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REVIEW

Between a log and a hard place: European forests under competing demands

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Abstract

European forests provide essential ecosystem services, with current policies focused on four key demands: carbon sequestration, timber provision, bioenergy use, and biodiversity conservation. These policies pursue multiple objectives simultaneously, creating conflicts over forest resources and services that intensify as climate change reduces forests' capacity to deliver multiple services.

We synthesize here scientific evidence for these conflicting demands, their interactions and impacts on forests, revealing that current policy frameworks inadequately address fundamental trade-offs between them. Climate change impacts have begun to seriously challenge mitigation targets through negative impacts on the European forest carbon sink. Material substitution benefits face uncertainties in scale and timing as other sectors decarbonize. Bioenergy use conflicts with higher-value applications and biodiversity conservation, while existing policy frameworks inadequately enforce cascade use principles. Climate adaptation towards mixed forests faces implementation barriers including industry infrastructure optimized for softwood, fragmented ownership structures complicating coordination, and local management constraints. While innovative approaches such as Climate-Smart Forestry and landscape-scale triad zoning show potential for integrating multiple demands, they require substantial policy support and institutional capacity.

Our review shows that neither technical improvements nor current policies can resolve these fundamental resource conflicts. Sustainable European forest management in the twenty-first century requires enhanced adaptation efforts alongside demand-side management to avoid overexploitation of European forests and environmental impact displacement that could undermine intended policy benefits globally.

Keywords Carbon sink · Climate adaptation · Ecosystem services · Forest multifunctionality · Forest policy · Trade-offs

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Introduction

Policy background

European forests face multiple pressures arising from accelerating climate change and shifting societal demands. They should act as carbon sinks, be sources of biomass, serve as habitats for biodiversity, and provide many other forest ecosystem services (FES) such as water purification, local cooling, soil protection, flood control and recreation. Managing forests to provide multiple services simultaneously, often termed multifunctional forest management, is thus a key policy objective. Forests are hence addressed in several policies related to climate, energy, biodiversity, bioeconomy and trade, each with their own forest-related objectives and priorities regarding present and future ecosystem service provision (Elomina and Pülzl 2021; Beland Lindahl et al. 2023). However, given that these objectives are potentially conflicting, their simultaneous pursuit can lead to trade-offs that challenge a holistic multifunctional management of forest landscapes (Felipe-Lucia et al. 2018; Blattert et al. 2022; European Environment Agency 2023a; Leibniz-Forschungsnetzwerk Biodiversität 2024).

The European Union's (EU) Climate Law specifies that the EU should be climate neutral by 2050, with intermediate targets such as a greenhouse gas (GHG) emission reduction of 55% below 1990 levels by 2030 (European Parliament 2021; European Environment Agency 2023b). Numerous other EU policies prominently refer to forests and forest products as means to achieve their set objectives, including the New Forest Strategy for 2030 (European Commission 2021; Lier et al. 2022), the Biodiversity Strategy (European Commission 2020), the land use, land use change and forestry (LULUCF) Regulation (European Parliament and Council 2023a; 2023b), the Bioeconomy Strategy (European Commission, Directorate General for Research and Innovation 2018), and the Renewable Energy Directive (Kun 2022; European Parliament 2023). Tensions arise from the difficulty of integrating the different policy objectives of biodiversity conservation, carbon sink increase and wood harvest for material and bioenergy in a multifunctional manner (Blattert et al. 2023; Gregor et al. 2024b). They have been argued to not be properly harmonized in the larger context of the Green Deal (Aggestam and Giurca 2021), perpetuating a decades-long lack of coordination and integration in European forest policy (Aggestam and Giurca 2021; Fridén et al. 2024; Sotirov et al. 2024). Among manifold reasons for this lack of coordination are incremental development and weak institutionalization (Pülzl et al. 2018). Integration across conflicting policy targets and regulations is further impeded by a polycentric forest governance structure with around 90 national or sub-national governing bodies (Lazdinis et al. 2019). Progress in aligning forest policy is also hindered by conflicting fundamental framings (Elomina and Pülzl 2021), most prominently boiled down to whether forests should serve mainly environmental or economic objectives (Wolfslehner et al. 2020). In a longstanding central conflict, multiple forest-rich member states have historically opposed stronger EU forest policy that would limit national sovereignty, particularly regarding increased environmental regulation (Sotirov et al. 2021; Gordeeva et al. 2022).

European forest characteristics and management

Understanding whether forests can meet these diverse policy objectives requires examining their current state, management practices, and the pressures they face. The majority of EU forests are even-aged and heavily managed, with individual stands typically composed of one to three species (Köhl et al. 2020; Muys et al. 2022a). The even-aged structure predominantly reflects forest management practices, though low species diversity can also characterize natural boreal and some temperate forest ecosystems. The forest area is almost equally divided between public and private ownership (Kilpeläinen and Peltola 2022; Forest Europe 2024), with around 16 million private and public forest owners and a tendency towards more private ownership further north and west (Weiss et al. 2024). Forest resources such as total area, growing stock, net annual increment and harvest (Fig. 2) have steadily increased over the last decades in the EU-27 (Mauser 2023). Despite an increase in annual roundwood production from 387 to 499 Mm^3 between 1990 and 2020, the volume of carbon stored in living biomass in EU forests has been estimated to have increased by 43% over the same period due to simultaneous increases in forest area – from approx. 145 to 160 Mha – as well as increases in growing stock per ha (Mauser 2023). Reasons for this increase include natural forest expansion on abandoned land, afforestation efforts, forest demography effects, CO_2 fertilization, nitrogen deposition, and other anthropogenic environmental changes (Pugh et al. 2019b; Köhl et al. 2020; Mauser 2023).

These EU-wide patterns, however, mask substantial regional variation in forest management regimes. Northern European forests are dominated by even-aged rotation forestry with low-frequency but high-intensity clear-cutting systems (Scherpenhuijzen et al. 2025; Suvanto et al. 2025), while Poland and Czechia exhibit distinctive patterns of high-frequency but low-intensity harvest regimes under centralized public management (Suvanto et al. 2025). Western European countries emphasize multifunctional forestry with more frequent smaller interventions and fragmented private ownership, whereas Southern Europe displays geographic extremes from very intensive short-rotation plantations in Portugal to largely protected or abandoned forests in Mediterranean regions (Scherpenhuijzen et al. 2025; Suvanto et al. 2025). These differences reflect varying national policies, ownership structures, climatic conditions, and historical development trajectories that shape contemporary forest use (Suvanto et al. 2025).

Europe is the continent experiencing the fastest rate of anthropogenic climate change, warming at about twice the global average (Copernicus Climate Change Service (C3S) 2025). Correspondingly, European forest ecosystems are increasingly challenged by heatwaves, droughts, and windstorms (Seidl et al. 2017; Jandl et al. 2019; Anderegg et al. 2022; Gazol and Camarero 2022). Frequent extreme weather events exacerbate other forest disturbances such as insect outbreaks and fires (Patacca et al. 2022) that have already caused widespread tree mortality (Schuldt et al.

2020; Senf and Seidl 2020, 2021; Senf et al. 2020). These climate-related disturbances have contributed to a decline in forest condition (European Environment Agency 2025c), negatively affecting not only the forest carbon sink and quality of timber supply but also a multitude of other ecosystem services such as soil erosion control, recreation, biodiversity, and water regulation (European Environment Agency 2024a; Lecina-Diaz et al. 2024). Increased adaptation efforts are thus demanded across Europe, such as shifting conifer monocultures towards more resilient mixed-species forests (Stangler et al. 2022; European Scientific Advisory Board on Climate Change 2024). However, developing the necessary local adaptation strategies is challenging given large uncertainties around future GHG emissions, warming levels, and extreme weather events. Forests will likely experience rapid environmental changes over their lifetime that alter species suitability, growth conditions, and disturbance regimes, creating substantial uncertainty about which species and management approaches will remain viable and limiting the option space for silviculture (Wessely et al. 2024). Additionally, even current state-of-the-art models are not yet capable of accurately reflecting extreme events as well as induced tree and forest mortality (Bugmann et al. 2019; Maréchaux et al. 2021; Trugman et al. 2021; Li et al. 2022; Schumacher et al. 2024), giving rise to the assumption that predictions of future biomass stocks and potential harvest are most likely too optimistic (Anders et al. 2025; Windisch et al. 2025).

