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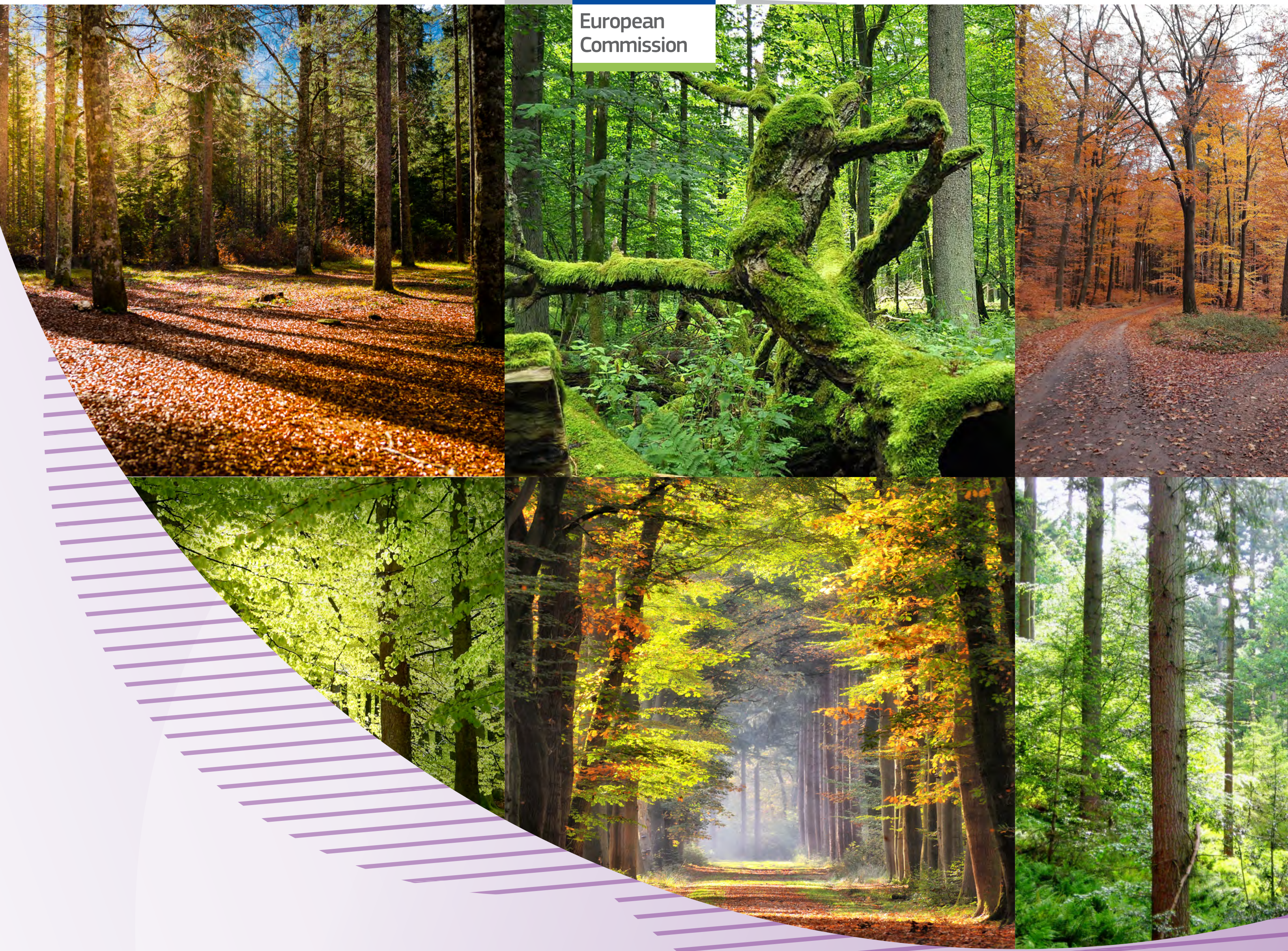

Science for Environment Policy

FUTURE BRIEF:
European Forests for biodiversity, climate change mitigation and adaptation

November 2021
Issue 25

Environment

Science for Environment Policy

European Forests for biodiversity, climate change mitigation and adaptation

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Print ISBN 978-92-76-21353-6 ISSN 2363-2771 doi:10.2779/972962 KH-BB-20-002-EN-C
PDF ISBN 978-92-76-21352-9 ISSN 2363-278X doi:10.2779/764847 KH-BB-20-002-EN-N

Luxembourg: Publications Office of the European Union, 2021

This Future Brief is written and edited by the Science Communication Unit, University of the West of England (UWE), Bristol.
Email: sfep.editorial@uwe.ac.uk

To cite this publication:

Science for Environment Policy (2021) *European Forests for biodiversity, climate change mitigation and adaptation.* Future Brief 25. Brief produced for the European Commission DG Environment by the Science Communication Unit, UWE Bristol. Available at: https://ec.europa.eu/science-environment-policy.

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Contents

1. Introduction

Europe's forests are, generally, not in a good ecological condition. The latest State of Nature report from the European Environment Agency found that up to 84% of Europe's assessed woodland and forest habitats were categorised as 'unfavourable-inadequate' (EEA, 2020c). Deforestation has been the dominant trend in Europe's landscape ecology over the past 6000 years, led by demand for agricultural land and wood for fuel (Roberts *et al.*, 2018). Today, existing forests are feeling increasing pressures from land-use changes, extreme weather events (fires, droughts and storms), overexploitation, and from pests, pathogens and invasive species. Almost half of Europe's tree species are under threat of regional extinction, and climate changes are increasing the pressures of pests, drought, storms and fires.

Yet, forests are still vital elements of Europe's landscape, performing a multitude of roles that all contribute to the health of the environment. They provide clean water and air, protect soil, cool down cities, protect them from heavy flooding, offer essential habitat to diverse species, contribute to human health and well-being, and are an essential ally in the fight against biodiversity loss and climate changes.

Forests also play a critical role in supporting the human economy, recreation and culture. Use of wood and wood products is projected to increase, as societies move away from fossil fuels and towards a 'bioeconomy'. Forests in Europe are currently used intensively, and the sustainability of current harvesting levels is under debate (Ceccherini *et al.*, 2020). Finding the right balance between wood harvesting and the other, indispensable functions of forests – protecting biodiversity and preserving and increasing the carbon sink – is vitally important over the next decade.

Like many ecosystems today, forests are under threat from disturbances, economic factors and competing pressures. In recent years, the pressing need to address the inter-related crises of biodiversity loss and climate change has resulted in greater emphasis on protecting, restoring and creating forests, and there is an increased public and policy awareness of the challenges forests are facing. Europe has been taking action regarding third countries' forests and timber supply chains (e.g. via the Timber Regulation, and the EU's FLEGT Action Plan), and the pressure of public opinion, and the need for integrity in domestic and external affairs means that the actions to preserve and restore forests within the European Union must be effective and credible.

This Future Brief brings together the latest evidence on the ability of Europe's forests to support biodiversity while removing and storing carbon from the atmosphere, while also providing ecosystem services necessary for climate adaptation and our well-being, and contributing to the bioeconomy and reduction in use of fossil fuels.

2. Current state of European forests

The European Union (EU) is home to approximately 5% of the world's total forest area. The EU27 has approximately 180 million hectares (ha) of forest and other wooded land in 2020 (European Commission, 2021b) which would account for approximately 40% of the EU's total land area – although estimates do vary,. Six Member states (Sweden, Finland, Spain, France, Germany and Poland) account for two thirds of the EU's forested areas.

Forests are the largest terrestrial ecosystem in the EU (Maes *et al.*, 2020), but the amount of forest area in the EU varies widely by Member State. In Finland for example, over three quarters of total land area is wooded, while in the Netherlands less than 10% is wooded, and in Malta less than 1% is (see Table 1).

Member State	Forest Europe data Forest area (1000 hectares)	Forest Europe data Forest area (% of land area)
Austria	3 899	47.2
Belgium	689	22.7
Bulgaria	3 893	35.9
Croatia	1 939	34.7
Cyprus	173	18.7
Czech Republic	2 677	34.7
Denmark	628	15.0
Estonia	2 438	56.1
Finland	22 409	73.7
France	17 253	31.5
Germany	11 419	32.7
Greece	3 903	30.3
Hungary	2 053	22.7
Ireland	782	11.4
Italy	9 566	32.5
Latvia	3 411	54.9
Lithuania	2 201	35.1
Luxembourg	89	36.5
Malta	0	1.1
Netherlands	370	11.0
Poland	9 483	31.0
Portugal	3 312	36.2
Romania	6 929	30.1
Slovakia	1 926	40.1
Slovenia	1 238	61.5
Spain	18 572	37.2
Sweden	27 980	68.7

Table 1: Forest cover of the EU-27, 2020. Source: Forest Europe, 2020 (data from Forest Europe/UNECE/FAO enquiry on pan-European Indicators.

By the end of the 17th century, more than half of Europe's original forest had disappeared, but in the 50 years after the Second World War, the forest area in western Europe increased rapidly, by almost 30% (in central and eastern Europe it increased by 20%, and in southern Europe by 16%). However, since the 1990s, increases in forest area have stabilised, and both afforestation and deforestation are now locally concentrated in a few European countries (EEA, 2018). Although natural forest area is decreasing at the global level (FAO, 2015), forest area in the EU has been slowly increasing, thanks to large-scale afforestation programmes, natural regeneration and reforestation practices.[1]

Forest coverage in the EU increased year-on year-from 2000–2015, by approximately 413 000 ha per year and 6.2 million hectares (Mha) in total (EC JRC, 2018). According to the latest data from Forest Europe (Forest Europe, 2020), forest area in the EU-28 continued to increase between 2015–2020, by more than 1 Mha. Forest area in Europe altogether has increased by 9% since 1990, reaching 227 Mha (Forest Europe, 2020).

Forest area is an important metric by which to measure carbon sequestration, a major ecosystem service provided by forests, with European forests estimated to contain one third of the world's temperate forest carbon sink (Moreno *et al.*, 2017).

Above-ground forest biomass, such as trunks and branches, hold a significant portion of a tree's total carbon stock. In the EU, there are an estimated 18 600 megatonnes (Mt) of above-ground biomass. The stock of above-ground biomass has also been increasing in the EU since 2000, by 1.3% or by 223 Mt per year on average (EC JRC, 2018).

However, the rate of forest expansion in the EU has overall declined since 2010 (EC JRC, 2018) and recent data suggest there has also been an important increase in the amount of clear-cut harvested forest area (Ceccherini *et al.*, 2020).

A recent study based on satellite imagery (Ceccherini *et al.*, 2020) found a relevant increase (by at least one third) in the clear-cut harvested forest area in Europe during 2016–2018, relative to 2011–2015, with the average size of harvested area also increasing. Since the recent surge in natural disturbances can explain only part of the increase in harvest, the remaining part is mainly attributed to an increase in wood demand. This increase in clear-cut harvest is likely an important factor when explaining the recent decline of forest carbon sinks as reported in national greenhouse inventories (European Commission, 2020).

In terms of forest composition, less than one third of Europe's forests contain trees of different ages, 30% have only one tree species, 51% have only two to three tree species, and only 5% have six or more tree species (EEA, 2020c). These low-diversity forests are a result of management practices, involving tree species selection and planting. Forest habitats are changing due to the removal of dead and dying trees, as well as broader land use changes, such as conversion to monocultures (EEA, 2020c).

