon storage

The global atmospheric $CO_2$ concentration increased from 417.2 ppm in 2022 to 419.3 ppm in 2023 and 422.45 ppm in 2024, exceeding pre-industrial levels by 51 and 52%, respectively (Friedlingstein et al. 2023, 2025). This rise, primarily driven by fossil fuel combustion, is further exacerbated by wildfires and deforestation, which together account for approximately 11% of annual $CO_2$ emissions (Friedlingstein et al. 2022). Conversely, forests function as critical carbon sinks, sequestering approximately 29% of total emissions and thereby playing an indispensable role

---

Roberto Tognetti and Chiara Torresan contributed equally and share responsibility for correspondence.

Communicated by Stefano Grigolato.

✉ Roberto Tognetti
roberto.tognetti@unibz.it

✉ Chiara Torresan
chiara.torresan@cnr.it

[1] Faculty of Agricultural, Environmental and Food Sciences, Free University of Bolzano, 39100 Bolzano, Italy

[2] Institute of BioEconomy, National Research Council of Italy, 38010 San Michele all'Adige, Italy

in climate mitigation (Friedlingstein et al. 2022; Pan et al. 2011, 2024). Strengthening these sinks provides a vital buffer, temporarily offsetting emissions while enabling broader societal transitions toward sustainability (Steffen et al. 2018; Armstrong McKay et al. 2022). Beyond their inherent capacity, targeted forest management offers substantial potential to enhance $CO_2$ uptake through increased photosynthetic activity (Waring et al. 2020). Numerous studies have demonstrated that forest-based solutions, such as reducing deforestation and expanding forest cover, provide cost-effective pathways for climate change mitigation (Kindermann et al. 2008; Davies-Barnard et al. 2015). However, in degraded ecosystems, such as Mediterranean forest landscapes, effective mitigation requires a participatory process that restores ecological function while enhancing human well-being, as advocated by the Forest and Landscape Restoration framework (Garrett et al. 2022; FAO 2024). This perspective ensures that carbon objectives do not undermine biodiversity or ecosystem resilience (Tognetti et al. 2022b). By prioritising the restoration of ecological functions alongside carbon sequestration, FLR offers a framework that safeguards non-wood forest products, preserves biodiversity and enhances ecosystem stability (Nabuurs et al. 2017).

Given that forest management, clearing, and abandonment have already significantly impacted around 70% of the global forested area (FAO 2010), and natural disturbance regimes are increasingly influencing all forests (Seidl et al. 2017; McDowell et al. 2020), it becomes imperative to incorporate disturbance and regeneration dynamics into long-term planning. Rather than assuming stable conditions, management must proactively anticipate these processes by implementing adaptive strategies that account for the increasing frequency and severity of events like wildfires, pest outbreaks, and drought. This foresight is crucial for offsetting tree mortality, sustaining forest ecosystems, and maintaining the provision of essential ecosystem services (Hanbury-Brown et al. 2022). Climate-smart forestry is a strategic, long-term approach aimed at maximising the climate benefits of forests and forest products while safeguarding the provision of ecosystem services and functions (Nabuurs et al. 2017; Bowditch et al. 2020; Cooper and MacFarlane 2023). This approach can reduce forest vulnerability to disturbances, thereby enhancing carbon storage. Key climate-smart forest management activities include maintaining and expanding forest extent, promoting forest stability and natural regeneration, restoring ecosystem functions, conserving forest biodiversity, encouraging sustainable harvesting practices, balancing timber supply and wood utilisation with tree growth, optimising age structure and diameter distribution across forest landscapes, assisting species migration, planning conservation and rewilding strategies, and preparing for the impacts of future disturbances (Papa et al. 2023). However, ongoing debates persist regarding the most effective management practices for strengthening forests' mitigation and adaptation capacities (Tognetti et al. 2022a). This has led to a wide range of recommendations for adapting forest management to climate change; nevertheless, there has been a lack of a comprehensive synthesis to guide forest researchers and land managers in navigating these diverse options.

## Key aspects of climate-smart forestry for sustaining carbon sequestration and ecosystem services

Demand for forest resources has increased over the past century, driven by population growth (Betts et al. 2021). Historical forest management practices, initially designed to satisfy the demand for wood products, have led to the simplification of forest structure and composition. These effects influence It is essential to acknowledge that the intensification of disturbances raises concerns about the long-term sustainabilitythe functions, processes, and services of forest ecosystems over an extended period, leading to a reduction in the diversity and complexity of forest ecosystems and to their fragmentation, causing a decrease in both the quantity and connectivity of habitats (Lecoq et al. 2021; Himes et al. 2022). The degradation of forest complexity and the loss of biodiversity affect the capacity of forest ecosystems to withstand environmental disturbance and secure carbon sequestration (Muys et al. 2022). Concurrently, land degradation threatens biogeochemical cycles and the integrity of species communities (Gámez-Virués et al. 2015). Effectively balancing carbon sequestration with forest resilience and the continued provision of ecosystem services is a complex challenge. Developing management strategies for these multi-objective goals requires a foundation of empirical evidence from diverse spatial and temporal scales (Ameray et al. 2021). This evidence base provides the fundamental understanding necessary to design interventions that remain robust across a range of projected climate uncertainties. The importance of forests to the global carbon cycle and the Earth's climate system has prompted intense interest in management strategies to increase carbon sequestration (Zhao et al. 2022). Considering the extensive interest among policymakers in utilising forests to offset $CO_2$ emissions, the obligations outlined in the Paris Agreement to mitigate the increase in atmospheric $CO_2$ levels have spurred a shift towards a carbon-focused approach to forest management (Ferreira 2018), such as carbon forestry and carbon farming. Carbon forestry refers to forest management approaches explicitly oriented towards maximising climatic benefits, encompassing decisions on harvesting intensity, rotation length, stand density, and the fate of wood products, all of which jointly determine whether a forest functions as a net carbon sink or source (Pukkala 2018). Carbon farming, applied to forest systems, extends this logic by treating the forest landscape as an integrated production system where carbon sequestration in living biomass, dead organic matter, soil, and harvested wood products is explicitly accounted for and optimised alongside other land management objectives. These concepts acknowledge that the carbon balance of forestry is shaped not only by in-forest accumulation but also by the substitution effects of wood products replacing fossil-based materials, and that trade-offs between near-term and long-term carbon gains depend critically on the time horizon considered (Pukkala 2018).The intensification of disturbances raises concerns about the long-term sustainability of the forest carbon sink, potentially undermining the effectiveness of management strategies aimed at enhancing carbon sequestration (Dye et al. 2024). Reliable quantification of the sources and sinks of atmospheric $CO_2$, including their trends, is crucial for monitoring progress in mitigating anthropogenic emissions under international agreements. While many countries routinely report forest carbon stocks through established frameworks like the FAO's Global Forest Resources Assessment (FRA), achieving a high degree of certainty remains challenging. Significant discrepancies often persist when reconciling national forest inventory data with long-term ecosystem studies and vegetation model assumptions, leading to large uncertainties in global integrated estimates (Petrescu et al. 2021). Improving the alignment between these diverse data streams is essential for verifiable climate mitigation. The most widely promoted $CO_2$ removal strategies, which entail enhancing forest and soil carbon sinks, are seldom explicitly quantified (Smith et al. 2022). Based on integrated ground and Earth observation data from 2001 to 2019, global forests were estimated to be a net carbon sink of $-7.6 \pm 49$ Gt $CO_2$ e $yr^{-1}$ (Harris et al. 2021). However, since 2019, the increasing frequency of disturbances, such as droughts, heatwaves, and catastrophic wildfires, has threatened the stability of this sink (e.g., Knutzen et al. 2025). These escalating climate-driven pressures complicate forest management assessment, making it difficult to distinguish the benefits of intentional mitigation strategies from the losses caused by natural disturbances. Consequently, the net impact of forest management on long-term climate mitigation remains a subject of ongoing debate.

Natural climate solutions (NCS), including conservation, restoration, and improved land management, have been proposed to provide significant climate mitigation potential, accounting for 37% of the cost-effective $CO_2$ mitigation needed by 2030 to keep warming below 2 °C (Griscom et al. 2017). In 2018, forests and harvested wood products removed approximately 360 Mt $CO_2$eq in the EU-27, offsetting about 10% of total greenhouse gas emissions (Grassi et al. 2021), and 547 Mt $CO_2$eq in the USA, compensating for 14% of fossil-fuel emissions (Domke et al. 2020). Climate-smart forestry and optimising stocking levels on understocked productive forestlands could further enhance carbon sequestration by 9–20%. This poses high expectations for forests and forest products, as well as afforestation and reforestation solutions to climate change (Zhang et al. 2023). As an example, the new EU forest strategy aims to contribute to achieving a greenhouse gas emission reduction target of at least 55% by 2030 (+50 Mt $CO_2$eq $yr^{-1}$) and climate neutrality by 2050 (+170 Mt $CO_2$eq $yr^{-1}$), recognising the central and multifunctional role of forests, and the contribution of the entire forest-based value chain.

The Paris Agreement aims to hold the increase in global average temperature below 2 °C above pre-industrial levels. However, limiting warming to 1.5 °C rather than 2.0 °C would be required to avoid risks to forest ecosystems and social systems (Hoegh-Guldberg et al. 2019; Alawode et al. 2026). Achieving climate targets requires integrating societal decarbonization with forest management by establishing, conserving, and restoring carbon sinks. Additionally, carbon storage in wood products and their substitution for fossil-based materials contribute to mitigation efforts, highlighting the need to enhance their use for material and energy substitution (Osborne et al. 2023). However, only a few studies have actively promoted, integrated, and linked the carbon-sink and substitution effects of wood value chains to enhance synergies between climate benefits and other advantages, such as supporting the bioeconomy and preserving biodiversity (Nabuurs et al. 2019). Although harvested wood products can contribute to climate mitigation by substituting for fossil-fuel-intensive materials, a reliance on bioenergy carries risks of local overharvesting (Yousefpour et al. 2018). In contrast, maintaining living tree biomass in the forest sequesters atmospheric $CO_2$, though this strategy avoids the immediate carbon release associated with harvesting. These divergent approaches highlight the trade-offs inherent in mitigation options; the most effective strategy is often a mixed approach that optimises a suite of region-specific solutions (Grassi et al. 2017).

## Scoping review objectives and research questions

Although forests are increasingly recognised as vital for carbon sequestration and for complementing societal decarbonisation efforts, the pursuit of maximising carbon benefits has been criticised for causing trade-offs and conflicts with other ecosystem services (Waring et al. 2020; Gregor et al. 2022). Despite increasing interest in the forest sector for climate change mitigation, the effectiveness and potential of mitigation strategies remain debated, with forest carbon management still largely theory-driven rather than evidence-based. Several reviews have provided broad insights into research applications and trends in this field (e.g., Jandl et al. 2007; Ameray et al. 2021; Mäkelä et al. 2023; Dye et al. 2024). However, given the long-term impact of forest management practices on ecosystem functions, processes, and services, a deeper examination of the intersection between environmental management and decarbonization, known as the decarbonization nexus, is essential for assessing climate-smart forestry (Alfieri et al. 2024, 2025).

Although extensive research has addressed forest-based climate change mitigation, it remains uncertain whether, and to what extent, trade-offs between management practices designed to enhance $CO_2$ sequestration and those intended to sustain a broader array of ecosystem services beyond regulatory functions have been examined in an integrated manner. To our knowledge, no previous review has synthesised emerging evidence and research gaps in climate-smart forestry, particularly regarding the establishment, conservation, and restoration of forest carbon sinks to reconcile climate change mitigation, adaptive forest management, and ecosystem service provision (Fig. 1).

A synthesis of climate-smart forestry's potential to enhance carbon sequestration is essential for balancing trade-offs among carbon storage, wood production, and biodiversity conservation (Paillet et al. 2010; Schall et al. 2018). A comprehensive, evidence-based projection of carbon dynamics across various management strategies and spatial–temporal scales is needed to optimise climate-smart forestry for multiple ecosystem services while accounting for uncertainty (Lindner et al. 2014; Luyssaert et al. 2018; Knoke et al. 2020).

To map the scope of peer-reviewed literature analysing and assessing options for establishing, conserving, and restoring forest carbon sinks within a climate-smart framework, we conducted a scoping review. A scoping review is a methodological approach to evidence synthesis that systematically explores and describes the extent of knowledge on a specific topic, particularly when questions extend beyond the effectiveness of interventions (Sharma and Goyal 2023). Its purpose is to identify and map the breadth of available evidence, across sources and contexts, on a given concept, field, or issue (Arksey and O'Malley 2005; Peters et al. 2015, 2022; Munn et al. 2022). By providing a comprehensive overview, scoping reviews help determine whether further analyses, such as systematic reviews or meta-analyses, are warranted and highlight existing research gaps (Munn et al. 2018). They are especially valuable when the literature is heterogeneous, underexplored, or when the aim is to examine how research has been conducted (Sharma and Goyal 2023).

We conducted a scoping review to map the evidence base and identify key characteristics of climate-smart forestry interventions that enhance carbon sequestration in boreal and temperate ecoregions, drawing on peer-reviewed publications from 1990 to 2025.

We intended to address the following research questions:

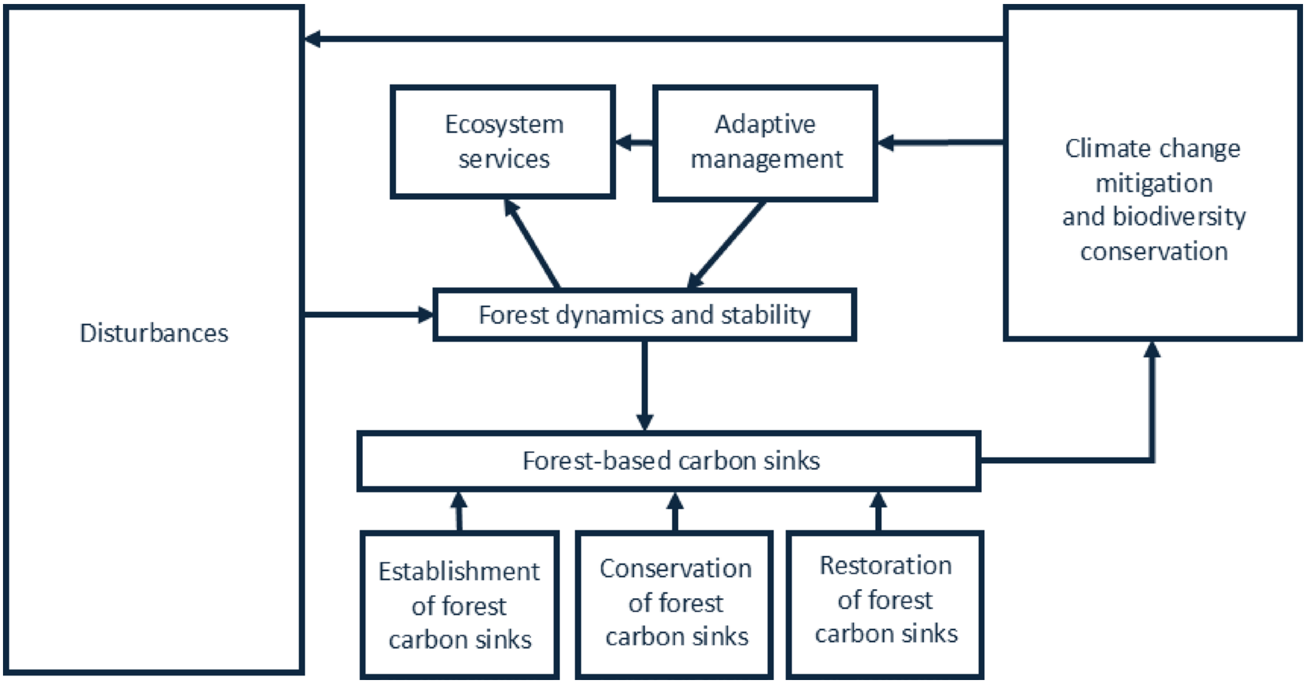

**Fig. 1** Conceptual framework under the scoping review: disturbances shape the dynamics and stability of forest-based carbon sinks, which can be established, conserved or restored. In turn, climate change mitigation and biodiversity conservation influence the adoption of adaptive forest management strategies, which impact the ecosystem services provided by forests

- which management interventions have been studied in peer-reviewed publications to assess the reported impacts of climate-smart forestry strategies in conserving (i.e., protecting), establishing, and restoring carbon sinks in forest ecosystems?
- what descriptive elements (e.g., indicators, metrics, qualitative dimensions) have been considered in the literature when assessing the effectiveness of climate-smart forestry strategies?
- how does the reviewed literature address limitations, synergies, and trade-offs in the implementation of climate-smart forestry strategies for protecting, establishing, and restoring forest carbon sinks?

## Methods

### Protocol

For our scoping review, we followed the methodology developed by the Joanna Briggs Institute (JBI) and its five collaborating centres (Peters et al. 2015), along with subsequent updates (Veroniki et al. 2025). According to this guidance, a scoping review protocol—defined as a comprehensive plan for conducting and reporting the review—should be finalised before the review begins and, ideally, submitted for publication. However, this is not mandatory (Peters et al. 2022). In our case, a protocol has not been published in previous papers and can be considered part of the present article.

