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Forest-based climate change mitigation and adaptation in Europe

Pieter Johannes Verkerk, Philippe Delacote, Elias Hurmekoski, Janni Kunttu, Robert Matthews, Raisa Mäkipää, Fredric Mosley, Lucia Perugini, Christopher P.O. Reyer, Stephanie Roe, Erik Trømborg

Authors

Pieter Johannes Verkerk, European Forest Institute

Philippe Delacote, INRAE, France

Elias Hurmekoski, University of Helsinki, Finland

Janni Kunttu, European Forest Institute

Robert Matthews, Forest Research, United Kingdom

Raisa Mäkipää, Natural Resources Institute Finland, Finland

Fredric Mosley, European Forest Institute

Lucia Perugini, Euro-Mediterranean Center on Climate Change, Italy

Christopher P.O. Reyer, Potsdam Institute for Climate Change Research (PIK), Member of the Leibniz Association, Potsdam, Germany

Stephanie Roe, World Wildlife Fund, United States of America

Erik Trømborg, Norwegian University of Life Sciences, Norway

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Executive summary

What is at stake?

Achieving the goals of the Paris Agreement requires (i) significant and urgent reductions in anthropogenic emissions of carbon dioxide (CO_2) and other Greenhouse Gases (GHGs) and (ii) an increase in CO_2 removals. The capacity of forests and forestry to remove CO_2 from the atmosphere at large scale is considered key in climate mitigation pathways.

The European Green Deal relies on forests and forestry for achieving the European Union's (EU-27) climate neutrality by 2050. Currently, forests and wood products remove approximately 380 $MtCO_2eq$ per year, which compensates for about 10% of EU-27's total greenhouse gas emissions. According to new policy targets proposed by the European Commission, the EU-27's Land Use, Land-Use Change, and Forestry (LULUCF) sector, which includes forests and wood products as well as other land uses, will **need to remove approximately an additional 50 $MtCO_2eq$ per year by 2030, 100 $MtCO_2eq$ per year by 2035 and 170 $MtCO_2eq$ per year by 2050**.

This report aims to review and synthesise (i) the scientific literature on the mitigation potential provided by forest-based activities in the EU-27, as well as Norway, Switzerland and the United Kingdom, (ii) the impacts of climate change on forest ecosystems, forestry, industries and markets and (iii) policies and tools for stimulating carbon removals and emission reductions. Based on these assessments, this report provides policy recommendations to realise the full climate change mitigation potential provided by forest-based activities.

How can forests and wood use contribute to climate change mitigation and by how much?

Forest-based mitigation activities can reduce emissions by sequestering carbon in forest ecosystems, retaining carbon in wood products and avoiding emissions through improved management and material or energy substitution. These activities can be broadly categorized as actions that protect (including avoiding deforestation and forest degradation and conservation), manage (including harvesting or active other management), or restore forests (including afforestation and reforestation), as well as actions that improve wood use (including shifting towards longer lived products, material substitution, cascading).

Based on a review of the scientific literature, mitigation activities such as **avoiding deforestation, afforestation/reforestation, shifts in wood use, cascading and increased efficiency can be combined** as they have limited effects on each other and can have positive impacts on biodiversity. When combined they could provide **an additional mitigation potential of up to 72 $MtCO_2eq$ per year by 2050 in the EU-27**. This additional EU-27 forest-based mitigation potential of 72 $MtCO_2eq$ per year could increase to (i) **125 $MtCO_2eq$ per year when combined with forest conservation activities**, or (ii) **138 $MtCO_2eq$ per year when combined with other active forest management**, or (iii) **143 $MtCO_2eq$ per year when combined with decreasing forest harvest**.

The estimated net mitigation potential is subject to a high degree of uncertainty due to the variability arising from individual studies. These studies use different data, methods, system boundaries, types of potential and scenario assumptions including the assumed counterfactual development. Nevertheless, these **findings suggest that, according to the estimates available in the scientific literature, it will be challenging to achieve the EU-27's climate targets for the LULUCF sector by 2035 and 2050** through forest-based mitigation activities alone. Moreover, **limited information is currently available on related costs and feasibility** to realise the mitigation potential.

Climate change is already affecting European forests, forestry activities, and forest product markets.

In the future, climate change may lead to substantial changes to carbon sequestration as a result of shifts in tree species ranges, changes in forest productivity and increased disturbance damage. Moreover, climate change may lead to changes in wood quality, supply and costs, which can affect carbon storage in wood products and possible substitution effects. It is important to assess to what extent adaptation measures are needed to counteract and cope with ongoing climate change and forest disturbances. Therefore, forest-based mitigation and adaptation need to be considered together.

How can the contribution by forest-based mitigation actions be maximised?

A holistic approach (both in research and policy-making) **is needed that considers the interactions between forest-based mitigation activities, adaptation and other sectors**. This must cover all the relevant carbon pools and fluxes of forest ecosystems (in biomass, deadwood and soil), wood products, avoided emissions through material and energy substitution, as well as any leakage and rebound effects along with their development **up to and beyond 2050**.

- ***European forests and wood products can provide a significant contribution to achieve climate neutrality by 2050.*** However, as the sector's contribution is finite, it cannot compensate for delayed actions in other sectors. The technology, capacity and strategies needed to deploy forest-based mitigation measures are readily available and have already been used for decades. Maximum efforts, starting with the most sustainable and cost-efficient mitigation activities, should urgently be pursued to reduce net emissions.

- ***Combine forest-based mitigation activities to maximise the forest-based mitigation potential.*** Rather than stimulating or focusing on single mitigation activities, policy and management strategies need to consider all the possible forest-based mitigation strategies, their synergies, interactions, co-benefits and regional applicability to maximise the contribution to climate change mitigation.

- ***Prioritise the types of wood use that give the largest net emission reductions.*** As the availability of woody biomass is and will be vastly insufficient to replace all emission-intensive products and fossil energy, there is a need to focus on wood uses that provide the largest emissions reductions. Wood-based products should be reused and recycled as many times as possible and energy recovery should be preferred over going to landfill.

- ***Forests across countries differ, and so do implementation strategies***. The sustainable implementation of forest-based mitigation activities that maximise the benefits and limit the risks must consider regional and country contexts, e.g., with regards to forest cover, forest ownership or wood use.

- ***Move to policy implementation and include appropriate support tools.*** Many policy and legislative proposals have been developed as part of the European Green Deal, and there is now a need to move towards implementation at European, national and sub-national levels. This will require a better understanding of all the possible forest-based mitigation strategies, how and if they can or should be combined, as well as their costs, risks and co-benefits. Appropriate incentive systems, the exchange of best practices between countries and regions as well as a transparent, harmonized, and robust monitoring framework should be established.

- ***Climate change mitigation and adaptation need to be considered together***. To strengthen forests' climate change mitigation role, especially beyond 2050, it is crucial that policy and management strategies consider forest-based mitigation together with the need for adaptive management.

- ***Extend climate targets beyond 2050***. Current EU policies focus on the period from 2030 to 2050, but the focus needs to be extended beyond 2050 because even if climate goals are met, climate change will continue.

1. Introduction

Aims of the report

This reports aims to review and synthesise:

- the scientific literature on the mitigation potential provided by forest-based activities in the European Union, Norway, Switzerland and the United Kingdom;
- the impacts of climate change on forest ecosystems, forestry, industries and markets ;
- policies and tools to stimulate carbon storage.

The Paris Agreement requires major societal and economic transformations to ensure that the increase in global average temperature remains below 2˚C (or even 1.5°C) compared to pre-industrial levels. Nevertheless, the year 2019 saw the highest CO_2 concentrations in 2 million years and the average global temperature rose by 1.09°C in the period 2011 to 2020 when compared to pre-industrial periods (IPCC 2021). Achieving the climate target **requires a significant and urgent reduction in gross anthropogenic emissions of carbon dioxide (CO_2) and other Greenhouse Gases (GHGs) as well as an increase in CO_2 removals** by all sectors. Forests and forestry play an important role in climate change mitigation in a number of ways: firstly, reducing deforestation and forest degradation lowers GHG emissions. Secondly, forest management and restoration can maintain or enhance forest carbon stocks and sinks. Thirdly, improving the use of wood products can allow for greater carbon storage over the long term and avoid emissions by substituting emissions-intensive materials (IPCC 2019, 2022).

To achieve the goals of the Paris Agreement, the European Union (EU) has set ambitious targets to reduce GHG emissions by at least 55% by 2030 and to become climate neutral by 2050 (European Green Deal, European Climate Law, EU 'Fit for 55' climate package). To achieve these targets, the European Commission presented a new proposal on Land Use, Land-Use Change, and Forestry (LULUCF; EC 2021a). In addition, the EU has developed new strategies (e.g., the Biodiversity Strategy and the new EU Forest Strategy) to tackle ongoing biodiversity loss by protecting nature and reversing the degradation of ecosystems. In this regard, mitigation and biodiversity efforts must be implemented together because climate change and poorly implemented mitigation measures may negatively impact biodiversity.

Climate change is already affecting Europe and its forests with projections indicating that temperatures in Europe will continue to rise at rates exceeding global mean temperature changes, independent of the climate change scenario considered (IPCC 2021). Northern Europe is projected to see increasing winter precipitation while the Mediterranean will receive less precipitation and suffer from droughts. Central Europe is projected to see more uncertain precipitation, but this will often be linked to extreme precipitation events (IPCC 2021). The projected changes in climate, together with serious and ongoing biodiversity loss, will further affect forests and the forest-based sector. In recent years, there has been increasing awareness of forest disturbances in Europe resulting from extreme weather and climate events, followed by outbreaks of pests and diseases, all of which may affect the future climate change mitigation potential of forests (Seidl et al. 2014; Pugh et al. 2019; Anderegg et al. 2020; Forzieri et al. 2021). As forests and the forest-based sector are and will continue to be affected by climate change, it is important to assess to what extent adaptation measures are needed to counteract and cope with these ongoing climate change and forest disturbances issues to enhance the long-term resilience and vitality of forests. As such, forest-based mitigation and adaptation also need to be considered and enacted in partnership. Indeed, recently emerged concepts, such as Climate-Smart Forestry (Nabuurs et al. 2017; Verkerk et al. 2020; Bowditch et al. 2020) and Natural Climate Solutions (Griscom et al. 2017), explicitly consider both mitigation and adaptation as well as biodiversity and ecosystem services, when presenting viable bases for sustainable forest management.

Many studies have estimated or reviewed the climate change mitigation potential of land use and forest-based activities (e.g., Rüter et al. 2016; Griscom et al.; 2017; Fuss et al. 2018; Roe et al. 2021; IPCC 2022), however, a synthesis for Europe that considers all the relevant carbon pools and flows is lacking. To support the LULUCF process, and policy making more generally, it is important to have up-to-date and comparable information on the climate change mitigation potential provided by forest-based activities. Such information is, for example, relevant for updates of the EU's Nationally Determined Contribution on cutting emissions and adapting to climate impacts. Moreover, policy implementation requires the consideration of the different measures, funding instruments and compensation mechanisms for forest owners to sequester carbon in their forests.

In summary, this report has three primary aims. Firstly, to review and synthesise the existing scientific literature on mitigation potential provided by forest-based activities in the EU-27, Norway, Switzerland and the United Kingdom (UK) while also providing a country-level breakdown. Secondly, to review the impacts of climate change (including forest disturbances) on forest ecosystems, forestry activities, forest industries and forest-product markets. Thirdly and finally, to review which policies and tools are available to stimulate carbon storage. Based on these reviews, this report provides policy recommendations to support decision-makers to realise the full climate change mitigation potential provided by forest-based activities

2. Forest-based mitigation potential

Chapter highlights

- Forest-based mitigation activities include the protection, management, and restoration of forests as well as improved wood use. These activities can reduce emissions by sequestering carbon in forest ecosystems, retaining carbon in wood products and avoiding emissions through substitution.
- Based on a synthesis of the estimates available from published studies in peer-reviewed literature, the additional mitigation potential offered by forest-based activities in the EU-27, Norway, Switzerland, and the UK to mitigate climate change is sizeable, providing an average of 136–155 $MtCO_2eq\ yr^{-1}$ by 2050, depending on how individual mitigation activities are combined.
- When considering all forest activities, improved forest management is the one that provides the greatest mitigation potential, closely followed by the restoration and protection of forests. The mitigation potential of wood use is primarily related to changes in the material uses of wood instead of primary uses, where the largest benefit is gained when increasing the use of wood in construction, or utilising novel wood-based textile fibres, while simultaneously maintaining or enhancing forest carbon stocks.
- Mitigation activities may have both positive and negative synergies. Hence, a holistic approach is needed that considers the interactions between forest-based mitigation activities and those of other sectors. Avoiding deforestation, increasing afforestation/reforestation, shifts to material uses of harvested wood, cascading and increased material and energy efficiency are all activities that can be combined and provide positive synergies and benefits beyond carbon removals.
- Considerable variations can be found in assessments regarding the mitigation potential of individual mitigation activities. These can be explained by differences in data, methods, system boundaries and scenario assumptions. There may be valid reasons for these differences between studies, however, a consequence is that different types of assessments cannot always be straightforwardly compared.
- Activities such as avoiding deforestation, less frequent or less intensive harvesting, retention of old and dead trees as well as the restoration of peatland hydrology can benefit both forest biodiversity and climate change mitigation.

2.1 The roles of forests and the forest sector in climate change mitigation

Forests provide many benefits to society and one such benefit is forests' role in regulating the climate through their role in the global carbon cycle. This role is the result of photosynthesis in which trees remove CO_2 from the atmosphere and emit it back to the atmosphere via the decomposition of litter and dead trees or (in case of wildfires) combustion. If this cycle was left to follow its natural course, it would result in a long-term balance between CO_2 removals and emissions despite the short-term variations inherent to it. The management of forests by humans can have a profound impact on CO_2 emissions and removals, both immediately and over time. Rising concentrations of CO_2 and the related climate change can influence the growth and development of forests both positively and negatively, with further consequent impacts on CO_2 emissions and removals in forests (see Chapter 3).

When forests are sustainably managed and wood is harvested, carbon is removed from the forest. The harvested wood (and the carbon it contains) can be utilised in various ways, such as in construction and for the production of textiles, chemicals, and energy. The use of wood may contribute to climate change mitigation through carbon storage in wood-based products as well as through substitution by avoiding or reducing GHG emissions. This happens when a wood-based product or energy feedstock replaces a functionally equivalent but more emission intensive material or energy product. Systematic review studies have concluded that wood products cause, on average, lower GHG emissions over their life cycle compared to alternative products (Sathre and O'Connor 2010; Geng et al. 2017; Leskinen et al. 2018; Myllyviita et al. 2021; Verkerk et al. 2021; see also Section 2.3). Such substitution benefits may, however, decrease towards 2050 due to the overall decarbonisation of the economy (e.g., Harmon 2019; Howard et al. 2021). Wood products also retain the carbon contained in harvested wood for years, decades or even centuries, delaying the release of that carbon into the atmosphere after harvest. Carbon is sequestered in wood products' carbon pool (often measured at the global or national scales) when the rate of inflow of carbon contained in harvested and processed wood to the carbon pool exceeds the rate of release of carbon from this pool through decomposition or the combustion of products that reach their end-of-life (see for example Pilli et al. 2015; Brunet-Navarro et al. 2017).

Compared to other emission sectors and activities, the contributions of forests, forestry and wood use to climate change mitigation is multi-faceted and complex. However, in broad terms, there are five principal ways these contributions affect climate change and climate change mitigation:

1. **Forest carbon sequestration.** Forest ecosystems can sequester carbon by removing CO_2 from the atmosphere through photosynthesis and tree growth, releasing oxygen and retaining carbon in trees and other vegetation, deadwood, litter and soil.

2. **GHG Emissions.** Forest ecosystems can release stored carbon back into the atmosphere through deforestation, degradation, harvest and natural disturbances, as a result of decomposition or combustion. There can, however, also be non-CO_2 GHG emissions associated with forest ecosystems, including emissions of methane (CH_4) and nitrous oxide (N_2O), particularly from biomass that is burnt and from soils and decaying organic matter; these types of emissions can be significant from the soils of peatland forests.

3. **Wood product carbon storage**. Wood harvested from forests can retain carbon that was originally removed from the atmosphere by forests in the form of wood-based products; although this carbon is ultimately released into the atmosphere when the products are disposed of at end of life. The disposal can also involve methane emissions under certain conditions if wood products are discarded in landfills.

4. **Substitution of GHG-intensive materials**. Using wood-based products and wood fuel can avoid or reduce the use of alternative non-wood products and fossil energy sources, whose manufacturing, use and disposal may involve higher GHG emissions than the equivalent wood products.

5. **Biophysical effects**. Forests can influence climate by affecting the reflectivity of the land surface (albedo), water evapotranspiration and releasing certain aerosols that also affect climate (see Box 1).

Numerous activities can mitigate climate change by reducing forest GHG emissions and/or sequestering carbon. These activities include forest interventions, which can be broadly categorized as any actions that protect, manage and/or restore forests and wood use, some details of which are shown in Table 1 and used throughout this report. Protecting forests includes avoiding deforestation and forest degradation, both of which lower GHG emissions to the atmosphere and maintain forest carbon sinks. Restoring forests entails afforestation (the establishment of new forests in non-forest biomes), reforestation (re-establishment of forests in converted or degraded forest biomes) and peatland-forest restoration (rewetting degraded peat forests, which suppresses emissions by slowing the decomposition of organic matter in degraded and/or drained peatlands). Forest management covers a broad spectrum of approaches, ranging from conservation-oriented (e.g., establishing conservation set-asides and disturbance management) to production-oriented (e.g., provenance and tree species selection, nutrient management, hydrology management, thinning and harvest regimes). Improved forest management refers to any of the forest management activities that reduce emissions and/or enhance forest ecosystem carbon storage while also minimising, or even eliminating, any negative environmental impacts. Changes in wood use may contribute to either the increased removal of CO_2 from the atmosphere (e.g., shift towards longer-lived products and increased cascading uses) or avoiding GHG emissions through material and/or energy substitution (e.g., shifts towards wood uses that displaces the use of greater fossil-CO_2 emitting materials; see also Leskinen et al. 2018; Verkerk et al. 2021).

Box 1. Non-GHG impacts of forest management.

In this report, the assessment of the climate change mitigation potential of forests and forest management focuses on GHG emission reductions and carbon removal. Forests, and particularly land-use change involving forests (afforestation or deforestation) can involve other impacts on climate not related to GHGs. Changes in forest cover can change the surface energy budget mediated by albedo (i.e., the proportion of solar radiation reaching the surface of the Earth that is reflected to the atmosphere and space), evapotranspiration from forests as well as the surface roughness of land and vegetation. Collectively, these are referred to as biophysical effects, phenomena that have a strong regional/local effect on climate and can have a non-negligible global impact on temperatures, with the direction of change highly dependent on where the land cover change occurs (Perugini et al. 2017). For example, deforestation or conversion to deciduous tree species can cause a strong increase in albedo and hence a cooling effect in boreal regions because coniferous vegetation is darker than open areas covered by snow. In tropical regions, the effect is reversed because changes in evapotranspiration resulting from deforestation are more important than changes in albedo. Several studies highlight the need to consider these biophysical effects in climate change mitigation assessments (e.g., Luyssaert et al. 2018; Grassi et al. 2019; Kalliokoski et al. 2020; Lawrence et al. 2022).

Table 1. Classification of forest-based mitigation activities as used in this report.

Mitigation category	Activity	Types of activities	Type of mitigation
Protect	Avoiding deforestation	Reduce conversion of forests	Emission reduction
	Forest conservation	Set-aside forest areas	Carbon removal
Manage	Forest harvesting (increased, decreased)	Stand thinning and harvesting practices and regimes	Carbon removal
	Active management (other than harvesting)	Provenance selection	Carbon removal
		Nutrient management (including biochar)	Carbon removal
		Disturbance management	Carbon removal
		Tree species selection Hydrology management	Carbon removal
Restore	Forest restoration (including peatlands)		Emission reduction, carbon removal
	Afforestation / Reforestation	Reforestation of forest biomes	Carbon removal
		Afforestation of non-forest biomes	Carbon removal
Wood use	Shifts in wood uses (including by-products)	Shift to long-lived wood products	Carbon removal, emission reduction
		Shift to material uses	Emission reduction
		Shift to primary energy uses	Emission reduction
	Cascading (end-of-life)	Reuse, recycling	Emission reduction, carbon removal
		Downcycling	Emission reduction, carbon removal
		Energy recovery from discarded wood	Emission reduction
	Increased efficiency	Increased material efficiency	Carbon removal
		Increased energy efficiency	Emission reduction

2.2 Mitigation potential of forest activities

Based on a review of the available scientific literature (see Box 2), **forest activities that protect, manage, and restore forests in the EU-27, Norway, Switzerland and the UK have the potential to mitigate on average an additional 142 $MtCO_2eq\ yr^{-1}$ by 2050, with estimates for individual mitigation activities ranging from 11 to 115 $MtCO_2eq\ yr^{-1}$** (see Figure 1). This aggregate potential is based on three forest mitigation activities (avoiding deforestation, decreased harvesting, and increased afforestation/reforestation), which limit (in)direct effects across forest activities. The potential from wood use is described in Section 2.3, and the total mitigation potential for all forest-based mitigation activities (i.e., forest and wood use together) is in Section 2.4. The estimated potential of forest mitigation activities represents the additional emission reduction or carbon sequestration relative to the forest sink in a counterfactual development without the mitigation action. When the sink of forest and wood products of the baseline counterfactual would be considered, and which has been estimated to decline over time (see Box 2), the total potential would be 464 $MtCO_2eq\ yr^{-1}$).