A Sunset inside a forest in Finland with direct sun, ©Getty Images, public domain

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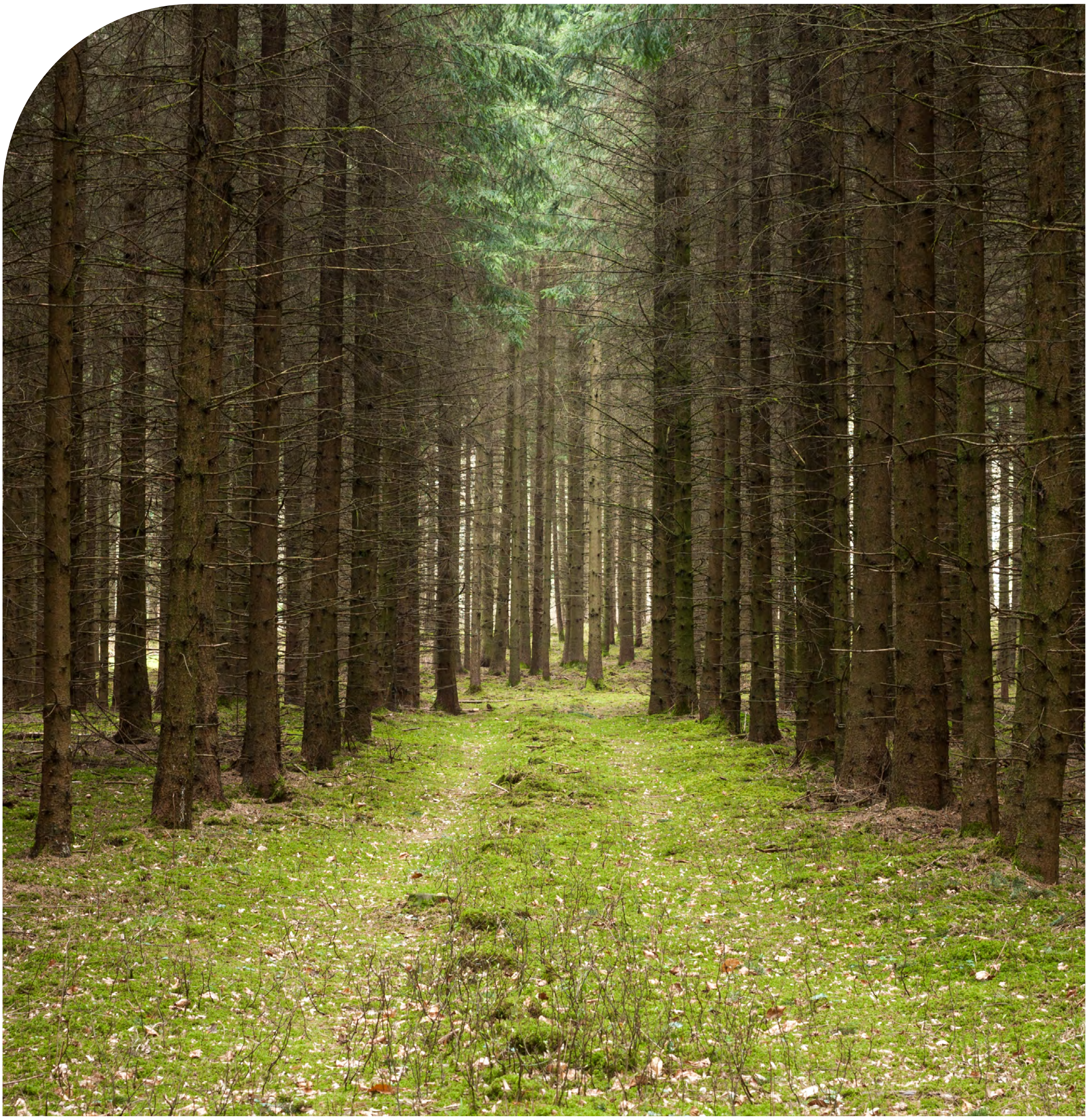
[1] For a definition of afforestation, see Box 2, below.

> **…currently, less than one third of Europe’s forests are uneven-aged, 30 % have only one tree species (mainly conifers), 51 % have only two to three tree species, and only 5 % of forests have six or more tree species. […] Forest habitats are especially affected by the removal of dead and dying trees as well as by broader land use changes, such as conversion to monocultures or other forest types”.**

EEA State of Nature in the EU, 2020



Way through spruce (Picea) monoculture, forestry in Germany. ©Getty Images, public domain

Initiatives such as Natura 2000, an EU-wide network of protected areas managed according to the Birds and Habitats Directives, are vitally important to the protection of forest area. The network, which covers almost 18% of EU land area, is about half forest. This means that around 23% of forest area in the EU-28 is protected under Natura 2000 (Maes *et al*., 2020; Sotirov, 2017).

The EU Habitats Directive aims to achieve favourable conservation status of the EU's natural habitats and species. Article 17 of the Directive requires Member States to report every six years on the status and trend of habitats and species of Community interest (listed in Annexes I and II of the Directive) in their territory. Under this reporting system, habitats are given a conservation status ranked as favourable ("good"), unfavourable-inadequate ("poor"), unfavourable-bad or unknown ("bad").

Data from the latest reporting period showed that the percentage of EU forests which had unfavourable status during 2013 to 2018 increased to 84.5%, up from 82% in the 2007–2012 assessment (EEA, 2020c).

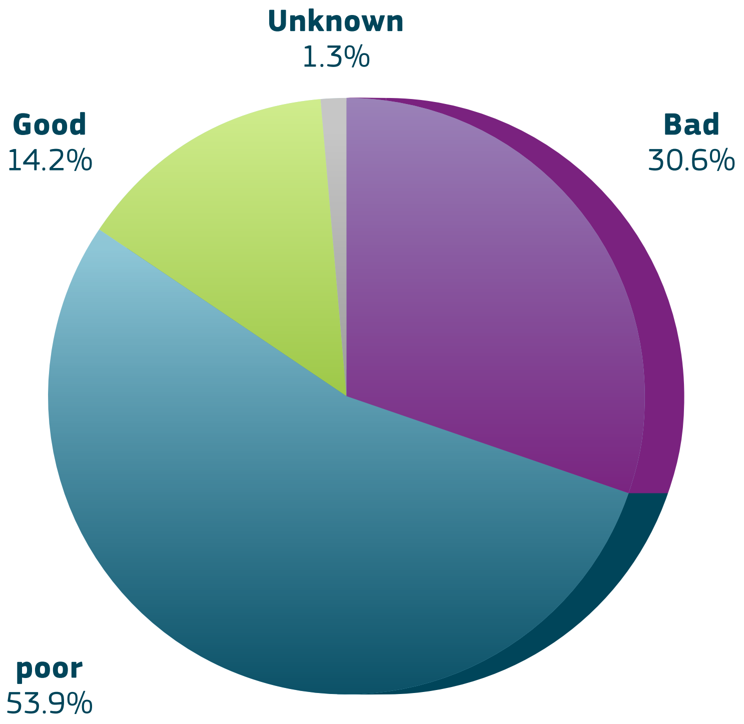


Figure 1: Conservation Status of Forests, 2013–2018, Habitat Assessment at EU Biogeographical Level (Overall Assessment). Source: Habitats Directive Conservation Status dashboard https://tableau.discomap.eea.europa.eu/t/Natureonline/views/SONConservationstatusandtrend/Story1?:isGuestRedirectFromVizportal=y&:display_count=n&:showAppBanner=false&:origin=viz_share_link&:showVizHome=n&:embed=y

By region, boreal forest habitats of Community interest had the highest proportion of unfavourable-bad assessments (56%) and the highest percentage of habitats with deteriorating trends (43%). In contrast, Macaronesian forests in the Azores, Madeira and the Canary Islands (which have a unique biogeography related to the flora of pre-ice age Mediterranean) had the highest percentage of confirmed good and improving assessments.

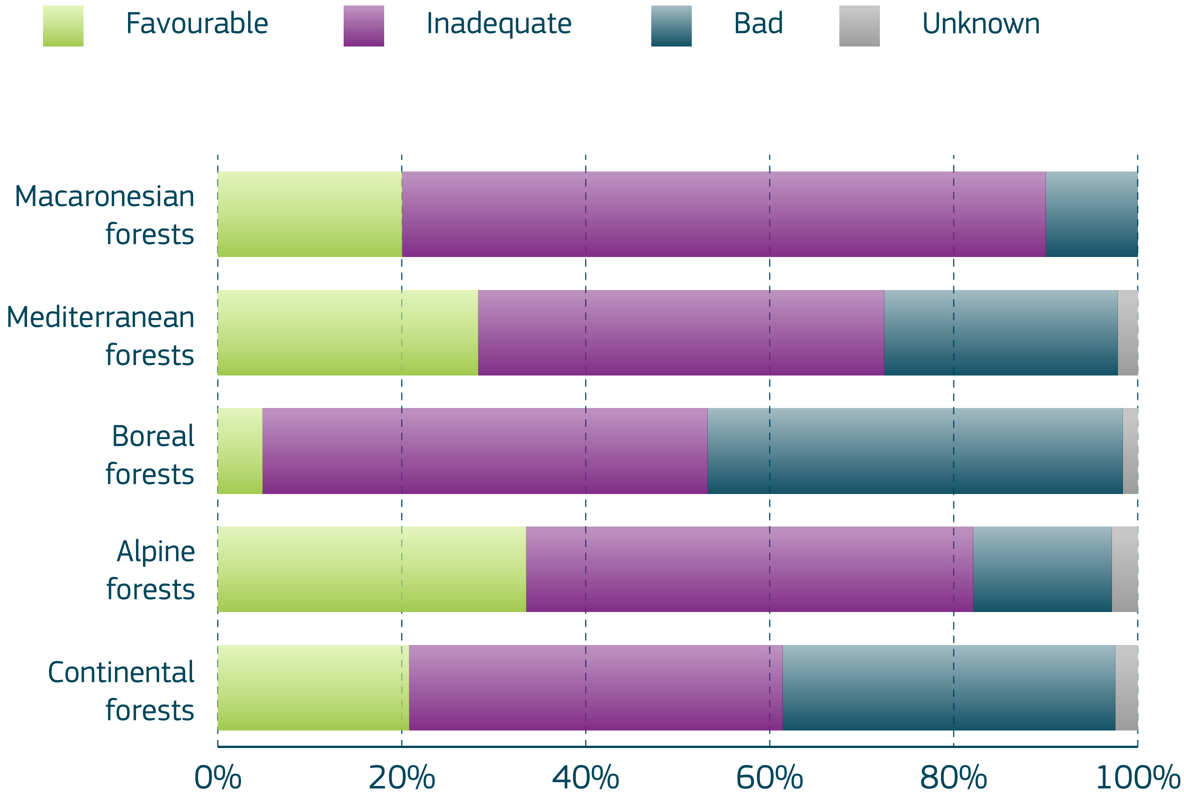


Figure 2: Conservation status of forests by region in the EU. Results from reporting under the nature directives 2013-2018. Source: State of Nature in the EU Conservation status and trends of habitats and species dashboard https://www.eea.europa.eu/themes/biodiversity/state-of-nature-in-the-eu/article-17-national-summary-dashboards/conservation-status-and-trends

Approximately 100 000 km2 of Natura 2000 forest area in the EU (around 20% of the total area of forest habitats listed in the Habitats Directive) are deemed to require restoration to improve their condition (the largest area of any habitat type under the Directive) (EEA, 2020c). However, if all forests in the EU were to achieve good conservation status, much more forest area will need restoration.