**Table 1** Eligibility criteria for inclusion in the review for population, concept, context and type of evidence source

| Eligibility criterion | Value |
|---|---|
| Population | Forests in boreal and temperate ecoregions |
| | All forest types, regardless of their composition, structure, etc. |
| Concept | All types of methods to assess the effectiveness of climate-smart forestry strategies in establishing, conserving, and restoring carbon sinks |
| | Explicit scale of analysis (i.e., single tree, plot, stand, landscape, region, country) |
| | Explicit duration of the analysis |
| | Explicit sample size |
| | Explicit size of the reference |
| | Explicit nature of the carbon sink (i.e., carbon pool) |
| | Explicit method of carbon sequestration estimation |
| Context | Interventions conducted from 1990 to August 4th, 2025 |
| Type of evidence source | Only published in peer-reviewed journals and books (i.e., not grey literature) |
| | Primary studies |
| | Only papers published (or pre-printed) in English |

In the following sections, as foreseen in the JBI guidance, we describe how we identified the eligibility criteria, defined the search strategy, selected relevant sources of evidence, defined the data extraction process, and completed data analysis and presentation.

### Identification of the eligibility criteria

The eligibility (or inclusion) criteria for our scoping review are presented in Table 1.

We considered all forest management scenarios applied in boreal and temperate ecoregions to assess the effectiveness of strategies for establishing, conserving, and restoring forest carbon stocks. In this context, establishing a carbon sink involves creating a new stock through reforestation (replanting on land recently lacking tree cover) or afforestation (planting on land that has lacked tree cover for over 50 years) (IPCC 2022). Conserving refers to maintaining or protecting existing carbon sinks under favourable conditions, while restoring involves active or passive management to improve the condition of a degraded sink.

We included all methods, e.g., forest inventories, dendrochronology, eddy covariance, modelling, and remote sensing, to assess the effectiveness of forestry strategies in establishing new and conserving and restoring existing forest carbon stocks.

The scale and duration of analysis, the sample size, the size of the reference, and the type of carbon pool had to be explicitly stated.

We excluded studies focusing on the financial and economic viability of forest plantations, afforestation, reforestation, or carbon sequestration projects, as well as studies assessing land potential for carbon sequestration. Because scoping reviews aim to map a body of literature comprehensively, the results of methodological quality assessment have not been used to determine inclusion or exclusion from the review.

We did not include grey literature in our scoping review, as searching for it online remains challenging due to the lack of standardised indexing, controlled vocabulary, and archiving, as well as the vast, unstructured nature of online information.

Only papers published (or pre-printed) in English have been considered for inclusion in the scoping review due to a lack of experience in non-English languages. In our search, the publication date was limited to between 1990 and the day of the search, i.e., August 4, 2025.

### Definition of the search strategy

To develop a preliminary search strategy, an initial general search in Google Scholar was undertaken to identify potentially relevant keywords and terms for creating a final search strategy across an "official" electronic database (Peters et al. 2022). Relevant terms from the titles and abstracts were identified and used to develop a comprehensive search strategy for the Web of Science (www.webofscience.com) and Scopus (www.scopus.com) databases.

In Table 2, the search strings used in the query builder Web of Science and Scopus platforms are reported. To document and manage search results, we exported the lists using the tools available in Web of Science and Scopus.

## Selection of the relevant sources of evidence

The selection of sources of evidence obtained by the search was based on whether they met the inclusion criteria reported in Table 1.

The screening of the identified sources of evidence was conducted first at the title and abstract level by one of the two authors of the present scoping review. The authors conducted a comprehensive review of the relevant sources and selected the final evidence sources. To streamline and synchronise the process, we independently reviewed studies in batches of five, compared and evaluated the examination approaches, and held iterative discussions to achieve homogeneous selections, until all the screened papers were examined. Disagreements regarding study eligibility were resolved through discussion between the two primary reviewers. To mitigate individual bias, each reviewer presented their rationale based strictly on the pre-defined inclusion and exclusion criteria. If consensus could not be reached, a third senior reviewer was consulted to provide an independent assessment and serve as an arbitrator, ensuring that the final selection remained objective and consistent with the study protocol.

**Table 2** Specific search strings used in the Advanced Search Query Builder web page of Scopus (TITLE-ABS-KEY = Doc Title-Abstract-Keyword, PUBYEAR = Year of Publication) and Web of Science (TS = Topic = Title-Abstract-Keyword plus-Author keywords, PY = Year Published)

| Database | Query string |
|---|---|
| Scopus | TITLE-ABS-KEY ("carbon sequestration" OR "carbon sink*" OR "carbon storage" OR "carbon stock*" OR "carbon uptake" OR "carbon balance") AND TITLE-ABS-KEY ("climate-smart forestry" OR "climate-smart forestry" OR "climate change mitigation" OR "forest management" OR "management intervention*" OR "silvicultur*" OR "management strateg*" OR "management practic*" OR "silvicultural strateg*" OR "silvicultural practic*" OR "carbon management") AND TITLE-ABS-KEY ( establish* OR creat* OR afforestation OR reforestation OR plantation* OR conservation OR proforestation OR protection OR restoration OR genet*) AND TITLE-ABS-KEY (boreal OR temperate) AND TITLE-ABS-KEY (limitation* OR barrier* OR constraint* OR synerg* OR "co-benefit*" OR "trade-off*" OR tradeoff* OR effectiveness OR impact* OR assessment) AND PUBYEAR > 1989 |
| Web of Science | TS = ("carbon sequestration" OR "carbon sink*" OR "carbon storage" OR "carbon stock*" OR "carbon uptake" OR "carbon balance") AND TS = ("climate-smart forestry" OR "climate-smart forestry" OR "climate change mitigation" OR "forest management" OR "management intervention*" OR "silvicultur*" OR "management strateg*" OR "management practic*" OR "silvicultural strateg*" OR "silvicultural practic*" OR "carbon management") AND TS = (establish* OR creat* OR afforestation OR reforestation OR plantation* OR conservation OR proforestation OR protection OR restoration OR genet*) AND TS = (boreal OR temperate) AND TS = (limitation* OR barrier* OR constraint* OR synerg* OR "co-benefit*" OR "trade-off*" OR tradeoff* OR effectiveness OR impact* OR assessment) AND PY = 1990–2025 |

To graphically depict the movement of sources through the search process to eventual inclusion, we decided to produce a flowchart of the article screening and selection process that conforms to the PRISMA 2020 Statement (Page et al. 2021).

Due to the nature of scoping reviews, it was likely that searching, screening, and selection could have revealed new, potentially relevant terms, concepts, and even evidence locations. We did not modify and expand the scoping review process to account for these eventualities.

## Data extraction

We extracted basic descriptive data about the selected sources of evidence (e.g., authors and publication year, DOI) and data consistent with the review questions and the inclusion criteria. We first produced a draft table detailing the extracted data, along with potential field names for data items that aligned with the previously described review questions, population, concept, and context (see Table 1). The field names were refined progressively to better match the content of the inclusion criteria. In the end, the data extrapolated through the full-text level analysis of the paper were used to valorise the location of the study area, the forest type, the scale of analysis, the size and number of the reference area, the duration of the study, the method used to estimate the carbon sequestration, and the carbon pool considered in the study. We decided to report in the final table not only the values referred to as parameters of the inclusion criteria, but also information and data about the eventual climate scenario, disturbances, synergies, and trade-offs in the implementation of climate-smart forestry strategies for protecting, establishing, and restoring forest carbon sinks considered in the study.

A cross-check was conducted to verify the information each author extracted. Discrepancies in data extraction between authors were resolved through joint review of the evidence until consensus was reached, with particular attention to accurately capturing the study area location for the corresponding table field.

A critical appraisal or risk of bias assessment was not performed because it is generally not recommended in scoping reviews, which aim to map rather than appraise the available evidence (Hart et al. 2023).

### Data analysis and presentation

To synthesise the collected data, we conducted a frequency analysis and presented the results in diagrams and tables. This approach enabled us to identify and illustrate trends in publication output, geographical scope, and interdisciplinary patterns in line with the research objectives.

## Results

Our search, spanning from 1990 to 2025, returned a list of 368 publications from Web of Science and 265 publications from Scopus published over 28 years (1997–2025). Following the removal of duplicate records and the initial screening of identified sources at the title and abstract level, a total of 411 reports were selected for retrieval. Of these, 4 could not be obtained despite attempts to contact the corresponding authors; consequently, 407 reports were available for eligibility assessment, and 61 studies were included in the scoping review (Fig. 2).

The scoping review revealed a strong skew toward carbon sink conservation strategies (n = 39), with comparatively fewer studies addressing establishment (n = 13), restoration (n = 2), or integrated approaches (n = 7), highlighting an

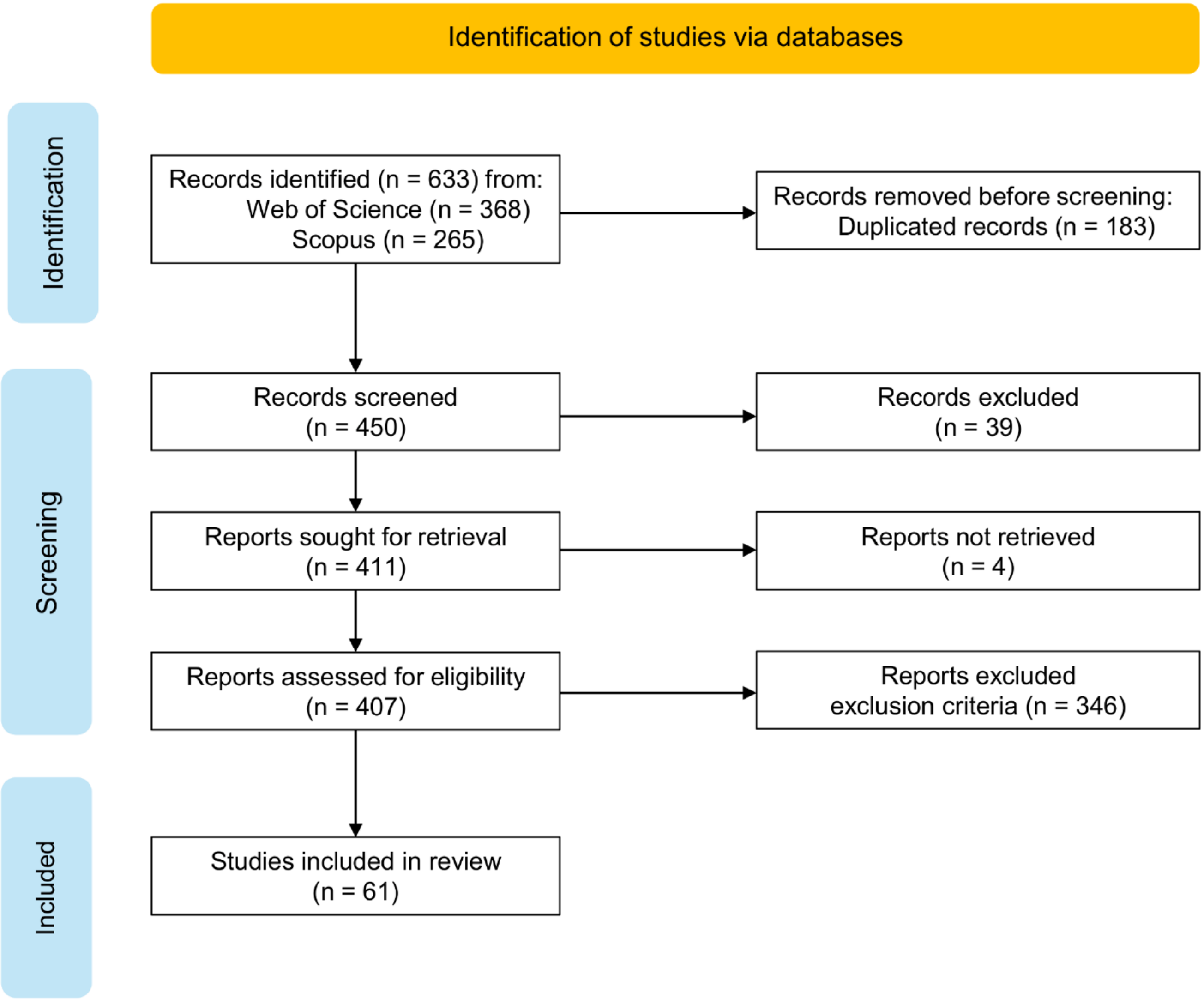

**Fig. 2** Flow chart of the article screening and selection process. The systematic workflow follows the ROSES reporting standards (Haddaway et al. 2022). In accordance with Page et al. (2021), a 'record' refers to the metadata (title/abstract) indexed in databases, whereas a 'report' refers to the full document retrieved for eligibility assessment

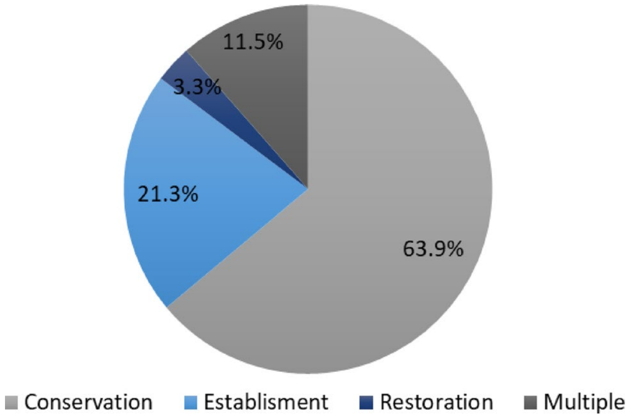

**Fig. 3** Distribution of reviewed studies across carbon sink strategies, showing a clear predominance of conservation-focused approaches (n=39) compared to establishment (n=13), restoration (n=2), and integrated strategies combining multiple approaches (n=7)

imbalance in research focus across management pathways (Fig. 3).

The final subset comprised data from 19 countries (Fig. 4). Evidence was primarily concentrated in Europe (49%, n=33) and North America (39%, n=26), with only 12% (n=8) of studies focused on Asia, highlighting a significant geographic evidence gap (Fig. 4). To facilitate further analysis, the reviewed literature is organized in the Appendix and within the main text. Table 1A in the Appendix provides an exhaustive overview of all studies, detailing methodological parameters such as management goals, silvicultural practices, climate scenarios, carbon-sequestration estimation methods, and ancillary measures (e.g., disturbances). Table 3 groups the studies by their strategic approach—conserving, establishing, or restoring carbon sinks—and summarises key metadata, including geographic coverage, the carbon sequestration estimation method and the authors. Comprehensive study characteristics, including the scale of analysis, the duration of interventions, and the specific carbon pools, are fully detailed in the Appendix.

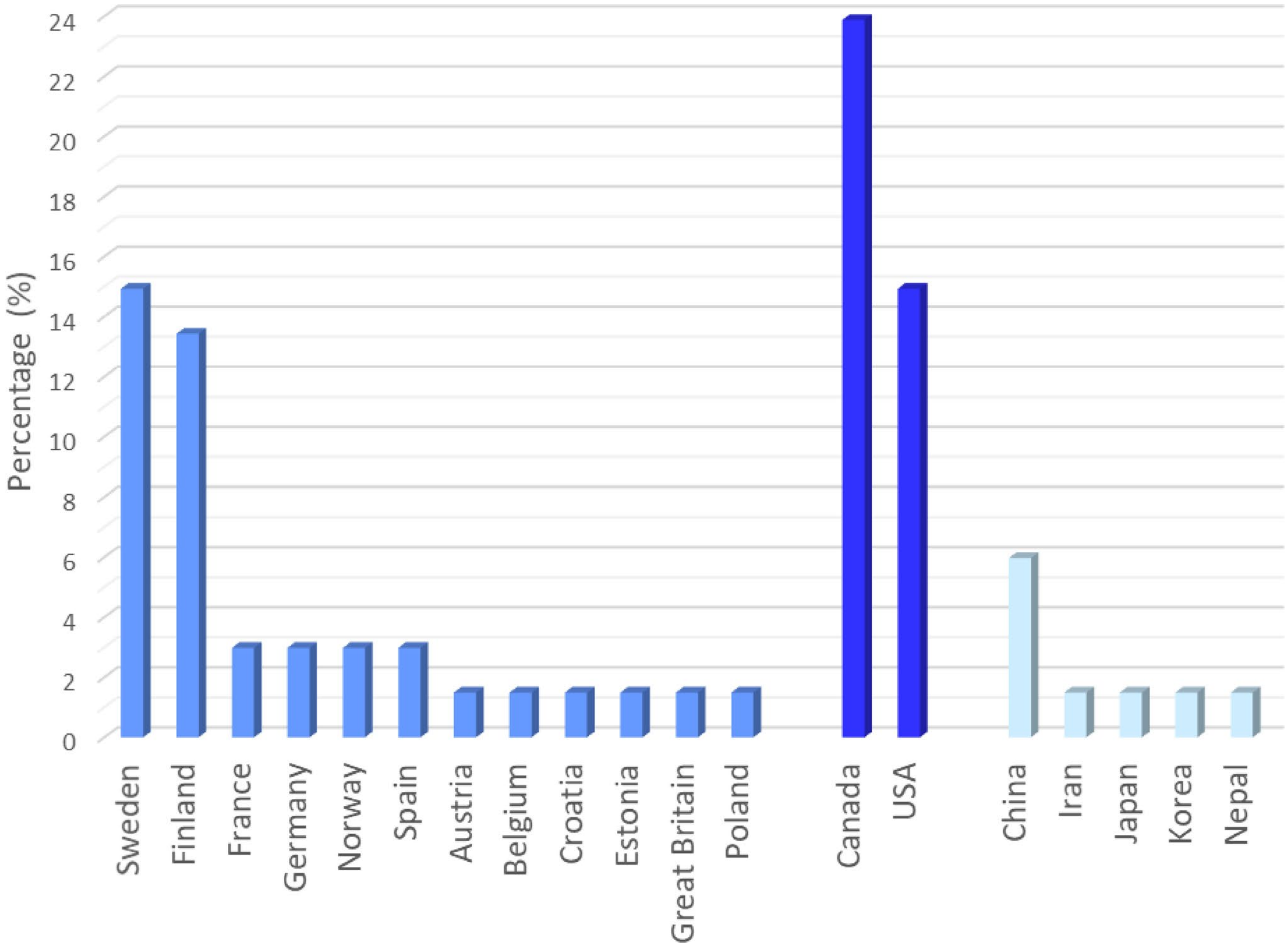

**Fig. 4** Percentage distribution of peer-reviewed studies per country in our final subset of articles (n=61). Data are grouped by region (Europe, North America, and Asia), reflecting the geographic concentration of research. Note: the studies by Osei et al. (2022) and Labadie et al. (2024) encompass multiple countries