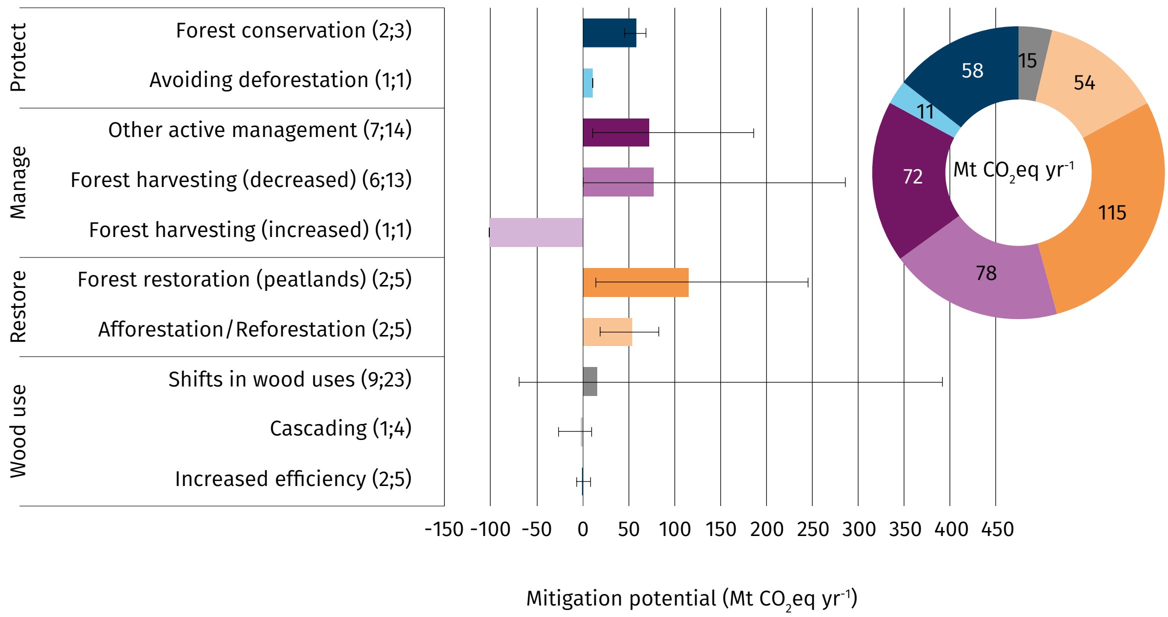


Figure 1. Forest-based mitigation potential by 2050 in the EU-27, Norway, Switzerland and the UK by mitigation activity type.

The solid bars represent the mean values across the full range of the literature reviewed, and the error bars illustrate the minimum and maximum values of the range. Mitigation estimates that combine forest management types are reported in the 'other active management' category. The pie chart represents the relative size of mitigation potential per activity (total mitigation per activity in MtCO$_2$eq yr^{-1} is indicated by numbers). The data sample size (number of studies; number of datapoints) is displayed next to activity type. Literature sources are listed in Annex I.

Out of all forest mitigation activities that aim to protect, manage and restore forests, peatland restoration is reported to provide the largest additional potential (an average of 115 MtCO$_2$eq yr^{-1}, Figure 1). Importantly, this potential is based on two studies of which one (Humpenöder et al. 2020) includes all types of peatlands (e.g., moss, reed, sedge peat, forest) and estimates exclusively for forested peatlands were not provided. Moreover, a distinction must be made between restoring peatland forests and restoring non-forest peatlands that have been afforested. Peatland restoration through rewetting will reduce emissions from the decomposition of peat soils but will often involve the loss of trees due to higher water tables and/or the removal of trees planted in non-forest peatlands (for example, conifer plantations established in bog and fen peatlands in the UK; Anderson et al. 2014). For various countries with high peatland distribution (Finland, the UK, Germany, Poland, Latvia, Estonia, Ireland and the Netherlands), the study by Humpenöder et al. reports substantial mitigation potential. However, country-level estimates of peatland emissions for Finland (15.7 MtCO$_2$eq yr^{-1}, including soil GHG emissions from both croplands and forests on peat soils (Lehtonen et al. 2021), as well as those in the UK (23 MtCO$_2$eq yr^{-1}; Evans et al. 2017), are much lower. Given these discrepancies and that peatland restoration in many areas may not reflect forest measures, the peatland restoration estimates are not included in the (country-level) aggregated potential presented in Figure 2 and Section 2.4).

Forest management provides the most significant contribution to mitigation potential based on the three activity types included in this Section, namely decreased forest harvesting, increased forest harvesting and other active management regimes. According to the literature, decreased forest harvesting could provide a

Box 2. Methods for literature review and meta-analysis to estimate mitigation potential.

In Sections 2.2 to 2.4, we present the results of a structured literature review and meta-analysis which compiles country-level data to estimate the mitigation potential of forest-based mitigation activities for the EU-27, Norway, Switzerland and the UK (30 countries). Mitigation potential is defined as the additional emission reduction or carbon sequestration of a given activity compared to a baseline counterfactual scenario.

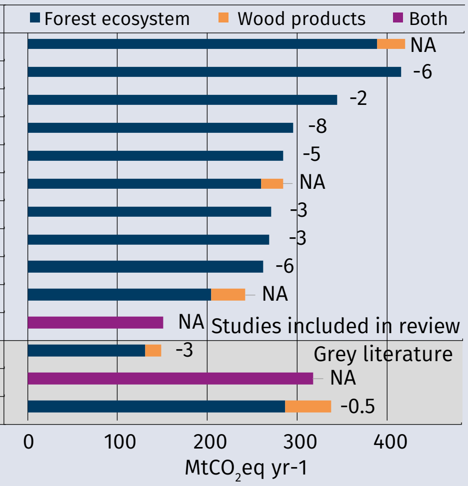
The literature review process was structured as follows:

1. Literature was identified using a common review protocol.
2. Relevant articles were selected from the scientific, peer-reviewed literature (excluding grey literature) from Scopus and Google Scholar by using keywords, including *forest, mitigation, carbon, scenario, EU, wood products*, and by limiting publications to those from the last 10 years (2011–2021).
3. Literature abstracts were screened to identify studies that estimated the climate change mitigation potential of forest management measures, including a reference (i.e., counterfactual) scenario. The geographic scope was limited to the EU-27, Norway, Switzerland and the UK, although national studies, EU-level studies and global studies with separate estimates for the EU or individual Member States were also included. Additional peer-review studies known to the authors were considered as well. As a result of the screening process, data were eventually extracted from 33 studies (see Annex I).
4. Data were extracted from all the selected studies and stored in a database where it was harmonised to facilitate comparison. For each study, the additional mitigation potential was taken from the study directly or estimated by calculating the amount of emission reduction and/or carbon removal attributed to a specific activity or set of activities when compared against a baseline counterfactual scenario (usually a business-as-usual scenario) specified in the study itself. This approach of estimating mitigation potential follows the method used in the 5^{th} and 6^{th} Assessment Reports by the IPCC.
5. To facilitate the comparability of European or EU-wide studies, which often vary in the number of countries considered, we scaled the estimated mitigation potential using the forest area in 2020 (Forest Europe 2020) to match the EU-27 and 30 countries covered by this study.
6. Mitigation data were categorised according to the classification of activities in Table 1, and mitigation potential were aggregated per activity (mean as well as range between minimum and maximum values).

We summarised the full range of mitigation potential from available estimates in scientific literature for the time between 2030 and 2050. The full range includes both the technical potential (the biophysical potential possible with current technologies) and economic potential (mitigation available constrained by costs, often expressed as a carbon price). Due to limited data availability, we report the mean and range of mitigation potential across all the selected studies and do not disaggregate the overall mitigation potential into type or by scenario.

The data in studies published in scientific literature often vary according to the methods, system boundaries, baselines and scenario assumptions used (see Section 2.5). There is a particularly large range in the baseline assumptions across the peer-reviewed literature we examined. To illustrate this, we extracted data on counterfactual scenarios from the EU-level studies that were included in our review and compared these with estimates from grey literature (see figure below). Based on the studies, the average annual baseline forest carbon stock change for the EU-27 was 291 $MtCO_2eq$ yr^{-1}, with estimates ranging from 150 to 418 $MtCO_2eq$ yr^{-1}. Most studies show a declining sink over the considered period. The baseline estimates for each study were generated using different models, considered different time periods and carbon pools and were based on different assumptions about policy, management and harvest rates.

Study	Model	Period
Pilli et al. 2017	CBM	2000/2012-2030
Jonsson et al. 2018	CBM	2000/2012-2030
Nabuurs et al. 2018 (S2)	EFISCEN	2010-2050
Nabuurs et al. 2018 (S1)	EFISCEN	2010-2050
Nabuurs et al. 2018 (S3)	EFISCEN	2010-2050
Jonsson et al. 2021	CBM	2030
Böttcher et al. 2012	EFISCEN	2010-2030
Verkerk et al. 2014	EFISCEN	2010-2030
Böttcher et al. 2012	G4M	2010-2030
Frank et al. 2016	G4M	2030
Luyssaert et al. 2018	ORCHIDEE	2010-2100
Rüter et al. 2016	G4M	2011-2030
Korosuo et al. 2021	Multiple	2021-2025
EC 2020	G4M	2020-2050



Average baseline (or counterfactual) sink development across studies with data for the EU-27. Bars show the average annual sink over the considered period in each study for different carbon pools (forests, wood products, or both), and number labels (where available) indicate the absolute change in the annual sink.

mitigation potential of, on average, 78 $MtCO_2eq$ yr^{-1}. In contrast, the mitigation potential for increased forest harvesting is strongly negative (-101 $MtCO_2eq$ yr^{-1}) in the time frame considered by Pilli et al. (2017) (i.e., up to 2030). However, the literature from which these potentials are obtained often only captures the carbon balances of forest ecosystems and excludes effects on wood uses, therefore these estimates may not provide a complete picture of the mitigation impact (see Sections 2.3 and 2.4). Other active management (tree and provenance selection, nutrient, water, and disturbance management) also provides a sizeable mitigation potential (average of 72 $MtCO_2eq$ yr^{-1}) according to the existing literature.

The potential derived from afforestation and reforestation (average of 54 $MtCO_2eq$ yr^{-1}) is reported as a combined total due to a lack of disaggregated data. However, afforestation and reforestation activities differ in how much carbon they sequester per hectare (Cook-Patton et al. 2020) and how they benefit biodiversity and other ecosystem services (see also Section 2.6), therefore factors such as the type of activity, ecosystem and management regime chosen will determine their efficacy and success.

Forest conservation and avoiding deforestation are mitigation activities that intend to protect forests and keep their carbon reservoir *in situ*. The potential derived from forest conservation (avoiding the use of forest areas or set-asides as a part of forest management) is estimated at an average of 58 $MtCO_2eq\ yr^{-1}$. Although forested areas in the EU-27, Norway, Switzerland and the UK have expanded over the last few decades, gross deforestation has taken place, e.g., as a result of the expansion of agricultural land (Kuemmerle et al. 2016; Levers et al. 2018; Nabuurs et al. 2013). While the total area affected is relatively small, every hectare of lost forest means a large immediate emission (Nabuurs et al. 2013) and, as such, avoiding deforestation could provide a mitigation potential of 11 $MtCO_2eq\ yr^{-1}$ (Nabuurs et al. 2017).

Sweden, Finland, Spain, France, Poland and Germany are the countries with the highest mean mitigation potential, all exceeding 10 $MtCO_2eq\ yr^{-1}$ by 2050 and, between them, represent approximately 60% of the EU's total mitigation potential (see Figure 2). The potential offered by forest management activities is the predominant contributor to forest-based climate change mitigation in most EU countries (Sweden, Finland, Spain, Poland, Germany, Denmark, Norway, Austria, the Czech Republic, Greece, Portugal, Latvia Slovak Republic, Estonia, Lithuania, Hungary, Slovenia, Belgium, Netherlands, Luxembourg and Cyprus). In contrast, more than 50% of such mitigation potential is provided by reforestation and afforestation in France, Italy, Romania, Bulgaria, Croatia, the UK, Switzerland, Ireland and Malta. It is worth noting that many of the studies that estimate country-level mitigation potential do not detail associated types of forest management and afforestation/reforestation activities implemented by region (e.g., species or provenance selection, nutrient management, etc), although such information would be helpful to improve further planning.

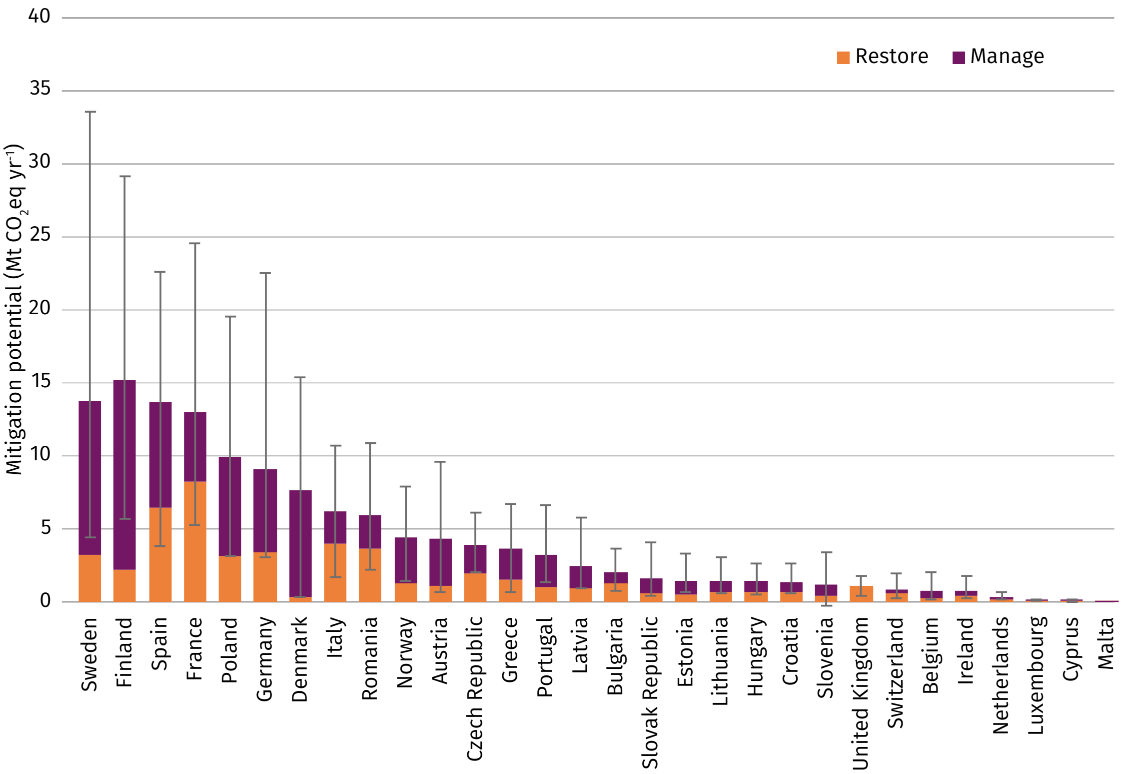


Figure 2. Forest-based mitigation potential by 2050 at the country level.

The solid bars represent the mean values across the full range of the literature reviewed, and the error bars illustrate the minimum and maximum values of the range. The activities captured include decreased harvest and other active management (Manage), and afforestation/reforestation (Restore). The national-level potential presented in this figure do not necessarily add up to the European-wide potential presented in Figure 1 as not all reviewed studies provided a breakdown by country. Literature sources are included in Annex I.

The mitigation potential captured in the literature review represent the average values from the full range of estimates in the literature and, thus, combine technical (the biophysical potential possible with current technologies), and economic potential (mitigation available constrained by costs, often as a carbon price), with the latter being likely more relevant for policymaking. Very few country-level studies provide both technical and economic mitigation potential estimates to compare across the two. A recent study by Roe et al. (2021), which mostly relied on results from global studies, found that the cost-effective economic potential (defined as mitigation costs up to US$100 /t$CO_2$eq, or approximately €88/tCO_2eq) of afforestation, reforestation and forest management is approximately 25% of what is technically possible (see Figure 3). The largest part of this cost-effective potential (69%) is related to forest management across the 30 countries. However, at the country level, Roe et al. found that the economic potential of afforestation/reforestation exceeds the potential by forest management in Bulgaria, France, Hungary, Italy, Malta, Romania, Slovenia, Switzerland, and the UK. Actively managed land and/or areas with high land prices generally increase the cost of mitigation activities and this, when coupled with the large regional range in cost-effective potential, illustrates some of the key underlying variations in each country's circumstances on the costs of implementation.

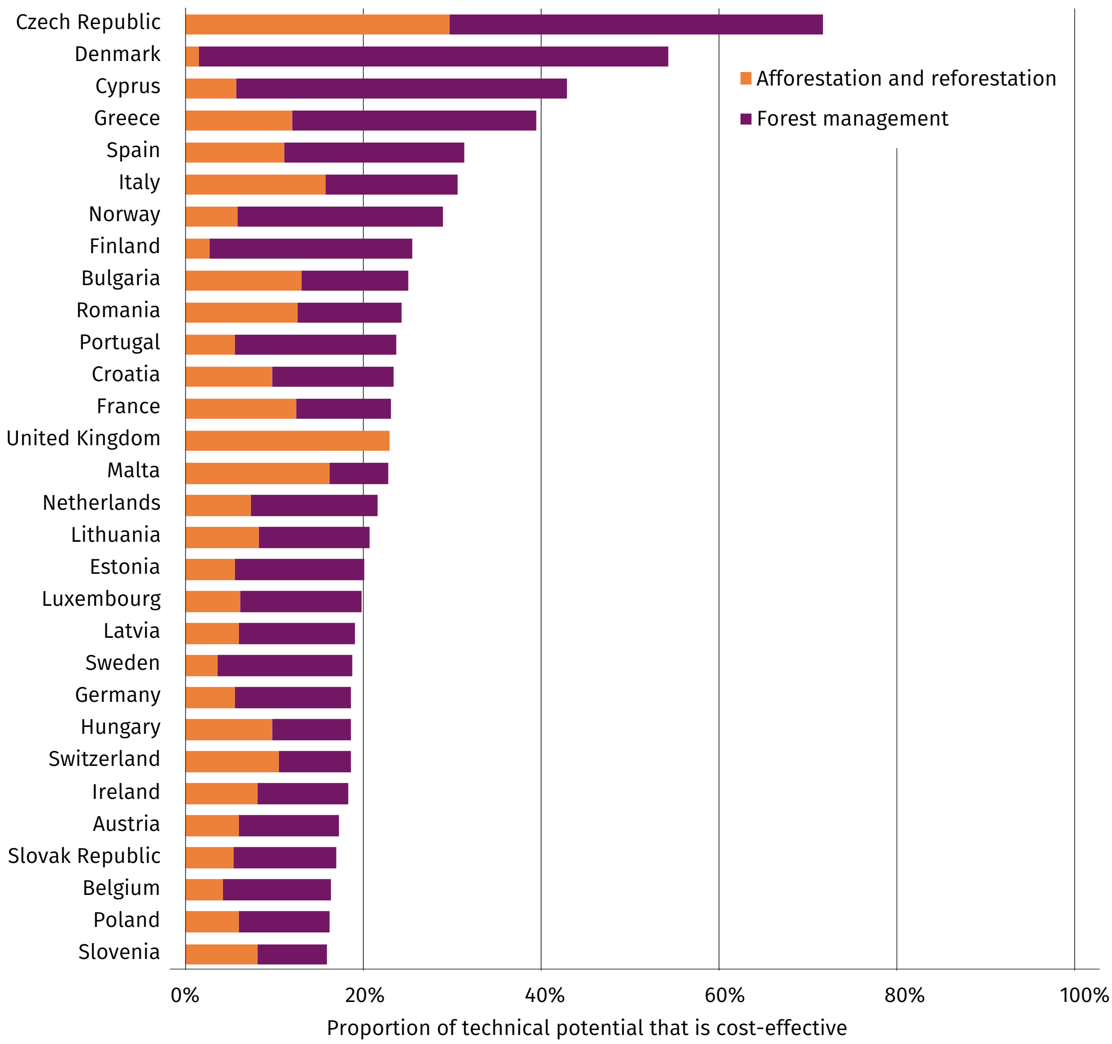


Figure 3. Cost effective mitigation potential by afforestation, reforestation and forest management activities as proportion (in %) of the technical potential, according to Roe et al. (2021).

In summary, forests in the EU-27, Norway, Switzerland and the UK provide substantial potential to mitigate climate change, offering the ability to both reduce emissions and enhance carbon removal. Although the technology, capacity and strategies to deploy forest activities are readily available and have been used to a greater or lesser extent in many areas for decades, sustainable implementation that optimises the benefits and limits risks will depend on the specifics of regional and country contexts.

2.3 Mitigation potential of wood use

According to our review of the scientific literature, **the additional climate change mitigation potential of wood use in the EU-27, Norway, Switzerland and the UK is mainly related to shifts in wood use and is estimated on average at 13 $MtCO_2eq\ yr^{-1}$**, with estimates from individual studies and scenarios ranging between -70 and 391 $MtCO_2eq\ yr^{-1}$ (see Figure 1). The large range in the mitigation potential for shifts in wood use is primarily caused by the assumptions used in the various studies considered (see also Chapter 2.5), particularly two EU-level studies (Brunet-Navarro et al. 2021; Jonsson et al. 2021) which apply opposite assumptions. The high end of the range results from an assumption that there will be no change in the level of harvest despite increased use of wood in construction, this suggests there will only be a change production from paper to construction, which results in very high substitution and carbon storage benefits compared to the baseline development. The lower end of the range assumes there is no change in production structures in response to an increased demand for wood in construction, but the harvest is increased from the baseline, which results in increased net emissions by 2050. Additionally, most studies calculate the substitution impacts using current emission factors, which is likely to greatly overestimate the results by 2050 due to the ongoing decarbonization of the economy. For other wood use-related developments, such as cascading and increased efficiency, the available literature is scarce but the additional mitigation potential appears relatively minor.