On a more positive note, forest habitats also showed the highest proportion of improving trends among the latest assessments. For example, over 54% of all forest habitats were either stable or improving and 34% of forest bird species showed an improving trend. This should be set within the overall context that the proportion of bird species with poor conservation status is increasing in the EU (EEA, 2020c).

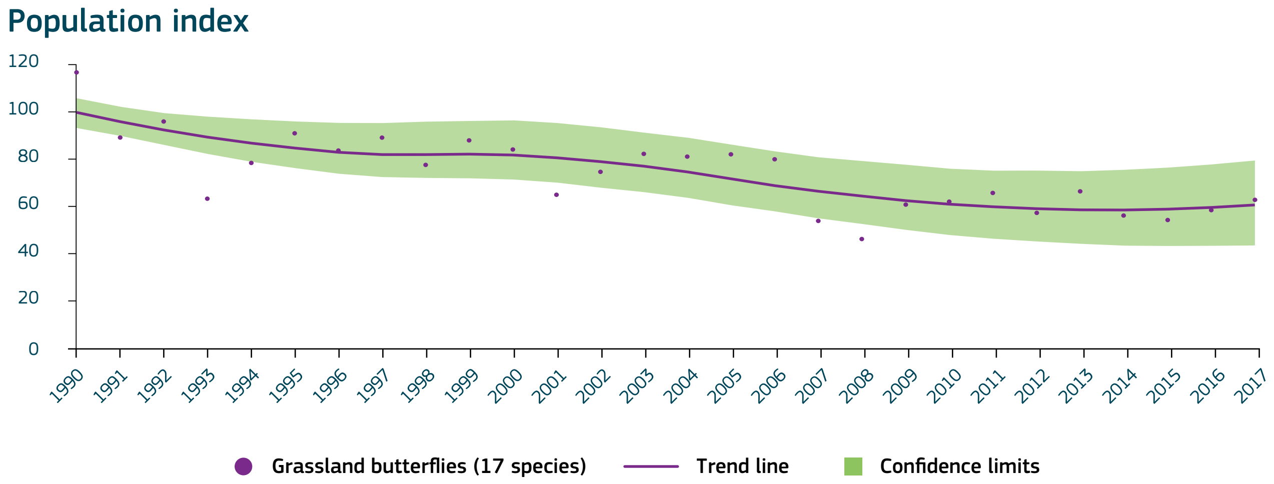


Figure 3a: EU common forest birds population index from 1990 to 2016. Source: from EEA (2020e)

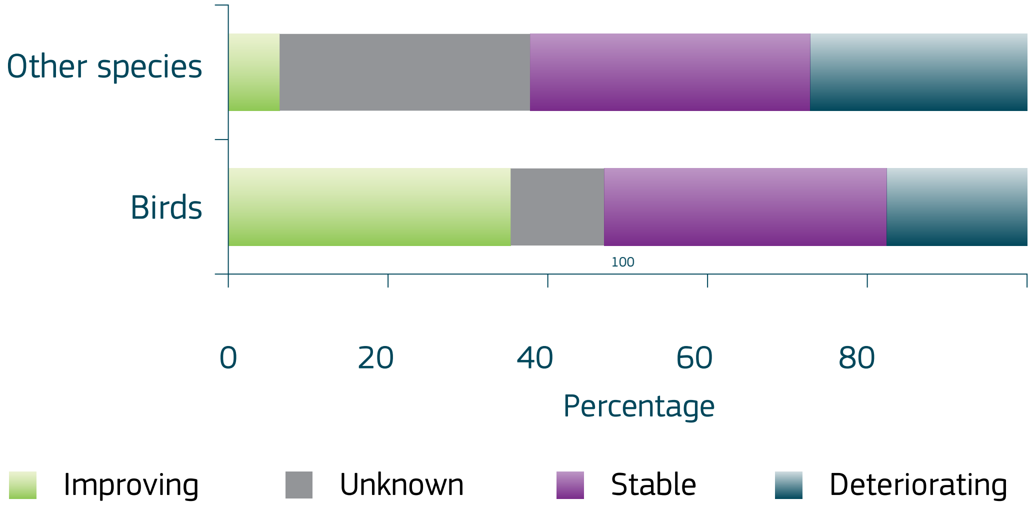


Figure 3b: Trends in status of forest non-bird and bird species. Source: Article 12 and Article 17 Member States' reports and EU assessments, in EEA (2020c).

It is important to note that different Member States may use different assessment approaches, indicators and criteria in their Article 17 reporting.

There are also differences in the assessment methods used in the 2013 and 2018 reports, driven partly by technological advances.

2.1 EU forest policy framework: current policies and management plans

The New EU Forest Strategy for 2030 (COM(2021)/572_final) was adopted in July 2021. An initiative of the European Green Deal, it builds on the EU Biodiversity Strategy for 2030, and was developed to set concrete actions for increasing the quantity and quality of forests in the EU, through strengthening their protection, restoration and resilience. It also aims to ensure the multi-functionality of forests into the future.

There have also been various other rules and regulations regarding the management of forests at an EU level. While the Treaties do not specifically list 'forest policy' among EU competences, the EU has a range of competences on related matters. The EU has exercised these competences and addressed forests in several legal texts. Forests and forestry consequently do not fall within the exclusive competency of Member States (a viewpoint also upheld by Court of Justice jurisprudence) and although there have been political debates on this matter, the EU has in fact exercised shared competencies over forests for several decades (Onida, 2020).

Policies and legislation that relate to forests include the Habitats and Birds Directives, the Invasive Alien Species (IAS) Regulation, the Regulation on the inclusion of greenhouse gas emissions and removals from land use, land use change and forestry (LULUCF), the Renewable Energy Directive (RED), the Directive on the marketing of forest reproductive material and the EU Biodiversity Strategy for 2030. Although each of these regulations and policies has different focal points, all aim at enhancing the sustainability of forest management and consider conservation goals. The most significant elements of the policy frameworks impacting on forests are outlined below.

European Green Deal

The European Green Deal (EC, 2019) is one of the major policy priorities of the European Commission over the coming years and outlines a set of strategies to make the EU economy sustainable and to achieve carbon neutrality by 2050 while preserving natural resources and biodiversity.

The European Green Deal recognises that forest ecosystems are under increasing pressure and sets out specific plans to improve the quality and quantity of the EU's forested area and to address the contributions of the sector to climate change. One of the key actions under the Green Deal has been the creation of a new EU Biodiversity Strategy for 2030 and, under this, the preparation of a new EU Forest Strategy, which was adopted in 2021.

EU Biodiversity Strategy for 2030

Responding to a European Green Deal commitment, the EU Biodiversity Strategy for 2030 (EC, 2020a) sets out a number of commitments and actions to protect Europe's nature, including to establish protected areas for at least 30% of land, with 10% to be strictly protected.

Forests will be important in achieving these targets, and the strategy aims to strictly protect all primary and old-growth forests in the EU, which store carbon over centuries and are therefore particularly important to preserve (Sabatini *et al.*, 2020). At present, only 2–4% of forests in the EU are primary forest (Maes *et al.*, 2020).

The strategy also aims to increase the overall area of forest and number or trees in the EU by planting three billion additional trees by 2030 according to ecological principles (EC, 2020a). A roadmap for implementing this pledge is included in the new EU Forest Strategy for 2030.

Guidelines will be developed on biodiversity-friendly afforestation and reforestation and an overarching set of practices for 'closer-to-nature' forestry, which aims to minimise human intervention and align productivity goals with conservation objectives.

Focus will also be on increasing the number of trees in urban areas, through a new European Urban Greening Platform, in combination with Common Agricultural Policy (CAP) plans for afforestation and reforestation in rural areas.

As well as increasing forest area, the new Biodiversity Strategy aims to increase the health and resilience of EU forests against threats which are increasing with climate change, such as fire, droughts, pests and disease (see Chapter 3 for more detail). These goals are covered by the combined aim of 'increasing the quantity of forests and improving their health and resilience'.

A further goal of the strategy, which overlaps with the bioeconomy strategy, is to provide better data on the status and management of forests in the EU, via the Forest Information System for Europe (FISE, n.d.) In addition, the new strategy sets out a number of 'win-win solutions for energy generation', several of which are relevant to forest management.

As part of the EU's efforts to source more sustainable bioenergy, the strategy explains that the shift to advanced biofuels based on residues and non-reusable and non-recyclable waste established in the recast Renewable Energy Directive should continue for all forms of bioenergy. The use of whole trees and food and feed crops for energy production – whether produced in the EU or imported – should be minimised. Additional legislation is planned to prevent products that are the result of forest degradation from being sold on the EU market.

Oak and hornbeam tree deciduous forest in spring with dead wood moss wrapped around (Bialowieza Forest - Poland, Europe), ©Getty Images, public domain

EU Forest Strategy

The new EU Forest Strategy for 2030 (adopted 16 July 2021) includes specific objectives on afforestation, forest preservation and restoration. The strategy aims to contribute to achieving the EU's biodiversity objectives as well as greenhouse gas emission reduction target of at least 55% by 2030 and climate neutrality by 2050, by increasing the quantity and quality of forests in the EU, increasing carbon sequestration, protecting old-growth forests, and encouraging the bioeconomy within sustainability boundaries (EC, 2019).

The new EU forest strategy will support the socio-economic functions of forests and boost the forest-based bio-economy within sustainability boundaries. It will also protect, restore and enlarge the EU's forests to combat climate change, reverse biodiversity loss and ensure resilient and multifunctional forest ecosystems by:

- promoting the sustainable forest bioeconomy for long-lived wood products;
- ensuring sustainable use of wood-based resources for bioenergy;
- promoting non-wood forest-based bioeconomy, including ecotourism;
- developing skills and empowering people for sustainable forest-based bioeconomy;
- protecting EU's last remaining primary and old-growth forests;
- ensuring forest restoration and reinforced sustainable forest management for climate adaptation and forest resilience;
- re- and afforestation of biodiverse forests, including by planting 3 billion additional trees by 2030; and
- providing financial incentives for forest owners and managers for improving the quantity and quality of EU forests.

The strategy also focuses on:

- strategic forest monitoring, reporting and data collection;
- developing a strong research and innovation agenda to improve our knowledge on forests;
- implementing an inclusive and coherent EU forest governance framework; and
- stepping up implementation and enforcement of existing EU law.

It recognises the central and multifunctional role of forests, and the contribution of foresters and the entire forest-based value chain for achieving a sustainable and climate neutral economy by 2050 and preserving lively and prosperous rural areas. Following on from the Communication on Stepping up EU Action to Protect and Restore the World's Forests,[2] the Commission will also take measures to promote imported products and value chains that do not involve deforestation and forest degradation.

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[2] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52019DC0352

EU Bioeconomy Strategy

Forests are considered an important element in the circular bioeconomy, particularly through new biomass-based products and services which can help to mitigate climate change.

In addition to traditional products such as paper and pulp, the forestry sector also accounts for over 60% of all EU domestic biomass supplied for energy purposes (Camia *et al.*, 2018). Other forest-based products include viscose fibres, which can be used to replace polyester in textiles, and construction materials, where they can offer low-carbon and low-cost alternatives.