**Table 3** Information gleaned from the ultimate subset of studies in peer-reviewed publications that assessed the effectiveness of climate-smart forestry strategies in conserving (i.e., protecting), establishing, and restoring carbon sinks in forest ecosystems

| Strategy | No. of studies | Locations | Carbon sequestration estimation methods | Authors |
|---|---|---|---|---|
| Carbon sink conservation | 39 | Finland, Canada, USA, Sweden, China, Nepal, Germany, Norway, Iran, Estonia, multi-country (Europe) | Model-based: LPJ-GUESS, LANDIS-II, FVS, MOTTI, SIMO, CBM-CFS3, timber supply models, ecosystem models<br>Empirical: allometric equations, soil sampling, forest inventories, dendrometric measurements, remote sensing<br>Hybrid: model calibration with field data, combined modelling + soil/biomass measurements | Alrahahleh et al. (2017), Botroh et al. (2023), Buotte et al. (2020), Burton et al. (2013), Colombo et al. (2012), Dymond et al. (2010), Eyvindson et al. (2018), Giasson et al. (2023), Griess et al. (2019), Gunn et al. (2014), Harris and Betts (2023), Islam et al. (2024), Jurevics et al. (2016), Labadie et al. (2024), Laganière et al. (2015), Lagergren and Jönsson (2017), Larsson et al. (2025), Liu et al. (2018a, b, 2025a, b), Lutz et al. (2016), Måren and Sharma (2021), Matsuzaki et al. (2013), Mazziotta et al. (2022), Moreau et al. (2022), Nabhani et al. (2024), Osei et al. (2022), Pang et al. (2017), Petersson et al. (2022), Pikkarainen et al. (2024), Pingoud et al. (2018), Pohjanmies et al. (2017), Price et al. (1997), Rana et al. (2024), Repo et al. (2024), Rosenvald et al. (2025), Santaniello et al. (2017), Sasanifar et al. (2024), Triviño et al. (2017), Ziter et al. (2013) |
| Carbon sink establishment | 13 | USA, Norway, Korea, China, France, Japan, Sweden, Canada, Spain, Croatia | Model-based: SiTree, LANDIS-II, CO2Fix, CBM-CFS3<br>Empirical: eddy covariance, biomass measurements, allometric equations, soil/lab analyses<br>Hybrid: model + field/lab data integration (e.g., biomass + soil + simulation outputs) | Bracho et al. (2012), Bright et al. (2020), Choi et al. (2002), Fang et al. (2013), Fanin et al. (2025), He et al. (2018), Hotta et al. (2023), Jörgensen et al. (2021), Ménard et al. (2022), Perez-Cruzado et al. (2012), Poirier et al. (2016), Ostrogović Sever et al. (2019), Yu et al. (2021) |
| Carbon sink restoration | 2 | Great Britain, USA | Model-based: FVS<br>Empirical: soil analysis, allometric equations, forest structure measurements<br>Hybrid: empirical data used within simulation frameworks | Beckert et al. (2016), Quick et al. (2024) |
| Multiple (Conservation, Establishment, Restoration) | 7 | Sweden, USA, Canada, Germany, Finland | Model-based: LPJ-GUESS, CBM-CFS3, FVS<br>Empirical: allometric equations, eddy covariance, dendrometric measurements<br>Hybrid: mass-balance approaches, remote sensing + modelling, integrated ecosystem assessments | Bergkvist et al. (2025), Law et al. (2018), Ma et al. (2022), Dore et al. (2010), Krause et al. (2020), Triviño et al. (2015), Smyth et al. (2014) |

The temporal distribution of included publications indicates a sparse output between 1997 and 2010, followed by a marked increase from 2011 onwards (Fig. 5). While this trend reflects a growing research focus on the intersection of forest management and climate goals, the sharp increase in recent years is also linked to the formalisation of 'Climate-Smart Forestry' as a specific conceptual framework. Earlier research addressing similar objectives may have been categorised under related terms such as 'adaptive management' or 'carbon-oriented silviculture.' Nevertheless, the peaks observed in 2017, 2022, 2024 and 2025, reaching up to 7 publications annually, suggest an accelerating rate of scientific production and a more unified approach to addressing the relevance of forest-based climate solutions.

Forest types ranged from species-specific systems (e.g., spruce, pine, beech) to broader mixed or regional classifications. The spatial scale of analysis extended from stand-level investigations to national or regional projections: in detail, of the final total subset, 34% (n = 21) of studies reported on studies at the plot level, 23% (n = 14) at the stand level, 18% (n = 11) at the landscape and region level, while 7% refers to studies at the country level (n = 4). The temporal coverage ranged from short-term interventions of less than a decade to century-long simulations under alternative climate scenarios. A variety of approaches were employed to estimate carbon sequestration, including process-based forest ecosystem models, empirical sampling methods, and, less frequently, remote sensing techniques (Table 3). Across all strategies, model-based approaches dominated, often combined with empirical data, highlighting a strong reliance on hybrid frameworks for carbon sequestration assessment (Fig. 6). The scope of carbon pools considered varied considerably: while aboveground biomass was consistently assessed, fewer studies accounted for soil carbon, litter, or

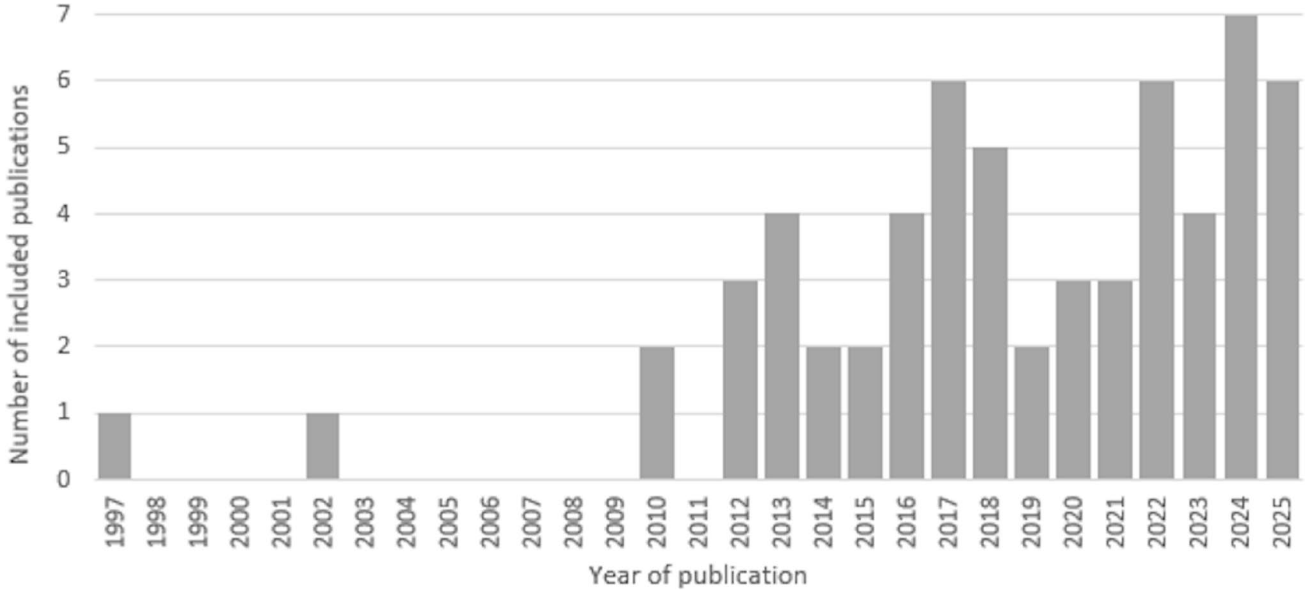

**Fig. 5** Number of papers in our final subset (n = 61) published per year between 1997 and 2025

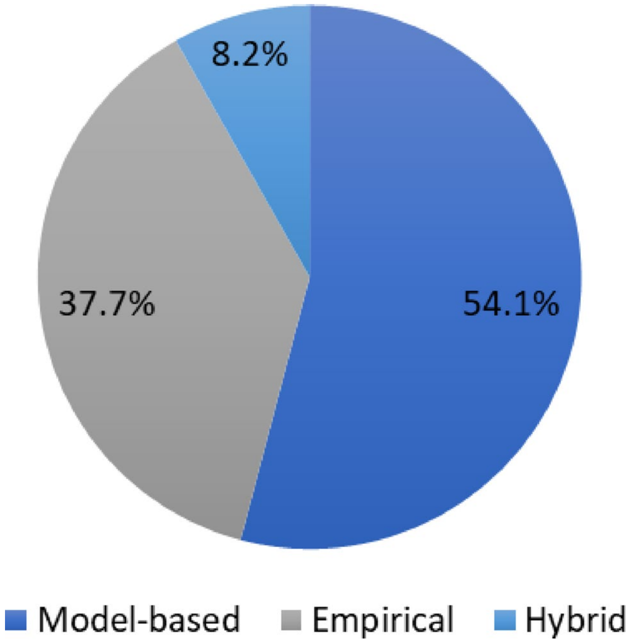

**Fig. 6** Proportional distribution of methodological approaches used to estimate carbon sequestration across our final subset of articles (n = 61). Model-based approaches represent the majority (n = 33), followed by empirical methods (n = 23) and hybrid approaches combining modelling and empirical data (n = 5), highlighting the predominance of modelling frameworks in carbon sequestration assessments

deadwood. Finally, while some studies have explored synergies and trade-offs—most notably between carbon storage, timber yield, and biodiversity—such assessments have not been systematically addressed, highlighting an essential gap in the literature.

## Discussion

### Navigating climate-smart complexity

Sustainable forest management is a pivotal component of climate change mitigation strategies aimed at achieving the global targets outlined in international agreements (Verkerk et al. 2022; Ellison et al. 2024; Pan et al. 2024; Bava and Caselli 2025). However, forest ecosystems are currently under increasing pressure due to the combined impacts of human activities and natural disturbances (Patacca et al. 2023). Our synthesis highlights the diverse climate-smart management strategies available to enhance forest carbon sinks, along with the complex mitigation and adaptation pathways they entail (see the references listed in Table 1A). It also highlights the trade-offs involved in balancing these strategies with the provision of ecosystem services (Tognetti et al. 2022a). We observed a modest increase in peer-reviewed research addressing the outcomes of forest sink conservation/protection, establishment, and restoration studies since 2012. While much of this research supports the notion that forest management options can rapidly and extensively increase carbon sinks (Ameray et al. 2021), we also noted limitations in the generalisability of the results due to contextual factors and geographical biases (Nabuurs et al. 2018; Gregor et al. 2022).

Additionally, the complexity involved in quantifying carbon sequestration outcomes across various social-ecological domains and spatial and temporal resolutions remains a significant limiting factor (Ali 2023; Wu et al. 2023; Alawode et al. 2026). This difficulty is largely due to the challenge of scaling local measurements to broader resolutions and the historical reliance on static variables for carbon accounting. For example, rather than being a constant parameter, wood density, which is fundamental to carbon stock estimation, is mediated by long-term drought dynamics and growth traits (Torresan et al. 2024). These changes underscore the dynamic nature of wood properties and emphasise the need to account for temporal variability to avoid errors in forest carbon estimation.

## Conservation, establishment, and restoration of carbon sinks to hold the line

Forest protection is a key strategy for mitigating anthropogenic impacts. Although 27% of the global net forest carbon sink is located within protected areas (Harris et al. 2021), substantial uncertainty persists regarding the extent to which unmanaged forests contribute to climate change mitigation through avoided deforestation (e.g., Soares-Filho et al. 2010; Grassi et al. 2022). Moreover, the specific contribution of protected areas to global climate targets remains insufficiently quantified in the literature (Table 1A). While forest growth facilitates carbon sequestration, the net climatic impact is governed by a complex interplay between carbon dynamics and biophysical properties. In boreal and temperate ecosystems, rising $CO_2$ and temperatures may enhance net photosynthesis; however, this response is frequently constrained by nitrogen availability, which limits the capacity for sustained increases in biomass (Finzi et al. 2007; Norby et al. 2010). Beyond $CO_2$ uptake, forests regulate the surface energy budget through albedo, evapotranspiration, and surface roughness (Bonan 2008; Devaraju et al. 2015). For instance, feedback mechanisms such as increased evapotranspiration can have opposing effects: amplifying warming via atmospheric water vapour or promoting cooling through enhanced cloud cover and water recycling (Singh et al. 2021; Ellison et al. 2024). Conversely, deforestation disrupts these processes, reducing surface roughness and boundary-layer turbulence, thereby intensifying local warming regardless of carbon flux (Davin and de Noblet-Ducoudré 2010).

While conservation sentiments may be relevant to highly developed societies, local ambitions for carbon preservation must contend with the global expansion of wood consumption (Daigneault et al. 2022; Gregor et al. 2022). Without human intervention, existing global forests could increase their aboveground biomass by up to 44.1 petagrams of carbon (161.4 Gt $CO_2$eq) under current climate and $CO_2$ conditions. This represents a 15–16% increase over current levels, equivalent to approximately four years of anthropogenic $CO_2$ emissions (Roebroek et al. 2023). Therefore, without substantial reductions in emissions, releasing forests from management has low mitigation potential, adding to uncertainties about the costs of climate change mitigation and changes in land surface albedo (Fargione et al. 2021; Ellison et al. 2024). The forest sink should therefore be preserved to offset residual carbon emissions (i.e., those that persist after implementing all technically feasible measures to reduce carbon emissions through extensive and comprehensive gross emissions reductions) rather than to compensate for present emissions (Buck et al. 2023).

Forest harvests may result in substantial soil carbon losses, particularly in hardwood stands compared to conifer mixed stands (Nave et al. 2010). In contrast to secondary forests or tree plantations, logging in pristine primary and old-growth forests raises concerns for both biodiversity and climate, as it releases $CO_2$ that has accumulated over centuries (Liu et al. 2018a, b). Indeed, some older forests continue to sequester soil organic carbon (Zhou et al. 2006), binding soil organic matter more tightly than younger ones (Lacroix et al. 2016). As large-diameter and old trees consistently enhance biomass growth and contribute to carbon sequestration under changing climatic conditions (Begović et al. 2023), their dynamics and sensitivities to environmental changes have the potential to exert significant control over global forest carbon cycling (Lutz et al. 2018). Nevertheless, whereas large trees store most of the forest biomass and carbon, small trees make a significant contribution to forest dynamics (Piponiot et al. 2022). If young forests sequester more carbon than older ones due to the maximisation of wood production and carbon storage, carbon storage increases with forest age as ecosystem structural and biotic complexity increases (Keeton et al. 2007). While old trees and old-growth forests may persist in accumulating and storing carbon (Luyssaert et al. 2008; Stephenson et al. 2014), thereby challenging the long-standing belief that they are carbon–neutral, these forest systems are vulnerable to disturbances (Qie et al. 2017), and carbon stocks in protected forests can be unpredictable. Nevertheless, restricting tree harvests and lengthening rotation periods may increase net ecosystem carbon balance in temperate managed forests (Nunery and Keeton 2010; Motta et al. 2011; Law et al. 2018).

As forests age, these forests may accumulate ecosystem services and provide habitats for various species (Moomaw et al. 2019). Allowing existing forests to reach their ecological (and social) potential may represent a cost-effective nature-based solution (Buotte et al. 2020). This approach, termed proforestation, may maximise carbon sequestration and biodiversity enhancement (Seddon et al. 2021), though reducing harvests in regions more inclined to conservation (advanced regions) may increase harvests from forests outside those regions. While managed forests can reduce pressure on unmanaged forests and provide wood products that serve as additional carbon stocks, contributing to fossil fuel displacement, the same wood cannot simultaneously be used for both material and energy substitution.

Among forest management options for mitigation, afforestation and reforestation practices are the most frequently reported in the reviewed studies (see the list of references reported in Table 1A). Suppose forest conversion (degradation of sink) is the most significant loss in carbon. In that case, active reforestation (establishing sinks where they previously existed) and afforestation (establishing new carbon sinks) on marginal land can yield the most significant benefits. However, the effectiveness of commercial forestry involving young tree plantations is a subject of debate (Lewis et al. 2019). Even though the incorporation of sustainable wood products may constitute a viable NBS (Zhang et al. 2023), considering the impact of escalating natural disturbances. Life cycle assessment studies indicate that forest growth rate is the primary determinant of cumulative mitigation potential, regardless of whether trees are harvested (Forster et al. 2021). Mitigation from harvested stands typically exceeds that of unharvested stands, and commercial afforestation may provide an effective mitigation strategy (Grassi et al. 2017). The establishment of large-scale forest carbon sinks, through reforestation of degraded lands and planting one trillion trees, may help mitigate climate change (Bastin et al. 2019). This controversial modelling exercise, which estimates that 205 Gt of carbon would be sequestered globally by planting trees, was deemed unrealistic due to the overestimation of soil organic carbon gains (Veldman et al. 2019; Taylor and Marconi 2020), assumption of degraded lands (Veldman et al. 2015, 2019), and warming effect of trees due to decreased albedo (Mykleby et al. 2017; Rohatyn et al. 2022). Equalising carbon uptake and surface albedo across temporal and spatial scales may help reduce warming, but its effectiveness in cooling needs to be tested (Graf et al. 2023).