Review rationale

Given these mounting climate pressures, diverse management regimes, and fragmented governance structures, managing forests to simultaneously meet competing demands poses fundamental challenges. Previous reviews on sustainable supply of multiple FES in Europe have predominantly examined general governance approaches and solution pathways, including enhanced policy integration, shifting management paradigms towards pluralistic ecosystem valuation, payments for ecosystem services, and bottom-up participation (Hernández-Morcillo et al. 2022; Winkel et al. 2022). Recent assessments have also highlighted urgent needs for improved forest monitoring and modelling to address the declining European carbon sink (Migliavacca et al. 2025). Building on these contributions, we address a gap: competing demands on European forests create resource conflicts that intensify under climate change and cannot be resolved through technical or governance improvements alone without demand-side management.

We synthesize scientific evidence on these competing demands and their interactions, revealing fundamental trade-offs. Climate change simultaneously increases societal dependence on forests while reducing their capacity to deliver multiple services, intensifying conflicts between objectives. Current policies pursue these demands in parallel without adequately addressing inherent trade-offs, creating unsustainable trajectories. We examine both the ecological constraints documented in scientific literature and the policy responses to address them, revealing that sustainable twenty-first century European forest management requires enhanced adaptation efforts alongside demand-side management to avoid environmental impact displacement globally.

Review approach

This narrative review (Sutton et al. 2019) synthesizes scientific literature on four key demands on European forests: carbon sequestration, material provision, bioenergy production, and biodiversity conservation. We organized the review by demand category. Each section opens with a brief overview of key findings before examining relevant policies, current status and potential, required management approaches, and existing challenges and trade-offs. Certain topics appear across multiple sections as they intersect with multiple demands. The discussion synthesizes these perspectives to assess overall patterns, knowledge gaps, and implications for forest management and policy.

Literature was identified through database searches (Web of Science, Google Scholar) for topics including European forests, ecosystem services, carbon storage, timber production, bioenergy, biodiversity, and forest policy. We prioritized peer-reviewed literature from 2018 onwards to capture forest responses to recent extreme climate events, notably the 2018–2022 drought period, while including foundational earlier work establishing baselines and concepts. Primary EU policy documents and reports from European and national institutions provided policy context as well as data on forest conditions and trends. Given the interdisciplinary breadth of the review – covering forest ecology, climate science, resource economics, and policy – literature identification was iterative rather than following a systematic protocol. Searches were supplemented by citation tracking (examining reference lists of key papers, identifying subsequent citing work, and using citation mapping tools) and authors' knowledge of the field, enabling identification of relevant work not yet captured by database searches.

Scientific evidence synthesis and interpretation of trade-offs reflect authors' expertise across these disciplines. We employed a narrative review approach to integrate heterogeneous evidence across domains with incompatible study designs and scales (Grant and Booth 2009). This approach enables cross-sectoral synthesis while acknowledging limitations including inability to quantify publication bias or provide reproducible protocols.

Forests for carbon sequestration

The European forest carbon sink is declining despite opposite policy targets, due to climate-related disturbances and ageing forests. Current LULUCF targets appear increasingly unrealistic given observed trends. Management strategies for enhancing carbon storage, such as reduced harvest intensity and species diversification, may face trade-offs with material and energy provision objectives while offering potential synergies with biodiversity conservation.

Policy, status and potential

The European Union has recently increased its climate ambitions significantly through the revised LULUCF regulation, which now targets an annual LULUCF net sink of -310 $MtCO_2$-Eq. (85 TgC) for the EU-27 by 2030 (European Parliament and Council 2023a). Since other land use and land use change categories primarily constitute GHG sources, such as emissions from drained peat soils, the forest sink must exceed this target through increases in standing biomass, soil carbon, deadwood, and harvested wood products (HWP) (European Commission, Directorate General for Energy et al. 2021; Korosuo et al. 2023). For the impact of HWP (Pilli et al. 2015; Johnston and Radeloff 2019; Grassi et al. 2021) and their mitigation benefits via substitution effects see the sections on material and energy. We focus here on effects directly related to the forest carbon cycle. We further acknowledge that climate change impacts on forests also include other processes related to, e.g., albedo, evapotranspiration, and particle formation (Bonan 2008; Alkama and Cescatti 2016; Baldocchi and Penuelas 2019; De Frenne et al. 2021; Portmann et al. 2022; Weber et al. 2024), but these are beyond the scope of this review.

The total forest carbon stock in Europe has been estimated in various studies (Table 1), ranging from approximately 22 PgC (Pilli et al. 2017) up to 27 PgC (Köhl et al. 2020) and 32 PgC (Pan et al. 2024), including an HWP pool of 1–2 PgC (Pilli et al. 2017; Köhl et al. 2020; Grassi et al. 2021). Regional variations are significant, with soil carbon dominating in boreal regions while both soil and living biomass are major contributors in temperate zones (Pan et al. 2024). Recent assessments of the European forest carbon sink show considerable methodological differences

Table 1 Estimated carbon stock and annual stock change (net sink) of EU forests

Carbon stock change [$MtCO_2$-eq. yr^{-1}]	Carbon stock [PgC]	No. of European countries	Time point/period	Reference system	References
363 (426) a)		25	1990–2005	Forests	Luyssaert et al. (2010)
447	21.7 b)	26	2000–2012	Forests including HWP	Pilli et al. (2017)
535 (675) c)		37	2001–2005	Land ecosystems	Luyssaert et al. (2012)
618 d)		28	2010	Woody biomass potential	Verkerk et al. (2019)
555 e)	32.0 e)	33	2010–2019	Forests	Pan et al. (2024)
439.9 f)	27.3	28	2020	Forests	Köhl et al. (2020)
281 (245 + 41 g))		27	2021	Living forest biomass	Korosuo et al. (2023)
275 h)		27	2021–2025	Forests (via forest reference levels)	Vizzarri et al. (2022)
338 i)		29	2021–2030	Forests	Seidl et al. (2014)
464 (410 + 54 g), 142 j))		30	2021–2050	Forests including HWP (via model)	Verkerk et al. (2022a)
198 k)		27	2023	LULUCF sector (latest data)	European Environment Agency (2025b)
310		27	2030	LULUCF sector (legal target)	European Parliament (2023)

To translate carbon dioxide into carbon units: 44/12 $tCO_2 \triangleq 1$ tC; 1 Mt = 1 Tg = 10^{-3} Pg a) depending on forest definition; b) including 1.84 PgC of HWP; c) inventory-based and flux-based estimates, including all land ecosystems; d) calculated from 401 TgDM yr^{-1} * 0.84 EU-28 contribution from 39 countries; e) European temperate and boreal, includes EU-28 + Albania, Bosnia Herzegovina, Norway, Serbia, and Switzerland (stock change also includes HWP); f) average over period 2010–2020; g) old and new forests, excluding emissions from drainage and rewetting; h) decreased by 13% HWP; i) calculated from 92.2 TgC net ecosystem productivity change; j) average increase due to additional management activity and afforestation/reforestation; k) including 274 + 30 $MtCO_2$-eq. from forest land and HWP net sinks, along with other LULUCF categories as net sources in spatial coverage, time frames, system boundaries, and modelling approaches as well as assumptions about future policy and management. Petrescu et al. (2020) discuss how large spreads in net CO$_2$ removal estimates of forests can arise from different methodologies such as the ones used by the United Nations Framework Convention on Climate Change or Food and Agriculture Organization, as well as a variety of inventory-based, bookkeeping or dynamic global vegetation models. Even where models are based on similar raw data, estimates have been shown to differ by up to 50%, with the uncertainty partially arising from the difficulty to account for impacts of disturbances and represent forest regrowth (O'Sullivan et al. 2024). Despite these variations, there is broad agreement that increases in living biomass have driven the forest carbon sink in both temperate and boreal regions over the last decades.