To support the uptake of carbon removals and encourage the agriculture and forestry sectors to deliver on climate action, the Commission announced in 2021 in the Farm to Fork Strategy that it would launch a Carbon Farming initiative to promote a new green business model that rewards climate–friendly practices by land managers, based on the climate benefits they provide. In addition, as announced in the Circular Economy Action Plan, the European Commission will develop a regulatory framework for certifying carbon removals based on robust and transparent carbon accounting to monitor and verify the authenticity of carbon removals. These commitments were echoed by the new EU Forest Strategy.

Carbon farming will provide financial incentives to the actors of the bioeconomy for climate-friendly activities resulting in carbon removals and storage, thus creating a new source of income and helping them adapt their businesses to withstand the effects of climate change.

A further goal, overlapping with the Biodiversity Strategy, is to provide better data on the status and management of forests in the EU, via the Forest Information System for Europe (FISE, n.d.), which will help to improve data availability. The new EU Forest Strategy announced a legislative proposal for an EU-wide, Forest Observation, Reporting and Data Collection framework, which intends to improve the accuracy of monitoring by using remote sensing technologies and geospatial data integrated with ground-based monitoring. The Strategy also includes a ‘Roadmap of the Commission’s action to implement the pledge to plant 3 billion additional trees by 2030’, which sets out clear criteria for improving forest monitoring. This will be supported by a more comprehensive, inclusive and coherent EU Forest governance framework.

Gribskov Forest in the northern part of Zealand, Denmark. ©Wikipedia Commons CC-BY-3.0

Common Agricultural Policy (CAP)

The Common Agricultural Policy (CAP) is the tool by which the EU provides financial support for forestry. This can include investment in the development of forested areas and improving the viability of forests.

Over €8 billion was allocated to forests for the period 2015–2020 under the CAP, including €2.16 billion for reforestation, €1.48 billion for forest resilience and €1.48 billion for damage prevention. Under the current, long-term budget of the EU for 2021–2027, CAP will be supported by €387 billion in funding, including €95.5 billion for rural development.

Under the European agricultural guarantee fund (income support for farmers), 5% of arable land (on farms with arable land exceeding 15 hectares) needs to be dedicated to Ecological Focus Areas (EFAs). Member States draw up national lists of EFAs, which may include hedges, trees and land left fallow. Under the European agricultural fund for rural development, countries may choose to apply a range of measures through their rural development programmes, one of which involves investments and improvements in forests, i.e.: afforestation; establishment of agro-forestry systems; restoration of forests; improving the resilience of forest ecosystems; and investments in forestry technologies and forest products. At least 30% of funding for each rural development programme must be dedicated to measures relevant for the environment and climate change, and 5% of funding needs to go towards community-led approaches (EC, n.d.; EC, n.d.a.; European Parliament, 2020).

2.2 Forests in the socio-economy

Forests have a long and critical history in the European economy and society, where they have provided resources and jobs for many and they are, in many places, a critical cultural asset. They will play an important role in the future bioeconomy and have an important social role, providing ecosystem services necessary for human health and ground for recreation and cultural and spiritual value to EU citizens.

'Productive forests', forests that are actively managed to generate revenue (Talberth and Yonavjak, 2011) generate critical resources: conventionally, this is timber. Approximately 84% of the EU's forest area is currently available for wood supply. Within this area, 444 mega tonnes (Mt) of wood grow each year, excluding losses due to the natural death of trees (EC, 2018).

The MAES report (2020) concluded that, on the basis of the available data, the amount of fellings reported in the EU did not exceed the amount of timber that forest could supply annually (i.e. the maximum possible supply in a year – or 'National Annual Increment'), guaranteeing in general and quantitative terms the use of the EU's forest within the availability of resources.[3] However, it has been shown that wood fellings are strongly underreported, leading therefore to an amount of fellings closer to the maximum possible supply than the one reported here (Camia *et al.*, 2018).[4].

The top three EU Member States for mean growing stock density (i.e. the average volume of living trees per hectare) are Slovenia, Germany and Luxembourg (EEA, 2017b). Although the forestry sector makes critical economic contributions, the sector also represents the greatest pressure on forest habitats in the EU, greater than agriculture, transport or climate change, according to the latest State of Nature report (EEA, 2020c).

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[3] Maes *et al.*, 2020.

[4] It is worth noting that the data available for the MAES analysis had significant gaps, with some of the data being rather outdated (e.g. 2010 or 2011 values).

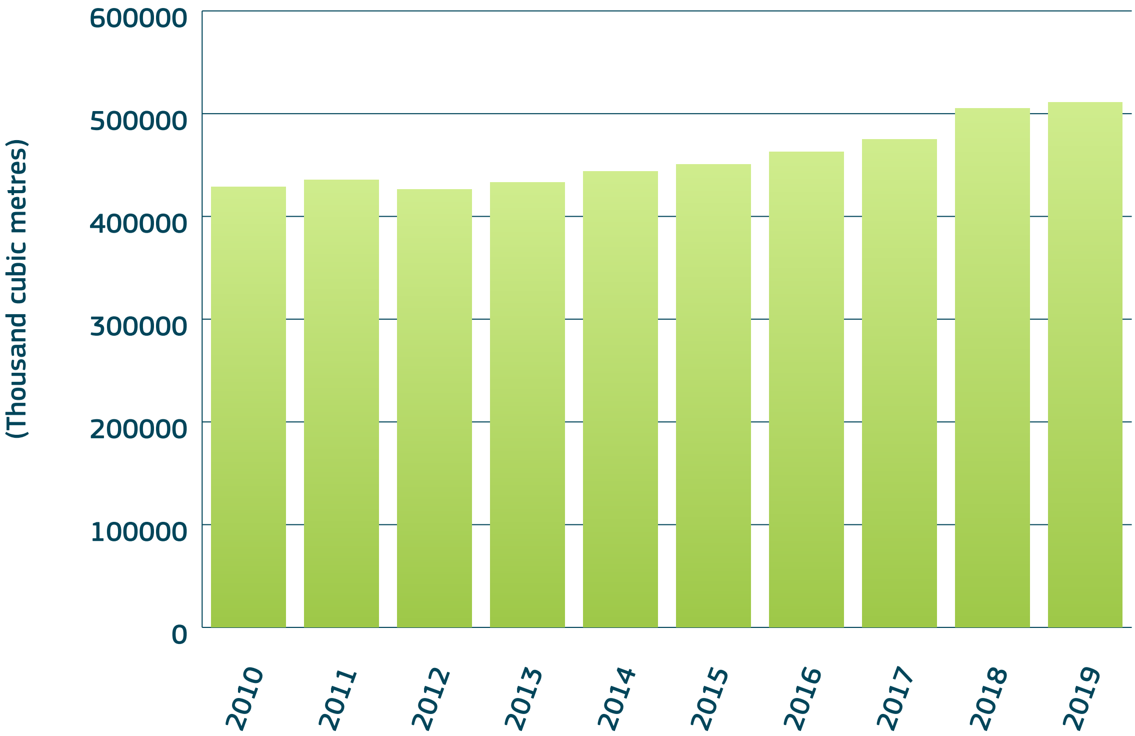

Figure 4: Roundwood production in the EU. Notes: Roundwood is the length of a cut tree, such as a log. Source: Eurostat, 2020a.

Europe is one of the largest producers of roundwood in the world (Forest Europe, 2020; SAF, 2015). Roundwood describes all the wood obtained from removals, including wood recovered due to natural losses and felling, and can be further split into industrial roundwood (that used for materials) and wood fuel (that used directly for energy) (Forest Europe, 2015b).

Roundwood production in the EU has increased steadily in recent decades, temporarily declining in 2007/2008 due to the global financial crisis. Production recovered from 2010 onwards, returning to more stable production by 2013 to 458 million m3 (Eurostat, 2017). More recent data shows a continued increase; 470 million m3 roundwood was produced in the EU in 2017 (Eurostat, 2019).

The total gross value added by the forest sector for the EU-27 in 2017 was €26 220 million, increasing from €23 181 million in 2012 (Eurostat, n.d.). The forestry sector is estimated to provide a total turnover of €50 billion, and a value added of €24 billion, in the EU. Wood products and furniture generate an additional €174 billion turnover (€47 billion value added), while the paper industry generates €187 billion turnover (€46 billion value added) (EC, 2018).

Additional uses for wood include construction materials and bio-based products, including, for example, textile fibres made from microfibrillated cellulose, carbon nanofibres and adhesives (EC, 2018). Wood can also be used as bioenergy feedstock, and by-products from domestic and imported sources, post-consumer wood and bark (i.e. ‘secondary woody biomass’) are all used for energy in the EU (Giuntoli *et al.*, 2015) (See Chapter 5.3 for more on bioenergy). The Sankey diagram (Figure X) depicts woody biomass flows in the EU, showing how primary woody biomass is used in the material and energy sectors. There are also a variety of non-wood-based goods available from forests, such as food (e.g. mushrooms, honey) and raw materials for medicines (EC, 2020). The value of non-wood goods from forests and other wooded lands in Europe was reported to be €4 000 million in 2015 (Forest Europe, 2020).

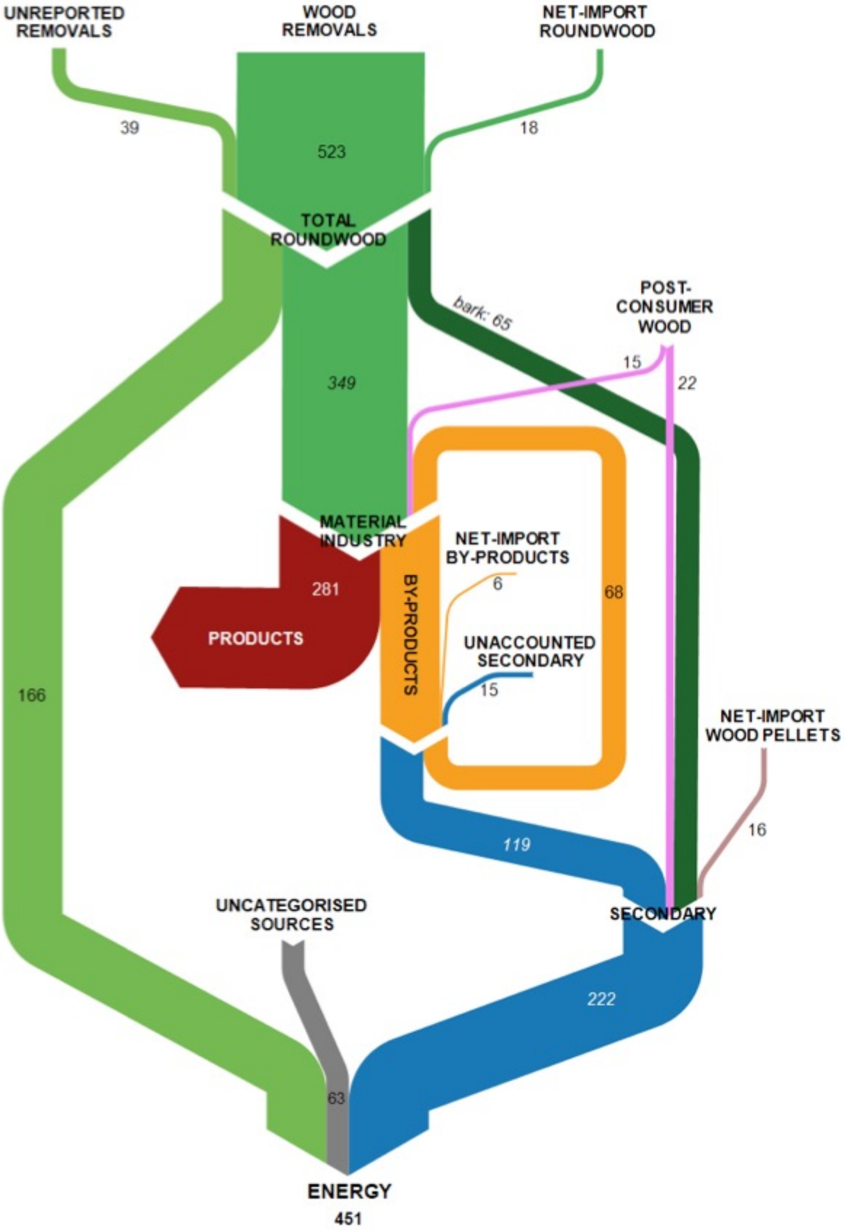

Figure 5: Sankey diagram of woody biomass flows in the EU (2015 data in Mm3 solid wood equivalents). Primary woody biomass is mainly obtained from domestic removals in the EU. Roundwood is primarily used in the material sector and generates intended products as well as by-products (shown here in blue), some of which are used by the wood-based industry. Both primary and secondary woody biomass are used for energy production. Secondary wood makes up almost half of all reported wood for bioenergy use. Source: Camia *et al.*, 2021, based on Cazzaniga *et al.*, 2019.