Large-scale global planting efforts would require the production of a massive number of tree seedlings annually; in turn, this necessitates expanding seed collection and implementing adequate pre- and post-planting practices (Fargione et al. 2021). Adaptive traits may vary with the climate of origin of the population, highlighting the need to enhance common-garden studies to assess trade-offs between growth and tolerance traits under both indoor and outdoor conditions (e.g., Bolte et al. 2016; Versace et al. 2022). These experiments may guide ecological applications and plantation efforts (Schwinning et al. 2022). However, the mortality rate of planted trees can be high in the first few years after planting (Banin et al. 2022). The mortality of trees induced by warming may counteract the benefits of plantation efforts, leading to reduced canopy cover. This reduction, in turn, directly affects forest evapotranspiration, canopy interception, and surface albedo, which indirectly alter hydrologic processes (e.g., Anderegg et al. 2013). Ultimately, this leads to reduced land evapotranspiration and carbon sequestration (Jung et al. 2010). Moreover, competition for land is intense. Thus, while there is considerable enthusiasm for tree planting, the regrowth of natural forests can be a more cost-effective and efficient way to capture carbon, promote the re-establishment of local biodiversity, and do so more rapidly and securely than plantations (Cook-Patton et al. 2020).

Forest restoration, primarily through natural regeneration, is a key NBS for mitigating climate change and land degradation. This approach differs from active reforestation and afforestation in that it relies on natural ecological processes to recover forest ecosystems. Expanding forest cover can enhance mitigation benefits while also improving regulation of the water cycle (Hoek van Dijke et al. 2022; Ellison et al. 2024). However, forest restoration approaches, including the emerging FLR framework (Garrett et al. 2024; FAO 2024), are underrepresented in the studies reviewed regarding carbon-sink targets (see the list of references reported in Table 1A). The structure, composition, and function of forest sinks, including soils, can also be restored through various proactive measures that involve integrating forests into landscape management (Chakraborty et al. 2024). This integration facilitates the restoration of ecological functionality (Marshall et al. 2023). For example, the emphasis on preserving mature stands for carbon storage may limit options aimed at actively restoring old-growth forest attributes in forests managed for purposes other than conservation (D’Amato and Palik 2021).

Reinstating natural processes that occur in the absence of human activity may require an active approach, including protection from further damage from grazing or fire, and the selective reintroduction of missing species—a controversial rewilding approach to conserving biodiversity (Pettorelli et al. 2019). Relying on natural forest regrowth, in conjunction with the preservation of natural disturbance regimes, would prevent inappropriate tree establishment in native non-forest areas, such as grasslands, savannas, and open-canopy woodlands (Veldman et al. 2015). Indeed, plant species diversity can be higher in forests that are still managed than in those that are no longer managed (Langridge et al. 2023).

Forest carbon recovery after a disturbance (fire, outbreaks, or utilisation) requires time, and increasing disturbance frequency and intensity have long-term effects on carbon storage (Kashian et al. 2006; Mikoláš et al. 2021). In wildfire scenarios, while disturbances cause short-term carbon losses, long-term carbon balance can benefit from forest thinning and prescribed burning. These management practices help restore stand structure and fire regimes, reducing the risk of high-intensity fires and enhancing ecosystem resilience (Hurteau et al. 2016). Vegetation carbon sequestration varies across different land management practices, and implementing climate-smart forestry practices, such as forest restoration, may help increase carbon sequestration. The global land vegetation could sequester an additional 13.74 Pg carbon per year if location-specific optimal land management practices are implemented (Sha et al. 2022). In the long term, with changing climatic conditions, managed forests may exhibit higher productivity and store more carbon than unmanaged forests, provided that thinning and tree harvesting are conducted at moderate intensities (Dalmonech et al. 2022). Whether managed forests are carbon sources or sinks will, therefore, depend on their management. Biomass and GPP (Gross Primary Productivity) of sustainably managed forests at the time of harvest can be as high as they would be without management (Herbst et al. 2015; Schulze et al. 2022). Nonetheless, trade-offs are inevitable when leveraging forests for climate mitigation, such as land use leakage, and these must be carefully evaluated when formulating concrete strategies for climate-smart forestry (Luyssaert et al. 2018; Gregor et al. 2022; Alawode et al. 2026). Certainly, forest management can alter forest cover, stand structure, and species composition, thereby affecting carbon, water, and energy exchange (Bonan 2008; Naudts et al. 2016).

## Forest management as the encompassing framework maximising carbon storage

Improved forest management aims to enhance stand adaptation to climate change while mitigating $CO_2$ increases by promoting species and structural diversity, thereby enhancing resilience and sustaining carbon storage for mitigation (Haya et al. 2023; Daigneault et al. 2024). Forest productivity and carbon storage benefits may result from transitioning from pure to mixed species stands and from stock size to stock resilience (Liang et al. 2016; Pretzsch and Hilmers 2024), although contrasting evidence also exists (Grossiord et al. 2014; Conte et al. 2018). Productivity improvements in mixed species stands may not be strongly influenced by tree age or stand species composition. Still, they could increase significantly with the availability of additional resources, such as increased local precipitation leading to greater water availability (Jactel et al. 2018). In favourable environments, therefore, tree species diversity may increase the intensity of competitive interactions through higher productivity, thereby increasing the risk of tree mortality. On the other hand, in forests with lower species diversity, mortality may increase more significantly as climate moisture availability decreases. In contrast, both growth and mortality may increase as the climate warms, regardless of species diversity (Hisano et al. 2019).

While intercropping with N-fixing species may enhance the productivity and water-use efficiency of the target tree species in agroforestry systems, it is essential to note that species interactions can change over time and space (Battipaglia et al. 2017). These interactions may also vary regionally (Versace et al. 2020), and they should be considered when establishing management criteria to maximise tree performance. Although promoting tree diversity has positive effects on stand productivity, increasing diversity in forest stands may also increase the probability of tree mortality (Searle et al. 2022). It is uncertain whether higher tree species diversity reduces tree mortality by minimising intraspecific competition, or if the increased competitive pressures resulting from higher productivity in more diverse stands ultimately lead to an overall increase in tree vulnerability to climate change (Condés et al. 2025). Productivity may increase with species richness until reduced evenness (similarity of species abundances) limits the increases in community diversity (Torresan et al. 2020; Hordijk et al. 2023).

Altered stand age is a fundamental consequence of forest management and a powerful predictor of structure and function (Bradford and Kastendick 2010). Higher structural complexity may reduce individual mortality probabilities because vertical stratification among trees reduces direct competition (Gough et al. 2019). Nevertheless, the relationship between stand age and either complexity or carbon storage and sequestration, especially trade-offs between the two, is not well characterised. Age-related stand dynamics, driven by past management and natural disturbances, may affect forests' contributions to mitigation outcomes. The carbon dynamics of forests following the cessation of management are poorly understood. While high tree stocking, structural complexity, and abundant deadwood are forest stand structural conditions associated with high carbon storage (Lewis et al. 2013; Nagel et al. 2023), it is essential to note that higher carbon stocks do not automatically equate to high forest ecological complexity.

Economically mature stands, characterised by high aboveground carbon density and low complexity, differ from old-growth forests, which exhibit the highest aboveground carbon density and the highest complexity, highlighting the mismatch between timber production and biodiversity management (Hilmers et al. 2018). High relative density and low stand complexity have implications for stock vulnerability and forest resilience. Ensuring the long-term stability of forest carbon benefits requires considering factors that enhance resilience in dynamic systems. Comparing the relative density based on the forest's current size-density relationship with a hypothetical maximum, using the coterminous US National Forest inventory data from 1999 to 2020, suggests opportunities to increase live tree stocking in understocked stands (Woodall and Weiskittel 2021). Additionally, density management can be employed to address tree mortality and enhance resilience to disturbances in increasingly dense forests.

A static forest land area with reduced tree abundance but significantly increased wood volume, tree biomass, and carbon storage, and therefore higher relative density, may contribute to reaching a threshold of canopy closure and self-thinning-induced mortality, especially in areas prone to drought conditions (Bradford et al. 2021). Adaptive management, rather than a passive approach, may become desirable to retain forests' carbon under warming-induced drought stress. The population density of trees may influence growth during drought (i.e., resistance) and growth after drought (i.e., resilience) compared to pre-drought growth (Bottero et al. 2017). If there is a negative relationship between relative tree population density and drought resistance and resilience, trees growing at lower densities can be less vulnerable to drought. Therefore, managing forest ecosystems with low tree density represents a promising adaptive strategy to reduce the adverse impacts of drought on forest growth and carbon sequestration in the years to come.

The emphasis on forests as carbon stores has often overshadowed other conservation goals, such as species richness and ecosystem complexity (Buřivalová et al. 2023). While these aspects are intrinsically linked to climate outcomes, they have not kept pace with the scale and diversification of forest conservation. Aligning local-scale co-benefits with global carbon objectives remains a key challenge and a priority for future forest conservation efforts. Nevertheless, trade-offs exist between carbon sequestration and biodiversity conservation (Ezquerro et al. 2024). While habitat restoration is considered a key strategy for recovering imperilled species, ecosystem restoration may collide with maximising carbon storage. For example, promoting early successional forest conditions does not maximise stand-level carbon storage, whereas uniformly promoting high stocking or mature forest conditions in the name of carbon storage may exclude species that require open or young stands (Littlefield and D'Amato 2022).

Prioritising climate targets may conflict with national policies and negatively impact ecosystem services and biodiversity, as observed in several EU countries (Blattert et al. 2023). In European forests, the stand volume growth and forest carbon sink remain high on fertile sites (e.g., Pretzsch et al. 2014). However, no direct transformation of the increased volume growth trend into carbon sequestration and biomass production can be generalised (Pretzsch et al. 2018). Additionally, emerging signals of sink saturation are evident in tree rings and forest inventories (Nabuurs et al. 2013). Global $CO_2$ fertilisation effects have declined across most terrestrial regions of the globe from 1982 to 2015 (Wang et al. 2020), in association with changing water availabilities, indicating a significant decline in the beneficial effects of elevated atmospheric $CO_2$ on terrestrial carbon absorption. This decline may diminish the capacity of land-based climate mitigation, potentially hastening global warming and intensifying the measures needed to achieve climate goals. Climate-smart practices and new forest areas may help reverse this trend, thereby increasing the annual net increment in forest growth and enhancing the potential for storing carbon in harvested wood products and through material substitution (Verkerk et al. 2022). However, high carbon stocks incentivised by carbon market baseline standards may encourage stand densities that are more vulnerable to carbon loss due to tree mortality, thereby harming the climate (Dye et al. 2024). In fact, carbon sequestration differs from temperature mitigation (Don et al. 2024), and it necessitates a comprehensive climate perspective to complement the carbon-centric approach.

## A pathway to forest stability under intensified disturbances emerges from the literature

The finite nature of forest carbon sinks, influenced by factors such as tree ageing, increasing temperatures, and sink saturation, may offset the additional tree growth resulting from rising atmospheric $CO_2$ concentrations (Peñuelas et al. 2008; Silva et al. 2010; Pretzsch et al. 2017). Nevertheless, these conclusions remain controversial (McMahon et al. 2010; Tognetti et al. 2014; Pretzsch et al. 2017). The rise in atmospheric $CO_2$ concentrations, driven by anthropogenic emissions, has overshadowed the broader role of forest ecosystems in water regulation, soil protection, and biodiversity conservation, often relegating these functions to secondary co-benefits in sustainable forest management (e.g., Piazza et al. 2024). Climate change–driven chronic stress at global scales, namely drought, contributes to substantial tree mortality each year (e.g., Allen et al. 2010). Recent observations of elevated tree mortality following climate extremes, such as heat and drought, raise concerns about the risks of climate change to global forest health (Cailleret et al. 2017; Hartmann et al. 2022). While simulation models predict that tree growth will continue to result in net carbon uptake in the coming decades, increased growth rates may shorten their lifespans (Liu et al. 2025a, b). Consequently, recent increases in forest carbon stocks can be temporary due to delayed increases in tree mortality and forest dieback, which might ultimately offset the carbon gains resulting from growth stimulation (Brienen et al. 2020).

Furthermore, water stress may shift species composition toward drought-tolerant but slower-growing trees (Csilléry et al. 2020). Competition for water may intensify the ecosystem's response to declining water availability, as the most competitive species under dry conditions tend to have lower biomass than less competitive ones (Zhang et al. 2018). Climate change is also influencing long-term ecological processes (e.g., vegetation shift), pushing forest tree species to the edge of their natural climate envelopes (Hanewinkel et al. 2013; Antonucci et al. 2017). Future disturbance-adapted species may restore tree spatial patterns shaped by forest gap dynamics (Wikle and D'Amato 2023) but could replace economically valuable, high-carbon-sequestering trees with gap specialists. However, forest management can facilitate this transition, helping maintain ecosystem functions and services while adapting to changing conditions (Millar et al. 2007). For example, regulating and driving species mixtures and size heterogeneity may result in stable stand productivity and carbon stock, despite species-specific changes (Diaci et al. 2017; Hilmers et al. 2020; Torresan et al. 2020). However, discrete extreme disturbance events have increased in recent decades (Ummenhofer and Meehl 2017; Patacca et al. 2023). Extreme events, such as outbreaks or heatwaves, exert disproportionately large and sometimes irreversible impacts on tree growth and forest productivity at large scales (Fierravanti et al. 2015; Salomón et al. 2022). Drought-induced tree die-off resulting from a megadrought is expected to bring about profound alterations in the structure, function, and composition of forest stands, as well as in the ecosystem services they deliver (Field et al. 2020). Carbon storage may gradually recover to peak levels over centuries following its release from disturbance (Mikoláš et al. 2021). Individual disturbances, their interactions, and climate variability collectively influence the resilience of forest ecosystems and their capacity to store carbon (Johnstone et al. 2016).

Reorienting forest management is necessary to maintain existing carbon sinks, enhance future sequestration capacity, and balance trade-offs and explore synergies between resilience mechanisms within social-ecological systems across spatial and temporal scales (Millar et al. 2007; Larsen et al. 2022; Alawode et al. 2026). Increasing forest fragmentation and tree mortality, as well as the loss of system resilience and species diversity, necessitate a shift in current management practices towards more flexible silvicultural strategies to enhance the adaptation and mitigation potentials of managed forests (Puettmann et al. 2015; Messier et al. 2019). Forest management options, maximising carbon sequestration, have been proposed to accomplish the range of objectives and scales in terms of conservation, establishment, and restoration of carbon sinks under climate change scenarios (e.g., Jacobsen 2001; Bergeron et al. 2002; Mason et al. 2003; Franklin et al. 2007; Putz et al. 2008; Baker and Read 2011; Bauhus et al. 2013; Donoso and Promis 2013; Nagel et al. 2017; Halofsky et al. 2018; Larsen et al. 2022, Weatherall et al. 2022).

A climate-smart perspective has been recently endorsed to identify good practice examples and recommend suitable metrics to effectively adopt and monitor the stability of forests, i.e., the ability of forests to maintain functioning over time and in the face of environmental stressors (Schnabel et al. 2021), and for safeguarding carbon sequestration, among other ecosystem services forests provide (Nabuurs et al. 2017; Yousefpour et al. 2018; Bowditch et al. 2020; Verkerk et al. 2020; Sterck et al. 2021; Cooper and MacFarlane 2023; Nagel et al. 2023). Climate-smart forestry aims to guide sustainable forest management towards increasing ecosystem resilience and addressing natural disturbances, based on indicators that inform decision-making (Santopuoli et al. 2021; Tognetti et al. 2022b). Integrating remote sensing and terrestrial monitoring is crucial for determining the extent to which an adaptation strategy diverges from current practices and the necessity of innovative transition approaches (Torresan et al. 2021).

To avoid interferences among mitigation options and adaptation strategies, a mosaic forest landscape that combines multifunctionality with production and conservation requirements can be envisioned to help ensure a positive carbon balance (Seymour and Hunter 1992; Ceddia et al. 2014; Schall et al. 2018; Muys et al. 2022). It is therefore valuable to determine which forest management option has the greatest potential for carbon sequestration and how to balance the different options at the landscape scale, while accounting for trade-offs related to landscape fragmentation and habitat loss. Given the growing concern over tree mortality driven by climate change, enhancing tree functional trait diversity and stand structural complexity may play a crucial role in mitigating the impacts of drought and supporting climate-smart forestry practices (Hisano et al. 2024).

## Current limitations and future needs

Scoping reviews do not aim to provide an exhaustive survey of all available literature; instead, they follow a rigorous methodological framework to systematically map the scope, key concepts, and knowledge gaps within a specific field of interest (Munn et al. 2022; Peters et al. 2022). By documenting both existing literature and research gaps, they provide valuable insights into the panorama of knowledge within a given area (Tricco et al. 2016). Furthermore, scoping reviews can serve as invaluable tools for informing the design and execution of subsequent systematic reviews (Munn et al. 2018). A systematic review is the most valid approach for assessing the feasibility, appropriateness, meaningfulness, or effectiveness of a treatment or practice. However, if the goal is to identify, map, report, or discuss specific characteristics or concepts in the literature, a scoping review is more appropriate (Peters et al. 2020). Given the increasing urgency to maximise carbon benefits from forests and the heightened expectations for achieving a sustainable, climate-neutral economy, the volume of studies in this domain is steadily expanding. Consequently, we deemed it essential to situate the methodological and reporting issues of this expanding field within the ongoing debate on the trade-offs and synergies characterising closer-to-nature forestry scenarios (Larsen et al. 2022). By doing so, our review assesses the capacity of current research to inform synthesis and policy, and identifies routes to enhanced methodological consistency and transparency (Peters et al. 2020, 2022).