Forest growth in Europe has slowed in recent years despite increasing carbon sequestration targets, due to factors such as increasing forest maturity and reduced nitrogen deposition (Nabuurs et al. 2013; Pilli et al. 2022; Avitabile et al. 2023; 2024). In addition, extreme weather and related events result in increased disturbances and reduced carbon uptake (Allen et al. 2010; Lindner et al. 2014; Seidl et al. 2014; 2017; Patacca et al. 2022). Heat, drought stress, storms, fires and insect outbreaks have been estimated to decrease carbon sequestration by about 40 MtCO$_2$-eq. yr^{-1} over the last decades (Patacca et al. 2022). Salvage logging has almost doubled across the EU between 2010 and 2020 (Mansuy et al. 2024). For the near future, Seidl et al. (2014) estimated a further decrease in carbon sequestration rates in European forests due to increasing disturbances of 184 MtCO$_2$-eq. yr^{-1} (amounting to 503 TgC from 2021 to 2030, over 29 countries). For most regions, those rates are by far outweighing productivity gains from warming or increasing CO$_2$ (Reyer et al. 2017). Southern and northern regions show particularly high vulnerability due to warming-induced stress (Forzieri et al. 2021; Patacca et al. 2022). Recent extreme drought events have triggered tree mortality directly or by predisposing forests to subsequent fire and bark beetle outbreaks. This increased mortality and reduced carbon uptake has been observed throughout Europe, particularly during the hot and dry periods from 2018 to 2022 (Buras et al. 2020; Schuldt et al. 2020; Haberstroh et al. 2022; van der Woude et al. 2023; Knutzen et al. 2025; Li et al. 2025). Tree mortality has risen especially in conifers that seem more susceptible to heat, drought and related stressors (Senf et al. 2020; George et al. 2022). From a LULUCF target perspective, most available growth simulations projecting initial productivity increases followed by drought-related losses are likely unrealistically optimistic, as models inadequately capture stress-induced mortality (Mahnken et al. 2022). This is compounded by weakened and transitioning forest systems showing increased susceptibility to further disturbances (Niinemets 2010; Obladen et al. 2021; Senf and Seidl 2021).

Current trends indicate the forest carbon sink will not meet LULUCF regulation targets (Korosuo et al. 2023; see also Fig. 1), and it is projected to decline further under existing management practices and expected climate change (Pilli et al. 2022). The European Commission recently estimated a shortfall of 45–60 MtCO$_2$-eq. yr^{-1} for the 2030 target (European Commission 2024). This gap is likely to widen as an increasing number of countries report their forests becoming net CO$_2$ sources (European Commission 2023a; 2024; European Environment Agency 2025a; Natural Resources Institute Finland 2025). New data from Germany's recent revision alone could more than double the gap estimated by the European Commission, as its latest LULUCF data reports a substantial annual net source of around 70 MtCO$_2$-eq. (Riedel et al. 2024; Expertenrat für

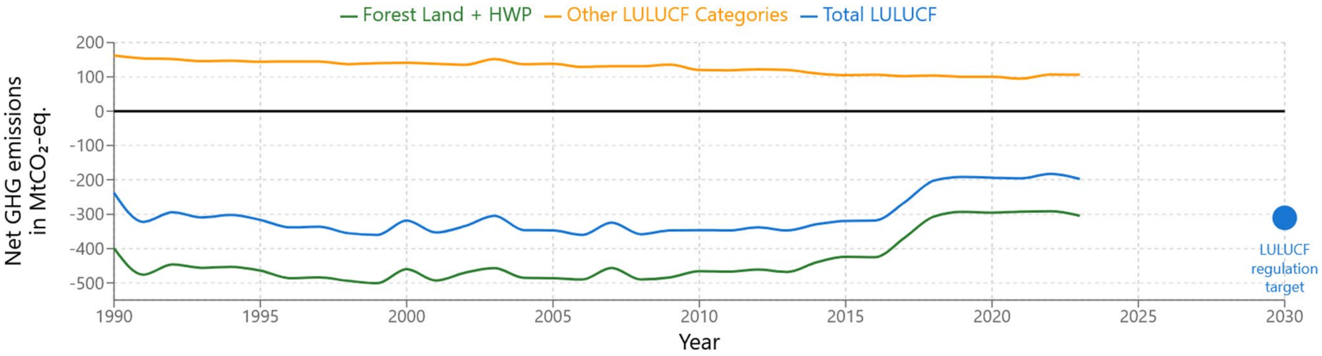

Fig. 1 Decreasing sink trend in European forests. Historical trends in net greenhouse gas emissions from the Land Use, Land-Use Change and Forestry (LULUCF) sector in the EU-27 from 1990 to 2023, as reported in the most recent official greenhouse gas inventory. While Forest Land and HWP function as net sinks, other LULUCF categories are net emission sources. Following the drought from 2018 onwards, the observed trend diverges strongly from the 2030 target of -310 MtCO$_2$-eq. Due to long time intervals between forest data collections, national greenhouse gas inventories are always a lagging indicator. After repeated revisions in direction of a decreasing net sink, the currently available values range around -200 MtCO$_2$-eq. Data obtained from European Environment Agency (2025a; 2025b), plot concept inspired by as well as adapted and updated from Korosuo et al. (2023)

Klimafragen 2025), compared to a sink contribution target of -25 MtCO₂-eq. in 2030.

Forest management impacts, challenges, trade-offs and synergies

Increases in carbon sink strength can result from expanding the forest area, increasing the productivity of existing forests, improved management practices, and positive environmental drivers. The forest area in Europe increased by about 10% from 1990 to 2020 (Kilpeläinen and Peltola 2022), with some scenario projections suggesting up to an additional 10% increase by 2050 at the expense of cropland and grassland (Duscha et al. 2019). Forest productivity improvements through optimized stand composition, density management, and reduced disturbance susceptibility offer additional potential, though local outcomes are not always straightforward (Ontl et al. 2019). Finally, estimates of increasing carbon sink capacity of forests also rely on environmental changes, e.g. prolonged growing seasons or the increase of CO_2 (Walker et al. 2021). Forest management for increased carbon sequestration aims to facilitate faster growth and ensure stable conditions to extend carbon turnover time. Such improvements in growth conditions benefit both woody vegetation and soil carbon stocks (Jandl et al. 2007). Potential management options to approach a higher continuous growth are (1) a suitable selection of species and/or species combinations, (2) facilitating a multilayer stand structure, (3) an adjusted rotation length, and (4) the modification of stand density—though the feasibility and effectiveness of each approach varies substantially across Europe (Scherpenhuijzen et al. 2025; Suvanto et al. 2025).

However, forest managers face substantial uncertainty regarding optimal species composition in specific locations given the rapid rate of warming in Europe, and a lack of historical analogues for projected climate and CO_2 conditions that challenges long-term planning. Alongside a generally limited option space for suitable species (Wessely et al. 2024), traditionally widely used European species such as *Fagus sylvatica* (European beech) and *Picea abies* (Norway spruce) have been projected to potentially lose 55–60% of their distribution ranges (Thurm et al. 2018). Adaptive management approaches increasingly consider assisted migration, describing deliberate movement of suitable species or provenances to locations matching projected climate requirements (Mauri et al. 2023). Some thermophilic species show potential as alternatives for northward distribution shifts, though their introduction involves trade-offs between climate resilience and growth performance, along with potential invasive species concerns. Changing species composition might not necessarily be the only, or even the most successful adaptation. Chakraborty et al. (2024) demonstrated that utilizing seed provenances adapted to future climates could maintain or even increase carbon sequestration, whereas using locally adapted provenances with the same species changes could significantly reduce current carbon sinks. This highlights the importance of integrating species selection as well as consideration of genetic diversity and functional traits as key components of adaptive strategies (Bussotti et al. 2015). Ample evidence suggests that structured forests sequester more carbon (Kazempour Larsary et al. 2021) and, at least when mature, also grow better than forests with uniform structural and compositional traits (Zeller and Pretzsch 2019). Recent evidence also suggests that species diversification can strongly increase sequestration in young stands (Warner et al. 2023). Forests with a higher degree of structure and species mixture are less vulnerable to stressful environmental conditions due to facilitation effects (Pardos et al. 2021) and better niche exploitation (Pretzsch 2022). However, higher structural diversity also implies a larger share of species and tree sizes with suboptimal competition strength, resulting in peak standing volume and yield achieved at moderate structural diversity (Pretzsch et al. 2024). The magnitude of economic trade-offs of increasing structure and mixture varies depending on species combinations and their specific properties. Further complexity arises from uncertainty surrounding the performance in future climatic conditions, of both native and introduced species (Mauri et al. 2023; Chakraborty et al. 2024). Extended rotation lengths represent another strategy for increasing carbon storage, though this entails reduced economic yields. The impact of prolonging the growth period on carbon storage depends strongly on site conditions (Kaipainen et al. 2004; Carlisle et al. 2023). Stand density management presents further trade-offs between carbon storage and resilience. While no or minor thinning (e.g. in protected forests) generally produces a higher stand density holding more carbon (Mäkelä et al. 2023), reducing stand density can improve individual tree resilience, e.g. through enhanced water availability (Sohn et al. 2016; Bose et al. 2024). Optimal long-term carbon uptake may occur at lower than maximum stand densities, despite potential short-term yield reductions. Conversely, excessive stand density reduction that prevents full resource utilization has been linked to decreased carbon sequestration in parts of Europe (Winkler et al. 2023).