As you might expect from these figures, the forestry sector is also a major provider of **employment** in the EU27, providing work for over 517 000 people in total in 2017 (Ronzon *et al.*, 2020).

Related sectors (wood products and furniture, paper) employ an additional 2 million people (EC, 2018). In total, 3.3 million people in the EU were employed in wood-based industries in 2017 (Eurostat, 2019). The real number is likely even higher due to informal employment arrangements which are not accounted for in official statistics.

Forests are also an important part of a sustainable **bioeconomy** through the provision of bio-based materials. In the construction sector, using wood instead of concrete can generate an average reduction of 2.1 tonnes of CO2 emissions for every tonne of wood products used (EC, 2018), assisting progress towards a low-carbon society. On average, 281 Mt of trees were felled from EU forests between 2004 and 2013. There is a trend of increased fellings as a proportion of the maximum extent of forest available for wood supply (net annual increment) (Camia *et al.*, 2021).

Some of the value provided by forests is more difficult to quantify in economic terms; however, progress is being made in this area. **Cultural forest services** can be defined as the "nonmaterial benefits people obtain from ecosystems through spiritual enrichment, cognitive development, reflection, recreation and aesthetic experiences" (Haines-Young and Potschin, 2011).

This includes the use of forests for recreation; walking, hiking, cycling, spending time in nature in many forms. 'Forest bathing', a Japanese practice, involves spending mindful time in a forest for health and wellbeing purposes and is becoming increasingly popular across Europe as a form of 'nature therapy' (The Forest Bathing Institute, n.d.; Sherwood, H., 2019). Spending time in nature also has implications for tourism and the tourism economy.

Many forests in Europe are available for recreation, as shown by a recently compiled database (EC JRC, 2015), and many also have unique cultural and spiritual value. Forests have a special place in the history and folklore of many cultures, and may be historical sites, sites of nonmaterial cultural heritage, sites of worship, or used for ceremonies.

For the EU28, the European project on ecosystem accounting (INCA) estimated that in 2012, EU Forests provided for more than 81 billion Euros worth of ecosystem services. Less than 15 billion were from timber provision; the rest of the services were carbon sequestration, flood control, water purification and nature-based recreation (Eurostat, 2021).

3. Factors affecting the resilience of European forests

Forests are facing great threats to their stability. One of the most significant threats facing forests and their biological diversity is climate change – a threat which is rapidly increasing (see Box 1, below) and intensifying the threat from other pressures, such as land use change. Trees are especially sensitive to changes in climate due to their long lifespan, which prohibits rapid adaptation (Linder *et al.*, 2010), and when tree cover changes, the structure of the ecosystem and the ability of the system to host other organisms changes too.

The average age of a forest in Europe is 60 years (Vilén *et al.*, 2010), yet many primary or 'old-growth' forests are much older (Sabatini *et al.*, 2018). Although some tree species can live for long periods (an oak tree can live for more than 1000 years), only 2-4% of EU forested area has not been modified by human intervention (Maes *et al.*, 2020; European Parliament, 2021).

Box 1: What are the major pressures on forest biodiversity?

The mid-term review of the EU Biodiversity Strategy to 2020 presents trends in the major pressures on Europe's forest ecosystems.

Climate change: Low impact but rapidly increasing

- E.g. Fires, storms, drought and increasing range of pests.
- Changes in temperature
- Changes in rainfall and soil moisture

Habitat change: High impact but decreasing

- Forest cover change
- Tree loss
- Forest fragmentation

Invasive species: Moderate impact, continuing

- Introduction of invasive, alien species

Over-exploitation: Moderate impact, continuing

- Land use changes that encroach on forest land
- Reduced forest area
- Ratio of fellings to increment

Pollution and nutrient enrichment: Moderate impact, increasing

- Acidification
- Eutrophication
- Tropospheric ozone (smog)

(EEA/EC, n.d.)

The Forest Europe 'State of European Forests' 2015 states that the condition of European forests is deteriorating, with an increase in defoliation. It further adds: "pests, diseases, wildlife (especially browsing by large ungulates) and grazing by domestic animals, fires and weather extremes such as storms were reported as important causes of damage. The frequency and intensity of storms is increasing over time. More recent data (Maes *et al.*, 2021) also show that forest condition is, on average, degrading and that there is an increasing trend for forest defoliation, with one out of four trees showing defoliation levels indicating damage. Pressures such as climate change, wildfires, storms, harvesting, pollutants, insect infestations, and invasive alien species remain a concern.

The last ten years was the warmest decade on record for Europe and models predict that the annual average land temperature over Europe will increase between 1°C and 5.5°C by the end of the century (EEA, 2019a).

These increases in temperature may extend the growing season for some trees but will have further detrimental effects due to changes in precipitation and water availability. Indeed, climatic changes are likely to increase the frequency and severity of storms and droughts, which can be catastrophic for forests. Future, hotter droughts will also be significantly drier than those that current forests have adapted to endure and will increase the risk of fires (Linder *et al.*, 2010; McDowell and Allen, 2015).

Other threats to Europe's forests include pests and alien species, development and land-use change and, in some cases, the forestry industry itself. Many of these threats are deeply interconnected, with climate change a central, aggravating factor, itself exacerbated by the current condition of many European forests (i.e., mono-species plantations, large-scale clear-cutting, fragmentation, etc.).

The ability of forests to cope with these threats depends on their **resilience**, which can be defined as:

> **“The capacity of an ecosystem to return to the pre-condition state following a perturbation, including maintaining its essential characteristics, taxonomic composition, structures, ecosystem functions, and process rates.”**
>
> (Holling, 1973)

As well as resilience, the **resistance** of a forest is also important in shaping its stability.

Resistance includes the ability of a forest to buffer the changes around it, and can be defined as:

> **“The capacity of the ecosystem to absorb disturbances and remain largely unchanged.”**
>
> (Holling, 1973)

Resistance can be thought of as the ‘immovability’ of a system, and resilience the ‘recoverability’ of a system once its resistance has been exceeded. The balance between these two elements determines the overall stability of an ecosystem (Larsen, 1994). Factors that influence this balance include biodiversity. A more biodiverse forest is more likely to maintain its taxonomic composition, structure, ecological functions and process rates over time (Thompson *et al.*, 2009).

Efforts to increase the resilience, resistance and biodiversity of forests and to mitigate the threats around them are essential, as the timespan for damage and recovery are far from equal. While damage to a forest often occurs rapidly, the re-establishment of a forest can take years, with recovered forests often being dominated by smaller trees or shrubs with a lower carbon storage capacity (McDowell and Allen, 2015). Such efforts must begin with an understanding of the major threats facing forests. To follow is an overview of these threats in Europe.

3.1 Land use change

Land use change, including the conversion of forest land for agricultural purposes, plantations, urbanisation and roads, is a significant threat to the extent of European forests.

Forest loss is particularly significant in the context of climate change because of its relationship to **carbon emissions**. Unharvested, primary forest serves as an important carbon sink; contrary to previous views, new evidence also suggests that these forests continue to accumulate carbon after reaching maturity, with potential to remain as active carbon sinks for centuries (Barredo *et al.*, 2021). Although actively managed forests also store carbon, old-growth forest accumulates carbon over centuries, with half of the global primary forest area sequestering around 1.3 gigatonnes (Gt) of carbon each year (Luyssaert *et al.*, 2008). Disturbances to primary forest rapidly return carbon to the atmosphere (Luyssaert *et al.*, 2008).

Since the start of human civilisation, the number of trees on earth is thought to have almost halved and over 15 billion trees continue to be felled each year (Crowther *et al.*, 2015). Deforestation in Europe reduced total forest area by 190 000 km2 between 1750 and 1850; however, afforestation practices resulted in a net gain of forest area between 1750 and 2010 (Naudts *et al.*, 2016).

Although emissions from deforestation are more than compensated for by afforestation practices (Pilli *et al.*, 2016) and the area of forest in the EU increased by almost 10% between 1990 and 2019 (Eurostat, 2021), pressures and degrading conditions mean that, in general, the condition of forests in the EU is poor. Almost 85% of forests in the EU have a poor or bad conservation status and a quarter of trees show defoliation levels indicating damage (Maes *et al.*, 2020).

Box 2: Afforestation vs Reforestation

Both of these terms describe the conversion of non-forested land into forest. However, while **afforestation** can occur on any land that has not been covered by forest for at least 50 years, **reforestation** describes the foresting of land that was historically forested but has only recently (i.e. within the past 50 years) been subject to another land use.

(IUCN, 2004)

Future Forest Growth, ©Getty Images, public domain

Afforestation is one way to combat this problem and a cost-efficient means of removing carbon from the atmosphere (Humpenöder *et al.*, 2014), but alone is not sufficient. A study of the global potential for tree restoration found room for an additional 0.9 billion hectares of canopy cover, resulting in storage of more than 200 gigatonnes of carbon (Bastin *et al.*, 2019). Although afforestation practices resulted in a net gain of forest area between 1750 and 2010, European forests still have a carbon debt compared to 1750 (Naudts *et al.*, 2016).

This is due in part to wood extraction, which releases carbon, as well as the conversion of deciduous forests into fast growing forests (e.g., conifers, eucalypts), resulting in changes to the canopy and albedo (the amount of solar energy that is reflected by a forest surface), generating a warming effect (see Chapter 5.1).

The growth of homogenous plantation forests consisting of mainly a single species have had consequences for the condition, biodiversity and carbon storage of forests in Europe.

When considering land use, there is a link between biodiversity, on the one hand, and climate change mitigation and adaptation, on the other hand. More biodiverse forests absorb more carbon than species-poor plantations (Osuri *et al.*, 2020) and even than agro-forestry (Lewis *et al.*, 2019).

In addition, they used to be more resilient to pests and other extreme events. Conversion of primary or old-growth forests, or native, naturally regenerating forests into plantations, incentivised by policy support, is considered a negative practice for both climate and biodiversity (Camia *et al*. 2021).

3.2 Extreme weather events

Levels of carbon dioxide and methane in the earth's atmosphere are now higher than at any time in the past 800 000 years, generating a profound effect on climate. Increasing carbon dioxide levels and rising temperatures may increase forest growth in the short term, but will also increase the risk of extreme weather events. Recent measurements reveal increasingly common heat waves in Europe, as well as more frequent and intense precipitation (Lindner *et al.*, 2010; Norwegian Meteorological Institute, 2013).