We analysed how climate-smart forestry studies report outcomes related to the establishment, conservation, and restoration of carbon sinks, assessing the consistency of methodologies for cross-study comparison. Our review revealed a notable dearth of comprehensive analyses of synergies and trade-offs, specifically juxtaposing climate-smart management approaches against conventional land management practices and their respective capacities for carbon sequestration. Presently, the literature provides scant references to management tactics aimed at mitigating the risks inherent in forests' carbon capture and storage functions (Bowditch et al. 2020; Verkerk et al. 2020; Littlefield and D'Amato 2022; Weatherall et al. 2022; Blattert et al. 2023; Cooper and MacFarlane 2023; Nagel et al. 2023; Alawode et al. 2026). The validation of recommendations and conclusions will be paramount in identifying any gaps in conceptualisation and evidence, thereby providing essential insights to inform further research, practical applications, and policy development (Weatherall et al. 2022).

## Conclusion

As global warming persists and natural disturbances accumulate, the task of evaluating forests' contributions to mitigating climate change becomes increasingly complex. With disturbances becoming increasingly significant, the long-term impact of forest management on carbon sequestration potential remains uncertain (Nabuurs et al. 2013; Pretzsch et al. 2014; Wang et al. 2022; Patacca et al. 2023). While forest-based measures are key components of mitigation strategies, a decrease in the rate of carbon sequestration coincides with the need for increased climate-neutrality objectives. Minimising human intervention can enhance forest carbon sinks, but it offers limited mitigation potential (Roebroek et al. 2023). Alternatively, harvested wood products and material substitution may provide additional benefits, though uncertainties remain regarding their utilisation (Grassi et al. 2018).

Forestry was initially viewed as a victim of climate change, with increasing disturbance regimes posing new threats to forest ecosystems. However, it has also been recognised as a contributor, with deforestation generating greenhouse gas emissions, alongside those from agriculture and land-use change. Forestry is increasingly recognised as a solution to climate change due to its role in climate mitigation. Climate-smart forestry can integrate adaptation and mitigation across scales, contributing to effective land-use strategies that support climate targets. This review emphasises the growing significance of forests in achieving climate targets, particularly through the establishment of carbon sinks via afforestation and reforestation practices. However, the research impact on the conservation and restoration of carbon sinks remains constrained by significant factors, including the lack of empirical evidence on effectiveness, unresolved trade-offs in application, and substantial geographic evidence gaps. Given the interconnected nature of the silvicultural and agricultural sectors, future analyses of carbon sequestration potential could benefit significantly from a more comprehensive examination of intersectoral dynamics (Bravo et al. 2024). Additionally, conducting simultaneous impact assessments of climate change alongside the dynamics of wood and food product markets will be crucial for generating more robust projections of climate mitigation potentials through NBS within global climate commitments.

A climate-smart perspective should adopt a holistic and quantitative approach to sustain carbon sequestration in the future, recognising that, while valuable, it may not fully offset trade-offs with other ecosystem services (Gregor et al. 2022). This approach should account for the inherent trade-offs in conserving, establishing, and restoring carbon sinks. Effectively assigning value to management measures aimed at maintaining or enhancing forest carbon sinks necessitates comparison with overarching principles such as sustaining ecosystem functions and processes, minimising species loss, optimising social-ecological resilience to disturbances, moderating temperature increases, and reducing land degradation. This evaluation can be facilitated through analytic hierarchy processes (Prober et al. 2019). Consequently, the most effective mitigation strategy may be one that attains the highest ranking as the most flexible and optimal landscape-specific combination. While these considerations hold for boreal and temperate forests, it is important to note that significant uncertainties hinder verification of management options in tropical forests, where substantial carbon sinks are located (Erb et al. 2018).

Currently, predetermined climate and biodiversity targets are shaping forest policies in temperate and boreal countries. However, the prevailing discourse on the governance of agricultural and silvicultural systems is characterised by sectoral approaches rather than harmonious ones. This sectoral approach, which also encompasses research, hinders the development of integrated, synergistic management schemes that foster mosaic landscapes in which primary production, biodiversity conservation, and multifunctional uses can coexist seamlessly (Bravo et al. 2024). Enhancing efficiency in production, protection, adaptation, and mitigation within landscapes requires a complementary approach to landscape management forms. As climate-smart forestry evolves, future research should address sectoral integration, explore innovative forestry-agroforestry-agriculture models, including emerging carbon farming frameworks, and assess the long-term impacts of climate-smart practices on ecosystem stability and food security. Researchers must explore innovative and creative strategies for harmonising land management regimes. This endeavour is crucial for informing policy decision-making and aiding practitioners in implementing comprehensive, balanced management plans.

**Supplementary Information** The online version contains supplementary material available at https://doi.org/10.1007/s10342-026-01915-4.

**Acknowledgements** This study was generated within the COST Action CLIMO (Climate-Smart Forestry in Mountain Regions - CA15226) and the H2020 Project Skill-For-Action (An innovative concept to enforce carbon-sensitive forest management and forest utilisation), both funded by the European Union.

**Author contributions** R.T. and C.T. contributed equally and share responsibility for correspondence.

**Funding** Open access funding provided by Libera Università di Bolzano within the CRUI-CARE Agreement.

**Data availability** No datasets were generated or analysed during the current study.

## Declarations

**Conflict of interest** The authors declare no conflict of interest.

## References

Alawode GL, Oluwajuwon TV, Adegbola FO, Oyefara AO, Daniel OI (2026) Climate-smart forestry: a review of research trends and implementation approaches. Mitig Adapt Strateg Glob Change 31:19. https://doi.org/10.1007/s11027-026-10293-6

Alfieri D, Tognetti R, Santopuoli G (2024) Exploring climate-smart forestry in Mediterranean forests through an innovative composite climate-smart index. J Environ Manag 368:122002. https://doi.org/10.1016/j.jenvman.2024.122002

Alfieri D, Caicoya AT, Tognetti R, Santopuoli G (2025) Is climate-smart forestry affected by thinning intensity and tree species composition? A case study in long-term experimental plots of central Europe. J Environ Manage 394:127603. https://doi.org/10.1016/j.jenvman.2025.127603

Ali A (2023) Linking forest ecosystem processes, functions and services under integrative social–ecological research agenda: current knowledge and perspectives. Sci Tot Environ 892:164768. https://doi.org/10.1016/j.scitotenv.2023.164768

Allen CD, Macalady AK, Chenchouni H et al (2010) A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. For Ecol Manag 259:660–684. https://doi.org/10.1016/j.foreco.2009.09.001

*Alrahahleh L, Ikonen VP, Kilpeläinen A et al (2017) Effects of forest conservation and management on volume growth, harvested amount of timber, carbon stock, and amount of deadwood in Finnish boreal forests under changing climate. Can J for Res 47:215–225. https://doi.org/10.1139/cjfr-2016-0153

Ameray A, Bergeron Y, Valeria O et al (2021) Forest carbon management: a review of silvicultural practices and management strategies across boreal, temperate and tropical forests. Curr for Rep 7:245–266

Anderegg WRL, Kane JM, Anderegg LDL (2013) Consequences of widespread tree mortality triggered by drought and temperature stress. Nat Clim Change 3:30–36

Antonucci S, Rossi S, Deslauriers A et al (2017) Large-scale estimation of xylem phenology in black spruce through remote sensing. Agric for Meteorol 233:92–100. https://doi.org/10.1016/j.agrformet.2016.11.011

Arksey H, O'Malley L (2005) Scoping studies: towards a methodological framework. Int J Soc Res Methodol 8:19–32. https://doi.org/10.1080/1364557032000119616

Armstrong McKay DI, Staal A, Abrams JF et al (2022) Exceeding 1.5°C global warming could trigger multiple climate tipping points. Science 377:1–10. https://doi.org/10.1126/science.abn7950

Baker SC, Read SM (2011) Variable retention silviculture in Tasmania's wet forests: ecological rationale, adaptive management and synthesis of biodiversity benefits. Aust for 74:218–232. https://doi.org/10.1080/00049158.2011.10676365

Banin LF, Raine EH, Rowland LM et al (2022) The road to recovery: a synthesis of outcomes from ecosystem restoration in tropical and sub-tropical Asian forests. Phil Trans R Soc B: Biol Sci 378:20210090. https://doi.org/10.1098/rstb.2021.0090

Bastin J-F, Finegold Y, Garcia C et al (2019) The global tree restoration potential. Science 365:76–79. https://doi.org/10.1126/science.aax0848

Battipaglia G, Pelleri F, Lombardi F et al (2017) Effects of associating *Quercus robur* L. and *Alnus cordata* Loisel. on plantation productivity and water use efficiency. For Ecol Manag 391:106–114. https://doi.org/10.1016/j.foreco.2017.02.019

Bauhus J, Puettmann KJ, Kuhne C (2013) Close-to-nature forest management in Europe. Compatible with managing forests as complex adaptive forest ecosystems? In: Messier C, Puettmann KJ, Coates KD (eds) Managing forests as complex adaptive systems. Rouledge, London. https://doi.org/10.4324/9780203122808

Bava JO, Caselli M (2025) Forestry, from theory to practice: Central European ideas in native Patagonian forests in a context of climate change. Front for Glob Change 8:1377026. https://doi.org/10.3389/ffgc.2025.1377026

*Beckert M, Smith P, Chapman S (2016) Of trees and sheep: trade-offs and synergies in farmland afforestation in the Scottish uplands. Land use competition. Springer International Publishing, pp 183–192. https://doi.org/10.1007/978-3-319-33628-2_11

Begović K, Schurman JS, Svitok M et al (2023) Large old trees increase growth under shifting climatic constraints: aligning tree longevity and individual growth dynamics in primary mountain spruce forests. Glob Chang Biol 29:143–164. https://doi.org/10.1111/gcb.16461

Bergeron Y, Leduc A, Harvey BD et al (2002) Natural fire regime: a guide for sustainable management of the Canadian Boreal Forest. Silva Fenn 36:81–95. https://doi.org/10.14214/sf.553

*Bergkvist J, Lagergren F, Islam MdR et al (2025) Quantifying the impact of climate change and forest management on swedish forest ecosystems using the dynamic vegetation model LPJ-GUESS. Earth's Future. https://doi.org/10.1029/2024EF004662

Betts MG, Phalan BT, Wolf C et al (2021) Producing wood at least cost to biodiversity: integrating Triad and sharing–sparing approaches to inform forest landscape management. Biol Rev 96:1301–1317. https://doi.org/10.1111/brv.12703

Blattert C, Mönkkönen M, Burgas D et al (2023) Climate targets in European timber-producing countries conflict with goals on forest ecosystem services and biodiversity. Commun Earth Environ 4:119. https://doi.org/10.1038/s43247-023-00771-z

Bolte A, Czajkowski T, Cocozza C et al (2016) Desiccation and mortality dynamics in seedlings of different European beech (*Fagus sylvatica* L.) populations under extreme drought conditions. Front Plant Sci 7:751. https://doi.org/10.3389/fpls.2016.00751

Bonan GB (2008) Forests and climate change: forcings, feedbacks, and the climate benefits of forests. Science 320:1444–1449

*Botroh AM, Paré D, Cavard X et al (2023) Nine-years effect of harvesting and mechanical site preparation on bryophyte decomposition and carbon stocks in a boreal forested peatland. For Ecol Manage 540:121020. https://doi.org/10.1016/j.foreco.2023.121020

Bottero A, D'Amato AW, Palik BJ et al (2017) Density-dependent vulnerability of forest ecosystems to drought. J Appl Ecol 54:1605–1614. https://doi.org/10.1111/1365-2664.12847

Bowditch E, Santopuoli G, Binder F et al (2020) What is climate-smart forestry? A definition from a multinational collaborative process focused on mountain regions of Europe. Ecosyst Serv 43:101113. https://doi.org/10.1016/j.ecoser.2020.101113

*Bracho R, Starr G, Gholz HL et al (2012) Controls on carbon dynamics by ecosystem structure and climate for southeastern U.S. slash pine plantations. Ecol Monogr 82:101–128. https://doi.org/10.1890/11-0587.1

Bradford JB, Kastendick DN (2010) Age-related patterns of forest complexity and carbon storage in pine and aspen–birch ecosystems of northern Minnesota, USA. Can J for Res 40:401–409. https://doi.org/10.1139/X10-002

Bradford JB, Andrews CM, Robles MD et al (2021) Landscape-scale restoration minimizes tree growth vulnerability to 21st century drought in a dry forest. Ecol Appl 31:e02238. https://doi.org/10.1002/eap.2238

Bravo F, van der Werf W, Tognetti R, Mazia N, Anten NPR, Piazza M-V, Tomelleri E, Pretzsch H (2024) Unleashing the power of plant structural and functional diversity. From common observations to theory and management models. Food Energy Secur 13:e70005. https://doi.org/10.1002/fes3.70005

Brienen RJW, Caldwell L, Duchesne L et al (2020) Forest carbon sink neutralized by pervasive growth-lifespan trade-offs. Nat Commun 11:4241. https://doi.org/10.1038/s41467-020-17966-z

*Bright RM, Allen M, Antón-Fernández C et al (2020) Evaluating the terrestrial carbon dioxide removal potential of improved forest management and accelerated forest conversion in Norway. Glob Chang Biol 26:5087–5105. https://doi.org/10.1111/gcb.15228

Buck HJ, Carton W, Lund JF, Markusson N (2023) Why residual emissions matter right now. Nat Clim Chang 13:351–358. https://doi.org/10.1038/s41558-022-01592-2

*Buotte PC, Law BE, Ripple WJ, Berner LT (2020) Carbon sequestration and biodiversity co-benefits of preserving forests in the western United States. Ecol Appl 30:e02039. https://doi.org/10.1002/eap.2039

Buřivalová Z, Yoh N, Butler RA, Sagar HSC, Game ET (2023) Broadening the focus of forest conservation beyond carbon. Curr Biol 33:R621–R635

*Burton JI, Ares A, Olson DH et al (2013) Management trade-off between aboveground carbon storage and understory plant species richness in temperate forests. Ecol Appl 23:1297–1310. https://doi.org/10.1890/12-1472.1

Cailleret M, Jansen S, Robert EMR et al (2017) A synthesis of radial growth patterns preceding tree mortality. Glob Chang Biol 23:1675–1690. https://doi.org/10.1111/gcb.13535

Ceddia MG, Bardsley NO, Gomez-Y-Paloma S et al (2014) Data from: governance, agricultural intensification, and land sparing in tropical South America. Proc Natl Acad Sci U S A 111:7242–7247. https://doi.org/10.1073/pnas.131796711

Chakraborty D, Schüler S, Ciceu A, Bauhus J, Bou Dagher M, Đodan M, Kramer K, Svensson J, Schatzdorfer E (2024) How to strengthen the European forest carbon sink through prestoration: integrating active restoration and adaptation. Policy Brief 11. European Forest Institute

*Choi S, Lee K, Chang Y (2002) Large rate of uptake of atmospheric carbon dioxide by planted forest biomass in Korea. Global Biogeochem Cycles 16:1089. https://doi.org/10.1029/2002GB001914

*Colombo SJ, Chen J, Ter-Mikaelian MT et al (2012) Forest protection and forest harvest as strategies for ecological sustainability and climate change mitigation. For Ecol Manag 281:140–151. https://doi.org/10.1016/j.foreco.2012.06.016

Condés S, Bielak K, Brazaitis G et al (2025) Influence of species interactions and climate on tree mortality in mixed stands of *Pinus sylvestris*, *Betula* spp., and *Picea abies*. Eur J for Res 144:909–924. https://doi.org/10.1007/s10342-025-01760-x

Conte E, Lombardi F, Battipaglia G et al (2018) Growth dynamics, climate sensitivity and water use efficiency in pure vs. mixed pine and beech stands in Trentino (Italy). For Ecol Manag 409:707–718. https://doi.org/10.1016/j.foreco.2017.12.011

Cook-Patton SC, Leavitt SM, Gibbs D et al (2020) Mapping carbon accumulation potential from global natural forest regrowth. Nature 585:545–550. https://doi.org/10.1038/s41586-020-2686-x

Cooper L, MacFarlane D (2023) Climate-smart forestry: promise and risks for forests, society, and climate. PLoS Clim 2:e0000212. https://doi.org/10.1371/journal.pclm.0000212

Csilléry K, Buchmann N, Fady B (2020) Adaptation to drought is coupled with slow growth, but independent from phenology in marginal silver fir (*Abies alba* Mill.) populations. Evol Appl 13:2357–2376. https://doi.org/10.1111/eva.13029

D'Amato AW, Palik BJ (2021) Building on the last "new" thing: exploring the compatibility of ecological and adaptation silviculture. Can J for Res 51:172–180. https://doi.org/10.1139/cjfr-2020-0306

Daigneault A, Baker JS, Guo J, Lauri P, Favero A, Forsell N, Johnston C, Ohrel SB, Sohngen B (2022) How the future of the global forest sink depends on timber demand, forest management, and carbon policies. Glob Environ Change 76:1–13. https://doi.org/10.1016/j.gloenvcha.2022.102582

Daigneault A, Simons-Legaard E, Weiskittel A (2024) Tradeoffs and synergies of optimized management for maximizing carbon sequestration across complex landscapes and diverse ecosystem services. For Policy Econ 161:103178