More structured and mixed forests generally have positive influences on biodiversity and other ecosystem services (Messier et al. 2022; Prütz et al. 2024; see also biodiversity section). Specific outcomes depend on how species composition affects factors such as albedo, local climate and air chemistry, or groundwater supply (Luyssaert et al. 2018). The relative shift in harvestable biomass from softwood to

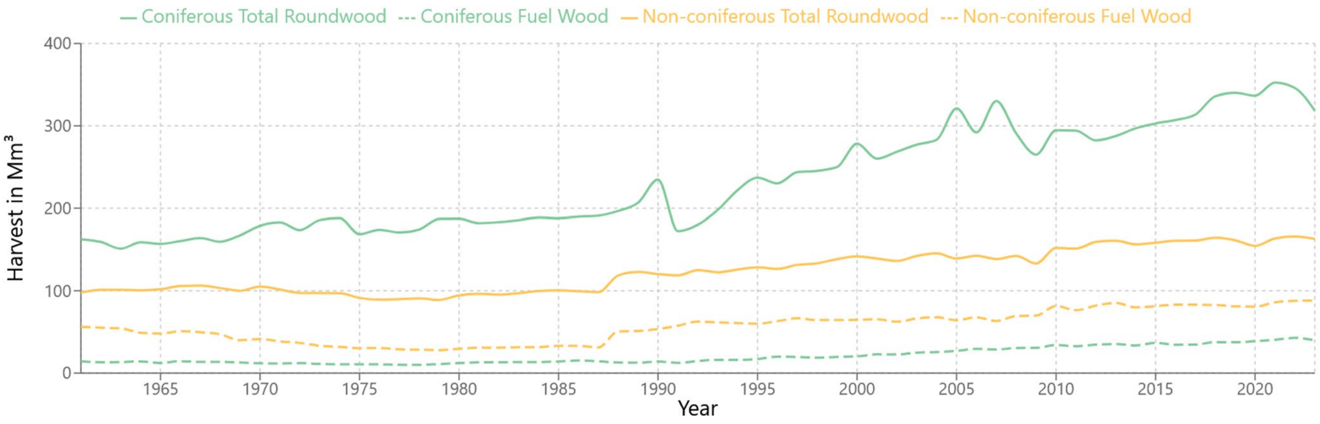

Fig. 2 Increasing harvest trend and high non-coniferous fuel fraction in European forests. Historical trends in roundwood harvest in the EU-27 from 1961 to 2023, as estimated by FAOSTAT (2025). Total roundwood harvest has increased over the last decades for both coniferous (from needleleaved trees) and non-coniferous wood (from broad-leaved trees), also often described as soft- and hardwood, respectively (FAO 2022). The fraction of direct utilization as fuel differs significantly between wood types, with only around an eighth of coniferous compared to more than half of all non-coniferous roundwood being directly used as fuel throughout the last decades

hardwood in mixed forests creates trade-offs with current industry needs (see material section). While timber yields could also be reduced, the enhanced resistance and resilience of structured forests to disturbances may outweigh slight productivity decreases over multi-decade timescales (Biber et al. 2020), especially since maintaining current structures and productivity will hardly be possible (Jandl et al. 2019). Overall, current literature suggests that enhancing ‘natural’ resilience of forests offers a number of synergies and involves relatively minor trade-offs. In contrast, maintaining resilience through intensive and repeated human intervention (‘coerced resilience’) may accelerate biodiversity loss and narrow the range of provided FES (Felton et al. 2024).

Forests for material production

Wood products offer climate mitigation potential through material substitution and carbon storage, yet the magnitude and timing of these benefits remain uncertain as other sectors decarbonize. Policies promote increased use of long-lived wood products while climate adaptation pushes forests toward hardwood-dominated stands, creating mismatches with industry infrastructure optimized for softwood.

Policy, status and potential

Forest products are recognized by the EU as a key mitigation measure in meeting the obligations under its Climate Law (European Parliament 2021). This is reflected in the EU’s Forest Strategy for 2030, which emphasizes the importance of long-lived wood products and reinforces reporting and accounting of carbon stock changes in wooden products (European Commission 2021). Across member states, approaches to promote long-lived wooden products range from vaguely stated national goals like in Germany (Bundesministerium für Wohnen, Stadtentwicklung und Bauwesen 2023), concrete targets set out in national policies in Finland (Ministry of Agriculture and Forestry of Finland 2024) to bottom-up local initiatives in the Netherlands (AMS Institute 2021). Ten member states have already explicitly specified the use of HWP for construction in their national energy and climate plans for 2030 (Sikkema et al. 2023). Providing a striking example for what is already technically possible today, six of the world’s ten tallest laminated-timber buildings are located in EU countries (Biro 2023).

In 2023, around a quarter of the EU’s harvested primary woody biomass was directly used for energy (Fig. 2), including substantial portions of non-coniferous stemwood (European Commission Joint Research Centre 2021; Sikkema et al. 2021; Food and Agriculture Organization of the United Nations 2025). A significant portion of the remainder is utilized for short-lived products or energy as by-products of further processing stages (Köhl et al. 2020). Studies consistently show that shifting wood use towards longer-lived products could enhance both the HWP carbon sink and overall climate benefits including substitution effects, wherever such applications are feasible (European Commission, Directorate General for Climate Action and Johann Heinrich von Thünen Institut 2016; Nabuurs et al. 2017b; Leskinen et al. 2018; Brunet-Navarro et al. 2021; Grassi et al. 2021; Myllyviita et al. 2021; Bozzolan et al. 2024; Gregor et al. 2024a). The HWP pool already functions as a significant carbon sink, sequestering an estimated annual 91 MtC globally in 2015 (Johnston and Radeloff 2019) and 11 MtC in Europe averaged over 2016–2018 (Grassi et al. 2021).

The building sector's use of cement, iron, and steel currently accounts for approximately 10% of global GHG emissions, reaching around 1.37 GtC (5.03 $GtCO_2$-eq.) in 2020 (Mishra et al. 2022). Under optimistic assumptions regarding speed of uptake and per capita floor area, a cumulative global carbon storage potential in buildings of about 8 GtC by 2050 has been estimated, compared to current global estimates ranging from 2.9 (X. Zhang et al. 2020b) to 7.3 (Suyari et al. 2020) GtC for all HWP (in 2015 and 2016). Production of construction materials in such a timber system would generate approximately 2 GtC in cumulative emissions, much less than the 4.4 GtC projected for the same amount of construction using steel and concrete (Churkina et al. 2020). The corresponding harvest requirements of around 0.5 GtC yr^{-1} from global forests could however require a drastic increase of current plantation forest area, threatening unprotected forests and other natural ecosystems (Churkina et al. 2020; Mishra et al. 2022).

Uncertainties about the magnitude of the carbon sink, and consequent potential GHG emissions savings in Europe are large. In a scenario that assumed a share of 80% of all new residential buildings to be wooden with high carbon storage potential per floor area, Amiri et al. (2020) reported an upper limit of annual carbon storage of 55 $MtCO_2$-eq. yr^{-1} by 2040 – which is equivalent to nearly 50% of Europe's cement industry emissions in 2018. Assuming a smaller increase of the share of wood in buildings, Hildebrandt et al. (2017) found potential annual emissions savings of about 18–46 $MtCO_2$-eq. in 2030 compared to conventional building materials. In comparison, if the share of wooden buildings remains as it was in 2015, only 1% of the cement industry's emissions could be substituted (Amiri et al. 2020).

Overall European-scale and national-level studies to date seem to converge on the notion that even with optimistic assumptions of a rapid increase of wood use in the building sector, the contribution to short-term mitigation would be rather modest (Hildebrandt et al. 2017; Hafner and Rüter 2018; Amiri et al. 2020; Brunet-Navarro et al. 2021; Schulte et al. 2023), given the EU's target of reducing total emissions to 2121 $MtCO_2$-eq. by 2030 (European Environment Agency 2023b). However, when compared to the relevant emission sectors such as the cement industry and in perspective of the net-zero emission target of 2050, the simulated results appear more impactful – especially when also considering non-residential buildings, refurbishments, and the potential of increased EU policy incentives (European Commission, Directorate General for Climate Action 2021).