These changes increase the likelihood of droughts (and consequently wildfires) and storms, each of which pose threats to forest stability.

3.2.1 Droughts

Warming temperatures combined with more frequent periods of low precipitation result in droughts, which present a significant risk of disruption to forests (McDowell and Allen, 2015).

Droughts have a number of impacts on trees, including reducing CO2 uptake, tree growth and vitality, and the ability to defend against pests such as bark beetles. Droughts also change trees' nutritional qualities and in particular their nitrogen content, reducing the amount of water in tree tissue, and prompting earlier senescence (ageing – i.e. leaves turning colour) (Vose *et al.*, 2016).

Tree tops and forest dieback - aerial view. Many trees are suffering from drought and pest infestation. ©Getty Images, public domain

Box 3: Case study: 2018 droughts in central Europe

The summer of 2018 saw record breaking temperatures in many parts of Europe (EC, 2019b). Climate change made these conditions more than twice as likely (World Weather Attribution, 2018) and led to the most severe drought in Europe for at least 500 years (Schuldt *et al.*, 2020).

In the hottest regions of central Europe in 2018 – Austria, Germany and Switzerland – the mean growing season air temperature between April and October 2018 was 3.3°C higher than the long-term average (Schuldt *et al.*, 2020).

The event placed severe stress on several tree species of economic and ecological importance, leading to early discolouration and leaf senescence of deciduous species, such as European beech, and in some cases leading to complete defoliation. Coniferous tree species, such as the Norway spruce, also displayed needle discoloration.

Partial or complete canopy dieback was observed throughout Austria, Germany and Switzerland in the autumn of 2018, followed by the death of isolated trees, groups of trees and entire stands (mainly Norway spruce). In Germany alone, millions of trees were affected with an area of around 2 500 km2 to be afforested (Schuldt *et al.*, 2020).

Beyond the immediate damage, there were also longer-term effects caused by the droughts. The capacity of trees to recover was seriously impaired, making trees more vulnerable to attack by insects, such as bark beetle, and fungi (Schuldt *et al.*, 2020).

Droughts can make a forest more vulnerable to insects and fungal pathogens in multiple ways, including through tissue dehydration and carbon starvation (Schuldt *et al.*, 2020).

Drought may also change a tree’s defences and increase their attractiveness to insects, for example through leaf yellowing, and induce the production of volatile compounds that are olfactory attractants to some insects (Vose *et al.*, 2016). Warmer temperatures also benefit some tree pests by expanding their range (see Chapter 3.3).

The large-scale death of trees brought about by insect attack in turn makes a forest more susceptible to fire (de Rigo *et al.*, 2018), discussed below.

Adaptation measures will include the change to more drought-resistant tree species including species mixtures, and the maintenance of the forest climate through small-scale management. At the same time provisions for maintaining and enhancing biodiversity should ensure the good conservation status of habitat and species, exclude the use or release of invasive alien species and exclude the use of non-native species (unless it can be demonstrated both that the use of the ‘forest reproductive material’[5] leads to favourable and appropriate ecosystem conditions and, also, the native species currently present on the site are no longer adapted to projected climatic and pedo-hydrological conditions).

However, a forest is a complex ecosystem, not just a group of trees. During spontaneous migration, a tree never moves alone, but with a host of organisms that facilitate its local integration. A tree settles and lives in a place by recruiting fungi that help its roots to feed, and that decompose its dead wood, etc.

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[5] https://ec.europa.eu/food/plants/plant-reproductive-material/legislation/future-eu-rules-plant-and-forest-reproductive_en

In this context of adaptation of forest stands to present or future changes, the choice of tree species is therefore a bet that must be based on the capacity to monitor and diagnose ongoing changes and on the integrative and adaptive management necessary in a time of crisis and, as much as possible, based on nature. The biodiversity of forests will undoubtedly determine their capacity for resilience and evolution.

The forest must be adapted to climate change, but through an ecological and evolutionary vision. The precautionary principle must be applied: poorly adapting the forest can accelerate its decline. A global, integrated and interdisciplinary approach, combining foresters, ecologists, geneticists and others is needed.

3.2.2 Fire

Climate change is increasing the frequency and severity of fire weather – periods of high temperatures, low humidity, low rainfall and often high winds (Jones *et al.*, 2020). This has been evidenced by recent events in the western United States, the arctic tundra, and in Australia, which saw one of the worst bushfire seasons in history in 2019, also the hottest year on record for Australia (Boer *et al.*, 2020). But climate change is not only precipitating wildfires in the Southern Hemisphere; 2019 also saw unprecedented forest fires in Spain, Portugal and Sweden.

Record droughts and heatwaves also precipitated forest fires in several European countries in 2017 and 2018, including in regions where wildfires are not typical. Sweden for example experienced its worst fire season in 2018 since records began (EEA, 2019b).

Aftermath of a forest fire in Spain, ©Getty Images, public domain

Box 4: Fast facts about forest fires

- Forest fires are uncontrolled fires that occur in forested areas. The risk of a forest fire is increased by long, dry spells of weather, which are becoming more frequent as a result of climate change. Certain species of tree (e.g. pines or eucalyptus) can also be more prone to fires.
- More severe fire weather, expansion of the fire-prone area and longer fire seasons are predicted for most regions of Europe due to climate change.
- In 2018, more European countries suffered from large forest fires than ever before.
- Between 2007 and 2019, forest fires were responsible for almost a third of all requests for assistance via the EU's Civil Protection Mechanism.
- In 2019, 161 473 hectares (ha) of Natura 2000 and other protected area was burnt (this figure includes other natural and agricultural land as well as forest areas) – three times that recorded in 2018. Spain was the worst hit by forest fires (83 963 ha), followed by Portugal (42 084 ha) and Italy (36 034 ha).
- Fires can have long-term impacts on forest soil, which can in turn affect ecosystem function and forest productivity.
- Wildfires are also a big contributor to global biomass burning and a major source of carbon emissions.

(Bowd *et al.*, 2019; EC, 2020; EEA, 2019b; EC, 2020; Knorr *et al.*, 2015; San-Miguel-Ayanz *et al.*, 2020)

Pinewood forest in sunrise, Sognsvann, Oslo. ©Getty Images, public domain

Eucalyptus globus (Portugal), ©Getty Images, public domain

The composition of a forest can also be a driver of fires, with plantations dominated by eucalyptus or pines being more prone to fires. In Portugal for example, eucalypt plantations occupy more than 20% of total forest area, generating a vulnerability to fire in these regions (Garcia-Gonzalo *et al.*, 2012).

Overall in the EU, fire risk is highest in the Mediterranean region (EEA, 2019b). Although there is significant variability in wildfires in the region over time (Figure 1), the fire hazard in the region has overall increased since 1980, as a result of climate change (EEA, 2019b).

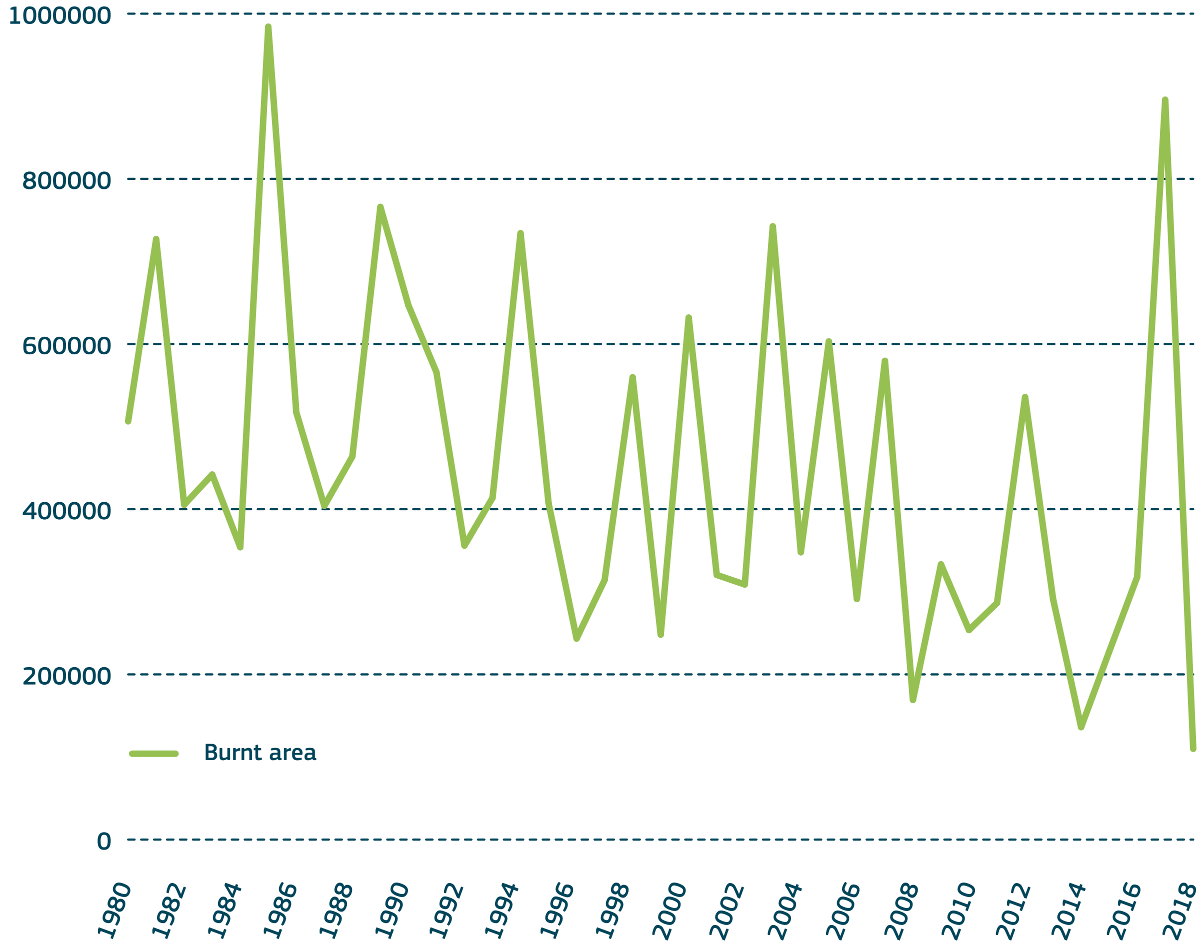

Figure 6: Burnt area in the EUMED5 (France, Greece, Italy, Portugal and Spain) due to forest fires, 1980–2018. Data source: EFFIS European Fire Database – Total burnt areas (EEA, n.d.) https://www.eea.europa.eu/data-and-maps/indicators/forest-fire-danger-4/assessment. Reductions in burnt area have been achieved through fire protection measures such as fire breaks, detailed below.

Estimated future increases to burnt area in the region are 40%, under a 1.5°C global warming scenario, increasing to 100% under a 3°C global temperature rise (Turco *et al.*, 2018).

Adaptation measures will be important to mitigate the increased fire risk in Europe. Proposed measures include prescribed burning (reducing the fuel load), which describes the controlled application of fire to vegetation and has been used in Europe since the 1980s (Silva *et al.*, 2010). Managing the forest through silviculture techniques can reduce the amount of available fuel. Creating and maintaining vegetation free strips ‘fire breaks’ can also help to mitigate the spread of fire. Other fire suppression efforts include increasing fire detecting and firefighting capacity in at-risk areas.