Dalmonech D, Marano G, Amthor JS et al (2022) Feasibility of enhancing carbon sequestration and stock capacity in temperate and boreal European forests via changes to management regimes. Agric for Meteorol 327:109203. https://doi.org/10.1016/j.agrformet.2022.109203

Davies-Barnard T, Valdes PJ, Singarayer JS et al (2015) Quantifying the relative importance of land cover change from climate and land use in the representative concentration pathways. Global Biogeochem Cycles 29:842–853. https://doi.org/10.1002/2014GB004949

Davin EL, de Noblet-Ducoudre N (2010) Climatic impact of global-scale deforestation: radiative versus nonradiative processes. J Clim 23:97–112. https://doi.org/10.1175/2009JCLI3102.1

Devaraju N, Bala G, Nemani R (2015) Modelling the influence of land-use changes on biophysical and biochemical interactions at regional and global scales. Plant Cell Environ 38:1931–1946. https://doi.org/10.1111/pce.12488

Diaci J, Rozenbergar D, Fidej G, Nagel TA (2017) Challenges for uneven-aged silviculture in restoration of post-disturbance forests in central Europe: a synthesis. Forests 8:378. https://doi.org/10.3390/f8100378

Domke GM, Oswalt SN, Walters BF, Morin RS (2020) Tree planting has the potential to increase carbon sequestration capacity of forests in the United States. Proc Natl Acad Sci U S A 117:24649–24651. https://doi.org/10.1073/pnas.2010840117

Don A, Seidel F, Leifeld J, Kätterer T, Martin M, Pellerin S, Emde D, Seitz D, Chenu C (2024) Carbon sequestration in soils and climate change mitigation—definitions and pitfalls. Glob Chang Biol 30:e16983. https://doi.org/10.1111/gcb.16983

Donoso P, Promis A (2013) Silvicultura en bosques nativos: avances en la investigación en Chile, Argentina y Nueva Zelandia. Marisa Cuneo Ediciones

*Dore S, Kolb TE, Montes-Helu M et al (2010) Carbon and water fluxes from ponderosa pine forests disturbed by wildfire and thinning. Ecol Appl 20:663–683. https://doi.org/10.1890/09-0934.1

Dye AW, Houtman RM, Gao P et al (2024) Carbon, climate, and natural disturbance: a review of mechanisms, challenges, and tools for understanding forest carbon stability in an uncertain future. Carbon Balance Manag 19:35. https://doi.org/10.1186/s13021-024-00282-0

*Dymond CC, Neilson ET, Stinson G et al (2010) Future spruce budworm outbreak may create a carbon source in Eastern Canadian forests. Ecosystems 13:917–931. https://doi.org/10.1007/s10021-010-9364-z

Ellison D, Pokorný J, Wild M (2024) Even cooler insights: on the power of forests to (water the Earth and) cool the planet. Glob Chang Biol 30:e17195

Erb KH, Kastner T, Plutzar C et al (2018) Unexpectedly large impact of forest management and grazing on global vegetation biomass. Nature 553:73–76. https://doi.org/10.1038/nature25138

*Eyvindson K, Repo A, Mönkkönen M (2018) Mitigating forest biodiversity and ecosystem service losses in the era of bio-based economy. For Pol Econ 92:119–127. https://doi.org/10.1016/j.forpol.2018.04.009

Ezquerro M, Pardos M, Diaz-Balteiro L (2024) The inclusion of improved forest management in strategic forest planning and its impact on timber harvests, carbon and biodiversity conservation. Sci Total Environ 949:174813. https://doi.org/10.1016/j.scitotenv.2024.174813

*Fang L, Zhongkui J, Lvyi M (2013) The effects of thinning on carbon stocks and fluxes in a Chinese arborvitae plantation. For Chron 89:199–204. https://doi.org/10.5558/tfc2013-038

*Fanin N, Augusto L, Altinalmazis-Kondylis A et al (2025) Soil secrets and tree tales: an in-depth comparison of carbon storage in mixed and pure stands of pine and birch. For Ecol Manag 592:122827. https://doi.org/10.1016/j.foreco.2025.122827

FAO (2010) Global forest resources assessment 2010: main report. Food and Agriculture Organization of the United Nations. 925106654X, 9789251066546

FAO (2024) Restoring the Mediterranean region: status and challenges. Unasylva No. 255—Vol. 75 2024/1. Rome. https://doi.org/10.4060/cd1720en

Fargione J, Haase DL, Burney OT et al (2021) Challenges to the reforestation pipeline in the United States. Front for Glob Chang 4:629198. https://doi.org/10.3389/ffgc.2021.629198

Ferreira PG (2018) The Paris agreement on climate change: analysis and commentary. In: Klein D, Carazo MP, Doelle M, et al. (ed) Canadian Yearbook of international Law/Annuaire canadien de droit international. Oxford University Press, Oxford, 2017. pp 447 + xxxii. https://doi.org/10.1017/cyl.2018.14

Field JP, Breshears DD, Bradford JB et al (2020) Forest management under megadrought: urgent needs at finer scale and higher intensity. Front for Glob Chang 3:502669. https://doi.org/10.3389/ffgc.2020.502669

Fierravanti A, Cocozza C, Palombo C et al (2015) Environmental-mediated relationships between tree growth of black spruce and abundance of spruce budworm along a latitudinal transect in Quebec, Canada. Agric for Meteorol 213:53–63. https://doi.org/10.1016/j.agrformet.2015.06.014

Finzi AC, Norby RJ, Calfapietra C, Gallet-Budynek A, Gielen B et al (2007) Increases in nitrogen uptake rather than nitrogen-use efficiency support higher rates of temperate forest productivity under elevated $CO_2$. Proc Natl Acad Sci U S A 104:14014–14019. https://doi.org/10.1073/pnas.0706518104

Forster EJ, Healey JR, Dymond C, Styles D (2021) Commercial afforestation can deliver effective climate change mitigation under multiple decarbonisation pathways. Nat Commun 12:3831. https://doi.org/10.1038/s41467-021-24084-x

Franklin JF, Mitchell RJ, Palik BJ (2007) Natural disturbance and stand development principles for ecological forestry. United States Department of Agriculture, Forest Service, Northern Research Station, General Technical Report NRS-19. https://doi.org/10.2737/NRS-GTR-19

Friedlingstein P, O'sullivan M, Jones MW, Andrew RM, Gregor L, Hauck J et al (2022) Global carbon budget 2022. Earth Syst Sci Data 14:4811–4900

Friedlingstein P, O'Sullivan M, Jones MW, Andrew RM, Bakker DCE, Hauck J et al (2023) Global carbon budget 2023. Earth Syst Sci Data 15:5301–5369

Friedlingstein P, O'Sullivan M, Jones MW, Andrew RM, Hauck J, Landschützer P et al (2025) Global carbon budget 2024. Earth Syst Sci Data 17:965–1039

Gámez-Virués S, Perović DJ, Gossner MM et al (2015) Landscape simplification filters species traits and drives biotic homogenization. Nat Commun 6:8568. https://doi.org/10.1038/ncomms9568

Garrett L, Lévite H, Besacier C, Alekseeva N, Duchelle M (2022) The key role of forest and landscape restoration in climate action. FAO, Rome. https://doi.org/10.4060/cc2510en

Garrett R, Ferreira J, Abramovay R, et al (2024) Transformative changes are needed to support socio-bioeconomies for people and ecosystems in the Amazon. Nat Ecol Evol 8:1815-1825. https://doi.org/10.1038/s41559-024-02467-9

*Giasson LA, Thiffault E, Lebel L et al (2023) Carbon balance of forest management and wood production in the boreal forest of

Quebec (Canada). Front for Glob Chang. https://doi.org/10.3389/ffgc.2023.1242218

Gough CM, Atkins JW, Fahey RT, Hardiman BS (2019) High rates of primary production in structurally complex forests. Ecology 100:e02864. https://doi.org/10.1002/ecy.2864

Graf A, Wohlfahrt G, Aranda-Barranco S et al (2023) Joint optimization of land carbon uptake and albedo can help achieve moderate instantaneous and long-term cooling effects. Commun Earth Environ 4:298. https://doi.org/10.1038/s43247-023-00958-4

Grassi G, House J, Dentener F, Federici S, den Elzen M, Penman J (2017) The key role of forests in meeting climate targets requires science for credible mitigation. Nat Clim Change 7:220–226. https://doi.org/10.1038/nclimate3227

Grassi G, Camia A, Fiorese G et al (2018) Wrong premises mislead the conclusions by Kallio et al. on forest reference levels in the EU. For Pol Econ 95:10–12

Grassi G, Fiorese G, Pilli R et al (2021) Brief on the role of the forest-based bioeconomy in mitigating climate change through carbon storage and material substitution. In: Sanchez Lopez J, Jasinevičius G, Avraamides M (eds) JRC Publications Repository, European Commission, JRC124374. https://publications.jrc.ec.europa.eu/repository/handle/JRC124374

Grassi G, Conchedda G, Federici S et al (2022) Carbon fluxes from land 2000–2020: bringing clarity to countries' reporting. Earth Syst Sci Data 14:4643–4666. https://doi.org/10.5194/essd-14-4643-2022

Gregor K, Knoke T, Krause A, Reyer CPO, Lindeskog M, Papastefanou P et al (2022) Trade-offs for climate-smart forestry in Europe under uncertain future climate. Earths Future 10:e2022EF002796. https://doi.org/10.1029/2022EF002796

*Griess VC, Man CD, Leclerc ME et al (2019) Carbon stocks and timber harvest. Alternative policy approaches for the Great Bear rainforest and their consequences. For Policy Econ 103:147–156. https://doi.org/10.1016/j.forpol.2017.06.001

Griscom BW, Adams J, Ellis PW et al (2017) Natural climate solutions. Proc Natl Acad Sci U S A 114:11645–11650. https://doi.org/10.1073/pnas.1710465114

Griscom Knutzen F, Averbeck P, Barrasso C, Bouwer LM, Gardiner B, Grünzweig JM, Hänel S, Haustein K, Johannessen MR, Kollet S, Müller MM, Pietikäinen J-P, Pietras-Couffignal K, Pinto JG, Rechid D, Rousi E, Russo A, Suarez-Gutierrez L, Veit S, Wendler J, Xoplaki E, Gliksman D (2025) Impacts on and damage to European forests from the 2018–2022 heat and drought events. Nat Hazards Earth Syst Sci 25:77–117. https://doi.org/10.5194/nhess-25-77-2025

Grossiord C, Granier A, Ratcliffe S et al (2014) Tree diversity does not always improve resistance of forest ecosystems to drought. Proc Natl Acad Sci USA 111:14812–14815. https://doi.org/10.1073/pnas.1411970111

*Gunn JS, Ducey MJ, Whitman AA (2014) Late-successional and old-growth forest carbon temporal dynamics in the Northern Forest (Northeastern USA). For Ecol Manag 312:40–46. https://doi.org/10.1016/j.foreco.2013.10.023

Haddaway NR, Page MJ, Pritchard CC, McGuinness LA (2022) PRISMA2020: an R package and Shiny app for producing PRISMA 2020-compliant flow diagrams, with interactivity for optimised digital transparency and open synthesis. Campbell Syst Rev 18:e1230. https://doi.org/10.1002/cl2.1230

Halofsky JE, Andrews-Key SA, Edwards JE et al (2018) Adapting forest management to climate change: the state of science and applications in Canada and the United States. For Ecol Manag 421:84–97. https://doi.org/10.1016/j.foreco.2018.02.037

Hanbury-Brown AR, Ward RE, Kueppers LM (2022) Forest regeneration within Earth system models: current process representations and ways forward. New Phytol 235:20–40. https://doi.org/10.1111/nph.18131

Hanewinkel M, Cullmann DA, Schelhaas MJ et al (2013) Climate change may cause severe loss in the economic value of European forest land. Nat Clim Chang 3:203–207. https://doi.org/10.1038/nclimate1687

*Harris SH, Betts MG (2023) Selecting among land sparing, sharing and Triad in a temperate rainforest depends on biodiversity and timber production targets. J Appl Ecol 60:737–750. https://doi.org/10.1111/1365-2664.14385

Harris NL, Gibbs DA, Baccini A et al (2021) Global maps of twenty-first century forest carbon fluxes. Nat Clim Chang 11:234–240. https://doi.org/10.1038/s41558-020-00976-6

Hart EE, Haigh A, Ciuti S (2023) A scoping review of the scientific evidence base for rewilding in Europe. Biol Cons 285:110243. https://doi.org/10.1016/j.biocon.2023.110243

Hartmann H, Bastos A, Das AJ et al (2022) Annual review of plant biology climate change risks to global forest health: emergence of unexpected events of elevated tree mortality worldwide. https://doi.org/10.1146/annurev-arplant-102820

Haya BK, Evans S, Brown L, Bukoski J, Butsic V, Cabiyo B, Jacobson R, Kerr A, Potts M, Sanchez DL (2023) Comprehensive review of carbon quantification by improved forest management offset protocols. Front for Glob Chang 6:958879. https://doi.org/10.3389/ffgc.2023.958879

*He Z, Chen L, Du J et al (2018) Responses of soil organic carbon, soil respiration, and associated soil properties to long-term thinning in a semiarid spruce plantation in northwestern China. Land Degrad Dev 29:4387–4396. https://doi.org/10.1002/ldr.3196

Herbst M, Mund M, Tamrakar R, Knohl A (2015) Differences in carbon uptake and water use between a managed and an unmanaged beech forest in central Germany. For Ecol Manag 355:101–108. https://doi.org/10.1016/j.foreco.2015.05.034

Hilmers T, Friess N, Bässler C et al (2018) Biodiversity along temperate forest succession. J Appl Ecol 55:2756–2766. https://doi.org/10.1111/1365-2664.13238

Hilmers T, Avdagi A, Bartkowicz L et al (2020) The productivity of mixed mountain forests comprised of *Fagus sylvatica*, *Picea abies*, and *Abies alba* across Europe. Forestry 92:512–522. https://doi.org/10.1093/forestry/cpz035

Himes A, Betts M, Messier C, Seymour R (2022) Perspectives: thirty years of triad forestry, a critical clarification of theory and recommendations for implementation and testing. For Ecol Manag 510:120103. https://doi.org/10.1016/j.foreco.2022.120103

Hisano M, Chen HYH, Searle EB, Reich PB (2019) Species-rich boreal forests grew more and suffered less mortality than species-poor forests under the environmental change of the past half-century. Ecol Lett 22:999–1008

Hisano M, Ghazoul J, Chen X et al (2024) Functional diversity enhances dryland forest productivity under long-term climate change. Sci Adv 10:eadn4152. https://doi.org/10.1126/sciadv.adn4152

Hoegh-Guldberg O, Jacob D, Taylor M et al (2019) The human imperative of stabilizing global climate change at 1.5°C. Science 365:eaaw6974. https://doi.org/10.1126/science.aaw6974

Hoek van Dijke AJ, Herold M, Mallick K, Benedict I, Machwitz M, Schlerf M, Pranindita A, Theeuwen JJE, Bastin J-F, Teuling AJ (2022) Shifts in regional water availability due to global tree restoration. Nat Geosci 15:363–368. https://doi.org/10.1038/s41561-022-00935-0

Hordijk I, Maynard DS, Hart SP et al (2023) Evenness mediates the global relationship between forest productivity and richness. J Ecol 111:1308–1326. https://doi.org/10.1111/1365-2745.14098

*Hotta W, Haga C, Morimoto J et al (2023) Leaving disturbance legacies conserves boreal conifers and maximizes net $CO_2$ absorption under climate change and more frequent and larger windthrow regimes. Landsc Ecol 38:1785–1805. https://doi.org/10.1007/s10980-023-01680-4

Hurteau MD, Liang S, Martin KL et al (2016) Restoring forest structure and process stabilizes forest carbon in wildfire-prone southwestern ponderosa pine forests. Ecol Appl 26:382–391. https://doi.org/10.1890/15-0337

IPCC (2022) Annex II: Glossary [Möller, V., R. van Diemen, J.B.R. Matthews, C. Méndez, S. Semenov, J.S. Fuglestvedt, A. Reisinger (eds.)]. In: Climate change 2022: impacts, adaptation and vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp 2897–2930. https://doi.org/10.1017/9781009325844.029.