In addition to uncertainties arising from a broad range of scenarios, the available literature exhibits considerable heterogeneity in methods (material flow analysis in units of mass of carbon; life cycle assessment in units of global warming potential; dynamic life cycle assessment in units of global warming impact; process-based ecosystem modelling), in the applied displacement factors (up to 100-fold), and spatial scales addressed (De Rosa et al. 2018; Leskinen et al. 2018; Harmon 2019; Andersen et al. 2021; Arehart et al. 2021; Howard et al. 2021; Hurmekoski et al. 2021; Myllyviita et al. 2021). In addition, although typically smaller than substitution benefits or carbon sequestration, harvesting operations, sawmills, wood processing facilities, and transport generate direct emissions that are often not considered – despite affecting the overall carbon balance of forestry systems (Sonne 2006; Cosola et al. 2016). Thus, comparing results on the overall climate change mitigation impact of using long-lived wood products remains challenging, and studies often result in conflicting policy recommendations. Despite these challenges, shifting harvests in sustainably managed forests from short- to long-lived products has been robustly demonstrated to have an overall positive effect on climate change mitigation.

Forest management impacts, challenges, trade-offs and synergies

Increasing wood use in construction without negatively affecting the existing carbon sinks in forests through increased timber extraction is a key challenge. Further increases in current harvest rates are expected until 2050 in policy-relevant EU scenarios (European Commission, Directorate General for Energy et al. 2021). While this might appear feasible given recent expansions in European forest area and growing stock, along with enhanced growth rates from CO_2 fertilization and atmospheric nitrogen deposition (Pugh et al. 2019a, ; Erb et al. 2022; Pretzsch et al. 2023), these positive trends are increasingly offset by unfavourable climatic conditions significantly reducing potential sequestration (see carbon section). Intensifying harvest through shortened rotation times or expanded harvest areas carries significant carbon costs. These include decreased forest soil carbon due to increased residue removal and disturbance of litter and upper soil layers, as well as the opportunity cost of 'foregone' forest carbon sequestration (Pilli et al. 2017; Mayer et al. 2020; Erb et al. 2022; Mäkipää et al. 2023). Studies for Europe and Finland indicate that by 2030 and 2050, increased carbon storage in wood products and material substitution benefits would not compensate for the reduced forest carbon sink under increased harvest scenarios (Seppälä et al. 2019; Jonsson et al. 2021; Hurmekoski et al. 2023). However, since the European forest sink is increasingly suffering from climate change impacts itself, those results need to be placed in a more complex context. Gregor et al. (2024a) found that reduced harvest intensities can have positive near-term impacts on the carbon sink, but the balance shifts around 2050, and losses from climate change-induced disturbances significantly diminish the sink strength later in the century. These impacts might be moderated by transitioning to more mixed and naturally resilient forests (Pretzsch et al. 2021), also benefiting biodiversity.

Long-lived wood products used in construction have been predominantly softwood-based since its lower density and stiffness allows for easier materials engineering, along with the advantages of conifers usually growing straighter and faster than their broadleaved counterparts (Ramage et al. 2017; Krtschil et al. 2022). The German timber industry, for instance, currently uses around 85% softwood and 13% hardwood, which will need to change as future timber supply from climate change adapted forests is expected to shift towards more hardwood (Krtschil et al. 2022). Innovations regarding hardwood-based construction and other higher-value applications are developing, but still lagging behind for the foreseeable future (Ramage et al. 2017; Adhikari et al. 2021; Beims et al. 2022; Verkerk, Hassegawa, et al. 2022b; Pramreiter and Grabner 2023). Still, the building sector could accommodate increasing harvest rates from currently conifer dominated forests in the short term, providing the opportunity to rapidly transition towards more climate-resilient mixed forests containing larger shares of broadleaved species. However, this will also depend on development of labour skills and public acceptance (Howard et al. 2021), as well as adoption of appropriate building regulations, to facilitate a potentially rapidly increasing demand for wooden building material in the near future.

The need and benefit for wood as a substitute for construction material may even decline over the next decades as the decarbonization of steel and cement production through use of hydrogen or carbon capture and storage progresses (Rissman et al. 2020). In this context, prioritizing resilient carbon sinks through 'climate-smart' forests could emerge as the preferred strategy, offering co-benefits for the forest carbon sink, biodiversity, and other ecosystem services (Gregor et al. 2022; Gregor et al. 2024a) (see carbon and biodiversity sections). Yet a rapid transition between ‘more wood in buildings’ now, and ‘more wood in forests’ in only few decades seems unrealistic due to time lags inherent in the land system (Brown et al. 2019). Similar to dietary change, which has been consistently identified as a crucial lever for reducing land competition (Poore and Nemecek 2018; IPBES 2019; Hayek et al. 2020; Intergovernmental Panel On Climate Change 2022; Sun et al. 2022), it appears prudent for policy approaches to address per capita demand for building material (Erb et al. 2022). Initial studies indicate the importance of addressing demand aspects (Churkina et al. 2020), and such scenarios are increasingly investigated among other demand-side climate mitigation options (van Heerden et al. 2025).

Upscaling wood product re-use within a more circular economy offers another promising pathway towards resolving competing demands, though challenges remain with engineered wood products containing adhesives that complicate recycling. Future developments in modern timber construction should integrate circularity principles from early design phases to increase re-use potential, an area in which knowledge is advancing but requiring deeper implementation across the building sector (Hafner et al. 2014; Ghobadi and Sepasgozar 2023; Garcia et al. 2024; Ottenhaus et al. 2025). End-of-life handling represents another crucial aspect, as landfilling significantly reduces climate benefits of wood products. Varying landfill rates across countries like France, the Netherlands and Czechia represent an often overlooked policy lever (Sathre and O’Connor 2010; Bais-Moleman et al. 2018; Caro et al. 2024; Nwamaka Ikenze et al. 2024). With salvage logging approaching a quarter of total harvests after recent drastic increases in climate-related disturbances, improved deadwood management and salvage logging practices will gain importance and could provide additional biomass streams for cascading use (European Commission, Joint Research Centre 2023; Mansuy et al. 2024). However, these practices significantly impact regulating ecosystem services and biodiversity, particularly saproxylic organisms dependent on deadwood, requiring careful consideration of retention strategies that balance economic recovery with ecological objectives (Thorn et al. 2018; Leverkus et al. 2020). Given complex supply and demand dynamics and particularly considering the high fraction of harvested hardwood used as fuel (Fig. 2 and energy section), various studies (Brunet-Navarro et al. 2021; Bozzolan et al. 2024) emphasize the advantages of redirecting harvested wood from energy use towards long-lived products.

Forests for energy provision

Forest bioenergy constitutes the largest renewable energy source in the EU, yet its climate benefits are contested due to carbon debt from combustion and harvest impacts on forest sinks. Substantial volumes currently go into energy applications rather than long-lived products, conflicting with cascade use principles and potentially creating trade-offs with carbon storage, biodiversity conservation, and material provision objectives.

Policy, status and potential

Forest biomass currently remains the largest renewable energy source in the EU-27(European Commission, Directorate-General for Energy 2024), though wind and photovoltaic energy are showing rapid growth and will soon overtake it (Ember 2024). Total EU bioenergy use has increased by 150% since 2000, largely driven by policy incentives and commitments towards non-fossil energy sources when wind and photovoltaic sources were still less cost-competitive (Roser 2020; European Environment Agency 2023a). In 2021, approximately 263 Mm^3 (79 MtC) of domestically supplied forest biomass provided around 2.85 EJ of renewable energy (European Commission 2023c), covering around 11% of total primary energy production (Eurostat 2025). An additional 48 Mm^3 was sourced from imported feedstock, mainly in the form of wood pellets and roundwood. The EU's mix of wood for energy production is divided almost equally into primary (directly harvested from forests, see Fig. 2 for a breakdown by wood type) and secondary (by-products and cascade use) woody biomass (Köhl et al. 2020; European Commission Joint Research Centre 2021). Forest bioenergy utilization varies significantly across Europe, with higher relevance in Northern countries and different proportions used for heating and electricity (Wu and Pfenninger 2023; Kożuch et al. 2024). From a policy perspective, forest-based bioenergy will continue to play a significant role in achieving the EU's recently raised 42.5% renewable energy target for 2030 (European Parliament 2023), and wood harvests for energy are projected to increase beyond that date (European Commission, Directorate General for Energy et al. 2021).