3.2.3 Storms

Storms are responsible for more than half of all primary damage to European forests due to catastrophic events (EFI, 2000; Gardiner *et al.*, 2013).

Destroyed forest as an effect of strong storm, ©Getty Images, public domain

Although storms have always been a part of forest ecosystem dynamics, the increasing use of storm-susceptible conifer plantations, in combination with climate change is increasing the risk of severe storms in many regions of Europe, in particular the North Atlantic and northern, north-western and central Europe (EEA, 2017a).

Climate change can also reduce a forest's capacity to endure a storm via changes to the soil. Climate change will lead to longer periods of unfrozen soils during European winters, which can reduce the strength of root anchorage. Storms are also projected to be accompanied by heavier rainfall under climate change, which increases the risk of damage (EFI, 2000).

Predicted climate change suggests that storm damage to Europe's forests will double, and could quadruple, by the end of the century.

Box 5: Storm case studies

Winter Storm Gudrun and Sweden

- Storm Gudrun hit Sweden in January 2005.
- Maximum wind gusts were the highest on record for the region, at 35 metres per second (126 km/h).
- ~75 million m3 of stem wood was uprooted – equivalent to the total annual harvest in Sweden (the storm only affected a smaller part of Sweden).
- The year following the storm, the carbon sink was reduced by an estimated 3 million tonnes. The total effect of the storm on the Swedish carbon balance is in the order of 5.8 million tonnes.

The "Vaia" storm and Italy

- Storm Vaia (also known as Storm Adrian) formed over the Mediterranean Sea in October 2018.
- The storm hit north-eastern Italy on October 29, with wind gusts reaching 200 km/h and higher.
- Many areas of forest were damaged, with 494 Italian municipalities registering forest damage as a result of the storm.
- Destroyed or damaged forest stands totalled 42 500 ha with a volume of fallen (growing stock) trees in the region of 8.5 million m3.

(Lindroth *et al.*, 2008; Chirici *et al.*, 2019; Bolte *et al.*, 2009)

Over 130 individual windstorms caused damage to European forests between 1940 and 2000, which is more than two storms per year. Conifers in general are more susceptible to storms (especially Norway Spruce because of its shallow roots), although some broadleaf species such as poplar are also vulnerable. Broadleaf species such as oak are the most resilient – and silver fir, which is a conifer, is also less vulnerable. However, this vulnerability does also depend on management approaches and planting sites.

Storms can cause severe damage to forests, affecting their carbon sequestration, water balance and biodiversity (Gardiner *et al.*, 2013).

3.3 Pests, pathogens and invasive alien species

Pests and pathogens, including insects and fungi, are the greatest biotic threat to forests. The IUCN's latest European Red List of Trees identifies the main threat to tree species in Europe as problematic (e.g., invasive) species, impacting 38% of tree species.[6]

Several examples exist where previously widespread species are now suffering due to new pests and diseases. There has been a severe decline in species of Ulmus due to Dutch elm disease (Caudullo & de Rigo, 2016), and the more recent outbreak of common ash dieback has also led to concerns about the rapid decline and extinction risk of Fraxinus excelsior (Pautasso *et al.*, 2013; Stocks *et al.*, 2017). Both Dutch elm disease and common ash dieback are caused by types of fungus, the dynamics of which may be affected by climate change (La Porta *et al.*, 2008).

The vulnerability of Europe's forests to pests seems to have been increased by management practices, such as the extensive planting of the Norway spruce across Europe, including outside of its native range. These 'secondary forests' are prone to various disturbances, including bark beetle infestations (Hlásny *et al.*, 2018). Intensifying global trade has also increased the spread of pest and pathogen species (Klapwijk *et al.*, 2016; Santini *et al.*, 2012).

The economic impact of pest outbreaks can be huge, including directly reducing the revenue of a country and indirect impacts through trade restrictions (Klapwijk *et al.*, 2016). Pest outbreaks are also a major threat to sequestered carbon. It has been estimated that 10% of the total carbon sequestered in Europe's forests could be at risk from alien pest invasions (Seidl *et al.*, 2019).

Box 6: The case of the bark beetle

In the majority of cases, bark beetles breed in dead trees and tree parts.

However, some species of bark beetle, including the European spruce bark beetle, are a threat to living trees. These beetles colonise stressed trees when population numbers are low, going on to attack large numbers of healthy trees when the beetle population has grown.

The European spruce bark beetle blocks the circulation of sap and bores holes in the tree to lay its eggs and can result in the death of a tree in less than four weeks. These species are therefore a major threat to Norway spruce forests and can have adverse social, economic and ecological impacts.

European spruce bark beetle, (Ips typographus), ©Getty Images, public domain

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[6] Followed by deforestation and wood harvesting, and urban development (both affecting 20% of tree species).

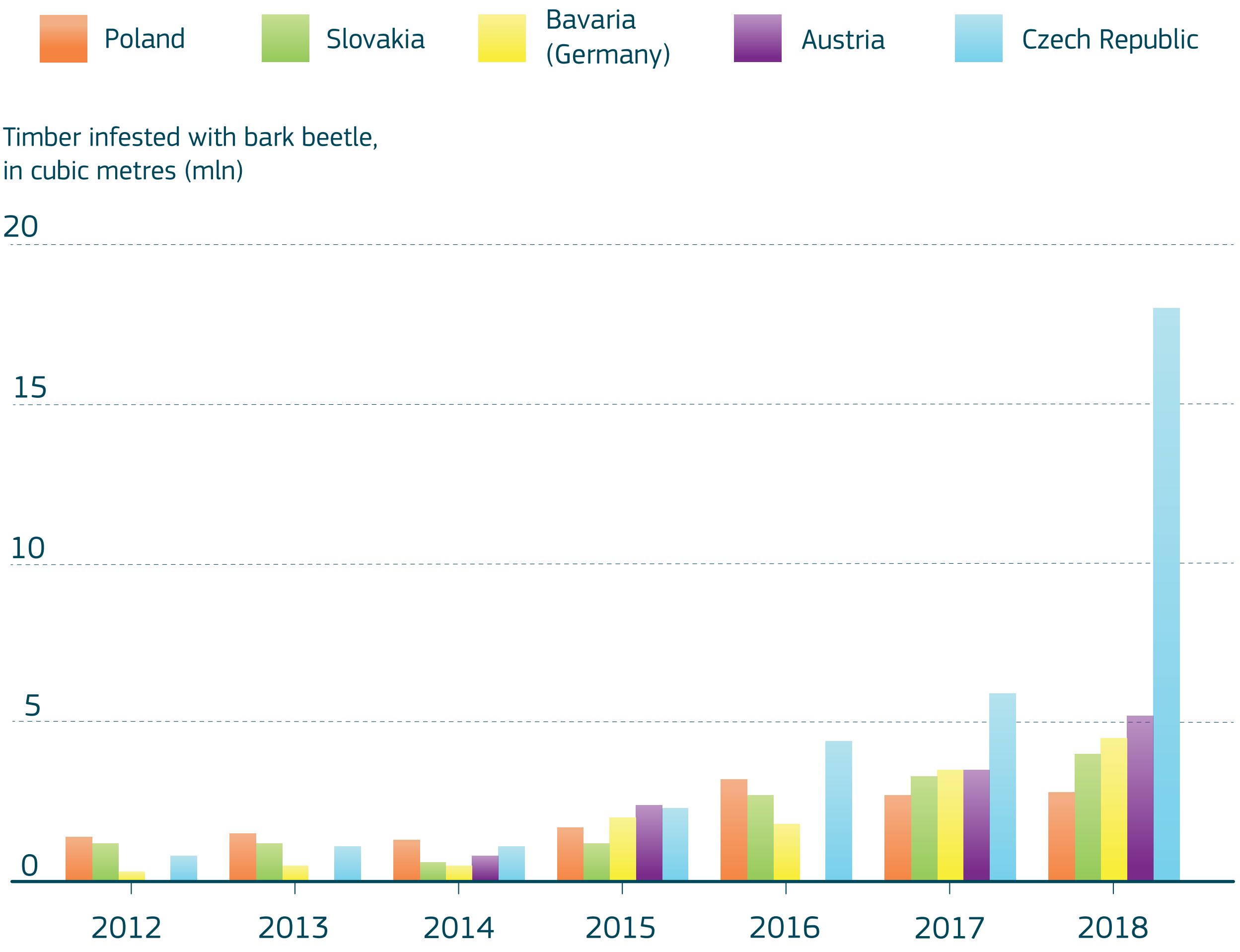

Figure 7: Timber infested with bark beetle in Europe (million cubic metres). Source: Redrawn from Jazon Hovet and Jan Lapatka at Reuters Graphics, data drawn from the Czech Statistical Office (CSU), Bavarian State Institute of Forestry, Austrian Federal Research and Training Centre for Forests, Natural Hazards and Landscape (BFW), Slovak National Forest Centre, Polish State Forests.

Climate change intensifies bark beetle outbreaks by diminishing tree defences and allowing bark beetles to expand to new regions. Species selection aggravates the impact, and spruce monocultures are more vulnerable. Outbreaks are especially likely following extreme weather events (see Chapter 3.2) such as storms and droughts, where they are likely to occur over several areas simultaneously.

The impact of bark beetle outbreaks is already increasing in Europe. There has recently been an increase in outbreaks in Norway spruce forests in regions including Austria, Czech Republic, Germany and Slovakia (Hlásny *et al.*, 2018).

Exact figures are hard to obtain, but spruce and pine timber damaged by bark beetles increased by nearly 700% in the four decades leading up to 2002-2010 (to 14.5 million m3/year) (Seidl *et al.*, 2014). In Czech Republic, this caused losses in excess of $750 million (€636 million) (Lopatka, 2019). Management of bark beetle outbreaks requires an integrated approach, including monitoring, sanitation, silviculture and, in some cases, non-intervention (Hlásny *et al.*, 2018). De Groot and Ogris (2019) report that Czech Republic, Poland, Germany and Slovakia are all experiencing intense beetle attacks on Norway Spruce – and that high temperatures and extreme weather linked to climate change make trees more vulnerable to beetle attacks.[7]

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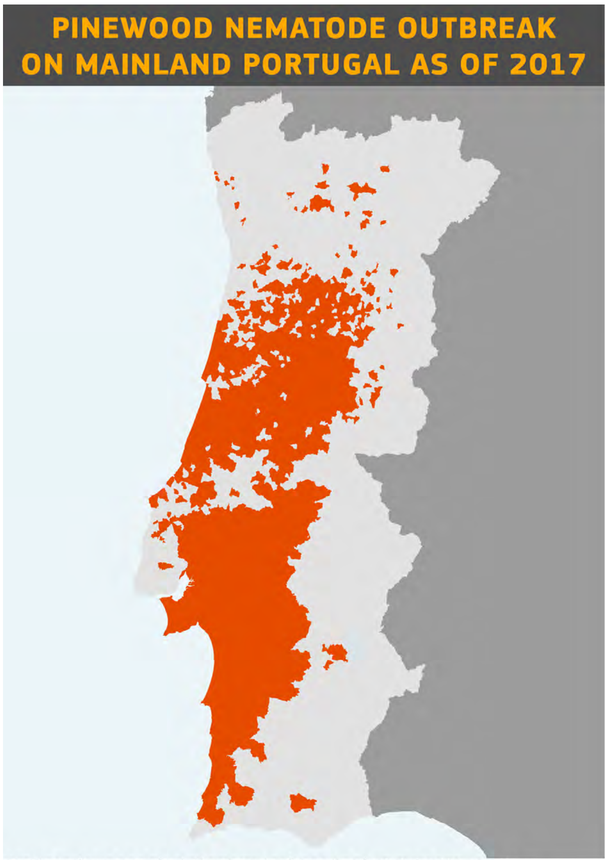
[7] De Groot and Ogris (2019) also summarised in SfEP article from 4th May 2020, Issue 541: https://ec.europa.eu/environment/integration/research/newsalert/pdf/new_research_predicts_which_trees_are_at_greatest_risk_of_beetle_outbreak_541na1_en.pdf

Other pests include the pine wood nematode, an invasive microscopic worm originally from North America, which reproduces rapidly in the wood of European pine trees, blocking their sap flow which causes the leaves to turn brown, and ultimately kills the tree.