Figure 4 complements Figure 1 and provides more detail on the mitigation potential associated with shifts in wood use, including cascading and increased efficiency. On average, a much higher potential is associated with moves towards expanding the material uses of wood (87 $MtCO_2eq\ yr^{-1}$) rather than primary energy uses (-3 $MtCO_2eq\ yr^{-1}$). Typically, the increased material uses involves an increase in wood use for construction, which can simultaneously increase both the substitution impact and the average product life span. Only two studies provided estimates for the climate change mitigation potential of cascading wood use and, in those studies' estimates, only the increased recycling of wood products at the end of their life cycle yielded positive potential (5–9 $MtCO_2eq\ yr^{-1}$) as opposed to their combustion for energy (-26 $MtCO_2eq\ yr^{-1}$). However, even this modest gain is likely to be further diminished given the likely decarbonization of the energy sector in the years ahead (Brunet-Navarro et al. 2017, 2021). Likewise, only two studies examined the impacts of increased efficiency (Johnston and Radeloff 2019; Frank et al. 2016), although the net impacts that cover all the relevant carbon pools are not provided by these studies and the mitigation potential estimates are partly explained by different economic growth rates.

The relatively low potential for cascading wood use in this review arises from the considered scenarios' assumptions, system boundaries and definitions employed. The studies in the review assume relatively modest increases in product lifespans and recycling rates while also suggesting that the avoided roundwood harvest due to cascading or increased efficiency may provide greater mitigation potential than the direct impacts, such as reduced energy demand (Budzinski et al. 2020; Höglmeier et al. 2014; Sathre and Gustavsson 2006). As for the definition, shifts in by-product use could also be considered a cascading effect, however, our review only refers to the end-of-life fate of wood products as cascading, so that some of the mitigation potential associated with a broader definition for cascading falls under the "shifts in wood uses" activity. The negative average potential for cascading is explained by the relatively modest assumptions concerning the rate of material cascading uptake, the limited number of available estimates in the literature and the single large negative estimate for energy cascading. Material cascading has been reported to provide only modest net benefits.

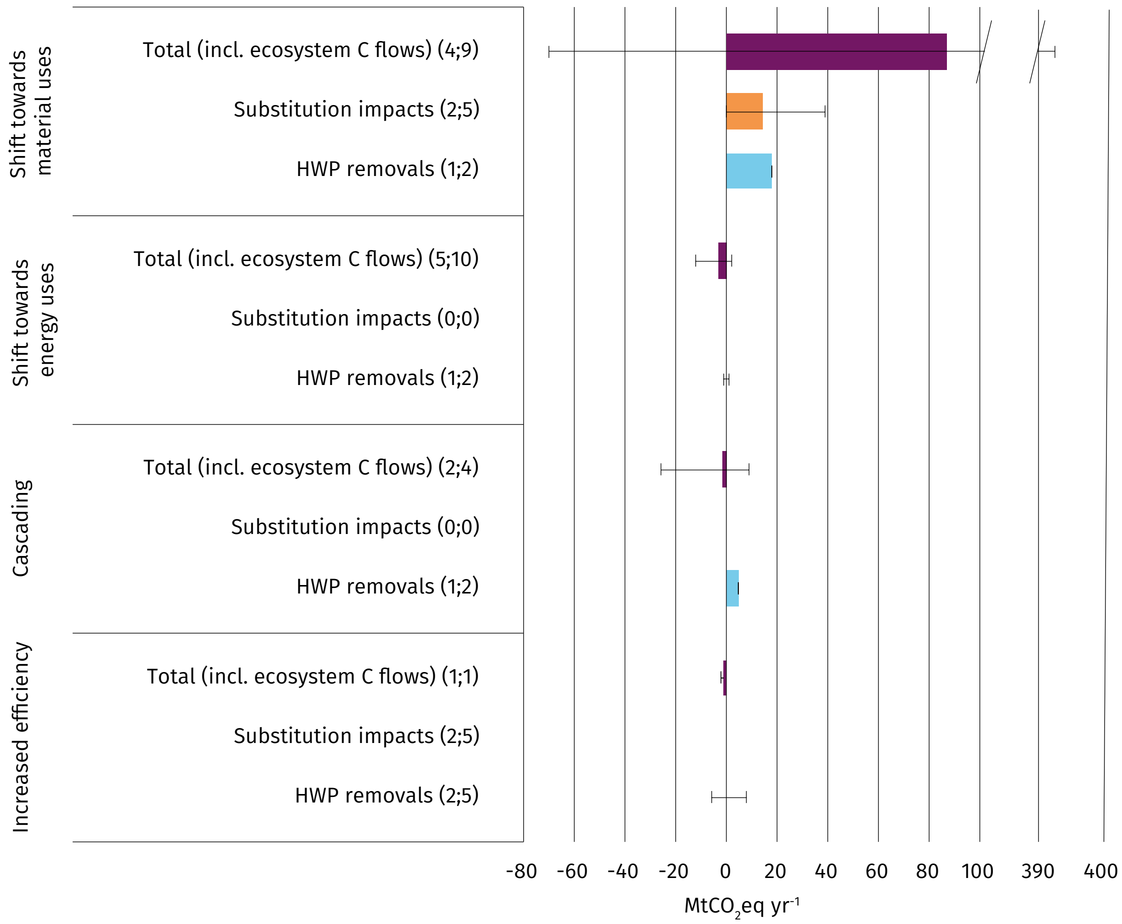


Figure 4. Mitigation potential by 2050 provided by changing wood use patterns in the EU-27, Norway, Switzerland and the UK by activity type. The data sample size (number of studies; number of datapoints) is displayed next to each activity type. Solid bars represent the mean values across the full range of the literature reviewed while the error bars illustrate the minimum and maximum values of the range.

The only country-level net mitigation potential estimates for shifts in wood uses are for Austria (-5 $MtCO_2eq\ yr^{-1}$ on average), Finland (10 $MtCO_2eq\ yr^{-1}$ on average) and Lithuania (-1 $MtCO_2eq\ yr^{-1}$ on average). This range results from the highly influential scenario-specific assumptions and methodological choices used in each study and should therefore be interpreted with great caution. For example, the positive value for Finland as opposed to Austria and Lithuania can be explained by a higher number of scenarios assuming no additional roundwood harvest associated with shifts in wood uses and vice versa.

Importantly, the average substitution impact and product longevity can, at least in principle, be increased by changing the product portfolios or the end uses of wood products regardless of the harvest level. This potential relates more likely to shifts in by-product uses from direct energy use to products such as panels, packaging, textiles and chemicals, rather than a shift from paper and paperboard to increased wood use in construction. This is because, at least in part, the share of log and pulpwood harvest cannot change as much as the end uses of by-products. However, a large-scale reduction in the energy uses of wood requires satisfying the operational energy demand of the pulp mills and sawmills be met through alternative, low-emission energy sources (e.g., hydro- or wind power) or by increasing the energy efficiency of such mills. One clear opportunity relates to the declining demand for newsprint and graphical paper, and the resulting increased availability of pulpwood for alternative uses, such as textiles and packaging (Hurmekoski et al. 2020) or even for construction (Brunet-Navarro et al. 2021). However, it remains uncertain to what extent industry can reform beyond the current trend of digitalization as the market structure is simultaneously influenced by consumer demand and the competitive advantages and the strategies of the industries.

Shifts in wood uses may also lead to changes in the volume and allocation of the harvest to different assortments and tree species, with any such shifts also influencing the carbon balance of forests ecosystems. To offset the loss of carbon from the ecosystem due to harvest, and to achieve an immediate net reduction of emissions, several studies estimated that the required substitution factor would need to be between 1.7 and 2.3 tons of fossil CO_2eq. emissions avoided per m^3 of wood harvested (Seppälä et al. 2019; Köhl et al. 2020). This is approximately four times higher than the present average substitution impact (estimated at 0.5 tCO_2eq./m^3 globally; Hurmekoski et al. 2021). These findings suggest that the average substitution impact needs to be strengthened to compensate for the loss of the forest carbon sink if shifts in wood use lead to additional harvesting. However, this conclusion remains contingent on the realism of the counterfactual (what would happen in the absence of increased wood use) and the definition of the system boundary (the extent that affecting factors have been considered and quantified).

Camia et al. (2020) estimate that primary woody biomass (stemwood, treetops, branches, etc.) harvested from forests and used directly for energy production accounts for more than a third of all wood-fuelled energy production in the EU. According to Jåstad et al. (2020), one terawatt hour of wood-based bio-heat holds the potential to reduce fossil emissions by 10–17 MtCO2eq $yr^{-1}$by 2040, however, this potential considers fossil-fuel emissions only. According to our review, the net mitigation potential of bioenergy remains limited and in the 30 countries studied here, the utilisation of residues for bioenergy could already be close to its full potential. This means that the mitigation scenarios construed here portray shifts away from material uses towards bioenergy uses rather than, for example, increased efficiency of residue utilisation and, thus, often lead to increased net emissions compared to the baseline. As with wood use in general, the overall climate impact of bioenergy continues to be debated, with the specifics of each argument or finding dependent upon the system boundaries and scenario assumptions used (e.g., Mäkipää et al. 2015; Berndes et al. 2016; Favero et al. 2020; Cowie et al. 2021). However, the combustion of logging residues is often considered to provide more immediate climate benefits than the combustion of large diameter stemwood (Pingoud et al. 2016; Giuntoli et al. 2022). Furthermore, it should be noted that the material substitution impacts attributed to wood use arise, to a large extent, from the use of wood residues for internal mill energy in the manufacture of wood products. This is because the biogenic GHG emissions of bioenergy are held to be zero to prevent double counting with ecosystem carbon stock changes in the LULUCF sector (Rüter et al. 2016).

The uptake of bioenergy with carbon capture and storage (BECCS) could influence bioenergy mitigation potential. In scenarios that seek to limit warming to 1.5˚C or 2˚C, there is substantial deployment of CCS and BECCS (IPCC 2022). BECCS can be applied to district heating and CHP-plants, as well as pulp and paper mills. Pulp and paper mills have been suggested to hold the largest technical potential in the EU, with a technical removal potential of 62 $MtCO_2$ yr^{-1} (Rosa et al. 2021). However, there is a dearth of studies assessing the potential of BECCS based on forest biomass in the EU and in individual European countries. The only available study estimating additional mitigation potential compared to a baseline suggested minor gains associated with forest-based BECCS in the EU by 2050 (Rosa et al. 2021; Roe et al. 2021). There are many technical and economic hindrances of large-scale deployment (e.g., Budinis et al. 2018; Levihn et al. 2019), as well as risks related to land use competition, food security issues and trade-offs with biodiversity (Hanssen et al. 2020). The technical potential should be interpreted against a backdrop of feasibility concerns involving crop yields, available land, storage basins, economic costs, technological readiness, policy frameworks and so forth, as well as sustainability concerns, such as the extensive amount of land, water and fertilizer required, particularly for crop-based BECCS (Roe et al. 2019). Due to these constraints and risks, most studies deem that significant negative emission impacts as a result of employing BECCS are only expected to manifest after 2040 and even then, the feasible potential remains uncertain. Ultimately, and adding to the above concerns, any meaningful deployment of BECCS will depend on the technical availability of suitable biomass feedstocks that can contribute towards net negative emissions (see Box 3).

Due to the low number of estimates in the literature for the mitigation potential of wood uses in Europe, as well as the high number of assumptions influencing these estimates, an analysis of their reliability or breakdown into the technological- and economic-potential components is complicated. Besides high variation between estimates (see Section 2.5), the estimates contain considerable uncertainty, especially regarding substitution impacts. As substitution occurs at the product level, the number of possible substitution cases is immense, which leads to using secondary data sources and simplifications in an attempt to estimate market-level substitution impacts (Howard et al. 2021). In most cases, it is simply unknown which wood product can be used to replace which non-wood products, where and when, to what extent and what the consequences of that would be. Life Cycle Assessments (LCA) and market data only exist for some of the most established product groups, and even then, these values are likely to evolve over time. Notably, in the long-term, ambitious climate policy should result in an increase of renewables in the energy mix so that that emissions from fossil energy-intensive materials will reduce, leading to considerably lower substitution impacts (Harmon 2019; Brunet-Navarro et al. 2021). Indeed, the higher end of the presented range for mitigation potential assumes that the average GHG emissions of the substituted products and energy carriers will remain unchanged in the next few decades and, indeed, the next few centuries, which does not align with the Paris Agreement targets. Nevertheless, in the long term, harvested wood can continue to provide a low-emissions source of materials and energy as long as the required levels of wood supply can be met whilst maintaining or enhancing forest carbon stocks.

Box 3. BECCS, biomass sources and carbon impacts.

When considering the potential role of bioenergy and BECCS in Europe, it must be recalled that woody biomass are globally traded commodities. On the whole, Europe imports relatively small quantities of biomass for energy uses even though some European countries make substantial use of wood pellets sourced from outside of Europe for energy generation. Hence, the implication is that these countries would likely look beyond European forests to supply the quantities of biomass required for any large-scale deployment of BECCS. For BECCS to be effective, the biomass feedstocks used need to cause very low to zero net emissions to the atmosphere when the full life-cycle balance between forest carbon stock changes and biomass combustion is considered. However, sharply divided views exist in the scientific literature about whether net emissions from forest bioenergy are high or low (see for example, Ter-Mikaelian et al. 2015; Cowie et al. 2021). Some studies indicate that the increased use of bioenergy from forests in North America and Europe can be combined with actions to maintain, improve or expand forest areas and make more effective use of harvested wood for products (see e.g., Smyth et al. 2018; Cintas et al. 2017). Nevertheless, the net effects of bioenergy production on forest carbon stocks and sequestration are complex and context specific. Changes in forestry practices to supply additional woody biomass from forests for energy generation can result in both negative and positive impacts on the development of carbon stocks and sinks, with negative impacts on carbon balances becoming more likely as the scale of biomass extraction from forests is increased (Aguilar et al. 2020; Birdsey et al. 2018; Xie et al. 2021; Cintas et al. 2016). A cautious approach is therefore needed to determine how and at what scale woody biomass could potentially be supplied, either from Europe and/or elsewhere, in support of BECCS and the extent to which any biomass supply from forests can be combined with forest management actions that maintain or enhance forest carbon stocks and sinks.

2.4 Total forest-based mitigation potential

Our literature review of mitigation potential by forest activities and wood use revealed a portfolio of measures that are available to policy makers, forest owners/managers and industry. Nevertheless, caution should be exercised when implementing multiple measures simultaneously as they may cause indirect counterproductive impacts which are not easy to foresee. As such, the estimated mitigation potential briefly detailed in Sections 2.2 and 2.3 cannot be easily summed up.

Halting deforestation, promoting afforestation and reforestation, shifts in wood use, cascading and increased material/energy efficiency are activities that can be implemented with limited or no effects on each other, although they may have implications for other sectors (e.g., agriculture, energy). There are, however, activities that will potentially conflict with each other, especially those related to activities that aim to protect and restore forests on the one hand and those that manage and use wood on the other. For example, protective measures, such as conservation or reduced harvest, may focus on storing carbon within forest ecosystems and will necessarily require restricted wood use. Conversely, measures that focus on carbon storage in wood products or on substitution effects (Johnston and Radeloff 2019; Churkina et al. 2020) will likely have negative implications for carbon storage in forest ecosystems. Such impacts have, in many cases, been ignored for different reasons even though they are crucial for defining optimal mitigation strategies (Fehrenbach et al. 2022). In addition to such direct effects of mitigation activities on each other, there may also be indirect effects. Reduced harvesting in forests that are currently under active management (including management that impacts wood production), may lead to gains in carbon storage in forest ecosystems at one location, but these gains may be offset elsewhere in the landscape, or even globally through international trade (Kastner et al. 2011; Pendrill et al. 2019a, b). Altogether, a holistic and integrated approach is needed that considers all relevant carbon pools and fluxes and their impacts that may vary over time and space.

To provide an estimate of the total forest-based mitigation potential based on individual mitigation activities reviewed in Sections 2.2 and 2.3, we bundled mitigation activities that can be combined with limited effects on each other. These bundled activities illustrate the options space with regards to the total forest-based mitigation potential, however, they are not presented simply as alternative packages to select from. The bundles are presented in Figure 5 and are based on results from the scientific literature although, as previously noted, it has to be kept in mind that the aim and scope of the studies in the literature sample vary significantly. As a result, the development of all carbon pools of forest ecosystems (living biomass, litter, soil, deadwood) and wood products, as well as substitution effects are not always consistently covered by all studies. We refer to Section 2.5 for a more in-depth discussion about methodological challenges.

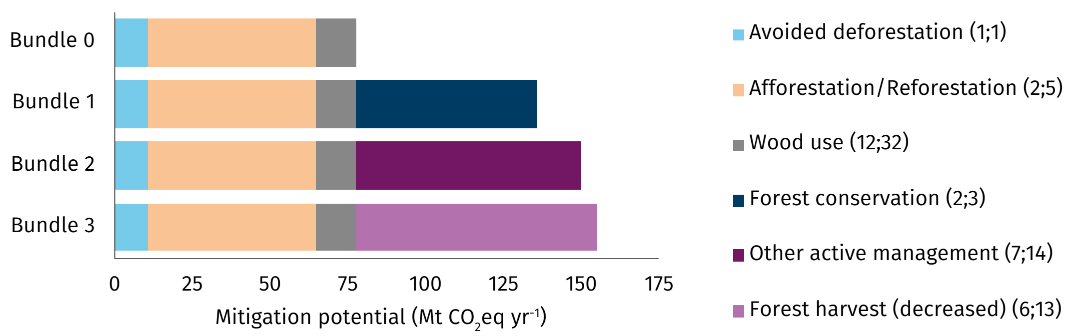


Figure 5. Forest-based mitigation potential by 2050 in the EU-27, Norway, Switzerland and the UK of bundled mitigation activities as reviewed in Sections 2.2 and 2.3.

Colour coding for activity types and the data sample size (number of studies; number of data points) are displayed in the legend. Literature sources are included in Annex I.

Table 2. Additional mitigation potential (in $MtCO_2$eq. yr^{-1}) of forest management and wood use activities for the period 2021-2030 in the EU-28 as estimated by Rüter et al. (2016).

Scenario	Forest biomass and soils	Wood products	Substitution	Leakage	Total
Increasing C stock in existing EU forests	205.6	-14.5	-44.1	-40.1	107
Cascading – increased recovery of solid wood products	-0.02	0.03	11.8	1.4	13.2
Cascading – prevent first use of bio-mass for energy	-30.3	22.8	-1.4	37.3	28.4
Strongly increase material wood use	-18.3	14.1	15.2	-5.4	5.6

According to the existing literature, **avoiding deforestation, afforestation/reforestation and wood use could provide a mitigation potential of up to 78 $MtCO_2$eq yr^{-1} by 2050** in the EU-27, Norway, Switzerland and the United Kingdom when compared to a business-as-usual scenario (see Figure 5). **Combining these activities with (i) forest conservation (bundle 1) could mitigate 136 $MtCO_2$eq yr^{-1}, (ii) other active management (bundle 2) provides a mitigation potential of 150 $MtCO_2$eq yr^{-1} while (iii) lower harvest (bundle 3) would result in a total mitigation potential to 155 $MtCO_2$eq yr^{-1}.** For comparison, Table 2 shows the mitigation effects of several measures, as estimated by Rüter et al. (2016) for the EU-28. This study comprehensively estimated the mitigation impacts of several strategies while covering all the relevant carbon pools and fluxes.

2.5 Sources of variability in estimated mitigation potentials

Sections 2.2–2.4 reveal large ranges in the estimated potential for individual mitigation strategies both at EU and country level. This variability in estimates can be explained by differences in data, methods, system boundaries, the types of potential and scenario assumptions, including the assumed counterfactual development, all of which will be explored in more detail in this section.

One basic reason for differences in estimated mitigation potential is that studies can refer to different data sources. Studies can rely on international data sources that follow international definitions or use national level data following national definitions. As an example, a fundamental consideration is the area of land that counts as forest. In international assessments, forest areas have been taken to consist of those land areas reported by European countries as forest. Under the UNFCCC GHG reporting framework, land anthropogenic fluxes are considered as all those occurring on *managed lands*, defined as "*lands where human interventions and practices have been applied to perform production, ecological or social functions*" (IPCC 2006). Each country has the possibility to set its own definition of managed lands within the broad definition above, based on specific national circumstances. Generally, European countries consider all their forest area as managed, but the precise definition referred to in determining areas of forest varies from country to country (e.g., in terms of minimum area that counts as a forest). Forest areas reported by national forest inventories and included in international forest resource assessments by FAO and Forest Europe can be different from those included when reporting national GHG inventories to the UNFCCC. Typically, forest resource assessments will report on all forest areas in a country, regardless of whether they are being managed. Forest areas referred to in GHG inventories are limited to managed areas, but this can be based on a relatively broad definition for the area of managed forests, for example, often including protected areas such as in national parks, where there are active measures to mitigate disturbances.