*Islam MdR, Jönsson AM, Bergkvist J et al (2024) Projected effects of climate change and forest management on carbon fluxes and biomass of a boreal forest. Agric for Meteorol 349:109959. https://doi.org/10.1016/j.agrformet.2024.109959

Jacobsen MK (2001) History and principles of close to nature forest management: a Central European perspective. Tools for preserving woodland biodiversity. NACONEX 2001. https://biescaingenieria.com/media/17779/history-and-principles-of-close-to-forestry.pdf

Jactel H, Gritti ES, Drössler L et al (2018) Positive biodiversity–productivity relationships in forests: climate matters. Biol Lett 14:20170747. https://doi.org/10.1098/rsbl.2017.0747

Jandl R, Vesterdal L, Olsson M, Bens O, Badeck F, Rock J (2007) Carbon sequestration and forest management. CAB Reviews: Perspectives in Agriculture, Veterinary Science, Nutrition and Natural Resources 2(017). https://doi.org/10.1079/PAVSNNR20072017

Johnstone JF, Allen CD, Franklin JF et al (2016) Changing disturbance regimes, ecological memory, and forest resilience. Front Ecol Environ 14:369–378

*Jörgensen K, Granath G, Lindahl BD et al (2021) Forest management to increase carbon sequestration in boreal *Pinus sylvestris* forests. Plant Soil 466:165–178. https://doi.org/10.1007/s11104-021-05038-0

Jung M, Reichstein M, Ciais P et al (2010) Recent decline in the global land evapotranspiration trend due to limited moisture supply. Nature 467:951–954. https://doi.org/10.1038/nature09396

*Jurevics A, Peichl M, Olsson BA et al (2016) Slash and stump harvest have no general impact on soil and tree biomass C pools after 32–39years. For Ecol Manag 371:33–41. https://doi.org/10.1016/j.foreco.2016.01.008

Kashian DM, Romme WH, Tinker DB et al (2006) Carbon storage on landscapes with stand-replacing fires. Bioscience 56:598–606. https://doi.org/10.1641/0006-3568(2006)56[598:CSOLWS]2.0.CO;2

Keeton WS, Kraft CE, Warren DR (2007) Mature and old-growth riparian forests: structure, dynamics, and effects on Adirondack stream habitats. Ecol Appl 17:852–868. https://doi.org/10.1890/06-1172

Kindermann G, Obersteiner M, Sohngen B et al (2008) Global cost estimates of reducing carbon emissions through avoided deforestation. Proc Natl Acad Sci USA 105:10302–10307. https://doi.org/10.1073/pnas.071061610

Knoke T, Paul C, Rammig A, Gosling E, Hildebrandt P, Härtl F et al (2020) Accounting for multiple ecosystem services in a simulation of land-use decisions: Does it reduce tropical deforestation? Glob Chang Biol 26:2403–2420. https://doi.org/10.1111/gcb.15003

*Krause A, Knoke T, Rammig A (2020) A regional assessment of land-based carbon mitigation potentials: bioenergy, BECCS, reforestation, and forest management. GCB Bioenergy 12:346–360. https://doi.org/10.1111/gcbb.12675

*Labadie G, Cadieux P, Moreau L et al (2024) Are forest management practices to improve carbon balance compatible with maintaining bird diversity under climate change? A case study in Eastern North America. PLoS Clim 3:e0000293. https://doi.org/10.1371/journal.pclm.0000293

Lacroix EM, Petrenko CL, Friedland AJ (2016) Evidence for losses from strongly bound SOM pools after clear cutting in a Northern hardwood forest. Soil Sci 181:202–207. https://doi.org/10.1097/SS.0000000000000147

*Laganière J, Cavard X, Brassard BW et al (2015) The influence of boreal tree species mixtures on ecosystem carbon storage and fluxes. For Ecol Manag 354:119–129. https://doi.org/10.1016/j.foreco.2015.06.029

*Lagergren F, Jönsson AM (2017) Ecosystem model analysis of multi-use forestry in a changing climate. Ecosyst Serv 26:209–224. https://doi.org/10.1016/j.ecoser.2017.06.007

Langridge J, Delabye S, Gilg O et al (2023) Biodiversity responses to forest management abandonment in boreal and temperate forest ecosystems: a meta-analysis reveals an interactive effect of time since abandonment and climate. Biol Conserv 287:110296. https://doi.org/10.1016/j.biocon.2023.110296

Larsen JB, Angelstam Per, Bauhus J, et al (2022) Closer-to-nature forest management. From Science to Policy 12. European Forest Institute. https://doi.org/10.36333/fs12

*Larsson M, Dahl J, Lundmark T et al (2025) Conversion of unmanaged boreal forest to even-aged management has a stronger effect on carbon stocks in the organic layer than the mineral soil. For Ecol Manag 578:122458. https://doi.org/10.1016/j.foreco.2024.122458

*Law BE, Hudiburg TW, Berner LT et al (2018) Land use strategies to mitigate climate change in carbon dense temperate forests. Proc Natl Acad Sci U S A 115:3663–3668

Lecoq L, Ernoult A, Mony C (2021) Past landscape structure drives the functional assemblages of plants and birds. Sci Rep 11:3443. https://doi.org/10.1038/s41598-021-82851-8

Lewis SL, Sonké B, Sunderland T et al (2013) Above-ground biomass and structure of 260 African tropical forests. Philos Trans R Soc B Biol Sci 368:20120295. https://doi.org/10.1098/rstb.2012.0295

Lewis SL, Wheeler CE, Mitchard ETA et al (2019) Regenerate natural forests to store carbon. Nature 568. https://www.nature.com/articles/d41586-019-01026-8

Liang J, Crowther TW, Picard N et al (2016) Positive biodiversity-productivity relationship predominant in global forests. Science 354:3443. https://doi.org/10.1126/science.aaf8957

Lindner M, Fitzgerald JB, Zimmermann NE, Reyer C, Delzon S, van der Maaten E et al (2014) Climate change and European forests: what do we know, what are the uncertainties, and what are the implications for forest management? J Environ Manag 146:69–83. https://doi.org/10.1016/j.jenvman.2014.07.030

Littlefield CE, D'Amato AW (2022) Identifying trade-offs and opportunities for forest carbon and wildlife using a climate change adaptation lens. Conserv Sci Pract 4:e12631. https://doi.org/10.1111/csp2.12631

*Liu K, Liang Y, He H et al (2018a) Long-term impacts of China's new commercial harvest exclusion policy on ecosystem services and biodiversity in the temperate forests of Northeast China. Sustainability 10:1071. https://doi.org/10.3390/su10041071

Liu X, Trogisch S, He JS et al (2018b) Tree species richness increases ecosystem carbon storage in subtropical forests. Proc Biol Sci 285:20181240. https://doi.org/10.1098/rspb.2018.1240

Liu S, Brienen RJW, Fan C, Hao M, Zhao X, Zhang C (2025a) Tree lifespans in a warming world: unravelling the universal trade-off between growth and lifespan in temperate forests. Glob Chang Biol 31:e70023. https://doi.org/10.1111/gcb.70023

*Liu W, Ashton MS, Ducey MJ et al (2025b) Sustainable forest management for carbon, wood and biodiversity must consider natural disturbance regimes. Environ Res Lett 20:064020. https://doi.org/10.1088/1748-9326/add54d

*Lutz DA, Burakowski EA, Murphy MB et al (2016) Trade-offs between three forest ecosystem services across the state of New Hampshire, USA: timber, carbon, and albedo. Ecol Appl 26:146–161. https://doi.org/10.1890/14-2207

Lutz JA, Furniss TJ, Johnson DJ et al (2018) Global importance of large-diameter trees. Glob Ecol Biogeogr 27:849–864. https://doi.org/10.1111/geb.12747

Luyssaert S, Detlef Schulze E, Borner A et al (2008) Old-growth forests as global carbon sinks. Nat Lett 455:213–215. https://doi.org/10.1038/nature07276

Luyssaert S, Marie G, Valade A et al (2018) Trade-offs in using European forests to meet climate objectives. Nature 562:259–262. https://doi.org/10.1038/s41586-018-0577-1

*Ma Z, Chen S, Shahi C et al (2022) Trade-offs between economic gains and carbon stocks across a range of management alternatives in boreal forests. Forests 13:1777. https://doi.org/10.3390/f13111777

Mäkelä A, Minunno F, Kujala H et al (2023) Effect of forest management choices on carbon sequestration and biodiversity at national scale. Ambio 52:1737–1756. https://doi.org/10.1007/s13280-023-01899-0

*Måren IE, Sharma LN (2021) Seeing the wood for the trees: carbon storage and conservation in temperate forests of the Himalayas. For Ecol Manag 487:119010. https://doi.org/10.1016/j.foreco.2021.119010

Marshall AR, Waite CE, Pfeifer M et al (2023) Fifteen essential science advances needed for effective restoration of the world's forest landscapes. Phil Trans R Soc b: Biol Sci 378:20210065. https://doi.org/10.1098/rstb.2021.0065

Mason B, Kerr G, Pommerening A et al (2003) Continuous cover forestry in British conifer forests. Forest Research Annual Report and Accounts 2003–2004

*Matsuzaki E, Sanborn P, Fredeen AL et al (2013) Carbon stocks in managed and unmanaged old-growth western redcedar and western hemlock stands of Canada's inland temperate rainforests. For Ecol Manag 297:108–119. https://doi.org/10.1016/j.foreco.2012.11.042

*Mazziotta A, Lundström J, Forsell N et al (2022) More future synergies and less trade-offs between forest ecosystem services with natural climate solutions instead of bioeconomy solutions. Glob Change Biol 28:6333–6348. https://doi.org/10.1111/gcb.16364

McDowell NG, Allen CD, Anderson-Teixeira K et al (2020) Pervasive shifts in forest dynamics in a changing world. Science 368:eaaz9463. https://doi.org/10.1126/science.aaz9463

McMahon SM, Parker GG, Miller DR (2010) Evidence for a recent increase in forest growth. Proc Natl Acad Sci U S A 107:3611–3615. https://doi.org/10.1073/pnas.0912376107

*Ménard I, Thiffault E, Boulanger Y et al (2022) Multi-model approach to integrate climate change impact on carbon sequestration potential of afforestation scenarios in Quebec, Canada. Ecol Model 473:110144. https://doi.org/10.1016/j.ecolmodel.2022.110144

Messier C, Bauhus J, Doyon F et al (2019) The functional complex network approach to foster forest resilience to global changes. For Ecosyst 6:21. https://doi.org/10.1186/s40663-019-0166-2

Mikoláš M, Svitok M, Bače R et al (2021) Natural disturbance impacts on trade-offs and co-benefits of forest biodiversity and carbon. Proc R Soc B Biol Sci 288:20211631. https://doi.org/10.1098/rspb.2021.1631

Millar CI, Stephenson NL, Stephens SL (2007) Climate change and forests of the future: managing in the face of uncertainty. Ecol Appl 17:2145–2151. https://doi.org/10.1890/06-1715.1

Moomaw WR, Masino SA, Faison EK (2019) Intact forests in the United States: proforestation mitigates climate change and serves the greatest good. Front for Glob Chang 2:27. https://doi.org/10.3389/ffgc.2019.00027

*Moreau L, Thiffault E, Cyr D et al (2022) How can the forest sector mitigate climate change in a changing climate? Case studies of boreal and northern temperate forests in eastern Canada. For Ecosyst 9:100026. https://doi.org/10.1016/j.fecs.2022.100026

Motta R, Berretti R, Castagneri D et al (2011) Toward a definition of the range of variability of central European mixed–forests: the nearly steady-state forest of Lom (Bosnia and Herzegovina). Can J for Res 41:1871–1884. https://doi.org/10.1139/x11-098

Munn Z, Peters MDJ, Stern C et al (2018) Systematic review or scoping review? Guidance for authors when choosing between a systematic or scoping review approach. BMC Med Res Methodol 18:143. https://doi.org/10.1186/s12874-018-0611-x

Munn Z, Pollock D, Khalil H et al (2022) What are scoping reviews? Providing a formal definition of scoping reviews as a type of evidence synthesis. JBI Evid Synth 20:950–952

Muys B, Angelstam P, Bauhus J et al (2022) Forest biodiversity in Europe. From Science to Policy 13. European Forest Institute. https://doi.org/10.36333/fs13

Mykleby PM, Snyder PK, Twine TE (2017) Quantifying the trade-off between carbon sequestration and albedo in midlatitude and high-latitude North American forests. Geophys Res Lett 44:2493–2501. https://doi.org/10.1002/2016GL071459

*Nabhani A, Mardaneh E, Sjølie HK (2024) Multi-objective optimization of forest ecosystem services under uncertainty. Ecol Model 494:110777. https://doi.org/10.1016/j.ecolmodel.2024.110777

Nabuurs GJ, Lindner M, Verkerk PJ et al (2013) First signs of carbon sink saturation in European forest biomass. Nat Clim Chang 3:792–796. https://doi.org/10.1038/nclimate1853

Nabuurs GJ, Delacote P, Ellison D et al (2017) By 2050 the mitigation effects of EU forests could nearly double through climate-smart forestry. Forests 8:484. https://doi.org/10.3390/f8120484

Nabuurs GJ, Verkerk PJ, Schelhaas MJ, González Olabarria JR, Trasobares A, Cienciala E (2018) Climate-smart forestry: mitigation impacts in three European regions. In: Climate-Smart Forestry: Mitigation Impacts in Three European Regions. From Science to Policy 6, European Forest Institute)

Nabuurs GJ, Verweij P, Van Eupen M et al (2019) Next-generation information to support a sustainable course for European forests. Nat Sustain 2:815–818. https://doi.org/10.1038/s41893-019-0374-3

Nagel TA, Firm D, Pisek R et al (2017) Evaluating the influence of integrative forest management on old-growth habitat structures in a temperate forest region. Biol Cons 216:101–107. https://doi.org/10.1016/j.biocon.2017.10.008

Nagel R, Meyer P, Blaschke M, Feldmann E (2023) Strict forest protection: a meaningful contribution to climate-smart forestry? An evaluation of temporal trends in the carbon balance of unmanaged forests in Germany. Front for Glob Change 6:1099558. https://doi.org/10.3389/ffgc.2023.1099558

Naudts K, Chen Y, McGrath MJ et al (2016) Europe's forest management did not mitigate climate warming. Science 351:597–600. https://doi.org/10.1126/science.aad7270

Nave LE, Vance ED, Swanston CW, Curtis PS (2010) Harvest impacts on soil carbon storage in temperate forests. For Ecol Manag 259:857–866

Norby RJ, Warren JM, Iversen CM, Medlyn BE, McMurtrie RE (2010) CO2 enhancement of forest productivity constrained by limited nitrogen availability, Proc Natl Acad Sci USA 107:19368-19373. https://doi.org/10.1073/pnas.1006463107

Nunery JS, Keeton WS (2010) Forest carbon storage in the northeastern United States: net effects of harvesting frequency, post-harvest retention, and wood products. For Ecol Manag 259:1363–1375. https://doi.org/10.1016/j.foreco.2009.12.029

Osborne P, Aquilué N, Mina M et al (2023) A trait-based approach to both forestry and timber building can synchronize forest harvest and resilience. PNAS Nexus 2:254. https://doi.org/10.1093/pnasnexus/pgad254

*Osei R, del Río M, Ruiz-Peinado R et al (2022) The distribution of carbon stocks between tree woody biomass and soil differs between Scots pine and broadleaved species (beech, oak) in European forests. Eur J for Res 141:467–480. https://doi.org/10.1007/s10342-022-01453-9

*Ostrogović Sever MZ, Alberti G, Delle Vedove G et al (2019) Temporal evolution of carbon stocks, fluxes and carbon balance in pedunculate oak chronosequence under close-to-nature forest management. Forests 10:814. https://doi.org/10.3390/f10090814

Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD et al (2021) The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ. https://doi.org/10.1136/bmj.n71

Paillet Y, Bergès L, Hjältén J, Ódor P, Avon C, Bernhardt-Römermann M et al (2010) Biodiversity differences between managed and unmanaged forests: meta-analysis of species richness in Europe. Cons Biol 24:101–112. https://doi.org/10.1111/j.1523-1739.2009.01399.x

Pan Y, Birdsey A, Fang J et al (2011) A large and persistent carbon sink in the world’s forests. Science 33:988–993. https://doi.org/10.1126/science.1201609

Pan Y, Birdsey RA, Phillips OL et al (2024) The enduring world forest carbon sink. Nature 631:563–569. https://doi.org/10.1038/s41586-024-07602-x

*Pang X, Nordström EM, Böttcher H et al (2017) Trade-offs and synergies among ecosystem services under different forest management scenarios—the LEcA tool. Ecosyst Serv 28:67–79. https://doi.org/10.1016/j.ecoser.2017.10.006

Papa CC, DeLyser K, Clay K, Gadoth-Goodman D, Cooper L, Kurz WA, Magnan M, Ontl T (2023) Modeling climate-smart forest management and wood use forclimate mitigation potential in Maryland and Pennsylvania. Front for Glob Chang 6:1259010. https://doi.org/10.3389/ffgc.2023.1259010bette

Patacca M, Lindner M, Lucas-Borja ME et al (2023) Significant increase in natural disturbance impacts on European forests since 1950. Glob Chang Biol 29:1359–1376. https://doi.org/10.1111/gcb.16531

Peñuelas J, Hunt JM, Ogaya R et al (2008) Twentieth century changes of tree-ring $\delta^{13}$C at the southern range-edge of *Fagus sylvatica*: increasing water-use efficiency does not avoid the growth decline induced by warming at low altitudes. Glob Chang Biol 14:1076–1088. https://doi.org/10.1111/j.1365-2486.2008.01563.x

*Pérez-Cruzado C, Mohren GMJ, Merino A et al (2012) Carbon balance for different management practices for fast growing tree species planted on former pastureland in southern Europe: a case study using the CO2Fix model. Eur J for Res 131:1695–1716. https://doi.org/10.1007/s10342-012-0609-6

Peters MDJ, Marnie C, Tricco AC et al (2020) Updated methodological guidance for the conduct of scoping reviews. JBI Evid Synth 18:2119–2126. https://doi.org/10.11124/JBIES-20-00167

Peters MDJ, Godfrey CM, Khalil H, McInerney P, Parker D, Soares CB (2015) Guidance for conducting systematic scoping reviews. Int J Evid Based Healthc 13(3):141–146. https://doi.org/10.1097/XEB.0000000000000050

Peters MDJ, Godfrey CM, McInerney P et al (2022) Best practice guidance and reporting items for the development of scoping review protocols. JBI Evid Synth 20:953–968. https://doi.org/10.11124/JBIES-21-00242

*Petersson H, Ellison D, Appiah Mensah A et al (2022) On the role of forests and the forest sector for climate change mitigation in Sweden. GCB Bioenergy 14:793–813. https://doi.org/10.1111/gcbb.12943

Petrescu AMR, McGrath MJ, Andrew RM et al (2021) The consolidated European synthesis of $CO_2$ emissions and removals for the European Union and United Kingdom: 1990–2018. Earth Syst Sci Data 13:2363–2406