The Renewable Energy Directive III (RED III) serves as the primary policy framework (Kun 2022; European Parliament 2023). Its most recent revision introduced more rigorous sustainability criteria that require demonstrable GHG emissions savings and aim to ensure biomass feedstocks are not sourced from primary forests or areas with high conservation value. The directive also emphasizes the cascading use principle (Keegan et al. 2013; European Commission, Directorate General for Internal Market, Industry, Entrepreneurship and SMEs 2016; Brunet-Navarro et al. 2018; Besserer et al. 2021; European Commission Joint Research Centre 2021), prioritizing wood use for materials and higher-value applications before energy production, wherever feasible, in the following order (European Parliament 2023): wood-based products, extending their service life, re-use, recycling, bioenergy, and disposal. RED III represents a more nuanced approach to forest biomass utilization compared to previous EU policies (Haberl et al. 2012; Searchinger et al. 2018; Wu and Pfenninger 2023; Sotirov et al. 2024), but still contributes to conflicting demands in combination with other forest policies requiring increased conservation efforts, and its sustainability criteria have been argued to remain insufficient (Stubenrauch and Garske 2023; European Scientific Advisory Board on Climate Change 2025).

Future projections of woody bioenergy supply and demand in Europe vary by more than an order of magnitude, mainly due to differing aggregations of sources and uses as well as levels of constraints to theoretical potentials (Hamelin et al. 2019). The recently raised renewable energy target for 2030 has already rendered previous estimates partially outdated, with country-level implementation responses still trailing behind the new objectives (European Commission 2023b; European Parliament 2023). Mandley et al. (2020) recently estimated a technical potential range of 9–25 EJ yr^{-1} of domestically available biomass from all sources for energy in the EU by 2050, alongside demand projections of 5–19 EJ yr^{-1}. As is usually the case in mitigation analyses, technical potentials may considerably exceed what is economically or socially feasible (Brutschin et al. 2021; Perkins et al. 2023). Nearer term estimates suggest an additional woody feedstock use of about 50 Mm^3 by 2030 (Sikkema et al. 2021).

The literature lacks a widely accepted definition of biomass carbon neutrality (Selivanov et al. 2023), with the seemingly interchangeable use of different concepts obfuscating the complex nature of the issue. Emissions accounting schemes generally assume forest biomass to be carbon–neutral at the point of combustion, with harvest effects instead showing up in GHG balances of the LULUCF sector (Norton et al. 2019; Pulles et al. 2022).

Although we will explicitly point out that bioenergy is in principle not carbon neutral, we refer to Mather-Gratton et al. (2021) for a detailed description of various simplified narratives permeating the ongoing socio-political debate around the topic, as that is beyond the scope of this review. Overall emission saving effects and resulting trade-offs, and thus perceived potential of forest bioenergy, depend strongly on chosen system boundaries and counterfactual scenarios (Bentsen 2017; Leturcq 2020; Cowie et al. 2021; Giuntoli et al. 2022; Selivanov et al. 2023). Even in stylized cases where the literature generally agrees, studies identify widespread issues of overly optimistic displacement factor (Harmon 2019; Leturcq 2020; Howard et al. 2021) and carbon payback time estimates (Ter-Mikaelian et al. 2015; Buchholz et al. 2016; Soimakallio et al. 2022).

The exact potential role of forest bioenergy in European decarbonization efforts remains debated, with its value varying significantly depending on a multitude of factors. In energy systems set to rely primarily on wind and solar power in the near term, sufficiently flexibilized bioenergy, partially derived from forest biomass at the end of its life cycle, can complement the variable output of wind and solar and support the de-fossilization of the heating sector (Thrän et al. 2015; Lauer et al. 2023) while contributing to energy independence (Mandley et al. 2020; Hinrichs-Rahlwes 2023; Proskurina and Vakkilainen 2024). Sustainable implementation, given the competing demands on forest resources and potential trade-offs, requires careful governance frameworks (Giuntoli et al. 2022; Stubenrauch and Garske 2023; European Scientific Advisory Board on Climate Change 2025). Those need to ensure appropriate feedstock selection, realistic counterfactual assumptions and projections, consideration of alternative or potentially preceding wood uses in cascading systems, as well as include appropriate policies and incentives to avoid lock-in at high demand levels (Reid et al. 2020; Luhas 2022).

Forest management impacts, challenges, trade-offs and synergies

Forest biomass for energy use can be obtained from various sources, including living trees, harvest residues, salvage operation biomass, thinning residues, and mill by-products such as sawdust and wood chips (Cambero et al. 2015; Laganière et al. 2016; Mandley et al. 2020). Management decisions relating to feedstock and associated harvesting intensity significantly influence both climate and ecosystems. Low-intensity practices, such as collecting woody debris and using waste wood, are generally considered to support emissions reduction while limiting ecosystem damage. High-intensity management, particularly converting natural forests to plantations, offers limited climate benefits while significantly harming ecosystems (Sterman et al. 2018; Pohjanmies et al. 2021; Giuntoli et al. 2022).

The climate impact of forest bioenergy is complex and time-dependent. When biomass is burned, it releases stored carbon as CO_2, initially creating a ‘carbon debt’ (Mitchell et al. 2012; Ter-Mikaelian et al. 2015). At first, bioenergy typically releases more CO_2 per unit of energy than fossil fuel combustion due to its lower energy density and conversion efficiency (Mitchell et al. 2012; European Commission, Joint Research Centre, Institute for Energy and Transport 2014). While the released carbon can be reabsorbed through forest regrowth, the characteristic ‘payback time’ for this debt varies from decades to centuries, strongly depending on management practices and system boundaries (Mitchell et al. 2012; Lamers and Junginger 2013; Buchholz et al. 2016; Bentsen 2017; Nabuurs et al. 2017a, ; Soimakallio et al. 2022; Peng et al. 2023). Even though forest bioenergy may eventually offset its carbon emissions when compared to fossil fuel burning, it cannot compete with the immediate emission benefits of wind and solar energy (Giuntoli et al. 2022), which are also way more land use efficient (Dijkman and Benders 2010; Smil 2015). As unabated fossil fuels are aimed to be phased out across the EU (Victoria et al. 2020; Potrč et al. 2021; Hainsch et al. 2022; Council of the EU 2023), this limits the future potential for forest bioenergy as a meaningful climate change mitigation lever (Brunet-Navarro et al. 2021).

Intensive biomass extraction for forest bioenergy may significantly affect the forest carbon sink, habitat quality and other FES (see carbon and biodiversity sections). Long-lived wood products can more efficiently reduce GHG emissions by replacing GHG-intensive materials while storing carbon for extended periods of time (see material section), after which they might still be used as bioenergy resources in cascading systems. Use of woody materials for energy generally entails air quality and health risks from emissions of volatile organic compounds and particulate matter (Weldu et al. 2017; Cincinelli et al. 2019; Tran et al. 2023). Although work on advanced biomass conversion technologies remains ongoing, there are fundamental thermochemical limits to significant further efficiency gains (Shahbaz et al. 2021; Yu et al. 2021; Erb and Gingrich 2022; Saravanakumar et al. 2023).

Forests for biodiversity conservation and other non-material FES

European forest biodiversity faces persistent challenges despite policy commitments, with most forest habitats showing unfavourable conservation status and protection targets unlikely to be met by 2030. Management approaches for enhancing biodiversity seem to be in conflict with timber and energy provision targets while offering synergies with climate adaptation and long-term carbon sequestration.

Policy, status and potential

Despite increases in European forest area and biomass (see Introduction), only 15% of European forest habitats show a favourable conservation status (European Environment Agency 2019; Muys et al. 2022a) and the last few remaining old-growth forests in Europe are insufficiently protected (Sabatini et al. 2020). While broader threats to species and habitat diversity include atmospheric pollution, climate change, biological invasions and landscape fragmentation (IPBES 2018), forest biodiversity faces very direct pressures – such as the conversion of the few remaining old-growth forests (Mikoláš et al. 2023), intensive harvesting regimes and especially clear-cuts, creation of monocultures, removal of habitat trees and deadwood, cultivation of non-native species, soil compaction, and biocide application (Pötzelsberger, Bauhus, et al. 2021; Muys et al. 2022a; 2022b).

Recent additions to European forest policy such as the New Forest Strategy and Biodiversity Strategy for 2030 indicate a shift towards more ecological approaches compared to previous policies, emphasizing biodiversity preservation and protection (Mubareka et al. 2022; Sotirov et al. 2024). Specific objectives include strict protection of all remaining primary and old-growth forests, strengthened forest protection and restoration efforts, integration of ecological corridors, and expansion of biodiversity-friendly forest management practices, all within the broader goal of putting Europe's biodiversity on a path to recovery by 2030 (European Commission 2020; 2021). A key objective of the Biodiversity Strategy, in conjunction with the Kunming-Montreal Global Biodiversity Framework (UN Convention on Biological Diversity 2022), is the protection of 30% of EU land area by 2030, including 10% protected strictly. This represents an increase from current protection levels of approximately 26% (European Environment Agency 2024b) and 3.4% (Cazzolla Gatti et al. 2023) for the total EU land area as well as 23.6% (Forest Europe 2024) and 3.6% (Nagel et al. 2025), respectively, for forest land.