Besides data, different methods employed in studies can be an important reason for diverging results. In national GHG inventories, estimates of net CO_2 emissions and removals by forests are frequently derived by comparing results from periodic national forest inventories, which are based on direct measurements in forests. These estimates therefore, implicitly include dynamic responses of vegetation to enhanced atmospheric CO_2 and climatic change, as well as the impacts of forest management activities on carbon stocks. However, some countries use model-based methods applied to forest areas to estimate CO_2 emissions and removals; these models generally do not represent the effects of enhanced CO_2 and climate change. Estimates for forests in GHG inventories for some nations may not always be complete, or may involve uncertainties because of limitations in data and methods, notably on carbon stocks and stock changes in forest soils, deadwood and litter.

Some models, such as forestry bookkeeping models, Integrated Assessment Models (IAMs) and process-based forest (or vegetation) models, are sometimes used to estimate the global potential for mitigation activities in different sectors (such as forestry), notably the contributions of different sectors towards specific climate targets (e.g., 1.5°C or 2°C). These models and their associated frameworks involve many methodological differences to the methods employed in compiling national GHG inventories. Estimates of global land-related anthropogenic fluxes produced by these models do not agree with estimates derived by summing up the estimates reported in country GHG inventories. The discrepancy has been quantified at around 4–5 Gt CO_2 yr^{-1} (Grassi et al. 2018) and is largely attributable to differences in defining the anthropogenic land flux. Given the magnitude of these discrepancies, understanding and then resolving them is important when attempting to compare the results of models and country GHG data, for example, when assessing progress towards global and national and European targets for GHG emissions reductions.

The inclusion or non-inclusion of changes in certain carbon pools, such as soil or wood products, along with flows (e.g., substitution) and decisions over which forest areas to include in assessments can all be regarded as examples of system boundary choices. Generally, decisions about where to set system boundaries for assessments can have a significant impact on the results ultimately obtained. Another important example that underlies variability in estimates of potential is related to the extent to which impacts outside the forest system boundary are represented (in other words, the extent to which the system boundary is expanded to cover impacts outside forests). Some assessments are limited to carbon stock changes in forest carbon pools, thereby excluding carbon stock changes in wood products and material or energy substitution effects. Alternatively, studies may also include carbon stock changes in wood products but still exclude substitution effects, whilst other studies focus just on carbon stock dynamic and substitution impacts of wood products, excluding any impacts on forest carbon stock dynamics. One further example of an important system boundary choice is the extent to which land-use change dynamics are represented. A fixed forest area may be assumed in some studies, or dynamic changes in forest area may be allowed for as a result of afforestation, reforestation and/or deforestation. Secondary land-use change effects are also be considered in some studies, such as afforestation of cropland, leading to the conversion of other land areas for growing crops. The affected land areas may be in the same locality as the afforestation activities or they may be distantly located, even in other countries. The representation of such effects, if any, depends on the extent to which factors such as market-mediated linkages between land use and management decisions in different countries and regions are included or excluded in any given study. The above kinds of choices are not always presented explicitly in the descriptions of methods provided in a study and some choices may be made unconsciously as a part of the detailed description of calculation methods. Hence, the dependence of results on some system boundary decisions is not always immediately apparent in all studies.

Scenario assumptions represent another obvious source of variability in estimates. The choice of assumptions can have a significant influence on results and the conclusions drawn. For example, it is apparent that very different outcomes will be obtained from studies that assume that the level of wood harvest in a studied region will increases by one percent as opposed to studies that assume a fifty percent increase, and then whether the use of wood shifts towards construction or towards biofuels. Similarly, studies often define the counterfactual (or baseline) scenario differently. It is commonly understood that a baseline scenario is intended to portray a reality that would unfold in the absence of the set of mitigation activities that are being assessed. Often, a baseline scenario is defined as 'business-as-usual', essentially a continuation of activities (e.g., forest management practices or policy) from the past and present that persists into the future. However, the way this principle is put into practice can vary between studies.

The differences in data, methods, system boundaries and scenario assumptions, including the definitions of scenarios, may all be valid and reflect the different goals and questions addressed by the various types of assessments and models. However, a consequence is that the results produced by these different types of assessment cannot always be straightforwardly compared. Here, it is necessary to reiterate that the mitigation range summarised in this study is not a result of systematic analysis of all pools in all EU countries, but a synthesis of the estimates available in peer-reviewed literature which differ widely in their scope and objectives and contain several data gaps.

2.6 Synergies between climate change mitigation and biodiversity

Climate change mitigation measures that aim to enhance forest carbon sequestration or reduce soil GHG emissions also often impact biodiversity (Table 3). Here we focus on the biodiversity effects of climate change mitigation measures but acknowledge that such synergies are bi-directional and, indeed, a recent synthesis show that actions to halt biodiversity loss generally benefit the climate (Shin et al. 2022). Protecting carbon rich forest ecosystems from deforestation and from soil degradation is obviously a climate change mitigation measure that also has positive impacts on forest biodiversity (e.g., Pörtner et al. 2021). Furthermore, biodiversity can be maintained by forest conservation, where forests are set aside and not managed for wood production, which generally increases average forest carbon stock at the stand scale (e.g., Finer et al. 2003; Mäkipää et al. 2011). According to meta-analyses conducted by Paillet et al. (2010) and Wang et al. (2021), the overall species richness in unmanaged forests is higher than in managed forests and plantations, but this varies among taxonomic groups. Species dependent on forest cover continuity, deadwood, and large trees (bryophytes, lichens, fungi and saproxylic beetles), as well as carabids, are negatively affected by forest management while the richness of vascular plant species increased. The response for birds was heterogeneous and likely dependent on landscape patterns. Thus, the impacts of the intervention on biodiversity should be evaluated with its ecological significance to target ecosystems and the conservation status of the species involved; focusing on red-listed species or specialist species of a target habitat will have the greatest chance of avoiding local extinctions (Jong and Dahlberg 2017).

Forest-based climate change mitigation measures that focus on active management are often in direct or partial conflict with biodiversity goals, but positive synergies do exist (e.g., Muys et al. 2022, Giuntoli et al. 2022; Table 3). Less frequent harvesting and greater retention of forests' structural elements would increase carbon storage in forest ecosystems, decrease timber production and enhance biodiversity (Schwenk et al. 2012). Landscape scale planning of forest operations, which consider species requirements and dispersal ability, can enhance synergies between forest biodiversity and carbon sequestration (Sing et al. 2018). Large and intense harvest-induced disturbances followed by a change in tree species composition have the strongest detrimental effect on species richness (Paillet et al. 2010). Forest productivity is affected by tree species selection and the rate of forest carbon sequestration is shown to be higher in stand of multiple tree species than in monocultures (e.g., Shanin et al. 2014). Other management interventions can also affect forest biodiversity according to their intensity, for example, selection and retention systems have a less severe impact on species richness than rotation forestry that employs clearcutting (Chaudhary et al. 2016, Paillet et al. 2010). Forest thinning may even increase the biodiversity of the ground vegetation, primarily by influencing species richness after such a disturbance (Strengbom et al. 2017; Burton et al. 2013), even though it temporarily decreases forest carbon stock and carbon sequestration (Strengbom et al. 2017). However, in the long run, only slight differences in plant species richness can be detected when comparing clear-cutting and selection cutting (Økland et al. 2003). Planting non-native species that grow well and store a lot of carbon can also be a mitigation option, however, conflicts with biodiversity conservation may arise (Pötzelsberger et al. 2020).

Lengthened rotation times will increase the availability of older trees as well as the availability of coarse woody debris, both of which promote biodiversity (Ranius et al. 2003; Weslien et al. 2009; Felton et al. 2016). However, if reduced harvests are compensated for by expanding harvests elsewhere, the net biodiversity effect will depend on the initial biodiversity values of the areas involved and the success rate of species colonization.

Large-scale harvest of logging residues (e.g., for bioenergy) in managed forest landscapes significantly decreases habitat availability for many deadwood-associated species (Bouget et al. 2012; Geijer et al. 2014; Ranius et al. 2018; Johansson et al. 2016). Logging residue extraction can have significant negative effects, especially for species naturally adapted to sun-exposed conditions (Ranius et al. 2018) and a number of red-listed species may also be affected since several of them require stumps (Jonsell and Hansson 2011) and the branches and tops of deciduous trees on clearcuts (Felton et al. 2016). General consensus exists that coarse woody debris (e.g., snags, logs and high stumps) is ecologically more important than fine woody debris as a habitat for saproxylic species (Camia et al. 2020). However, species composition differs between coarse and fine wood habitats, and there is complementarity between species assemblages between different deadwood types, meaning it is impossible to substitute one deadwood category for the other (Bouget et al. 2012). Slash extraction may also pose risks for future biomass production due to the associated loss of nutrients, especially if fine fractions and needles are removed (Ranius et al. 2018; Mäkipää et al. 2015).

Forest nitrogen fertilisation increases tree growth in nutrient-limited boreal forests but not in nitrogen saturated ecosystems in Central and Southern Europe. Furthermore, nitrogen fertilisation decreases the biodiversity of understorey vegetation through a changed dominance hierarchy of the community, although it does increase timber production and carbon sequestration (Strengbom et al. 2017). Currently, nitrogen fertilisation is not widely applied in European forests as its use is still primarily limited to boreal, nutrient-limited sites.

Restoration-oriented mitigation measures provide synergies for climate change mitigation and biodiversity (Strassburg et al. 2020). In boreal forests, restoration and retention of trees can, for example, increase the carbon stock of deadwood and habitat availability for saproxylic species (Peltoniemi et al. 2013). However, the restoration of boreal peatlands that have positive biodiversity impacts may be an inefficient method to mitigate climate change (Juutinen et al. 2020; Tolvanen et al. 2020).

Afforestation of agricultural land and changing degraded land to forests seems a relatively cost-effective climate change mitigation option (Fuss et al. 2018) and is among the major mitigation measures included in Nationally Determined Contributions (NDCs) submitted by countries to the UNFCCC. While the afforestation of degraded land can deliver substantial mitigation benefits with co-benefits to biodiversity (Lewis et al. 2019; Fayet et al. 2022), the afforestation of cropland may compromise food production (Fuss et al. 2018). As a final note regarding afforestation, when employed on native grasslands, it has a significant negative effect on biodiversity as many species require rich, open habitats (Burrascano et al. 2016).

Given the ongoing trend, increased efforts are required to mitigate climate change and to simultaneously prevent further losses to forest biodiversity. Leclère et al. (2020) have shown that the extension of existing biodiversity management plans for the restoration and conservation of 40% of land area would avoid less than 50% of the predicted biodiversity losses, but through the sustainable intensification of production methods and changes in consumption patterns, more than two thirds of anticipated future biodiversity losses can be avoided. Such an integrated approach, where the production of raw materials and forest carbon sequestration is intensified simultaneously with reduced waste and consumption, is key for achieving both biodiversity and climate change mitigation targets.

Table 3. Forest-based mitigation activities and their biodiversity impacts.

Category	Activity	Type of activities	Synergies and conflicts between mitigation and biodiversity
Protect	Avoiding deforestation and degradation	Reduced conversion of forests, reduced forest degradation	• Synergy as forest biodiversity maintained
Manage	Forest conservation	Set-aside forest area	• Synergy through higher biodiversity in conserved and unmanaged forests compared to managed forests.
	Forest harvesting	Stand thinning as well as harvest practices and regimes	• Synergy if extended rotation length or lower thinning intensity increases habitat availability.
	Active management (other than harvesting)	Provenance selection	• Synergy or conflict, depending on the genetic diversity of the original stand.
		Nutrient management and soil preparation	• Conflict through reduction of diversity of plant species.
		Disturbance management	• Synergy when catastrophic disturbances can be avoided. • Conflict where fire-dependent species are threatened.
Restore	Forest restoration	Tree species selection, hydrology management	• Synergy when original community structures are restored and structural diversity as well as tree species diversity is increased. • Conflict if non-native and potentially invasive tree species are introduced
	Afforestation/Reforestation	Reforestation of forest biomes	• Synergy when degraded land, recently cleared croplands or peat mining sites are afforested
		Afforestation of non-forest biomes	• Conflict when grasslands or other ecosystems that host high or endemic biodiversity are converted to forest biomes.
Wood use	Shifts in wood uses (including by-products)	Shift to long-lived wood products	• Synergy when changes in manufacturing reduce eutrophication and pollution. • Conflict when shifts in wood use lead to increased harvest pressure
		Shift to material uses	
		Shift to primary energy uses	
	Cascading (end-of-life)	Reuse, recycling	• Synergy when cascading reduces harvest pressure on forests
		Downcycling	
		Energy recovery of discarded wood	
	Increased efficiency	Increased material efficiency	• Synergy when cascading reduces harvest pressure on forests
		Increased energy efficiency	

3. Climate change impacts and needs for adaptation

Chapter highlights

- While forests play an important role in climate change mitigation, forests are also affected by climate change and require adaptation. Forest-based mitigation and adaptation, therefore, need to be considered together.
- Tree species distribution modelling shows that, in a wide range of climate scenarios, the second half of this century will see almost all main European tree species experience reductions of their suitable areas, especially in eastern and southern Europe, although some species will gain substantial areas in the north. These range shifts would likely entail substantial changes to carbon sequestration.
- Model-based projections generally confirm that moderate climate changes in northern and central Europe will increase productivity, although it is still unclear whether there will be a strong CO_2-fertilisation effect. Projections of changing forest productivity are uncertain because models struggle to properly account for changing background mortality (i.e., mortality not linked to specific events) and disturbance-induced mortality.
- Disturbance damage has the potential to reduce productivity gains and amplify productivity losses induced by gradual climate changes. However, disturbance-damage projections and implications for carbon storage over large spatial scales and longer periods are notoriously difficult. Natural disturbances may increase biodiversity while simultaneously putting ecosystems services at risk, which may lead to releases of substantial amounts of stored carbon.
- Climate change could also affect forestry as forest industries and forest-product markets are sensitive to changes in wood supply and costs as well as wood assortments and quality, which can have implications on carbon storage in wood products and possible substitution effects.

3.1 Impacts of climate change on forest ecosystems

Climate change impacts on forest ecosystems result from gradual changes in growing conditions and rapid changes triggered by extreme events and disturbances (hereafter simply referred to as natural disturbances). These impacts are shaped by the current state of forests, management and land use legacies, local soil and site conditions, the connectivity of the forest landscape, as well as the changes in environmental driving variables, such as nitrogen deposition, atmospheric CO_2 concentration, temperature and precipitation. Ongoing climate change will affect the mitigation potential of Europe's forests, especially through shifts in tree species ranges, productivity changes and altered disturbance regimes, all of which can substantially affect the forest carbon balance.

3.1.1 Tree species range shifts

Climate change affects the distribution ranges of tree species by reducing the area in which species can grow or, conversely, by allowing them to expand into habitats that now increasingly provide the required environmental resources to sustain growth and competitiveness (Lindner et al. 2014). In a warming Europe, this usually means moving northward and up in altitude (Meier et al. 2012). Moreover, in Europe, with its long history of forest management and use, pure stands of economically important tree species (e.g., Norway spruce) have already been planted outside of their natural distribution area to increase timber yield (e.g., Hanewinkel et al. 2013), which has increased their vulnerability to disturbances (see Section 3.1.3). At the same time, forest management can actively shape the species composition in forests, favour species mixtures that make forest resilient to changes, and support species range shifts by planting or naturally regenerating species that are thought to cope better with changing local conditions. Nevertheless, projected high warming scenarios will likely be too extreme for tree species migration rates to cope.

Species range shifts have already been observed as is the case with holm oak replacing European beech in higher elevations in southern Europe (Peñuelas et al. 2007), and are projected to intensify under high warming scenarios. Recent species distribution modelling (Dyderski et al. 2017) shows that for 2061–2080, under a wide range of climate scenarios (RCPs 2.6, 4.5 and 8.5 from three different global climate models each), almost all the main European tree species will see reductions in their suitable ranges, especially in eastern and southern areas. However, tree species such as the European silver fir, European beech, European ash, common and sessile oak will gain substantial areas in the north. The non-native Douglas fir, northern red oak and black locust are also projected to gain areas, but uncertainties about these species are larger since their current distribution is strongly determined by management actions. Silver birch, European larch, Norway spruce and Scots pine, which are already growing in northern latitudes and in high elevation areas, are projected to encounter substantial range contractions with the latter two species being projected to almost vanish from low and mid-elevation areas in central, eastern, and southern Europe. This is particularly relevant since Norway spruce and Scots pine are the economically most relevant tree species in Europe. A regional study focussing on the Mediterranean area, and based on statistical species distribution modelling, confirms range contractions and reductions in tree species diversity and highlight the importance of the Alpine regions for maintaining species niches (Noce et al. 2017). A complementary study relying on a process-based model, but only covering a few of Europe's main tree species, showed that frost damage will actually decrease and allow European beech, Norway spruce and sessile oak to expand their ranges but, that at the same time, the mortality risks from extreme climatic events increased so that in the high-level warming scenarios, the model projections are as dire as those from the species distribution models (Petit-Cailleux et al. 2021). It is important to note here that, in these studies, although the general trends are consistent among climate models, projected spatial changes in climate are strongly dependent upon the individual climate model being used and scenario considered. Furthermore, tree species distribution is strongly affected by decisions made by forest owners/managers and the predicted range shifts may not be realised if managers opt to regenerate commercially valuable species.

Species range shifts would likely entail substantial changes to European carbon sequestration. Currently, young stands and fast-growing species, primarily pine and spruce, are making a substantial contribution to the European carbon sink. However, forests dominated by these species face increasing disturbance risks and are increasingly being converted into mixed stands. Nevertheless, if these species are mixed with species that are less productive in terms of carbon capture, carbon sequestration potential may well decrease (Shanin et al. 2014). Schelhaas et al. (2015) used a modelling approach to simulate if anticipatory planting of climate-adapted species could match the species distribution projected by Hanewinkel et al. (2013). They found that by 2070, out of 52.6 million hectares that are considered unsuitable for the species currently present, only 21.1 million hectares of forest can be converted in line with projected species shifts. This is because, under conventional management practices, new species can mainly be introduced during the forest regeneration phase, even though rotation lengths were reduced in the analysed scenarios. These conversions would reduce the average growing stock by approximately 20 m^3 ha^{-1} (almost 10% of projected growing stock) and increment by 0.4 m^3 $year^{-1}$ ha^{-1} (around 5% of projected net annual increment) by 2070 compared to current species distributions because the conversions introduce slower growing species. The impact on carbon sequestration is not clear as such, however, slower growing species may contain more carbon in the wood and may be more resilient to disturbances. Thus, while tree species range changes represent a natural way of adapting forests to climate change, they also affect both the carbon sequestration potential of forests and wood availability, which is relevant in the context of a forest-based bioeconomy. Shifting ranges of naturally available species can be complemented by planting non-native species (e.g., Douglas fir) although these species need to be carefully evaluated for their potential invasiveness (see Section 2.6).

3.1.2 Forest productivity

Changes in and interactions between temperature, precipitation, atmospheric CO_2 concentrations, nitrogen deposition and improved forest management have been driving productivity changes in Europe for some time (e.g., de Vries et al. 2009; Ciais et al. 2008, Erb et al. 2013; Luyssaert et al. 2010; Henttonen et al. 2017; Etzold et al. 2020) and will continue to do so in the future (Reyer et al. 2014). Higher CO_2 concentration, longer growing seasons and higher photosynthetic activity due to warmer spring conditions have contributed to a greening of northern Europe (Zhu et al. 2015). Similarly, evidence from long-term forest monitoring plots and forest inventory data suggest that climate change and nitrogen deposition together have contributed to increasing forest productivity in central and northern Europe (Pretzsch et al. 2014; Etzold et al. 2020; Henttonen et al. 2017). In the Mediterranean, both productivity gains and declines have been reported depending on tree species, competition, site productivity and the local climate conditions (Sarris et al. 2011; Martin-Benito et al. 2011; Tegel et al. 2014; Charru et al. 2017).

Model projections generally confirm that moderate climate changes in northern and central Europe will increase productivity (Reyer et al. 2014, Reyer 2015), although it is still unclear whether the strong CO_2-fertilisation effect (i.e., an increase in photosynthesis because of higher CO_2-levels in the atmosphere) that contributes to this increase in the models will materialise (Hickler et al. 2015; Babst et al. 2020). Conversely, productivity may decrease when water availability becomes a limiting factor (Kint et al. 2012; Sperry et al. 2019) and, especially in northern Europe, warmer winters can lead to decreased growth at the beginning of the growing season since trees maintain their photosynthetic capacity and consume resources during the warm winters (Miina 2000; Linkosalo et al. 2014). Moreover, growth increases in spring may be compensated for by lagged effects later in the growing season (Buermann et al. 2018) while various other climate changes may increase the background mortality of forest stands (Bugmann and Bigler 2011; Yu et al. 2019). In general, projections of changing forest productivity are uncertain because models struggle to properly account for mortality in terms of changing background mortality and disturbance-induced mortality (Bugmann et al. 2019), both of which are likely to gain importance as Europe's climate changes.

When assessing the role of changing forest productivity under climate change for the European forest-based mitigation potential, it is important to note that the additional carbon gained through increasing productivity may be allocated into different carbon pools (stem, roots, leaves etc.) depending on environmental conditions and species traits. If a tree allocates more carbon to short-lived pools, such as leaves or fine roots, it will be stored for a shorter time in that pool than if carbon is held in the trunk (Campioli et al. 2008). Thus, only productivity increases that result in more harvestable biomass can contribute to increasing the production capacity of wood products whereas increasing non-harvestable tree parts will increase carbon storage in the forest itself. While increases in short-lived pools may not increase the carbon stored in living biomass, it will influence the carbon stored in soils (see also Box 4).