Pettorelli N, Durant SM, du Toit JT (2019) Rewilding: a captivating, controversial, twenty-first-century concept to address ecological degradation in a changing world. In: Rewilding. Cambridge University Press, pp 1–11

Piazza N, Malanchini L, Nevola E, Vacchiano G (2024) Where to start with climate-smart forest management? Climatic risk for forest-based mitigation. Nat Hazards Earth Syst Sci 24:3579–3595. https://doi.org/10.5194/nhess-24-3579-2024

*Pikkarainen P, Strandman H, Vento E et al (2024) Effects of forest conservation and management on timber, ecosystem carbon, dead wood and habitat suitability area in a boreal forest under climate change. Silva Fennica. https://doi.org/10.14214/sf.23045

*Pingoud K, Ekholm T, Sievänen R et al (2018) Trade-offs between forest carbon stocks and harvests in a steady state—a multi-criteria analysis. J Environ Manag 210:96–103. https://doi.org/10.1016/j.jenvman.2017.12.076

Piponiot C, Anderson-Teixeira KJ, Davies SJ et al (2022) Distribution of biomass dynamics in relation to tree size in forests across the world. New Phytol 234:1664–1677. https://doi.org/10.1111/nph.17995

*Pohjanmies T, Triviño M, le Tortorec E et al (2017) Conflicting objectives in production forests pose a challenge for forest management. Ecosyst Serv 28:298–310. https://doi.org/10.1016/j.ecoser.2017.06.018

*Poirier V, Coyea MR, Angers DA et al (2016) Silvicultural treatments and subsequent vegetation impact long-term mineral soil biogeochemistry in mixedwood plantations. For Ecol Manag 368:140–150. https://doi.org/10.1016/j.foreco.2016.03.016

Pretzsch H, Biber P, Schütze G et al (2014) Forest stand growth dynamics in Central Europe have accelerated since 1870. Nat Commun 5:4967. https://doi.org/10.1038/ncomms5967

Pretzsch H, Biber P, Uhl E et al (2017) Climate change accelerates growth of urban trees in metropolises worldwide. Sci Rep 7:15403. https://doi.org/10.1038/s41598-017-14831-w

Pretzsch H, Biber P, Schütze G et al (2018) Wood density reduced while wood volume growth accelerated in Central European forests since 1870. For Ecol Manag 429:589–616. https://doi.org/10.1016/j.foreco.2018.07.045

Pretzsch H, Hilmers T (2024) Structural diversity and carbon stock of forest stands: tradeoff as modified by silvicultural thinning. Eur J Forest Res

*Price DT, Halliwell DH, Apps MJ et al (1997) Comprehensive assessment of carbon stocks and fluxes in a Boreal-Cordilleran forest management unit. Can J for Res 27:2005–2016. https://doi.org/10.1139/x97-161

Prober SM, Doerr VAJ, Broadhurst LM et al (2019) Shifting the conservation paradigm: a synthesis of options for renovating nature under climate change. Ecol Monogr 89:e01333. https://doi.org/10.1002/ecm.1333

Puettmann KJ, Wilson SMG, Baker SC et al (2015) Silvicultural alternatives to conventional even-aged forest management - what limits global adoption? For Ecosyst 2:8. https://doi.org/10.1186/s40663-015-0031-x

Pukkala T (2018) Carbon forestry is surprising. Forest Ecosyst 5:11. https://doi.org/10.1186/s40663-018-0131-5

Putz FE, Zuidema PA, Pinard MA et al (2008) Improved tropical forest management for carbon retention. PLoS Biol 6:1368–1369

Qie L, Lewis SL, Sullivan MJP et al (2017) Long-term carbon sink in Borneo’s forests halted by drought and vulnerable to edge effects. Nat Commun 8:1966. https://doi.org/10.1038/s41467-017-01997-0

*Quick SA, Fischer DG, Case MJ (2024) Forest restoration thinning has minimal impacts on surface soil carbon in a second-growth temperate rainforest. Forests 15:1758. https://doi.org/10.3390/f15101758

*Rana P, Juutinen A, Eyvindson K et al (2024) Cost-efficiency analysis of multiple ecosystem services across forest management regimes. J Environ Manag 370:122438. https://doi.org/10.1016/j.jenvman.2024.122438

*Repo A, Albrich K, Jantunen A et al (2024) Contrasting forest management strategies: impacts on biodiversity and ecosystem services under changing climate and disturbance regimes. J Environ Manag 371:123124. https://doi.org/10.1016/j.jenvman.2024.123124

Roebroek CTJ, Duveiller G, Seneviratne SI et al (2023) Releasing global forests from human management: How much more carbon could be stored? Science 380:749–753. https://doi.org/10.1126/science.add5878

Rohatyn S, Yakir D, Rotenberg E et al (2022) Limited climate change mitigation potential through forestation of the vast dryland regions. Science 377:1436–1439. https://doi.org/10.1126/science.abm96

*Rosenvald R, Rosenvald K, Drenkhan R et al (2025) Balancing biodiversity, carbon, and profit with pathogen risk: effects of felling age and thinning in spruce forests. J Environ Manag 389:126066. https://doi.org/10.1016/j.jenvman.2025.126066

Salomón RL, Peters RL, Zweifel R et al (2022) The 2018 European heatwave led to stem dehydration but not to consistent growth reductions in forests. Nat Commun 13:28. https://doi.org/10.1038/s41467-021-27579-9

*Santaniello F, Djupström LB, Ranius T et al (2017) Simulated long-term effects of varying tree retention on wood production, dead wood and carbon stock changes. J Environ Manag 201:37–44. https://doi.org/10.1016/j.jenvman.2017.06.026

Santopuoli G, Temperli C, Alberdi I et al (2021) Pan-European sustainable forest management indicators for assessing climate-smart forestry in Europe. Can J for Res 51:1741–1750. https://doi.org/10.1139/cjfr-2020-0166

*Sasanifar S, Alijanpour A, Shafiei AB et al (2024) Understanding how forest ecosystem services are affected by conservation practices and differences in elevation: a study in the Arasbaran biosphere reserve, Iran. Ecol Eng 203:107230. https://doi.org/10.1016/j.ecoleng.2024.107230

Schall P, Gossner MM, Heinrichs S et al (2018) The impact of even-aged and uneven-aged forest management on regional biodiversity of multiple taxa in European beech forests. J Appl Ecol 55:267–278. https://doi.org/10.1111/1365-2664.12950

Schnabel F, Liu X, Kunz M et al (2021) Species richness stabilizes productivity via asynchrony and drought-tolerance diversity in a large-scale tree biodiversity experiment. Sci Adv 7:eabk1643. https://doi.org/10.1126/sciadv.abk1643

Schulze ED, Bouriaud O, Irslinger R et al (2022) The role of wood harvest from sustainably managed forests in the carbon cycle. Ann for Sci 79:17. https://doi.org/10.1186/s13595-022-01127-x

Schwinning S, Lortie CJ, Esque TC, DeFalco LA (2022) What common-garden experiments tell us about climate responses in plants. J Ecol 110:986–996. https://doi.org/10.1111/1365-2745.13887

Searle EB, Chen HHY, Paquette A (2022) Higher tree diversity is linked to higher tree mortality. Proc Natl Acad Sci U S A 119:e2013171119

Seddon N, Smith A, Smith P, Key I, Chausson A, Girardin C, House J, Srivastava S, Turner B (2021) Getting the message right on nature-based solutions to climate change. Glob Change Biol 27:1518–1546. https://doi.org/10.1111/gcb.15513

Seidl R, Thom D, Kautz M et al (2017) Forest disturbances under climate change. Nat Clim Chang 7:395–402. https://doi.org/10.1038/nclimate3303

Seymour RS, Hunter ML (1992) New forestry in eastern spruce-fir forests: principles and applications to maine. Maine Agricultural Experiment Station Miscellaneous Publication 716. https://digitalcommons.library.umaine.edu/aes_miscpubs/13/

Sha Z, Bai Y, Li R et al (2022) The global carbon sink potential of terrestrial vegetation can be increased substantially by optimal land management. Commun Earth Environ 3:8. https://doi.org/10.1038/s43247-021-00333-1

Sharma P, Goyal N (2023) How to write a scoping review? Int J Adv Med Health Res 10:53–56. https://doi.org/10.4103/ijamr.ijamr_91_23

Silva LCR, Madhur A, Leithead MD (2010) Recent widespread tree growth decline despite increasing atmospheric $CO_2$. PLoS ONE 5:e11543. https://doi.org/10.1371/journal.pone.0011543

Singh N, Singh J, Gupta AK et al (2021) Climate-driven acceleration in forest evapotranspiration fuelling extreme rainfall events in the Himalaya. Environ Res Lett 16:084042

Smith HB, Vaughan NE, Forster J (2022) Long-term national climate strategies bet on forests and soils to reach net-zero. Commun Earth Environ 3:305. https://doi.org/10.1038/s43247-022-00636-x

*Smyth CE, Stinson G, Neilson E et al (2014) Quantifying the biophysical climate change mitigation potential of Canada's forest sector. Biogeosciences 11:3515–3529. https://doi.org/10.5194/bg-11-3515-2014

Soares-Filho B, Moutinho P, Nepstad D et al (2010) Role of Brazilian Amazon protected areas in climate change mitigation. Proc Natl Acad Sci USA 107:10821–10826. https://doi.org/10.1073/pnas.0913048107

Steffen W, Rockström J, Richardson K et al (2018) Trajectories of the Earth system in the Anthropocene. Proc Natl Acad Sci USA 15:8252–8259. https://doi.org/10.1073/pnas.1810141115

Stephenson NL, Das AJ, Condit R et al (2014) Rate of tree carbon accumulation increases continuously with tree size. Nature 507:90–93. https://doi.org/10.1038/nature12914

Sterck F, Vos M, Hannula SE et al (2021) Optimizing stand density for climate-smart forestry: a way forward towards resilient forests with enhanced carbon storage under extreme climate events. Soil Biol Biochem 162:108396. https://doi.org/10.1016/j.soilbio.2021.108396

Taylor SD, Marconi S (2020) Rethinking global carbon storage potential of trees. a comment on Bastin et al. (2019). Ann for Sci 77:23. https://doi.org/10.1007/s13595-020-0922-z

Tognetti R, Lombardi F, Lasserre B et al (2014) Tree-ring stable isotopes reveal twentieth-century increases in water-use efficiency of *Fagus sylvatica* and *Nothofagus* spp. in Italian and Chilean Mountains. PLoS ONE 9:e1131336. https://doi.org/10.1371/journal.pone.0113136

Tognetti R, Smith M, Panzacchi P (2022a) An introduction to climate-smart forestry in mountain regions. In: Tognetti R, Smith M, Panzacchi P (eds) Climate-smart forestry in mountain regions. Springer, Cham. https://doi.org/10.1007/978-3-030-80767-2_1

Tognetti R, Smith M, Panzacchi P (2022b) Climate-smart forestry in mountain regions. Springer, Cham. https://doi.org/10.1007/978-3-030-80767-2

Torresan C, del Río M, Hilmers T et al (2020) Importance of tree species size dominance and heterogeneity on the productivity of spruce-fir-beech mountain forest stands in Europe. For Ecol Manag 457:117716. https://doi.org/10.1016/j.foreco.2019.117716

Torresan C, Garzón MB, O'grady M et al (2021) A new generation of sensors and monitoring tools to support climate-smart forestry practices. Can J for Res 51:1751–1765. https://doi.org/10.1139/cjfr-2020-0295

Torresan C, Hilmers T, Avdagić A et al (2024) Changes in tree-ring wood density of European beech (*Fagus sylvatica* L.), silver fir (*Abies alba* Mill.), and Norway spruce (*Picea abies* (L.) H.

Karst.) in European mountain forests between 1901 and 2016. Ann for Sci 81:49. https://doi.org/10.1186/s13595-024-01264-5

Tricco AC, Lillie E, Zarin W et al (2016) A scoping review on the conduct and reporting of scoping reviews. BMC Med Res Methodol 16:15. https://doi.org/10.1186/s12874-016-0116-4

*Triviño M, Juutinen A, Mazziotta A et al (2015) Managing a boreal forest landscape for providing timber, storing and sequestering carbon. Ecosyst Serv 14:179–189. https://doi.org/10.1016/j.ecoser.2015.02.003

*Triviño M, Pohjanmies T, Mazziotta A et al (2017) Optimizing management to enhance multifunctionality in a boreal forest landscape. J Appl Ecol 54:61–70. https://doi.org/10.1111/1365-2664.12790

Ummenhofer CC, Meehl GA (2017) Extreme weather and climate events with ecological relevance: a review. Philos Trans R Soc Lond B Biol Sci 372:20160135. https://doi.org/10.1098/rstb.2016.0135

Veldman JW, Overbeck GE, Negreiros D et al (2015) Where tree planting and forest expansion are bad for biodiversity and ecosystem services. Bioscience 65:1011–1018

Veldman JW, Aleman JC, Alvarado ST et al (2019) Comment on "The global tree restoration potential." Science 366:eaay7976. https://doi.org/10.1126/science.aay79

Verkerk PJ, Costanza R, Hetemäki L, Kubiszewski I, Leskinen P, Nabuurs GJ, Potočnik J, Palahí M (2020) Climate-smart forestry: the missing link. For Policy Econ 115:102164. https://doi.org/10.1016/j.forpol.2020.102164

Verkerk PJ, Delacote P, Hurmekoski E, Kunttu J, Matthews R, Mäkipää R, Mosley F, Perugini L, Reyer CPO, Roe S, Trømborg E (2022) Forest-based climate change mitigation and adaptation in Europe. From Science to Policy 14. European Forest Institute. https://doi.org/10.36333/fs14

Veroniki AA, Hutton B, Stevens A, McKenzie JE, Page MJ et al (2025) Update to the PRISMA guidelines for network meta-analyses and scoping reviews and development of guidelines for rapid reviews: a scoping review protocol. JBI Evid Synth 23:517–526. https://doi.org/10.11124/JBIES-24-00308

Versace S, Gianelle D, Garfì V et al (2020) Interannual radial growth sensitivity to climatic variations and extreme events in mixed-species and pure forest stands of silver fir and European beech in the Italian Peninsula. Eur J for Res 139:627–645. https://doi.org/10.1007/s10342-020-01274-8

Versace S, Antonucci S, Santopuoli G et al (2022) Local environment prevails over population variations in growth-climate relationships of *Pinus pinaster* provenances. Dendrochronologia 75:125983. https://doi.org/10.1016/j.dendro.2022.125983

Wang S, Zhang Y, Ju W et al (2020) Recent global decline of $CO_2$ fertilization effects on vegetation photosynthesis. Science 370:1295–1300. https://doi.org/10.1126/science.abb777

Wang J, Delang CO, Hou G et al (2022) Carbon sequestration in biomass and soil following reforestation: a case study of the Yangtze River Basin. J for Res 33:1663–1690. https://doi.org/10.1007/s11676-021-01445-2

Waring B, Neumann M, Prentice IC et al (2020) Forests and decarbonisation—roles of natural and planted forests. Front for Glob Chang 3:58. https://doi.org/10.3389/ffgc.2020.00058

Weatherall A, Nabuurs G-J, Velikova V et al (2022) Defining climate-smart forestry. In: Tognetti R, Smith M, Panzacchi P (eds) Climate-smart forestry in mountain regions. Springer, Cham. https://doi.org/10.1007/978-3-030-80767-2_2

Wikle JL, D'Amato AW (2023) Stand spatial structure outcomes of forest adaptation treatments in northern hardwood forests in North America. Can J for Res 53:721–734. https://doi.org/10.1139/cjfr-2022-0274

Woodall CW, Weiskittel AR (2021) Relative density of United States forests has shifted to higher levels over last two decades with important implications for future dynamics. Sci Rep 11:18848. https://doi.org/10.1038/s41598-021-98244-w

Wu B, Zhang Y, Wang Y et al (2023) Spatio-temporal variations of the land-use-related carbon budget in Southeast China: the evidence of Fujian province. Environ Res Commun 5:115015. https://doi.org/10.1088/2515-7620/ad0ca1

Yousefpour R, Augustynczik ALD, Reyer CPO et al (2018) Realizing mitigation efficiency of European commercial forests by climate smart forestry. Sci Rep 8:345. https://doi.org/10.1038/s41598-017-18778-w

*Yu Z, You W, Agathokleous E et al (2021) Forest management required for consistent carbon sink in China's forest plantations. For Ecosyst 8:54. https://doi.org/10.1186/s40663-021-00335-7

Zhang T, Niinemets Ü, Sheffield J, Lichstein JW (2018) Shifts in tree functional composition amplify the response of forest biomass to climate. Nature 556:99–102. https://doi.org/10.1038/nature26152

Zhang B, Lan K, Harris TB et al (2023) Climate-smart forestry through innovative wood products and commercial afforestation and reforestation on marginal land. Proc Natl Acad Sci USA 120:e2221840120. https://doi.org/10.1073/pnas.2221840120

Zhao X, Tang X, Du J et al (2022) A data-driven estimate of litterfall and forest carbon turnover and the drivers of their inter-annual variabilities in forest ecosystems across China. Sci Total Environ 821:153341. https://doi.org/10.1016/j.scitotenv.2022.153341

Zhou G, Liu S, Li Z et al (2006) Old-growth forests can accumulate carbon in soils. Science 314:1417. https://doi.org/10.1126/science.1130168

*Ziter C, Bennett EM, Gonzalez A (2013) Functional diversity and management mediate aboveground carbon stocks in small forest fragments. Ecosphere 4:1–21. https://doi.org/10.1890/ES13-00135.1