Subject to some management restrictions, non-strictly protected forests can typically still be harvested for timber (Verkerk et al. 2014), with 85% of European forest area available for wood supply at present (Köhl et al. 2020). Forests can be expected to feature prominently in both strict and non-strict protected area expansion, potentially providing co-benefits for biodiversity and carbon sink aspects, while incurring trade-offs with material and energy goals due to decreased harvest (Nagel et al. 2023; Keith et al. 2024). The total area of remaining primary and old-growth forests in Europe has been estimated at around 1.9 Mha, representing 1.1% of its forest area (Sabatini et al. 2020; Keith et al. 2024). Effective implementation of protection strategies requires robust assessment frameworks to track conservation success beyond mere spatial coverage (Rodrigues and Cazalis 2020; Li et al. 2024). Monitoring progress towards biodiversity targets requires meaningful, science-based yet practical indicators, whose development across temporal, spatial and species scales remains a complex challenge (Fraixedas et al. 2020; Nicholson et al. 2021; Linser and Wolfslehner 2022; Muys et al. 2022a). While advances have been made, such indicators remain limited by a lack of comprehensive data (Ćosović et al. 2020; Oettel and Lapin 2021; Linser and Wolfslehner 2022; Wolfslehner and Linser 2023; Paillet et al. 2024), complicating efforts to track progress effectively. The deterioration in biodiversity and ecosystem condition is expected to continue, with agreed policy objectives unlikely to be met by 2030 (European Environment Agency 2025c). Implementation gaps, insufficient resources, and lack of policy coherence present major barriers to achieving these forest-related sustainability targets (European Environment Agency 2025c).

Forest management impacts, challenges, trade-offs and synergies

Biodiversity-oriented forest management should prioritize maintaining and enhancing the ecological integrity of forest ecosystems. This involves effectively preserving the few remaining natural forest ecosystems (Whitlock et al. 2018; Sabatini et al. 2021), designating climate-adapted areas of high ecological value as nature reserves, restoring critical habitats, and establishing high minimum standards for biodiversity protection in managed forests. Resulting management approaches encompass adaptation to climate change and provision of diverse habitats, e.g. by shifting monocultures towards diverse uneven-aged mixed-species stand structures with considerable amounts of deadwood and old trees providing microhabitats (Brockerhoff et al. 2017; Asbeck et al. 2021; Larrieu et al. 2022; Muys et al. 2022a). Such a transition to more structured forests also helps to ensure the future stability of the forest carbon sink (see carbon section). Strategic withdrawal of forests from harvest through payment for ecosystem services (PES) schemes can incentivize biodiversity conservation while maintaining landowner participation, as demonstrated by Finland's METSO programme (2025). Such approaches recognize that some forest areas may provide greater societal value through biodiversity conservation than timber production. Reduced harvests can however lead to trade-offs with other policy targets (see material and energy sections), or an increase in imports potentially involving detrimental impacts on climate and biodiversity elsewhere (Fuchs et al. 2020; Meyfroidt et al. 2020; Q. Zhang et al. 2020a, ; Bruckner et al. 2023; Zhong et al. 2024; Wiebe and Wilcove 2025).

The conflict between forest multifunctionality and management intensity is well documented across various FES, including biodiversity (Chaudhary et al. 2016; Sing et al. 2017; Eyvindson et al. 2018; Aggestam et al. 2020; Pohjanmies et al. 2021). Moreover, societal and land manager demands for FES are often considerably mismatched – with society preferring multifunctional and mostly non-provisioning FES (Augustynczik et al. 2020; Winkel et al. 2022). Yet even though timber provision accounts only for around one-fifth of the total economic value of ecosystem services provided by woodland and forests, which has been estimated as 81 billion € for the EU-28 in 2012 (Vysna et al. 2021), forest managers have limited income streams beyond the sale of timber. This highlights the potential and need for future policy mechanisms that support biodiversity and other FES beyond biomass production (Ranacher et al. 2017; Ciesielski and Stereńczak 2018; Augustynczik et al. 2020; Winkel et al. 2022).

Given existing challenges and trade-offs, more holistic forest management approaches are needed to provide multiple FES simultaneously, which can be facilitated by various landscape management, policy and governance interventions. Market-based approaches to innovation focus on creating financial incentives such as PES to address services with high societal demand but currently limited or nonexistent economic compensation, such as carbon sequestration, local temperature reduction, habitat provision, erosion and flood control, water purification, aesthetics, and recreation (Wunder et al. 2020; Hernández-Morcillo et al. 2022; Winkel et al. 2022). While implementing European-wide PES schemes presents significant challenges, promising pilot projects are ongoing in multiple countries (Pötzelsberger, Bauhus, et al. 2021; Forest Europe 2022), and particularly small-scale forest owners seem willing to participate in contract-based management promoting environmental goals (Juutinen et al. 2022).

Strategic landscape-level planning approaches focus on optimizing the spatial distribution of different management intensities to minimize trade-offs between competing objectives. These approaches range from segregative 'land sparing' (spatial segregation with dedicated production and conservation zones) to integrative 'land sharing' (maintaining minimum standards across multiple objectives simultaneously), with hybrid 'triad' zoning dividing landscapes into intensive management, extensive ecological management, and strict protection zones (Krumm and Kraus 2013; Phalan 2018; Betts et al. 2021; Pötzelsberger, Schuck, et al. 2021; Himes et al. 2022). However, current forest zoning in Europe is overwhelmingly focused on wood production and lacking in strict protection, with direct biodiversity implications (Nagel et al. 2025). The predominant intensive management across European forests reflects existing ownership patterns and economic priorities, but may be insufficient to meet biodiversity conservation targets under current EU strategies. Climate-Smart Forestry (CSF) offers a potential holistic framework for forest management that applies complementary to spatial management approaches, as e.g. each triad zone can apply CSF principles differently (Nabuurs et al. 2017b; Verkerk et al. 2020). It aims to incorporate balance between short and long-term goals related to carbon sequestration, climate adaptation, wood production, protection of biodiversity and the provision of other important ecosystem services, by developing regionally adapted spatially diverse forest management strategies promoting local synergies. Building on long-standing concepts of sustainable forest management (Prins et al. 2023), implementation details are however strongly context-dependent and do not scale trivially across Europe's heterogeneous forest landscapes. Implementing CSF in practice requires comprehensive understanding of complex ecological processes and management trade-offs at the specific site, as well as challenging decision-making under uncertainty associated with future climate projections (Hanewinkel et al. 2022; Tognetti et al. 2022). Stakeholders are still missing crucial structural, financial and knowledge-sharing support (Lazdinis et al. 2019; Bowditch et al. 2022; Juutinen et al. 2022).

Combining economic and strategic innovations, alongside continued societal pressure for environmental goals, has the potential to yield significant benefits. Public demand for regulating and cultural ecosystem services can drive policy and management changes, while innovation in management approaches enables land managers to explore of a range of more sustainable options. Public financing for the provision of certain FES then has the potential to empower stakeholders to balance demands on a variety of forest functions and services more sustainably (Konczal et al. 2023).

Discussion and conclusion

A multitude of societal demands and environmental threats increasingly challenge the sustainable development of European forests. Fundamental tensions arise between FES such as carbon sequestration, timber provision for material and energy use, biodiversity, and other services, creating complex trade-offs that forest managers attempt to navigate but cannot fully resolve across spatial and temporal scales. As climate change impacts accelerate and further restrict management options, forest managers need to simultaneously increase the resilience of ecosystems and adapt utilization of forest resources. These challenges extend beyond Europe. Global analyses reveal similar tensions between forest management objectives when ecosystem services and climate change intersect. Approaches ranging from rewilding-inspired forestry to systematic multi-objective planning frameworks have been proposed to address trade-offs across diverse forest systems (Vizzarri 2024; Wang et al. 2025). However, European forests face distinctive pressures from high population density, fragmented ownership structures, polycentric governance, and warming rates exceeding global averages, which intensify these conflicts and constrain management responses.

A central conflict exists between maintaining forest carbon sinks and intensifying timber harvest. The annual European forest carbon sink continues to decline due to climate change impacts, disturbances, and forest maturity (Pilli et al. 2022; Korosuo et al. 2023), while wood demand grows, partially driven by decarbonization goals. Management intensification creates carbon opportunity costs, with temporal mismatches between immediate harvest impacts and long-term substitution benefits complicating impact assessment (Brunet-Navarro et al. 2021; Gregor et al. 2022).