While climate change may stimulate forest productivity in general, it may also increase the carbon turnover through increases in respiration, background mortality and disturbances. As a result, additional carbon is removed from the atmosphere but is also being released back more swiftly (Brienen et al. 2020). Modelling studies have shown that increasing disturbances and increasing productivity under climate change are indeed linked in such ways. Moreover, changes in disturbances have the potential to amplify productivity losses or at least reduce the increase substantially (Reyer et al. 2017). Furthermore, increased production will increase carbon input to forest soil, however, soil respiration will increase simultaneously with a warming climate.

Box 4. Climate change impacts on soil carbon.

Soils play a key role in the global carbon cycle and the global carbon stored in soils (excluding permafrost) is more than three times higher than the vegetation carbon stock (Canadell et al. 2021) Increasing temperatures increase soil respiration and foster carbon release, however, the rate of change is highly dependent on soil microbiota (Karhu et al. 2014; Johnston and Sibly 2018). In water limited forest ecosystems, increasing precipitation accelerates soil respiration while in peatlands, increasing precipitation may elevate the ground water table and decrease aerobic respiration and CO2 release from peat soil (Ojanen et al. 2013).

The carbon balances of forest soils are also affected by the changes happening above-ground. Changes in forest productivity and disturbances increase the input provided by organic matter to the soil, which subsequently increases the soil and deadwood carbon pools unless changes in soil microbiota and the rate of decomposition compensate for the increased input. In climate change modelling, the rate of deadwood decomposition is predicted to increase by 27% (Rinne-Garmston et al. 2019), which means that the deadwood carbon pool is likely to decrease without any remarkable increase in forest productivity and/or more frequent disturbances.

Understanding how unprecedented climatic conditions will affect the functioning of soil biota under future climate conditions is especially important since soil-inhabiting microorganisms and fauna affect long-term soil carbon sequestration and nutrient supply (e.g., Karhu et al. 2014, Delgado-Baquerizo et al. 2016, Li et al. 2019, Lubbers 2013).

3.1.3 Natural disturbances

Natural disturbances (e.g., storms, wildfires, pest and insect outbreaks and prolonged droughts) have complex effects on forest ecosystems while some, especially wildfires and storms, can even put people's live at risk. While natural disturbances may increase biodiversity they also put ecosystems services at risk and may lead to releases of substantial amounts of carbon (Forzieri et al. 2020; Seidl et al. 2014). Disturbances have the potential to strongly affect the carbon balance of a region (Thom and Seidl 2016; Pugh et al. 2019) and there is ample evidence, e.g., for storms in Sweden or bark beetles in Czech Republic, that these disturbances have dominated the forest harvesting activities and carbon sink strength of countries (Lindroth et al. 2009; Hlásny et al. 2021). In Europe, disturbance regimes have changed over the past few decades (Sutanto et al. 2020; Senf and Seidl 2021) and this has had significant implications for carbon sequestration in forests and their products. Recent analyses have found that disturbance frequencies have increased (Senf and Seidl 2021), canopy mortality has doubled (Senf et al. 2018) and, overall, Europe's forest vulnerability to climate change-driven disturbances, especially storms, fires and insects, is high (Forzieri et al. 2021; Figure 6). Changes in forest structure, forest management and climate are the main drivers for these developments (Seidl et al. 2011; Sommerfeld et al. 2018) and these trends are likely to intensify further, especially when warming is accompanied with drying and when disturbance agents interact more strongly, e.g., drier conditions predisposing trees to bark beetle attacks or drought fostering fires (Seidl et al. 2017).

Future projections rarely include disturbance projections with a level of detail and process understanding to really account for long-term changes in disturbance regimes over larger areas or that allow us to differentiate between different disturbance agents. However, Seidl et al. (2014) estimated that changing forest disturbance regimes under a range of climate scenarios could offset the effects of management strategies designed to increase the forest carbon sink. Furthermore, by using a set of process-based models that account

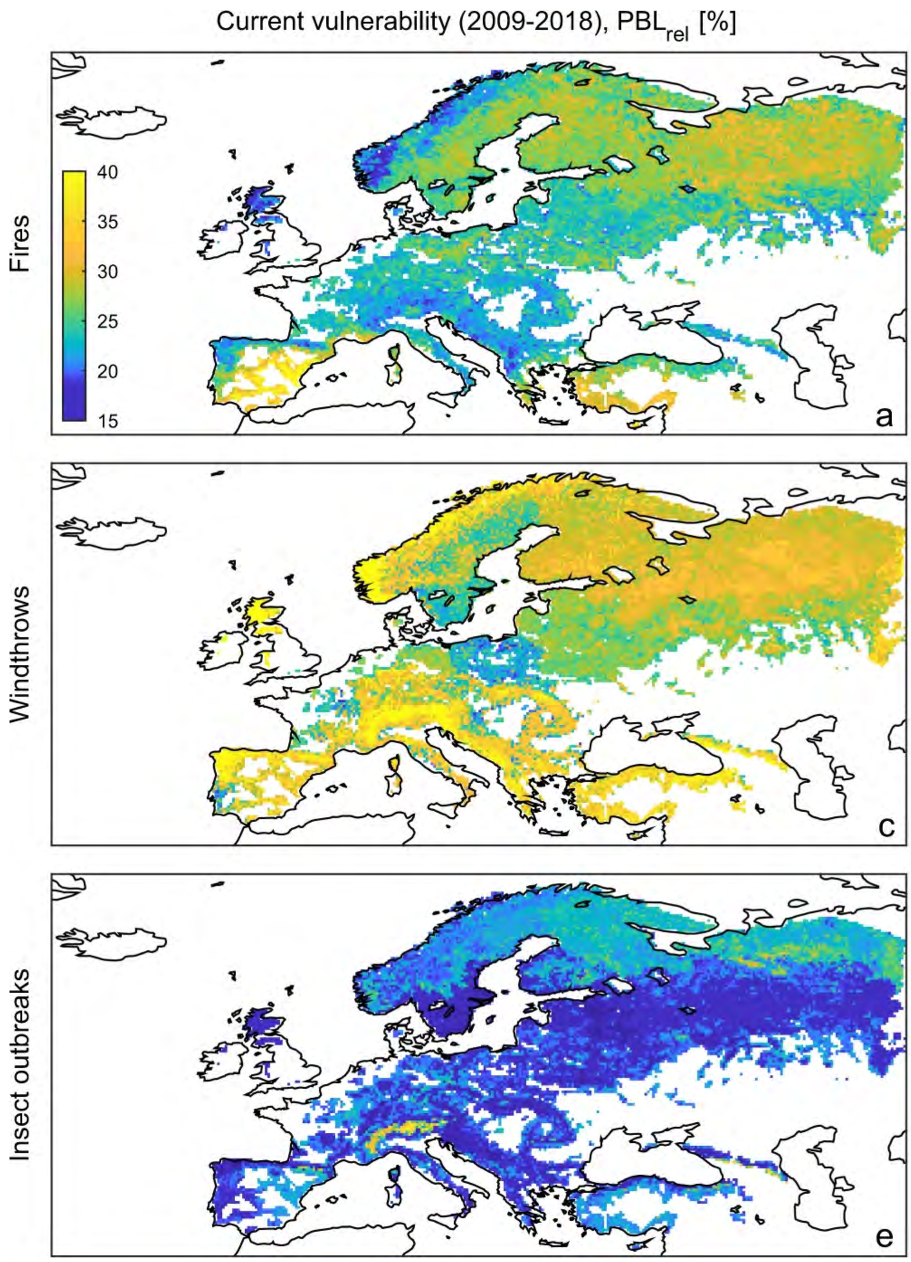


Figure 6. Current (2009–2018) vulnerability of European forests to natural disturbances.

Vulnerability is expressed as a potential relative (%) biomass loss. Forests with a cover fraction lower than 0.1 are masked in white (Forzieri et al. 2021).

for both climate change-induced productivity changes as well changing disturbance patterns at the stand and landscape scale, Reyer et al. (2017) showed that disturbance damage has the potential to reduce productivity gains and amplify productivity losses induced by gradual climate changes alone. Nevertheless, disturbance damage projections and implications for carbon storage over large spatial scales and longer time periods are notoriously difficult to calculate since not only climate and disturbance dynamics are changing and uncertain but also interact with changing growing conditions, species distributions and management changes, all of which strongly determine a forests vulnerability to disturbances and extreme events as well as their contribution to carbon storage.

3.2 Impacts of climate change on the forest-based sector and its markets

Besides impacting forest ecosystems, climate change will also affect forestry activities, forest industries and forest products markets, possibly in regionally differentiated ways.

One of the direct impacts of climate change on forestry relates to winter harvesting, which will primarily affect harvesting in northern Europe. Rising temperatures in winter will reduce the availability of frozen soil and which limits accessibility. Harvesting operations on vulnerable soil types may become impracticable (Rittenhouse 2015), with potential consequences for timber production and seasonal wood supply for some forest industries, as well as employment for forest workers. Reduced opportunities for winter harvest can increase damage on trees resulting in root rot (Hylen and Granhus 2018), soil damage that can cause long-term productivity losses (Toivio et al. 2017) and changes in both the species compositions and functioning of affected forest ecosystems (Closset-Kopp et al. 2019).

Several studies (e.g., Tian et al. 2016; UNECE 2021; Favero et al. 2021) explored how climate change would affect the development of the forest sector. They generally found that climate change induced productivity changes that would increase global timber supply and lead to lower global timber prices. However, these studies generally do not consider the effects of increasing disturbance risks. In contrast, Hanewinkel et al. (2013) suggest that the expected value of European forest land will decrease owing to the decline of economically valuable species in the absence of effective countermeasures. Moreover, increases in forest productivity may also affect timber quality as wood density may decline (Pretzsch et al. 2018). More irregular tree ring patterns, due to drier years alternating with years with better growing conditions, are expected to cause problems using such wood in construction and for furniture (Lachenbruch et al. 2010).

Large scale natural disturbances can result in immense damage and unexpected wood volumes coming to the market, thereby disrupting local timber markets both in the short- and the long-term. From 1950 to 2000, an annual average of 35 million m^3 of wood (approximately 8% of total annual fellings in the EU) originated from salvage logging, primarily as a result of windstorms and bark beetle damage (Schelhaas et al. 2020; Camia et al. 2021) (see Figure 7). An example in 2005 was the 'Gudrun' storm that hit Sweden and felled about 70 million m^3 of wood (Broman et al. 2009). Another example is the bark beetle outbreak in central Europe, which, in Czech Republic in 2018, resulted in salvage logging representing 90% of the country's annual roundwood production. Salvage logging yields wood of varying quality that enters the market within a short time, this can reduce local or regional wood prices and may extend up to the global level, affecting international trade and forest industries more generally, if the scale of salvage logging is large. As an example, wood prices in Czech Republic decreased to one fourth in response to the massive bark beetle outbreak in 2018 compared to average wood prices in 2011–2017 (Hlásny et al. 2019). Hlásny et al. (2021) additionally found that the countrywide outbreak resulted in not only a decrease in the timber price, but also an excessive workload for forestry workers along with other cascading effects that caused severe revenue loss for industry, requiring State interventions amounting to approximately €260 million in 2018–2019. Damaged wood is usually unsuitable for sawmilling and is typically used for energy, pulp production or wood-based panels, which has implications on carbon storage in wood products and possible substitution effects.

Furthermore, changes in forest composition, either directly through forest conversion as a part of adaptation activities or indirectly through increasing disturbances and mortality, can have profound effects on the forest sector in the long-term. Adaption strategies to reduce forest fires, windthrows, insect pests, root rot and fungal species, could entail changes in forest management and choice of tree species (e.g., Donis et al. 2018; Pukkala et al. 2016; Nabuurs et al. 2018). For example, converting forests from single-species coniferous forests to mixed forests, including broadleaved trees species, will increase forest resilience but will eventually decrease the availability of softwood, which is preferred by industry, and increase the availability of

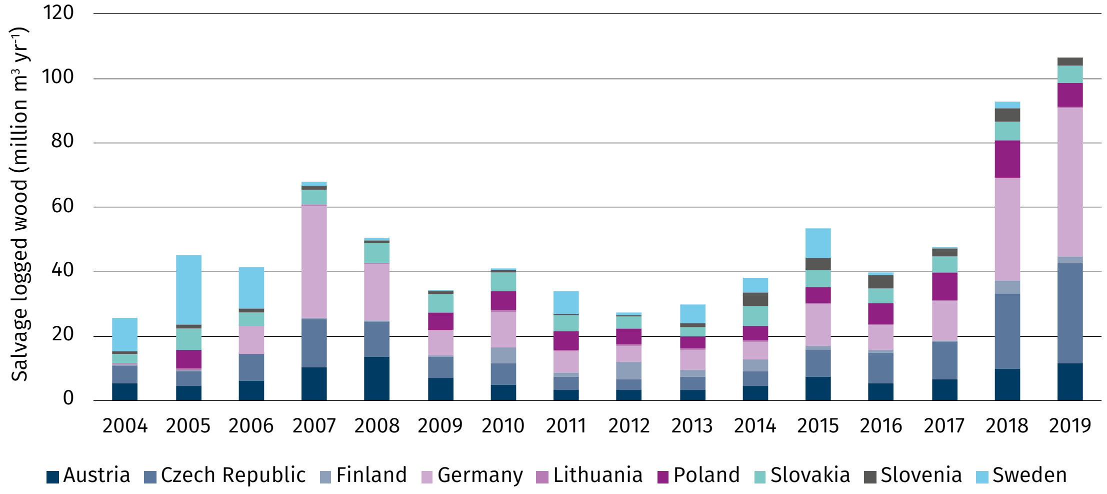


Figure 7. The volume of salvage logged wood in Europe

Volumes are based on available statistics (Schelhaas et al. 2020; Camia et al. 2021). Data are missing for some years for Poland and Sweden.

small diameter hardwoods in the medium term (e.g., Astrup et al. 2018; Bäucker and Bues 2009). Such changes will, in the long run, affect the roundwood assortments at local and regional levels and adaption strategies for these changes will require forest industries to prepare for changes in the use of species, transportation costs and location of capacities.

3.3 Interaction between climate change mitigation and adaptation

While forests, the forest-based sector and its markets play an important role in climate mitigation, they are also affected by climate change, which indicates the need to consider adaptation. Forest-based mitigation and adaptation therefore both need to be considered, a pairing which can potentially result in conflicts and synergies (see Table 4).

When climate change mitigation is the main objective, there will be implications for the type of adaptation measures undertaken. For example, mitigation can focus on maximising carbon stocks in forest ecosystems (i.e., protect, restore), focus on active management with wood use or a combination of both. Meeting these mitigation objectives could be in synergy with adaptation by keeping a canopy closed to avoid higher temperatures in the stand, and avoiding increased surface roughness and thereby susceptibility to wind damage or, alternately, by increasing thinning to reduce competition among the remaining trees and produce wood. Policy instruments such as carbon pricing to support mitigation activities could also have effects on the adaptation potential of forests. Carbon pricing may encourage forest managers not to conduct harvest activities (either intermediate or final harvests), which could delay active forest conversion towards more resilient forests and increase disturbance risks, which would affect the permanence of the carbon stored in the forest. As such, carbon pricing regimes should be structured to improve carbon storage in forests through active management that simultaneously improves adaptation by, for example, stimulating the use of productive and adapted species and provenances. Conversely, when adaptation is the main objective, there may be implications for the type of mitigation activities that can be undertaken. A prominent example in this regard relates to disturbance management. While disturbances reduce carbon stocks and are

Table 4. Potential conflicts and synergies between forest-based mitigation and adaptation.

Category	Activity	Type of activities	Synergies and conflicts between mitigation and adaptation
Protect	Avoiding deforestation and degradation	Reduced conversion of forests, reduced forest degradation	• Synergy as forests remain available as species, seed, and gene pools and landscape remains connected for tree species migration
	Forest conservation	Set-aside forest area	• Synergy by supporting natural adaptation • Conflict by decreasing options for anticipative planting, assisted migration and adaptive management interventions
Manage	Forest harvesting	Stand thinning as well as harvest practices and regimes	• Synergy as thinnings can foster drought tolerance of remaining trees and create open space for new species or individuals • Conflict when intensive thinnings lead to stand instability
	Active management (other than harvest)	Provenance selection	• Synergy or conflict due to possible trade-off between mitigation (e.g., high carbon storage) and adaptation (e.g., high fitness) of the selected provenance
		Nutrient management and soil preparation	• Synergy when more moisture is retained in soils, thus reducing drought stress • Conflict when nutrient additions increase drought stress
		Disturbance management	• Synergy when pre-emptive disturbance management (e.g., prescribed burning) increases resilience and avoids larger disturbances • Conflict when preventing disturbances that slow down natural adaptation
		Tree species selection, hydrology management	• Synergy or conflict due to possible trade-off between mitigation (e.g., high carbon storage) and adaptation (e.g., high fitness) of the selected species
Restore	Forest restoration		
	Afforestation / Reforestation	Afforestation of non-forest biomes	• Synergy or conflict, depending on whether reproductive material is well adapted to future climate conditions
		Afforestation of non-forest biomes	
Wood use	Shifts in wood uses (including by-products)	Shift to long-lived wood products	• Synergy when shift allows for management to focus on higher-added value products and leverage more revenues for adaptation • Synergy when shift leads to higher harvest pressure, which may facilitate adaptation (e.g., through species change) • Conflict when shift leads to higher harvest pressure, which may hamper adaptation • Conflict when narrower management objectives reduce adaptive options
		Shift to material uses	
		Shift to primary energy uses	
	Cascading (end-of-life)	Reuse, recycling	• Synergy when cascading reduces pressure on forests and allows silviculture to focus on adaptation and natural processes
		Downcycling	
		Energy recovery of discarded wood	
	Increased efficiency	Increased material efficiency	• Synergy when cascading reduces pressure on forests and allows focusing silviculture on adaptation and natural processes
		Increased energy efficiency	

generally detrimental to climate mitigation, they can be windows of opportunity for adaptation. Depending on their extent and severity, disturbances such as fires, windthrows and insect outbreaks may generate a heterogeneous landscape and open canopy space. Therefore, when managers actively consider disturbances in their planning, they will also need to promote forest rejuvenation, which is crucial for successfully adapting forests to the environmental challenges of the future while maintaining their active growth.

There are also important synergies between mitigation and adaptation activities regarding, for example, forest structure. Forest management has typically simplified forest structures by focusing on only a few tree species. However, tree species richness and forest productivity are positively related (Liang et al. 2016), which is important for both adaptation and mitigation. For example, greater tree-species diversity increases the resilience of forests to threats from fire, wind and pests (Jactel et al. 2009; Jactel et al. 2017; Astrup et al. 2018) while also reducing the emissions associated with these threats when they manifest. Indeed, in boreal forests, mixed stands of Norway spruce and Scots pine have been shown to be more productive and sequester more carbon than single-species stands because they use resources more efficiently and in a complementary way (Shanin et al. 2014). These forests are also more resilient to disturbances.

4. Policy context for forest-based climate change mitigation

Chapter highlights

- European forests and forestry represent a key component in achieving climate neutrality targets by 2050, especially given their unique roles in actively removing CO_2 from the atmosphere on a large scale.
- A set of EU policies has been developed within the European Green Deal that is connected with the forest sector, providing an integrated framework for forest management within the climate change context. Important policies in this context are the EU Forest Strategy, the EU Adaptation Strategy, the Biodiversity Strategy, revisions of the Renewable Energy Directive, the LULUCF Regulation within the EU Fit for 55 proposal and, finally, the new Common Agricultural Policy.
- The climate policy framework at the EU level is gradually including the land sector in its targets and calls for the maximisation of climate benefits through sustainable forest management, providing new guidelines, indicators and planning tools to assist Member States to efficiently plan and manage their forest resources sustainably.
- The forthcoming CAP strategic plans and the updated National Climate and Energy plans are considered the key programming tools at the country level where the optimal balance between synergies and trade-offs of the different functions of the forestry sector needs to be identified.
- There is no silver bullet to stimulate forest-based mitigation activities and ensure they effectively contribute to climate change mitigation. Rather, a mix of informational, regulatory and economic instruments will likely need to be pursued. An area for future investigation concerns understanding the most efficient way to combine those instruments to produce optimal results.

4.1 Forest-based mitigation efforts in European policy

European forests and forestry represent a key component in achieving climate neutrality by 2050, as laid out by the European Green Deal (EC 2019), given the unique role in actively removing CO_2 from the atmosphere on a large scale. Currently, forests and wood products remove 380 $MtCO_2eq\ yr^{-1}$ (340 $MtCO_2eq\ yr^{-1}$ and 40 $MtCO_2eq\ yr^{-1}$, respectively) from the atmosphere annually, which compensates for about 10% of total EU GHG emissions (EU-27 average for 2017–2019; EEA 2021). The capacity to remove CO_2 at large scale is considered of key importance in global and European climate change mitigation pathways to compensate for the most difficult to abate emissions, such as those from some industries (e.g., cement or fertilizer), waste, and non-CO_2 residual emissions from the agriculture sector. At the same time, forestry is essential in providing raw materials and energy sources that can substitute for currently employed high-emission intensity alternatives (e.g., concrete, steel and fossil-based plastics) and to support a sustainable, circular bioeconomy.

4.1.1 LULUCF policies and targets

Within the UNFCCC commitments, forests and forestry (including wood products) are considered a part of the LULUCF sector. While at the EU level, forests and wood products represent a net sink, cropland, grassland and the conversion of land to settlements represent net sources of GHG emissions. As a result, the entire LULUCF sector still represents a net sink (256 $MtCO_2eq\ yr^{-1}$, EU-27 average for 2017–2019; UNFCCC 2021). The LULUCF and agricultural sector together are commonly referred to as the AFOLU sector (Agriculture, Forestry

Table 5. Current and future emissions (positive value) and removals (negative values) in the EU-27 LULUCF and agriculture sectors in $MtCO_2eq\ yr^{-1}$.