Forest vulnerability to climate change exacerbates these challenges, threatening both carbon storage and material provision functions.

Those points build on and extend previous research on forest multifunctionality, while incorporating some often-neglected multisectoral perspectives: Structured, mixed-species forests can improve resilience. While they may reduce short-term productivity due to their generally longer rotation length, increased resilience may enhance long-term yields. They are also, at least for the foreseeable future, misaligned with the timber industry's preference for softwood. Nonetheless, there is an opportunity to increase the share of hardwoods in forests, and create co-benefits for climate-change mitigation, adaptation and biodiversity, by reducing demand for bioenergy (Pretzsch et al. 2021; Krtschil et al. 2022). Conflicts between different demands on European forests could further be mitigated by transforming society's increasing demand for multiple services into economic returns for forest managers, complementing timber sales with additional sources of income (Augustynczik et al. 2020; Vysna et al. 2021).

Our review identifies demand-side management as a crucial lever for addressing forest-use conflicts. In climate policy, over-reliance on volatile forest carbon sinks to meet emission targets appears increasingly risky (European Environment Agency 2024a; European Scientific Advisory Board on Climate Change 2024), suggesting forest-based mitigation should play a more complementary role than is currently foreseen in the Climate Law. This necessitates accelerated GHG emission reductions in other sectors, including traditionally 'hard-to-abate' sources (Shindell and Rogelj 2025; Windisch et al. 2025). The substitution benefits of wood products, while in many cases significant, may diminish as other sectors decarbonize (Brunet-Navarro et al. 2021; Gregor et al. 2022), requiring careful prioritization of actions to avoid 'lock-in' in forest management portfolio development. Technical innovations in hardwood processing and development of long-lived products can help align industry needs with forest adaptation goals, as forests transition from remaining vulnerable conifer monocultures towards more structured mixed forests with increased hardwood content. Sufficiency-oriented policy reforms could reduce per capita material demands while maintaining decent living standards (van Heerden et al. 2025). Woody biomass demand for energy use requires particular attention, as current usage patterns often conflict with higher-value applications and carbon storage goals. Strict implementation of cascade use principles and avoiding landfilling could significantly reduce primary wood demand and enhance mitigation benefits of harvests, restricting bioenergy to end-of-life products and processing by-products, while flexibly complementing more efficient renewable sources for electricity as well as heat production (European Commission, Directorate General for Internal Market, Industry, Entrepreneurship and SMEs 2016; Ramage et al. 2017; Köhl et al. 2020; Sotirov et al. 2024; European Scientific Advisory Board on Climate Change 2025). This transition requires coordinated policy action to ensure alternative energy sources are developed in parallel with reduced forest biomass harvesting as well as increased material utilization. The ever-present risk of indirect impacts further reinforces the need for demand management. An unbalanced reduction in harvests in the EU threatens increases in imports with negative environmental impacts elsewhere, as already shown for various aspects of the EU Green Deal (Fuchs et al. 2020; Bruckner et al. 2023; Zhong et al. 2024). Potential forest expansion likewise requires careful consideration of displacement effects. Similar to demonstrated effects of dietary change on land competition (Intergovernmental Panel On Climate Change 2022; Sun et al. 2022), addressing per capita demand for forest products appears crucial for avoiding leakage effects (Erb et al. 2022).

Several management innovations offer potential solutions to some of those complex challenges. Climate-Smart Forestry provides a framework for balancing multiple objectives (Verkerk et al. 2020), while triad zoning combines intensive, extensive, and protective management approaches across landscapes to balance harvests and environmental impacts (Betts et al. 2021). Increasing disturbance frequencies necessitate a new balance between ecological and economic objectives in deadwood management (Mansuy et al. 2024; Sotirov et al. 2024). However, these approaches must be regionally adapted and implemented with consideration for local conditions and constraints. A differentiated adaptive management approach based on stand conditions, embracing CSF principles and triad approaches at landscape scales, offers a practical framework for implementation, resolving local trade-offs while contributing to broader objectives under a changing climate (Jandl et al. 2019; Fehrenbach et al. 2022; Leibniz-Forschungsnetzwerk Biodiversität 2024). Already climate-resilient stands with high ecological integrity may benefit from prioritization of carbon storage and biodiversity through reduced harvesting. Vulnerable stands require continued harvesting to facilitate higher resilience, while stands producing high-value long-lived products need balanced approaches considering substitution benefits. Forest owners and planners require both technical guidance for adaptation measures and financial incentives. Enhanced support for forest owner networks can facilitate knowledge transfer on improved management and adaptation practices (André et al. 2017; Brown et al. 2018), while PES schemes could help bridge the gap between societal demands and economic realities (Wunder et al. 2020; Pötzelsberger, Bauhus, et al. 2021; Hernández-Morcillo et al. 2022). Policymakers should seek to align provided economic incentives with regulation and coordinate action across multiple domains in more holistic policy frameworks (Hernández-Morcillo et al. 2022; Winkel et al. 2022), while addressing the 'Four I's': Innovations, Institutions, Infrastructures, and Investments (Verkerk et al. 2020). However, translating these approaches into practice faces substantial political, economic, and institutional barriers that vary across member states' diverse governance structures and forest traditions. For instance, PES schemes encounter scaling challenges due to transaction costs and additionality verification, explicit triad zoning requires politically contentious decisions about production versus protection priorities, and transitioning towards more climate-adapted mixed forests faces resistance from supply chains optimized for softwood.

The significant regional variation in forest management regimes across Europe complicates the development of uniform policy approaches. Solutions that might work in Northern European even-aged systems, such as extending rotation lengths to enhance carbon storage, have different implications than in Central European continuous-cover systems or Mediterranean protected forests (Scherpenhuijzen et al. 2025; Suvanto et al. 2025). Ownership structure also shapes feasible interventions: centralized public management in Poland enables coordinated harvest scheduling, while fragmented private ownership in Germany requires different policy mechanisms to achieve similar outcomes (Suvanto et al. 2025). Property rights also differ significantly between private owners across Europe (Nichiforel et al. 2018). Climate-driven species transitions will interact differently with existing management traditions, such as Nordic clear-cut systems facing distinct challenges in diversifying stand structure compared to selective harvest systems already practiced in Central Europe. We conclude that this heterogeneity necessitates regionally adapted implementation of broader policy frameworks rather than prescriptive Europe-wide silvicultural guidelines.

Substantial knowledge gaps limit our ability to effectively manage the discussed competing demands. EU National Forest Inventories require more frequent updates incorporating recent data, particularly including the immediate and longer-term effects of the 2018–2022 droughts, as the current forest sink situation may well be more dire than available estimates suggest. Current vegetation models inadequately represent forest responses to climate stress, particularly regarding drought effects and mortality dynamics, limiting reliable projections of future species suitability and sink capacity (Anderegg et al. 2022). The complex interactions in forest and land system dynamics, including how harvest reductions affect trade patterns and trigger indirect land use change, remain incompletely understood. Better understanding of these processes and potential policy mechanisms to address displacement effects and prevent environmental burden shifting remains a critical research priority. Estimates of substitution benefits of wood products vary widely across the literature largely due to diverging methodological choices, which hinder the development of robust, broadly applicable policy recommendations. Additionally, actionable biodiversity indicators remain under development. Addressing these gaps is essential for evidence-based policy and adaptive management under increasing uncertainty, as recent comprehensive assessments demonstrate: forest condition and biodiversity continue to deteriorate despite policy ambitions, with implementation gaps and resource constraints remaining critical barriers (European Environment Agency 2025c).

The challenges documented in this review originate from a fundamental mismatch: European policies demand expanding forest carbon sinks, increasing timber harvest for material substitution and bioenergy production, as well as enhanced biodiversity protection – objectives that create irreconcilable resource conflicts intensifying under climate change. Current policy frameworks pursue these demands simultaneously without adequately addressing inherent trade-offs, creating unsustainable trajectories. Improvements in forest management and monitoring, while valuable, cannot resolve conflicts rooted in finite forest capacity and accelerating stress due to climate change related impacts. Successfully managing European forests in the twenty-first century requires acknowledging these constraints and implementing coordinated action across multiple domains: enhanced adaptation to maintain forest resilience, demand-side management to reduce competing pressures, and policy frameworks that explicitly address trade-offs rather than pursuing conflicting objectives in parallel.

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Declarations

Conflicts of interest RG is a subject editor for European Journal of Forest Research. All other authors have no competing interests to declare that are relevant to the content of this article.

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