Emission sector	Current (average 2017–2019)	Future		
		2030	2035	2050
LULUCF	-256#	-256* no measure scenario **-310*** LULUCF proposal target -225 Maximum contribution towards 55% target ∞	-360*	-425§ LULUCF+ scenario
Agriculture	+390#	+360* to +375§	+312 to +360*	+267*
AFOLU (LULUCF + agriculture)	+133	+50 to +119	−49 to zero	-158

*Sources: #UNFCCC country profiles https://di.unfccc.int/ghg_profile_annex1. *EC 2021a. §EC 2020b. ∞European Union, 2021*

and Other Land Use). The agricultural sector acts as a source of GHG emissions (390 $MtCO_2eq\ yr^{-1}$, EU-27 average for 2017–2019; UNFCCC 2021), which is larger than the LULUCF sink, and consequently, the AFOLU sector acts as a net source of emissions (133 $MtCO_2eq\ yr^{-1}$; EU-27 average for 2017–2019; UNFCCC 2021).

The LULUCF sector is currently bound by the LULUCF Regulation (2018/841; European Union 2018a), which was established as a new pillar in the 2030 EU climate policy. It contains no specific targets but includes the commitment that the LULUCF sector, as a whole, must continue to act as a net sink in the period 2021-2030 after the accounting rules are applied, and therefore should not generate net debits at the Member State level (the so-called 'no debit rule'). To stimulate action in the land sector, Member States (plus the UK) could use up to 280 $MtCO_2eq$ in credits accounted for within the LULUCF Regulation over the entire 2021–2030 period. In doing so, each country has to comply with their national targets under the Effort Sharing Regulation (ESR) (2018/842; European Union 2018b), which covers agriculture, transport, waste and buildings. The LULUCF Regulation also provides detailed accounting rules for forests, namely the so-called Forest Reference Levels. These Forest Reference Levels represent a counterfactual value of emissions and removals that would occur in managed forest land in the absence of any future change in management practices compared to the reference period of 2000–2009, taking into consideration forests' future age-class structure and keeping constant the ratio of energy to material use of wood. In other words, a Forest Reference Level is a benchmark against which forest emissions and removals are compared, therefore and by way of example, if during the period 2021–2025, forest management in a certain Member State leads to a decrease in the sink compared to its Forest Reference Level, then the difference results in debits. Conversely, if the sink exceeds the Forest Reference Level, then the difference results in credits. The Forest Reference Levels have been estimated by Member States individually and when tabulated, the projected forest sink for the EU and UK for the period 2021–2025 is 337 $MtCO_2eq\ yr^{-1}$, including the contribution from carbon storage in wood products (Korosuo et al. 2021).

In response to the Paris Agreement, in 2020 the EU submitted its *Long-term low greenhouse gas emission development strategy of the EU and its Member States* (EU 2020). This strategy sets a climate neutrality target for 2050 that relies on the compensation of residual emissions by absorption from the LULUCF sector, which requires the sector's net sink to nearly double to achieve net removals of 425 $MtCO_2eq\ yr^{-1}$ by 2050. In line with this carbon neutrality target, the EU has also recently updated its emission targets within the European Green Deal, proposing a net emission reduction target of 55% of 1990 levels by 2030 (EC 2021e) for all sectors, establishing a maximum contribution of the LULUCF sector of 225 $MtCO_2eq\ yr^{-1}$. With this figure, LULUCF would contribute around 2% to the 55% target, with the remaining 53% reduction coming from non-LULUCF sectors. Within this upgrade of the EU targets, the core elements of the 2030 framework that deals with the land sector, namely the LULUCF Regulation (European Union 2018a), the ESR (European Union 2018b) and the Renewable Energy Directive (REDII; European Union 2018c), were all revised in the "Fit for 55" policy package (EC 2021e) (see also Köhl et al. 2021).

The proposed revisions to the LULUCF Regulation (EC 2021a) contain a more stringent contribution from the LULUCF sector, simplifying the accounting rules and assimilating the forest sector to other emission sectors, which are all accounted for as deviations from 1990 levels. The proposal confirms the 'no-debit rule' and the use of the Forest Reference Levels for managed forest land until 2025 while establishing a 2030 EU-wide target for net GHG removals of 310 $MtCO_2eq\ yr^{-1}$ for the entire LULUCF sector. This target requires the additional annual removal of 42 $MtCO_2eq$ (in relation to the 2016–2018 average), with contributions to this figure being proportionally distributed between the Member States. This target is well above the 225 $MtCO_2eq\ yr^{-1}$ that the European Climate Law established as a possible contribution from the LULUCF sector to the Union 2030's climate target of a 55% reduction in net emissions. Furthermore, the possibility to use the LULUCF credits toward the targets established by the Effort Sharing Regulation remains capped at 280 $MtCO_2$ over the 10-year period (2021–2030). Unused credits generated by the sector can contribute a voluntary additional reserve to be used by Member States for compliance with their ESR 2030 target, subject to the condition that the EU's 55% emissions reduction target is reached with the maximum contribution of 225 $MtCO_2eq\ yr^{-1}$. This additional flexibility is meant to facilitate compliance by Member States that may have difficulties in coping with more stringent national targets in both the ESR sectors and the LULUCF sectors by the end of the period (EC 2021g). From 2031 onwards, the legislative proposal combines the agriculture and the LULUCF sector, thereby creating a newly regulated land sector, covering emissions and removals from Agriculture, Forestry and other Land Use (AFOLU; including wood products), with a proposed neutrality target to be achieved by 2035. At the time of writing (January 2022) the legislative proposals are still under consideration by the European Council and the European Parliament. The contribution attributed to the forest sector is not trivial in this equation, however, according to the impact assessment accompanying the legislative proposal (EC 2020), the forest sink is expected to decrease up to 2050 in absence of targeted mitigation action due to increased harvesting, forest ageing and the increased frequency and severity of disturbances driven by climate change. This creates foreseeable pressure as the LULUCF sector is called upon to increase its net GHG removals by more than 20% compared to its 2019 levels (from 256 $MtCO_2eq\ yr^{-1}$ to 310 $MtCO_2eq\ yr^{-1}$) by 2030 and to nearly double (425 $MtCO_2eq\ yr^{-1}$) its net carbon sink by 2050 compared to the current situation (see Table 5).

Box 5. Policy tools and mitigation actions in the forestry sector in selected European countries outside the EU.

The United Kingdom

In the UK, through the Climate Change Act 2008, the UK government has set a target of reducing GHG emissions by at least 100% of 1990 levels (net zero) by 2050. This includes reducing emissions from the devolved administrations (Scotland, Wales and Northern Ireland), which currently account for about 20% of the UK's emissions. The Act also requires the government to set legally-binding carbon budgets to achieve the 2050 target. A carbon budget is a cap on the amount of GHGs emitted in the UK over a five-year period and it includes a contribution from LULUCF. There are stated commitments to afforestation activities in England and Scotland, although the specifics are still under development. More generally, land use and agriculture policies in the devolved administrations are being readjusted following the separation of the UK from the EU.

Currently, two specific policy instruments address afforestation and forest management in the context of climate change mitigation. The first is the UK Woodland Carbon Code, a quality assurance standard for afforestation projects in the UK which generates independently verified carbon credits. The Code thus provides a framework for individuals and organisations to invest in afforestation projects to demonstrate a commitment to emissions reductions and where all forestry projects under the Code must be compliant with the UK Forestry Standard for sustainable forest management. The second current policy instrument is the Renewable Heat Incentive (RHI), a tool that indirectly supports stand thinning and harvesting practices by providing incentives for the domestic use of wood fuel. This was introduced partly to encourage improved management in a significant area of undermanaged broadleaved woodlands. The RHI is being replaced by the Clean Heat Grant, which will include some provisions for domestic use of wood fuel.

Norway

Although not a Member State, Norway is part of the EU's internal energy market and climate policies through the Agreement on the European Economic Area (EEA). Many directives and regulations on energy and climate change are incorporated into the EEA Agreement, which provides a framework for energy cooperation between Norway and the EU.

Norway updated its NDC in February 2020 to reduce emissions by at least 50% and ultimately towards 55% below its 1990 levels by 2030, up from its previous emission reduction target of 40% established by law in the Norwegian Climate Change Act (Government of Norway 2020). Norway intends to achieve this target in collaboration with the European Union and will regulate emissions from all its economic sectors through three pieces of legislation: the EU Emissions Trading Scheme, the EU Effort Sharing Regulation and the LULUCF Regulation. Under the LULUCF Regulation, Norway has committed to the 'no-debit rule' applicable to the LULUCF sector between 2021 and 2030 (Government of Norway 2020). With regard to the net sink in the LULUCF sector, Norway is allowed to use up to 1.6 $MtCO_2e$ in net removals from the land sector towards meeting its NDC target. Assuming this amount is unchanged when its NDC is updated, Norway's emission reduction targets equate to 47–52% below 1990 levels by 2030 once these net removals are excluded.

Norway's forests represent a substantial carbon sink – equal to approximately half of Norway's emissions of on average 51 $MtCO_2eq\ yr^{-1}$ over 2018–2020 (Statistics Norway 2022). The volume of Norway's growing wood stock increased between 2008–2017 by over 23% and, according to the National Forestry Accounting Plan, average removal from this sector will amount to slightly over 24 $MtCO_2eq\ yr^{-1}$ between 2021–2025 when current forest management practices are continued.

The most comprehensive and important legislation pertaining to Norwegian nature and its management is the Nature Diversity Act of 2009 as it applies to the natural environment (including forests) and to all sectors that are responsible for managing the environment or that make decisions that may have environmental impacts (Government of Norway 2009).

4.1.2 Energy policy

Forests are an important source of renewable energy and wood energy is expected to play a role in the energy mix to achieve the EU's 55% emission-reduction target by 2030. Wood-based bioenergy is currently the main source of the bloc's renewable energy, currently accounting for 60% of the EU's renewable energy use. This is to a large extent (49%) based on secondary woody biomass (forest-based industry by-products and recovered postconsumer wood), while the rest comes from primary woody biomass (37%; stemwood, treetops, branches and so forth harvested from forests) or from uncategorised sources (14%) (Camia et al. 2021). Half of the stemwood used for energy is assumed to be derived from coppice forests, which are particularly important in Mediterranean countries where this management system has relevant socio-economic functions in many rural areas (Camia et al. 2021). From an analysis of the National Energy and Climate Plans (NECPs), it appears evident that EU Member States plan to further increase the use of biomass as a source of renewable energy in the next 10 years, with bioenergy accounting for 70% of the generation of renewable heat in 2030 (Smith et al. 2021).

The Fit for 55 proposal (EC 2021e) aims to also revise the Renewable Energy Directive (REDIII) by increasing the current EU target of having at least 32% of energy coming from renewable sources by 2030 to 40% (EC 2021h). The existing version of the Renewable Energy Directive (REDII; European Union 2018c) already set out renewable energy targets and introduced forest sustainability criteria for bioenergy, to ensure compliance with legislation and where the principles on sustainable forest management and the carbon impacts of bioenergy are accounted for. In the new legislative proposal (REDIII), these criteria are further strengthened by applying the existing land criteria (e.g., no-go areas) for agricultural biomass to forest biomass (including primary, highly diverse forests and peatlands). Those strengthened criteria will also apply to small-scale biomass-based heat and power installations below a total rated thermal capacity of 5 MW. Furthermore, restrictions have been introduced regarding the use of sawlogs, veneer logs, as well as stumps and roots for energy, to avoid promoting the use of quality roundwood for energy except in well-defined circumstances.

Overall, the REDIII legislative Commission proposal (EC 2021h) introduces the obligation to phase out, with some exceptions, support for electricity production from primary biomass from 2026. This means prohibiting the sourcing of forest biomass from primary forests and limiting it in highly biodiverse forests to ensure there is no undermining of nature protection goals while simultaneously promoting the use of woody biomass according to the cascading principle. This entails the use of wood in the following order of priorities: 1) wood-based products, 2) extending products' service life, 3) re-use, 4) recycling, 5) bioenergy and, finally, 6) disposal. Specific guidance on how to apply the cascading principle for biomass is currently under development by the European Commission. While the REDIII proposal aims to limit the use of primary forest biomass for bioenergy, higher renewable energy demand will require bioenergy to continue to substantially contribute to the energy mix. To this end, Member States are required to include in their NECPs, considerations on carbon sink and biodiversity objectives as well as the overall availability of wood within sustainability boundaries. This requires a thorough assessment of current and future harvesting levels based on timely and robust monitoring systems, identification and mapping of highly biodiverse forests, primary and old-growth forests as well as a coordinated and intersectoral approach that considers all the relevant emission sectors. All the above-mentioned prerequisites are, to a greater or lesser extent, a challenge to meet, a situation compounded by the severe lack of data on the forest sectors of many European countries (e.g., Camia et al. 2021).

4.1.3 Forest policy

Forests in the EU are subject to national laws and international commitments to ensure their sustainability. The new EU Forest Strategy published in 2021 (EC 2021b) serves as a point of reference for the development of national forest-related policies, setting out the policy framework for the achievement of the European Green Deal and 2030 Biodiversity Strategy objectives in the EU. The Strategy aims to respond to multiple and competing demands on forests, including support for a sustainable forest bioeconomy and to ensure that the amount of wood used remains within the sustainability limits of EU forests that are regulated by the most sustainable forest management practices.

The Strategy outlines measures for strengthening forest protection and restoration (including through the planting of 3 billion trees by 2030), enhancing sustainable forest management and improving the monitoring and decentralised planning of forests in the EU (EC 2021b). The Strategy also proposes measures for innovation and the promotion of new materials and products to replace fossil-based materials. To achieve this, the Commission will develop a 2050 roadmap for reducing whole life-cycle carbon emissions in buildings, including through the development of a standard and methodology to quantify the climate benefits of wood construction products and other building materials via the revision of the Construction Products Regulation (EC 2022) by the Commission, as mandated by the European Green Deal. Another target linked to the Strategy is the one related to the pledge to plant 3 billion trees, as outlined by the Biodiversity Strategy that defines the criteria for tree planting, counting and monitoring. Ultimately, where and how the trees will be planted (on cropland, within an agroforestry system, in urban areas or by establishing new forest areas) and when (annual planting rates) will be left to the Member States. Nevertheless, the estimated contribution to the LULUCF target for 2030 would be largely symbolic (around 1%) as the planted trees will sequester an estimated 4 Mt CO_2 by 2030 and 15 Mt CO_2 by 2050 (EC 2021f).

The Forest Strategy was received with mixed feelings by forestry actors and civil society. On the one hand, some NGOs have lamented the lack of a stronger focus on biodiversity and climate change. On the other hand, European forest owners and managers expressed concerns regarding the implications of the strategy's limits on wood harvesting negatively affecting forest-based value chains and employment prospects, especially in rural areas, and recalling the principle of subsidiarity and national competences regarding forest management decisions.

4.1.4 Adaptation and biodiversity policy

Alongside their mitigation potential, there is a need to reinforce the adaptive capacity of forests to climate change and minimise their vulnerability to climate change impacts (see Chapter 3). The European Adaptation Strategy (EC 2021c) calls for a more integrated and systemic approach to adaptation where land management decisions need to integrate considerations on biodiversity, water, soil and all other natural resources with economic factors. Nature-based solutions on a larger scale are seen as options for increasing climate resilience while also contributing to the other European Green Deal objectives. Along this line, the Biodiversity Strategy calls for integrated action as well as increases in the quantity, quality and resilience of the EU's forests, notably against fires, droughts, pests, diseases and other threats likely to increase with climate change but while still contributing to the climate neutrality ambition. The Biodiversity Strategy (EC 2020c) sets a protection target of at least 30% of the land and 30% of the sea. This corresponds to a minimum extra 4% of the land area currently protected. Furthermore, a target of 10% of strictly protected areas is also set, specifically targeting primary and old-growth forests as priorities for conservation as these are estimated to only cover about 3% of the total EU forest land (EC 2021b). This nature restoration plan, protection of biodiversity-rich areas and creation of ecological corridors are also reinforced under the Biodiversity Strategy, with an integration of new monitoring and reporting duties of such areas within the LULUCF Regulation proposal. As previously mentioned, the Biodiversity Strategy also sets the target to increase tree cover at the EU level, having pledged to plant 3 billion additional trees in the EU by 2030. In support of this effort, the European Commission is currently developing guidelines on biodiversity-friendly afforestation and reforestation and closer-to-nature-forestry practices.

4.1.5 Trade policy

European sustainability choices, as well as consumption patterns, have impacts on forests globally due to imports of wood products (solid wood products, pulp, paper, etc.) and biomass for bioenergy (Pendrill et al. 2019a, 2019b; Hong et al. 2022). Currently, the EU's imported wood is regulated by the EU Timber Regulation, which aims to counter the trade in illegally harvested timber and timber products. REDII also established a set of sustainability criteria that apply also to imported woody biomass for energy.

Beyond wood imports, the EU's high per-capita consumption levels of products that are forest-risk commodities, such as soy, beef, palm oil, cocoa and coffee, places the EU among the leading international consumers of deforestation embodied in trade (Pendrill et al. 2019b). The deforestation associated with these EU imports is estimated to be responsible for 190,000 hectares of forest being cut down per year (2015–2017 data) (Pendrill et al. 2020). To address the deforestation in third countries linked to the EU's imported commodities, in autumn 2021 the European Commission delivered a regulation proposal that sets mandatory due diligence rules for importers who place specific commodities on the EU market that are associated with deforestation and forest degradation (i.e., soy, beef, palm oil, wood, cocoa and coffee as well as some derived products, such as leather, chocolate and furniture). To ensure that only deforestation-free and legal products (according to the laws of the country of origin) are allowed into the EU market, importers must undertake a strict traceability regime to determine the origin of the commodities to report on the geographic coordinates of the land where the commodities were produced. Countries of origin will be classified through a benchmarking system, aimed at identifying the level of risk of producing such commodities or products in a specific country or region. Consequently, the obligations of the operators will vary according to the level of the risk in such countries, with the level of complexity of due diligence duties being tethered to the level of the risks at the source.

4.1.6 Other policies

To achieve ambitious long-term EU objectives with the support of the land-use sector, farmers and foresters will be called on to play a more active role in increasing carbon uptake and reducing emissions (Savaresi and Perugini 2021). To promote a more direct incentive system, the Circular Economy Action Plan (EC 2020d) has anticipated a new regulatory framework for the certification of carbon removals by 2023, one that is designed to encourage EU farmers to store carbon in soils and vegetation while also reducing emissions linked to agriculture practices. A carbon farming initiative is also mentioned by the Farm to Fork Strategy (EC 2020e), which is designed to build a sustainable food system via a new business model that provides farmers with a new source of income and helps other sectors to decarbonise the food chain. The carbon farming initiative is also included in the EU Forest Strategy and the EU Adaptation Strategy as a tool for achieving adaptation objectives in the agriculture and forestry sector alongside mitigation efforts.

The European Commission has recently delivered a Communication on Sustainable Carbon Cycle (EC 2021d), outlining the actions needed to define and upscale carbon farming as a system to reward land managers for carbon sequestration and biodiversity protection. The financial incentives for this could come from public or private sources (e.g., voluntary market) and the Commission is exploring options to develop a framework for the certification of carbon removals in 2022. This will also entail establishing a robust monitoring, reporting and verification system for carbon removals at the individual landholdings level, including for the determination of co-benefits for biodiversity and ensuring permanence of carbon and additionality. The EC considers a robust certification system as a pre-condition for establishing a market-based carbon removal solution at the EU level, both of which could be fully operational post-2030.

In the short term, an important financing tool for the implementation of carbon sequestration measures at the EU level is identified in the new Common Agricultural Policy (CAP). The new CAP aims at supporting sustainable agriculture and rural development and promoting, among others, climate mitigation and environmental actions in the forestry sector, with at least 40% of its budget to be expected to contribute to climate-related objectives. While forestry measures have been poorly implemented by Member States under the previous programming period (2014–2020), for 2023–2027, more attention has been given by the Commission to encouraging Member States to reinforce their efforts on forest actions using the CAP Strategic Plans (EC 2021b). Member States are specifically encouraged to set up a payment scheme for ecosystem services for forest owners and managers, as well as to accelerate the rollout of carbon farming practices. The latter is particularly encouraged via eco-schemes on agroforestry or rural-development interventions to cover biodiversity-friendly re- and afforestation investments, agroforestry and other non-productive investments for environment- and climate-related objectives (EC 2021b, EC 2021d). Funding under the CAP will be key to providing land managers with improved knowledge through targeted advisory, data and monitoring services (EC 2021d).

Overall, the climate policy framework at the EU level is gradually including the land sector in its targets and calls for the maximisation of the climate benefits through sustainable forest management, providing new guidelines, indicators, and planning tools to assist Member States to more efficiently plan and manage their forest resources sustainably. The effectiveness to deliver the expected results will depend on the capacity of the Member States to assess the effects of their policies in different sectors. The forthcoming CAP strategic plans and the updated National Climate and Energy plans are the key programming tools at the country level where the optimal balance between synergies and trade-offs of the different functions of the forestry sector needs to be identified.

In an international context, the various commitments adopted by the international community, such as the SDG targets, the New York Declaration on Forests (NYDF 2014) and the Paris Agreement, have to date all fallen short in terms of delivering their expected outcomes (FAO 2020, Bager et al. 2020). Finance poses a critical barrier to progress in this area, with current funding barely covering 5% of the estimated needs of the forestry sector (Haupt and Manirajah 2021). Governance, accountability, institutional capacity, recognition of indigenous peoples and local communities' rights, including land tenure, are also important issues that will need an unprecedented effort to successfully resolve (IPCC 2022). A further endeavour of the international community was shown through the recent Glasgow Leaders' Declaration on Forests and Land Use (2021) where signatories committed to "*working collectively to halt and reverse forest loss and land degradation by 2030 while delivering sustainable development and promoting an inclusive rural transformation*". The declaration, signed by 141 countries whose territories account for 91% of global forest cover, was accompanied by a financial pledge from a group of countries (six, including the EU) of US$12 billion for forest-related climate finance between 2021–2025. Traceability of the origin of commodities is, as noted above, an important step to achieving transparent and sustainable supply chains and is an issue that is under discussion at the international level within the Forest, Agriculture and Commodity Trade (FACT) Dialogue, another COP26 joint statement. However, these voluntary pledges, although important to show governmental willingness and in mobilising public awareness, remain largely unfulfilled. Stronger accountability of countries, with mandatory actions and a related timetable are needed alongside an effective monitoring regime based on openly available and shared data (Nabuurs et al. 2022) with all sectors working together towards the common goal of pursuing the sustainable management of natural resources.

Table 6. Summary of the main European policy tools and related mitigation actions in the forestry sector.

Policy	Type of Mitigation activities		
	Protect and Manage	**Restore**	**Wood Use**
Biodiversity Strategy 2030 (EC 2020c)	• EU Nature Restoration Plan (restore degraded ecosystems by 2030 and manage them sustainably) • Establishing legally binding EU nature restoration targets in 2021 • At least 30% of the land should be protected in the EU (4% more land area than today) • 10% of EU land should be strictly protected Focus--> define, map, monitor and strictly protect all of the EU's remaining primary and old-growth forests	• Target: planting at least 3 billion additional trees in the EU by 2030 • Guidelines on biodiversity-friendly afforestation and reforestation and 'closer-to-nature' forestry practices	The use of whole trees for energy production, whether from the EU or imported, should be minimised.
European Forest Strategy 2030 (EC 2021b)	• Encouraging the bioeconomy to embrace sustainable principles • Creating payment schemes for forest owners and managers for the provision of ecosystem services • Identification of additional indicators concerning forest ecosystem conditions, including climate objectives • Development of a 'closer-to-nature' voluntary certification scheme (EU quality label) • All primary and old-growth forests will have to be strictly protected. • The Commission will provide common definitions for primary and old-growth forests and their strict-protection regime. • Member States completing the mapping and monitoring of these forests and ensuring no deterioration until they start to apply the protection regime.	• Planting 3 billion additional trees by 2030 • Creating payment schemes for forest owners and managers for the provision of ecosystem services • Establishing legally binding nature restoration targets for forests	• Promoting the uptake of sustainably harvested wood in the construction sector • EC will develop a 2050 roadmap for reducing whole life-cycle carbon emissions in buildings • EC will develop a standard methodology to quantify the climate benefits of wood construction products and other building materials. • Member States will design their support schemes for the use of biomass for energy sustainably • Delegate act to be adopted by the EC on how to apply the cascading principle for biomass, in particular, on how to minimise the use of quality roundwood for energy production
LULUCF Regulation proposal (EC 2021a); Fit for 55 proposal (EC 2021e)	• Changes in forest management that increase the carbon sink and reduce the losses (including through reducing harvesting intensity) are accounted for (forest land remaining, forest land categories) • The proposal includes enhanced reporting criteria for carbon-rich areas	• Changes in forest cover are accounted for (land converted to forest land category)	• The carbon stock change due to the use of harvested wood products produced by each country is included in the accounting system. • Wood used for biomass is accounted for in the LULUCF sector as a complete emission of the C content of the whole above-ground tree biomass (instantaneous oxidation)

Policy	Type of Mitigation activities		
	Protect and Manage	Restore	Wood Use
REDIII proposal (EC 2021h)	• Strengthened sustainability criteria for bioenergy, extending their scope of application and enlarging no-go areas for sourcing (including primary, highly-diverse forests and peatlands). • Extend criteria to small-scale biomass-based heat and power installations (< 5 MW). • Restrictions apply in the use of saw logs, veneer logs, stumps and roots for energy, except under well-defined circumstances. • Woody biomass should be used according to its highest economic and environmental added value (cascading principle). • Obligation to phase out, with some exceptions, support for electricity production from biomass from 2026 (Article 1(2)).	NA	• Biofuels with high indirect land-use change risk are assessed and a trajectory established for their gradual phase-out by 2030. • Member States will design their support schemes for the use of biomass for energy in a way that minimises undue distortive effects on the biomass raw material market and harmful impacts on biodiversity. • Commission will adopt a delegated act to specify how to apply the cascading principle for biomass
Common Agricultural Policy	• Eco-schemes (Pillar I) and rural development forest-environment-climate measures or investments (Pillar II) can directly support carbon farming practices (including afforestation and forest management) • Support from advisory services passes knowledge to land managers • The European Innovation Partnership for agricultural productivity and sustainability (EIP-AGRI) helps land managers cooperate and test new approaches • Continuation of support to forest holders to help address specific disadvantages resulting from the implementation of Directive 2009/147/EC and Directive 92/43/EEC and to contribute to the effective management of Natura 2000 sites.	• Eco-schemes and rural development forest-environment-climate measures or investments can directly support carbon farming practices (including afforestation and forest management)	• CAP Strategic Plan will have to contribute to achieving national targets and objectives derived from EU climate legislation and set out in the National Energy and Climate Plan

4.2 Incentivising climate change mitigation efforts

Forests and forestry sectors are complex systems and incentivising changes involves millions of forest owners and managers, consumers and many companies and industries. As shown in Section 4.1, many of the policies and targets discussed in this paper address issues related to land use, energy, trade and/or biodiversity. This complex mix of issues is also revealed in the variety of instruments that can be implemented to increase the mitigation efforts in the forestry sector. Incentives to bring about behavioural change and strengthen mitigation efforts can be divided into three broad categories: information, norms and economic incentives (see Table 7). Further to this, these instruments entail diverse levels of governance, both in terms of government involvement and private sector initiatives (Steurer 2013). Public policies encompass traditional regulatory instruments (including taxes and subsidies), as well as defining and clarifying various frameworks to facilitate voluntary actions from the private sector, such as product labelling and carbon certification.

Table 7. Overview of possible policy instruments.

Type of instrument	Aim	Advantages	Disadvantages	Examples
Information	Improve information	• Low cost • Applicable to both consumers and producers	• Only useful if the lack of action comes from poor information	• Timber certification, carbon certification • Product labelling • Awareness campaigns • Guidelines • Training
Norms	Set constraints	• Simple application	• Do not consider well the heterogeneity of situations	• Legal instruments • Forest codes • Building codes • Public procurement rules
Economic (taxes)	Increase the costs of detrimental actions	• Cost-efficient • Increases public revenue	• Political acceptability	• Carbon tax
Economic (subsidy, payment schemes)	Reward positive actions	• Political acceptability • Costly actions • Potential for co-benefits	• Requires good knowledge of mitigation action costs. • Potential leakage effects • Permanence issues when subsidy or payment ends • Additionality is not always clear	• Payments for carbon storage (carbon farming) • Tax cuts • Support for R&D

4.2.1 Informational instruments

A challenge to implementing mitigation actions may come from poor information about the mitigation benefits of forest management and wood use. On the forest management side, when there is imperfect information about best practices that can be implemented to maximise carbon benefits, training campaigns and informative planning may be used. Furthermore, reliable information is required to foster a good understanding of the implications of activities undertaken by the wood-processing industry for the climate and to inform consumers. On the consumption side, if consumers are not aware of the practices implemented by forest managers and the wood-processing industry, as well as the associated climate impacts, certification and environmental labels can be implemented. These labels may also be of use to inform consumers of any benefits of products made from wood over those made from fossil or emission-intensive materials. As such, product labelling and certification schemes are examples of instruments that provide information (see also Box 6) and constitute a form of market diversification where uncertified and certified products co-exist in a market and consumers choose products according to their 'informed' preference. In the case of climate change mitigation, these instruments are only of real value when the lack of mitigation efforts is due to asymmetric information. For example, if consumers are not aware of the climate benefits of purchasing wood products sourced via sustainable harvesting, certification may be of help to orientate climate-conscious consumers toward such products. Overall, the impact of informational instruments on mitigation efforts is limited (Delacote and Montagné-Huck 2012), especially if actors already have a good knowledge of what are the right actions to be undertaken. Informational instruments (informational and training campaigns, labelling and certification) may come from both public and private actors, however, there is an especially important role for public policies in defining stringent criteria and minimum requirements for certification to reduce the risk of 'green washing' by private actors.

Box 6. Carbon Certification.

Monitoring, reporting and verification are key elements to support the development of carbon offsets projects. Such projects need to provide evidence that the undertaken actions have effectively resulted in permanent carbon emission reductions (or increased carbon removals). Certification can help in providing such evidence. For a carbon offset project to become certified, it must detail the methodology used to estimate the emissions reductions or carbon sequestration generated to ensure it meets the standards set by certification schemes. It also needs to provide clear, transparent and trustworthy information about its evaluation processes and outcomes. For that matter, monitoring, verifying, and reporting should be overseen by institutions that operate independently from stakeholders seeking certification.

Many standards exist that can certify offset projects (for an overview, see Cevallos et al. 2019). Among those, the Verified Carbon Standard is the most used on voluntary markets (Hamrick and Goldstein 2016). Historically, carbon certification has primarily focused on afforestation and avoiding deforestation projects in developing countries, along the lines of the Clean Development Mechanisms of Kyoto Protocol. However, few similar but forest-related projects and programmes exist within Europe (e.g., the case of the UK Woodland Carbon Code described in Box 8). This low number of forest-carbon projects is due to some key barriers, such as high transaction costs, permanence issues and difficulties to assess additionality and double-counting problems with national accounting duties under the UNFCCC.

Box 7. The United Kingdom Woodland Carbon Code.

The UK Woodland Carbon Code (WCC, https://www.woodlandcarboncode.org.uk/) is a voluntary standard in the UK to provide assurances to buyers of carbon credits from forestry projects that offer carbon sequestration goals that are realistically achievable. The WCC is endorsed by the International Carbon Reduction and Offset Alliance (ICROA, https://www.icroa.org/standards) and meets international quality criteria for carbon standards, namely, that for carbon credits to be real, they must be measurable, permanent, independently verified, additional to 'business-as-usual' and unique. Carbon sequestration resulting from WCC projects also contributes directly to the UK's national targets for GHG emission reductions.

The WCC was established in 2011 and by March 2022, there were over 1,500 projects registered with it, covering almost 60,000 hectares of newly established forests that are estimated to sequester 18.7 Mt CO_2 over the next 100 years. This equates to approximately half of the total area of woodland created between 2011 and 2022. The number of projects registered doubled in 2020/21 and again in 2021/22.

The current WCC standard and methodologies cover carbon sequestration and emissions resulting from creating new forest areas. Additional carbon sequestration resulting from changes to the management of existing forests (forest management) is not covered by the standard. Forest project proponents are also interested in incentives for sequestering carbon in wood products and potentially contributing to reduced emissions through wood product substitution effects. However, there are significant methodological challenges, e.g., deciding who owns the carbon in wood products that are bought and sold as well as uncertainties over the magnitude of substitution effects.

Potentially, the WCC could be extended to cover forest carbon projects involving adjustments to the management of existing forest areas, and it could become one standard amongst others addressing a range of offsetting activities. While a Peatland Code (https://www.iucn-uk-peatland-programme.org/peatland-code-0) already exists that focuses on marketing the climate benefits of peatland restoration, standards could also be developed to cover carbon sequestration in (for example) soil, hedgerows, 'rewilding' projects and agroforestry systems.

4.2.2 Norms

Regulatory instruments are yet another type of policy instrument to incentivise climate change mitigation. They can be either norms or economic instruments and primarily come from public incentives. Norms refer to mandatory or forbidden practices, management rules, emission limits as well as quotas and may be applied uniformly to all agents or be dependent upon particular conditions. Their main advantage is that they incur lower implementation costs for policy makers. However, they can be more costly for economic agents as these instruments rarely consider their heterogeneity. For example, norms can include prescribed forest management practices, building and construction codes or requirements for public procurement rules.

4.2.3 Economic incentives

In a forestry context, economic instruments can help forest owners and managers, timber-processing industries and consumers take the social costs and benefits of their practices into account. For example, if a forest management practice brings negative or positive outcomes for climate, the incentive should accentuate this through increasing the costs of employing detrimental practices and/or reducing the costs of employing virtuous ones; based on the assumption that rational economic agents will take these costs into account when making their decisions. Price instruments refer to taxes aimed at averting actions with negative climate outcomes, or subsidies that reduce the costs of practices with positive climate impacts. For example, the implementation of a carbon tax could favour wood products associated with lower emissions and increase their share in overall consumption. Indeed, since wood products are often associated with lower emissions compared to their substitutes, the price increase from such a tax could induce a broad substitution trend from carbon-intensive products to wood-based products (Caurla et al. 2013). However, it is important to note that: (1) taxes generate public revenues that can be used for environmental (or other) purposes, but they are likely to generate political opposition; and (2) subsidies are costly to governments but generally more readily accepted by a population. As forestry and the forest-based sector is tightly connected to many other economic sectors, it is important to note here that policies applied to single a sector may create adverse reallocation effects and, as such, these policies should only be implemented within a holistic approach.

A final type of economic instrument that is particularly used when it comes to ecosystem management is payments for ecosystem services (PES). A voluntary, conditional agreement between at least one seller and one buyer over a well-defined environmental service or a land use presumed to produce that service (Wunder et al. 2008). Hence PES schemes may be implemented by both public institutions and private initiatives. When it comes to carbon and climate change mitigation, PES schemes may lead to carbon offsets that can be sold on carbon markets, which can be considered as quantitative economic instruments (Dales, 1968) while carbon credits from forestry may be sold on voluntary carbon markets if they have received the proper certification (see Boxes 6 and 7). In this context, offsetting is a way for private companies to reduce their net carbon footprint but it does not reduce emissions. It is important to mention here that carbon offsetting can only be one element of a corporate global strategy, truly addressing climate change requires PES schemes to be run alongside emission-reduction efforts from engaged companies. The role of public policies here is to define a clear and stringent framework for stakeholders to help them implement effective initiatives as is seen, for example, with the carbon farming initiative from the Farm to Fork EU strategy (see Box 8).

Box 8. Carbon Farming.

Within the EU Farm to Fork strategy (EC 2020e), the Carbon Farming initiative aims to promote climate-positive actions from the agricultural and forestry sectors. The initiative can be understood as a form of payment for ecosystem services in the sense that it provides financial incentives to agents of those sectors when they undertake beneficial climate-related actions.

When it comes to forests, the most strongly encouraged actions are the establishment of new forests through afforestation/reforestation, the restoration of degraded forests and improved forest management. The supply of biomass for long-lasting products to promote substitution from carbon-intensive products is also considered. Several options for funding the initiative have been explored, such as using the CAP funds as well as carbon market-related private funding. No forestry project has been launched yet within the Carbon Farming initiative.

A crucial element to have in mind here is the case of co-benefits (biodiversity, livelihoods), which may also be valued. Indeed, implementing some mitigation efforts in forests may enhance or impede those co-benefits. As shown in Simonet et al. (2016), synergies and trade-offs between income from timber harvesting, carbon sequestration and biodiversity may occur depending on the initial state of the forest and the actions undertaken. It has been shown, for example, that avoiding deforestation offsets may be more valuable than reforestation ones, partly because of their co-benefits. Sarira et al. (2022) estimate that forests could be protected through financially viable carbon projects in South-East Asia while also helping support dietary needs, retain nitrogen pollutants and safeguard key biodiversity areas. Cevallos et al. (2019) showed that explicitly taking co-benefits into account in carbon offset projects could lead to higher carbon prices, indicating that carbon credits buyers value forestry projects beyond just their carbon value.

There are several concerns related to PES schemes. Firstly, when implementing a PES scheme to increase carbon sequestration in standing forests, it is important to consider leakage effects, i.e., the indirect spatial effects that may decrease sequestration elsewhere (Delacote et al. 2016). For example, if one region implements efforts to increase carbon sequestration by reducing timber harvesting, it may lead to price increases in timber markets, which is likely to further increase timber harvesting and hence reduce carbon sequestration in neighbouring or other areas. Secondly, the question of permanence is also a source of concern. Once a PES scheme is over, especially one that had positive impacts, it is important that forest and land managers do not go back to their previous practices but continue to apply mitigation efforts. The additionality of PES schemes is frequently questioned (Chabé-Ferret and Voia 2021) as, for example, some studies report that reforestation activities do not necessarily increase forest cover and that trees tend to be planted in low-productivity areas with more productive areas still devoted to agriculture, which results in low carbon sequestration (Coleman et al. 2021). A meta-analysis by Snilsveit et al. (2019) reveals that PES schemes can reduce deforestation and increase forest cover but that there are many factors (e.g., the presence of strong governance structures and the involvement of local participants) that will ultimately determine the effectiveness of any given PES scheme.

To conclude, the successful implementation of forest-based mitigation activities requires policy makers to create incentives for the investments needed to activate forest management and finance mitigation and adaption measures, including the protection of biodiversity and other ecosystem services (Verkerk et al. 2020). Because forest-based mitigation activities interact with activities in other sectors, the implementation of a carbon tax that covers all sectors appears to be an efficient instrument to initiate climate-friendly behaviour and actions. Nevertheless, a carbon tax should be complemented by other instruments (e.g., certification, labelling, public procurement) to incentivise mitigation actions more effectively by a broader range of involved actors. Moreover, long-term investments are needed to incentivise actions and commitments that begin now and will persist into the future. These investments should be derived from securing funding, both from public sources and through commitments by the banking sector toward green investments. The commitment of governments to implement long-term policies is also required. The risk of non-permanence should be considered in carbon-related issues by favouring long-term contracts and deep transformative actions rather than those that are incremental and superficial. Overall, there is no silver bullet that can make forests and the forestry sector efficiently contribute to climate change mitigation, rather, a mix of informational, regulatory and economic instruments should likely be pursued. As previously noted, an area for future investigation here is to investigate the most efficient way to combine all of the above aspects into a holistic package that yields optimal results.

5. Synthesis, policy implications and recommendations

5.1 Main findings

European forests and forestry represent a key component in achieving climate neutrality by 2050, as laid out by the European Green Deal. The European climate-policy framework acknowledges forests' unique role in actively removing CO_2 from the atmosphere on a large scale and has included the land sector in its targets. Currently, all forests and wood products in the EU remove approximately 380 $MtCO_2eq\ yr^{-1}$ from the atmosphere, which compensates for approximately 10% of the EU's annual GHG emissions. According to new policy targets proposed by the European Commission, the EU-27's LULUCF sector, which includes forests and wood products as well as other land uses, will **need to remove approximately an additional 50 $MtCO_2eq$ per year by 2030, 100 $MtCO_2eq$ per year by 2035 and 170 $MtCO_2eq$ per year by 2050**. (Section 4.1), which broadly equates to adding the current combined annual forest sinks of Germany, France, Italy and Spain. The extension of the targets to the entire LULUCF sector should encourage the implementation of cost-efficient emission reductions that considers all land uses and avoids further deforestation and land degradation.

According to the available scientific literature, CO_2 removals by forests and wood products are generally expected to decrease in the period from 2030 to 2050. Compared to this development, **mitigation activities that aim to protect, manage, and restore forests in the EU-27 can seemingly provide an additional mitigation potential of 132 $MtCO_2eq\ yr^{-1}$ by 2050** (142 $MtCO_2eq\ yr^{-1}$ for the EU-27, Norway, Switzerland and the UK), with the **mitigation potential of individual activities ranging, on average, between 10 and 105 $MtCO_2eq\ yr^{-1}$ by 2050** (11–115 $MtCO_2eq\ yr^{-1}$ for the EU-27, Norway, Switzerland and the UK) (see Section 2.2 and Table 8). According to the literature, avoiding deforestation provides the smallest forest-based mitigation potential while decreased forest harvest and improved active forest management are reported to provide the greatest potential whereas afforestation/reforestation and forest conservation provide an intermediate mitigation potential. As shown in Table 8, forest restoration may indeed provide greater mitigation potential, but this estimate is based on a single study, which was not limited to just forest areas. Mitigation activities centred on wood use can also contribute to climate change mitigation both in the short and long term because of changes in the production structure of forest industries, such as shifting from communication paper manufacturing to textile manufacturing or shifting the use of by-products from energy to material uses. Based on the available scientific literature, **the additional climate change mitigation potential of mitigation activities centred on wood use in the EU is, on average, 12 $MtCO_2eq\ yr^{-1}$** (13 $MtCO_2eq\ yr^{-1}$ for the EU-27, Norway, Switzerland and the UK), with the potential from individual activities ranging, on average, from -0.5 to 14 $MtCO_2eq\ yr^{-1}$ (-0.6 to 15 $MtCO_2eq\ yr^{-1}$ for the EU-27, Norway, Switzerland and the UK) (see Section 2.3 and Table 7). The mitigation potential is achieved mostly by shifts in wood use.

The estimated **potential from individual mitigation activities cannot be straightforwardly tabulated** because they may interact and affect multiple carbon pools and fluxes simultaneously (Section 2.4). To provide an estimate of the total mitigation potential and illustrate the option space, we bundled mitigation activities that can be combined with limited effects on each other. These bundled activities illustrate the option space for the total forest-based mitigation potential. Mitigation activities such as **avoiding deforestation, afforestation/reforestation, shifts in wood use, cascading and increased efficiency** have limited effects on each other and when combined they **could provide a mitigation potential of up to 72 $MtCO_2eq\ yr^{-1}$ by 2050 in the EU** (78 $MtCO_2eq\ yr^{-1}$ in the EU-27, Norway, Switzerland and the UK). These activities also have limited impacts on biodiversity (see Table 8).

This additional EU-27 forest-based mitigation potential of 72 MtCO_2eq per year could increase to:

- **125 MtCO_2eq per year when combined with forest conservation activities** (136 MtCO_2eq yr^{-1} in the EU-27, Norway, Switzerland and the UK), or
- **138 MtCO_2eq per year when combined with other active forest management** (150 MtCO_2eq yr^{-1} in the EU, Norway, Switzerland and the UK), or
- **143 MtCO_2eq per year when combined with decreasing forest harvest** (155 MtCO_2eq yr^{-1} in the EU-27, Norway, Switzerland and the UK).

Altogether, **these findings suggest that, according to the estimates available in the scientific literature, it will be challenging to achieve the EU's climate targets for the LULUCF sector by 2035 and 2050 through forest-based mitigation activities**.

The forest-based mitigation potential that is reported on in the scientific literature includes technical, economic as well as other types of potential. Only limited information is available in the literature on the estimated costs of realising and implementing the needed forest-based mitigation activities. **The available information suggests that approximately only one-quarter of the mitigation that could technically be achieved through forest-based activities, could be achieved at a cost of US$100/t$CO_2$eq** (approx. €88/t$CO_2$eq) (Section 2.2). This limited pool of information on the costs of forest-based mitigation activities highlights an important knowledge gap that needs addressing to determine which activities be prioritised to reduce net emissions.

Table 8. Summary of mitigation activities assessed in this study

Category	Activity	Mitigation potential ($MtCO_2eq\ yr^{-1}$)*	Interaction with adaptation	Impact on other mitigation activities	Impact on biodiversity
Protect	Avoiding deforestation	EU 27 + 3: 11 (11 - 11) EU 27: 10 (10 - 10)	Supports adaptation of surrounding forests	Limited or no impacts	Avoids loss of biodiversity
Protect / Manage	Forest conservation	EU 27 + 3: 58 (46 - 69) EU 27: 53 (41 - 63)	Supports natural adaptation but decreases options for active adaptation	Potentially reduces active management and wood use	Supports biodiversity in protected forests
Manage	Forest harvesting (decreased)	EU 27 + 3: 78 (1 - 286) EU 27: 70 (1 - 259)	Can foster drought tolerance but decrease stand stability	Potentially reduces active management and wood use	Supports biodiversity in forests experiencing lower harvest pressure
	Active management (other than harvesting)	EU 27 + 3: 72 (11 - 186) EU 27: 65 (10 - 169)	Possible trade-off between carbon storage and fitness	Potentially reduces forest conservation	Supports or decreases biodiversity depending on the type of active management
Restore	Forest restoration	EU 27 + 3: 115 (14 - 245) EU 27: 105 (13 - 222)	Careful selection of species and forest types for restoration improves resilience	Limited or no impacts	Supports biodiversity when structural diversity and tree species diversity increases
	Afforestation/ Reforestation	EU 27 + 3: 54 (19 - 83) EU 27: 49 (17 - 75)	Possible trade-off between establishing resilient forests or maximising sequestration	Limited or no impacts	Supports biodiversity when degraded land is reforested. Reduces biodiversity when ecosystems with high biodiversity are afforested
Wood use	Shifts in wood uses (including by-products)	EU 27 + 3: 15 (-70 - 391) EU 27: 14 (-63 - 354)	Balance between generating revenues to support adaptation actions and increasing harvest pressure which may hamper adaptation	Limited or no impacts, if no additional harvest	Supports biodiversity when lowering harvest pressure on forests and when less polluting manufacturing processes are applied
	Cascading (end-of-life)	EU 27 + 3: -1.5 (-26 - 9) EU 27: -1.4 (-24 - 8)	Can reduce harvest pressure on forests to enable focus on adaptation and natural processes	Limited or no impacts	Supports biodiversity by when lowering harvest pressure on forests
	Increased efficiency	EU 27 + 3: -0.6 (-6 - 8) EU 27: -0.5 (-5.5 - 7.5)	Can reduce harvest pressure on forests to enable focus on adaptation and natural processes	Limited or no impacts	Supports biodiversity when lowering harvest pressure on forests and when less polluting manufacturing processes are applied

*Mitigation potential and ranges (between brackets) are reported for the EU-27, and separately for the EU-27 with Norway, Switzerland and the UK

The various estimates of mitigation potential in this report are based on a synthesis of the estimates available in peer-reviewed literature, although these sources differ widely in their scope and objectives. **It is stressed that the estimated net mitigation potential is subject to a high degree of uncertainty, as manifested by the large ranges in the various estimates** (Section 2.5). This uncertainty is connected to the variability arising from individual studies using different data, methods, system boundaries, types of potential and scenario assumptions, including the assumed counterfactual development. Very few studies exist in the scientific literature that coherently consider all the carbon pools and fluxes of forest ecosystems (in biomass and soil), wood products, avoided emissions through material and energy substitution, as well as those associated with leakage and rebound effects. For example, studies that estimate the mitigation potential of activities that aim to maximise carbon storage in forest ecosystems through forest conservation or reduced harvest often ignore or exclude the implications for wood use (including substitution effects) or leakage. Conversely, studies that focus on wood use options sometimes exclude implications for forest ecosystems. To understand the full mitigation potential offered by forest-based climate change mitigating activities, **a holistic approach is needed** (both in policy and research) **that considers forests and wood use options together for their overall contribution to achieving policy targets. Such a holistic approach must cover all the relevant carbon pools and fluxes of forest ecosystems (in biomass, deadwood and soil), wood products, avoided emissions through material and energy substitution, as well as any leakage and rebound effects along with their development up to and beyond 2050. Moreover, this holistic approach must consider the interactions with other emission sectors** because forest-based mitigation activities impact and are impacted by activities in other sectors (Sections 2.3, 2.4, 2.5, 4.1, 4.2). For example, policies to increase biomass use for bioenergy can reduce carbon storage in forests and actions in the agricultural sector (e.g., meeting demands for food and feed or bioenergy) may present opportunities and/or threats to forest conservation, afforestation and avoiding deforestation while the restoration of peatlands will, in some cases, involve removing tree cover. Finally, mitigation through wood product substitution effects will need to consider the emission reduction trajectories of all other sectors and be mindful of the market dynamics that may reduce the apparent substitution benefit. Conversely, choices about forest-based mitigation actions will involve trade-offs and synergies with the mitigation potential provided by other sectors. Such cross-sectoral effects have generally not been considered in the national and European-level studies reviewed in this report.

Results from the scientific literature generally indicate that when the level of harvest is increased compared to a baseline, it creates a trade-off between avoided fossil emissions and increasing wood product carbon stock on the one hand, and decreased forest carbon sinks on the other hand. These trade-offs are, at least partially, time-dependent and **activities that provide net mitigation benefits in the short-term may limit or complicate climate change mitigation in the long-term and vice versa**. For example, mitigation activities that aim to maximise carbon storage in forest ecosystems through forest conservation or reduced harvest may help to achieve policy targets in the short to medium term. This benefit will, however, become smaller as forests grow older and their growth rate reduces or when climate change-induced disturbance impacts on forests increase and lead to carbon losses. Moreover, as forests grow relatively slowly, it takes time for new measures to take effect and this means **immediate actions are needed to maintain and strengthen the climate change mitigation potential in the long-term** (i.e., beyond 2050).

Forestry is a cross-cutting sector that is subject to multiple demands from various climate and energy policies, including those implemented under the European Green Deal, which creates a risk of conflicts between policy objectives. The current debate on the role of forests in climate change mitigation focuses quite narrowly on harvest levels. This creates significant blind spots as forest management is about more than harvesting wood and forests are more than just pools of carbon. **Forest ecosystems are important for biodiversity and provide many ecosystem services to society**. A suite of management practices exists that support climate change mitigation, adaptation and biodiversity, for example, through the type of harvests, the selection of tree species and provenances, peatland hydrology management and so forth (see Sections 2.6, 3.1, 3.3 and Table 8). However, **whether synergies or conflicts occur strongly depends on how mitigation**

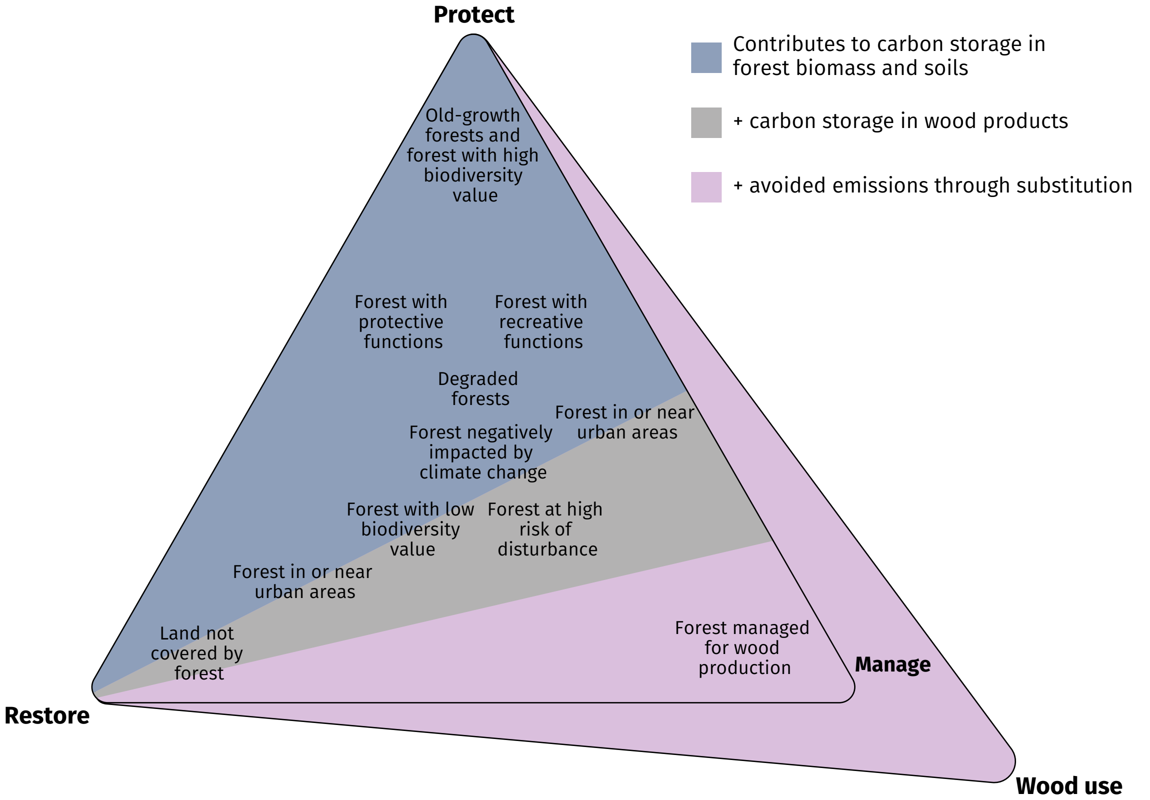


Figure 8. Illustration showing how different types of forests and management objectives can contribute to mitigation activities.

measures are implemented. Protecting carbon-rich forest ecosystems from deforestation and soil degradation is evidently a climate change mitigation measure with positive impacts on forest biodiversity. Active forest management that promotes species and structural diversity can also help meet climate and biodiversity goals while the often-considered strategy of afforestation can significantly contribute to climate change mitigation but may harm biodiversity if, for example, it is implemented on biodiverse grasslands (Section 2.6). This indicates that **regional environmental, social and economic conditions need to be considered when planning and implementing forest-based mitigation**. Suggestions on how different types of forests and management objectives can contribute to mitigation activities are provided in Figure 8.

Forests, forestry, and the forest-based sector play a key role in achieving climate goals to limit the average global temperature increase to less than 2°C above pre-industrial levels. However, meeting these goals will neither prevent climate change nor climate change impacts on forests. **Climate change is already taking place and is affecting both the physiological processes and ecological conditions that determine forest growth**. The resulting gradual changes must be interpreted in conjunction with changes in disturbance regimes induced by climate change as the combination of these processes, coupled with forest management regimes, will significantly determine the dynamic, future species composition of Europe's forests. All of these factors must be carefully understood and considered to minimise their impacts on forests to preserve the latter's ability to store carbon and continue contributing to the EU's climate change mitigation targets. **Climate change impacts on forests, especially those related to extreme events and natural disturbances, are often not considered in studies that estimate the climate change mitigation potential of forests.** Moreover, despite a growing body of literature that investigates climate change impacts on forests, **limited research is currently available on how climate change may affect forestry activities, forest industries and**

forest products markets. Possible impacts could include changing wood assortments due to the decline of economically important tree species or adaptation strategies to diversify forest structure, changes in wood quality and peaks in the supply of wood that is salvaged following major disturbances (Sections 2.2, 3.1, 3.2).

Implementing forest-based mitigation activities will represent a significant challenge as it involves millions of forest owners and managers, hundreds of millions of consumers and innumerable companies and industries. The forthcoming CAP strategic plans and the updated National Climate and Energy plans are currently being positioned as the key programming tools at the country level where the optimal balance between synergies and trade-offs of the different functions of the forestry sector needs to be identified. The flexibility provided in planning and designing forest-related interventions under the new CAP (2023–2027) offers an opportunity to link such actions to national forestry policies and climate objectives. Carbon farming practices can be promoted under the CAP through eco-schemes while simultaneously building country-based initiatives, such as local carbon markets. The development of the regulatory framework for certifying carbon removals currently under development by the European Commission appears to be a promising tool for promoting carbon farming in the forestry sector (Sections 4.1, 4.2). However, informed action needs to be based on robust data, that are often poor in the forestry sectors of many Member States, which indicates **an urgent need for a more transparent, harmonised and robust monitoring framework from which informed and strategic forest planning at (sub-)national level can be effectively undertaken**.

5.2 Policy implications and recommendations

Given the urgent need to significantly reduce GHG emissions and increase removals, this study reviewed the existing scientific literature on mitigation potential provided by forest-based activities in the EU-27, Norway, Switzerland and the UK. Based on this review, we provide recommendations to decision-makers to help realise the full potential of forest-based climate change mitigation activities:

- Within current policy plans, forest-based mitigation activities play an important role in achieving climate neutrality and compensating for harder to abate emissions from other sectors (e.g., agriculture, industry and transport). According to the available scientific literature, mitigation activities that rely on **European forests and wood products can provide a significant contribution to achieve climate neutrality by 2050** (Sections 2.2, 2.3, 2.4, 5.1, Table 8), but as the sector's contribution is finite, it cannot compensate for delayed actions in other sectors. Conversely, if forest-based and other land-use mitigation activities are not able to meet the sector's policy targets, stronger and even more difficult to achieve emission reductions will be needed in other sectors (or increased reliance on carbon removal technologies that are yet unproven) to achieve climate neutrality targets by 2050. **The technology, capacity and strategies needed to deploy forest-based mitigation measures are readily available and have already been used for decades. Maximum efforts, starting with the most sustainable and cost-efficient mitigation activities, should urgently be pursued to reduce net emissions.**

- **Forest-based mitigation activities such as avoiding deforestation, afforestation/reforestation, shifts in wood use** (e.g., shift to long-lived products and material uses of harvested wood)**, cascading** (e.g., reuse and recycling) **as well as increased material and energy efficiency all contribute to climate change mitigation and can be implemented or combined with limited or no negative effects on each other or biodiversity** (Sections 2.2, 2.3, 2.4, 2.6, 5.1, Table 8)**.** Mitigation activities that focus on the conservation of carbon in forest ecosystems, or which focus on active forest management (e.g., tree species or provenance selection, nutrient management, hydrology management), also contribute to climate change mitigation but come with the risk that they reduce the potential of some other activities to some degree. Rather than stimulating or focusing on a single set of mitigation activities, policy and management strategies need to consider all the possible forest-based mitigation strategies, their synergies, interactions, co-benefits and regional applicability to maximise the contribution to climate change mitigation. Furthermore, such **a holistic approach must cover all the relevant carbon pools and fluxes as well as their development over time and all the relevant emission sectors together for the EU's climate change targets to be met**. Such a holistic approach requires better integration across policy areas such as forestry, biodiversity, the bioeconomy, climate and energy, and this needs to be done at all policy-making levels (e.g., in Strategic Plans for Forests, National Biodiversity Strategies, CAP Strategic Plans, National Energy and Climate Plans, National Bioeconomy Action Plans, etc.). The generalisation of an economy-wide emission-based carbon tax can be an element in implementing mitigation as this would encourage consumers and producers to engage in more climate-friendly actions (Section 4.2). Such a tax needs to be an integral part of a larger set of public policies and private initiatives that consider and ensure the additionality and permanence of net-emission reductions.

- As the availability of woody biomass is and will be vastly insufficient to replace all fossil emission-intensive products and energy sources, there is a **need to be selective and to prioritise the types of wood use that give largest net emission reductions** (Section 2.3). The scientific evidence on how to realise major shifts in wood uses in practice remains thin and the net impacts of such shifts on the atmosphere are highly context and case-specific. Favouring the allocation of harvested wood to long-lived products over short-lived products and avoiding direct energy uses of harvested wood are general strategies that can contribute to climate change mitigation. However, these strategies do not hold universally as, for example, a shift from graphic paper to textile-fibre production may produce more mitigation potential than an increase in the use of wood for construction. Therefore, **the key criterion of mitigation activities needs to be minimising net emissions to the atmosphere by all sectors**. To this end, policies should aim at suppressing GHG emissions across sectors by, for example, stimulating product innovation and removing barriers that hamper uptake and implementation of climate change mitigation activities. Moreover, although the mitigation potential may remain limited, wood should be used according to the principles of a circular economy: **wood-based products should be reused and recycled as many times as possible and energy recovery should be preferred over landfilling**. This would require new production technologies that rely on biomass from by-products, side-streams, new ways of dealing with waste and a wider array of wood assortments and tree species, the development of new wood waste collection and recycling systems, as well as considering reuse and recycling at the design stage of a product.

- The type of activities that provide the largest mitigation potential varies across Europe. In some countries, especially those with a high percentage of forest cover, improved forest management provides the largest potential for climate change mitigation, while in other countries it is afforestation and reforestation. Concerning wood use, forest products are produced and traded globally, meaning effectiveness will improve if policies aim to foster, or even require, production technologies that cause no harm to the environment. Moreover, policies could aim to influence consumer behaviour towards sustainable consumption patterns, for example through labelling, certification and establishing economic incentives/penalties (Sections 2.2, 2.3, 4.2). **The sustainable implementation of forest-based mitigation activities that maximise the benefits and limit the risks must consider regional and country contexts as a one-size-fits-all approach cannot effectively address the vast majority of the complexities and specifics involved.**

- Many policy and legislative proposals have been recently developed as part of the European Green Deal that concern forests and climate (Section 4.1). **There is now a need to move towards their implementation at European, national and sub-national levels.** This will require a better understanding of all the possible forest-based mitigation strategies, how and if they can or should be combined, as well as their costs, risks and co-benefits. At the European level, policy implementation could focus on developing appropriate incentive systems, facilitating the exchange of best practices between countries and regions as well as developing a transparent, harmonised and robust framework for monitoring the progress and effectiveness of forest-based mitigation activities, as well as forests' biodiversity, health, management and uses for various socio-economic purposes. At the (sub-)national level, policy implementation could focus on translating European (EU-wide) policy targets and objectives into national or regional strategies, actions and activities that remove barriers to implement forest-based mitigation activities rapidly and effectively.

- Regardless of whether or not climate-neutrality targets for 2050 are met, there will still be climate change impacts on forests, forestry and the forest-based sector (Sections 3.1, 3.2). These impacts will become stronger the further short of these climate targets the world falls, which will make it even more challenging to find ways for forests to meaningfully contribute to mitigation targets. The current EU climate and energy policy framework only weakly acknowledges the need to strengthen the resilience of forests to climate change through adaptation (Section 4.1). **To strengthen the important role of forests in climate change mitigation, especially beyond 2050, it is crucial that policy and management strategies consider forest-based mitigation together with the need for adaptive management** (Section 3.3)**.**

- **Current EU policies that formulate climate targets focus on the period from 2030 to 2050** (Section 4.1) **but the focus in policy making needs to be extended beyond 2050 because, even if we meet the climate goals in 2050, climate change will continue**. To support policy development, long-term projections are needed that cover the regional and national level and include the multiple impacts and interactions between climate and forests, including disturbances, biophysical effects, material and energy uses of wood as well as other emission sectors (Sections 2.1, 2.5, 3.1, 3.2). In addition to investments to meet policy targets by 2050, investments in climate-smart forest management are needed (e.g., to activate forest management and to establish or reactivate tree breeding programmes, forest management trials and pilots, long-term forest monitoring, etc.) to ensure that forests can also contribute to climate change mitigation beyond 2050. The long-term nature of actions and impacts requires dealing with the risk of non-permanence which, in turn, requires strong government commitment, secured long-term green funding from the public and private sources and long-term voluntary agreements from all the key actors.

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Annex I

List of studies that have been considered in the literature review presented in Chapter 2.

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We are living in a time of accelerated changes and unprecedented global challenges: energy security, natural resource scarcity, biodiversity loss, fossil-resource dependence and climate change. Yet the challenges also demand new solutions and offer new opportunities. The cross-cutting nature of forests and the forest-based sector provides a strong basis to address these interconnected societal challenges, while supporting the development of a European circular bioeconomy.

The European Forest Institute is an unbiased, science-based international organisation that provides the best forest science knowledge and information for better informed policy making. EFI provides support for decision-takers, policy makers and institutions, bringing together cross-boundary scientific knowledge and expertise to strengthen science-policy dialogue.