This pest, which is not native to Europe, has affected Portugal's forests particularly badly. Due to its symbiosis with *Monochamus galloprovincialis*, a flying beetle native to Europe, it has since spread to more than 30% of the country, and caused extensive damage to Portugal's coniferous forests, which are made up largely of maritime pine trees.



Outbreak mapped at the level of local administrative units, courtesy of ICNF, Portugal (icnf.pt)

Figure 8: Pinewood nematode outbreak on mainland Portugal. Source: ICNF, Portugal, de le Fuente *et al.*, 2018. https://doi.org/10.1111/1365-2664.13177

Portuguese authorities have implemented a 20km-wide buffer zone along Portugal's mainland border with Spain, by identifying and removing coniferous trees in poor health, to prevent the spread of the beetle and the pest. Researchers in 2018 (de la Fuente, Saura and Beck, 2018) created a network-based model (see Figure 8) that simulates the natural spread of the nematode, aiming to support management efforts by forecasting when areas are at highest risk.

Another example is the "banda marrón" (Lecanosticta acicula), a fungus affecting pine trees (pinus radiata) in the Basque Country and Navarra. Pinus radiata is an exogenous species introduced in the 19th century, which now occupies around 20% of forest cover in these regions. This shows how plantations dominated by one or few tree species makes a forest more susceptible to pests linked to the dominant species.

The majority of plant pests and diseases are invasive, non-native species whose introduction causes harm to the ecosystem (IUCN, 2019a). Their lack of natural predators, and lack of evolved resistance in native trees, means their impact can be quick and devastating.

Invasive species can include tree species. The first introductions of alien (non-native) tree and shrub species to Europe happened over 200 years ago, and since then, more than 130 species, mostly from three families (Rosaceae, Fabaceae and Pinaceae) have become established (Rejmanek & Richardson, 2013).

A significant number of alien tree species are widely considered to be invasive, such as the Black Locust (Robinia pseudoacacia) or the Tree of Heaven (Ailanthus altissima) (Medina-Villar *et al.*, 2015; Vítková *et al.*, 2017). Various adaptations in these tree species (such as being fast-growing) allow them to outcompete native tree species, which can have strong negative impacts on ecosystem services, native species and native species richness (IUCN, 2019a). Hybridisation is also identified as a threat for some species (such as Populus nigra, Ulmus minor), which has led to difficulties in identification of natural populations and loss of local genotypes. Alien species also can have significant detrimental effect on hydrology, soil quality, biodiversity and safety as is the case with species from the genus Eucalyptus.

Climate change is a great concern for the risk of pest outbreaks and outcompetition by invasive species. Where, previously, an introduced pest or pathogen may die out due to unfavourable conditions, warmer temperatures can increase the range and development rate of tree pests (Wainhouse and Inward, 2016). The vulnerability of trees is also affected: changes in climate place stress on trees (through changes in temperature, rainfall and extreme events), which can increase their susceptibility to harmful organisms (IUCN, 2019b).

3.4 Climate change threats

Among all of these threats, the common thread is clear. Climate change is intensifying the many threats forests already face but will also have its own impacts on forests.

Increasing global temperatures are expected to support the expansion of tropical forests into areas where temperate forests are now, and the expansion of temperate forests into areas currently inhabited by boreal forests (Mendelsohn *et al.*, 2016). Boreal forests may be particularly affected by climate change, with mean annual temperature increases of 1.5 °C or more already being observed over much of the boreal forest biome. Under a global warming scenario of 4°C by the end of the century, boreal forests could shift to drier regions, with dramatic consequences for CO2 balance and habitat loss/gain (Gauthier *et al.*, 2015).

Changes to climate will also influence the diversity of tree species within existing forests. Modelling of forest composition in Europe under future climate scenarios suggests declines in species richness in lowland forests in the Mediterranean and Central Europe but increasing diversity in elevated forests in Scandinavia and Central Europe (Buras and Menzel, 2019).

In northern and western Europe, increasing levels of carbon dioxide in the atmosphere and warmer temperatures will likely increase forest growth and wood production in the short term (as is already evident in Finland, for example: Henttonen *et al.*, 2017), but an increasing risk of drought and fire might outweigh any positive effects. The risk is particularly severe in the Mediterranean region, which has limited capacity for adaptation (Linder *et al.*, 2010).

The drastic changes brought about by global warming will occur at rates exceeding the natural adaptive capacity of forest ecosystems, potentially leading to extinctions and loss of vital ecosystem services – including carbon storage.

The total carbon stored in forest ecosystems globally exceeds the carbon in the atmosphere (Pan *et al.*, 2011). Any loss of forest brought about by climate change will itself exacerbate climate change, making adaptive forest management approaches essential now. Such approaches should focus on avoiding monoculture plantations dominated by one or few species and fostering biodiverse forests which are likely to be less vulnerable to threats such as fires and pest invasions.

4. Forests and biodiversity

Forests cover approximately 40% of the EU's land area and hold a significant proportion of the EU's terrestrial biological diversity, acting as irreplaceable reservoirs of biodiversity (European Commission, 2021; 2020a).

However, very little of this forest remains pristine (or 'primary'); human land-use changes have shaped European forests through activity such as hunting, the grazing of domestic herbivores, the clearing of forests for agriculture, leaf litter and resource extraction and, more recently, the planting of monoculture crops and exotic species (Bengtsson *et al.*, 2000). Nowadays, most EU-28 forests are (89%) semi-natural (i.e. shaped and modified by humans) and the remaining share is covered by plantations (Maes *et al.*, 2020). Only 2-4% of the EU's forest area are now categorised as 'undisturbed' by human intervention (ibid.); however, all forests are to some extent influenced by human activity such as pollution (especially nitrogen deposition, CO2 enrichment and global warming), and it is likely that nearly all European forests have experienced extraction of wood in some form.

Fast-evolving patterns of consumption and production increasingly threaten forests' capacity to provide essential ecosystem services and withstand the impacts of climate change (Maes *et al.*, 2020). Only around 14% of EU-28 forests are designated for biodiversity and nature conservation (Forest Europe, 2015). European forests are facing serious threats (see Chapter 3), which are anticipated to worsen as demand for timber and wood resources increases (European Commission, 2020a). As outlined in Chapter 3, the health of forested regions, and their ability to support biodiversity, is threatened by human activities, and these effects are exacerbated by climate change and associated extreme weather (droughts, storms, wildfires) and pests and pathogens, with the biodiversity of old-growth natural and semi-natural forests being most at risk (EEA, 2016b). For example, forested areas have been converted into different types of land cover (e.g. into agricultural land, or into settlements and infrastructure for human use) and their valuable resources can be extracted used by households and industry (Philipp Benz *et al.*, 2020). Recently, the pressure on forests from conversion to urban and other artificial development particularly has shown a downward trend, decreasing by 46% between 2000-2006 and 2012-2018.

Moreover, according to the National Forest Inventories of Member States, the area of forests in the EU-28 increased by nearly 13 million hectares (or 130 000 km2; an area equivalent to the size of Greece) in the period 1990-2015 due to both natural processes and active afforestation. However, the total changes in extent of forest cover more recently (from 2000-2018) are negligible, meaning that the total extent of forest cover did not show significant changes over this timeframe. These figures are based on the net change – i.e. gains counterbalancing losses – however, forests still experienced significant changes over this period. From 2000-2018 alone, there were forest losses of 142 374 km2. Recent pressure also seems to have accelerated: tree cover loss increased by 74% per decade in the period 2009-2018, up from 26% per decade over the period 2001-2012.

Such changes make forest ecosystems less diverse – and less resilient. Forest resilience depends directly upon biodiversity, with the diversity of genes, species, and ecosystems present in a forested area contributing to its ecological stability, resistance, and ability to adapt to changing conditions (Thompson *et al.*, 2009). Currently, 27% of mammals, 10% of reptiles, and 8% of the amphibians linked to EU forest ecosystems are at risk of extinction (EEA, 2016b).

Tree species are also under threat, with more than half of European tree species under threat. The IUCN's European Red List of Trees evaluated the conservation status of all 454 tree species native to the continent and found that two fifths (42%)

are regionally threatened with extinction. Among the trees that are endemic to Europe's forests – trees that don't exist anywhere else on earth – 58% were found to be threatened, and 15% (66 species) assessed as Critically Endangered, or one step away from becoming extinct. While biodiversity remains a key objective, policies seek to simultaneously sustain the provision of forest commodities and ecosystem services that are essential to society and address the trade-offs between production and biodiversity conservation (Kremen, 2015). In general, efforts to conserve forest biodiversity rely on two overlapping approaches; 1) setting aside forest specifically for nature conservation in areas excluded from woody biomass production (functional separation or segregation) and 2) incorporating conservation measures within production-oriented forests (functional integration). These two approaches are largely interdependent: the better biodiversity is safeguarded through management while producing wood and other ecosystem services, the fewer areas must be set aside for pure biodiversity protection (Boncina, 2011; Larsen, 2009; Lindenmayer and Franklin, 2002).

Tree plantation in a forest, ©Getty Images, public domain

Functional separation/segregation	Functional integration
Setting forest completely aside for biodiversity conservation	Introducing biodiversity conservation measures into production-oriented forests, or elements of production into biodiversity-oriented forests
Leaving forest untouched – mainly forests with a high degree of naturalness	*Managing forests for wood production in a nature-friendly way*

In a functional integration approach, preserving biodiversity requires consideration of how different forestry practices – such as species selection, cutting regimes, regeneration methods, rotation ages, retention decisions – impact and interact with natural processes including forest dynamics. Most forestry practices thereby impact forest biodiversity and ecological functioning. However, certain improved practices of forest management and restoration (e.g. continuous cover forestry, selective logging, reduced impact logging, salvage logging, sanitary felling, retention of continuity through forest patches, establishment of protected areas, and forest certifications) can help to restore forests, and therefore impact biodiversity and ecological functioning less destructively (Smith *et al.*, 2020).

This chapter will summarise some of the main parameters of biodiversity monitoring and assessment in forests as well as some of the main challenges facing forest biodiversity in the EU.

4.1 Biodiversity monitoring and assessment in forests

Forests are critically important for biodiversity, and people have a key role to play in sustaining forests biodiversity. Assessing and monitoring biodiversity is challenging, especially for rare species or inaccessible regions, but in the EU, the mapping and assessment of ecosystems and their services (abbreviated to MAES) is seen as a key action for the advancement of biodiversity objectives.

The first ever EU-wide MAES Ecosystem Assessment Report was released in October 2020. It found that, for each six square kilometres of potentially productive forest land in the EU, there is only one square kilometre of forests protected for biodiversity (Maes *et al.*, 2020). This low proportion of protected forests represents the fragmented character of biodiversity valuable forests in the EU. The increasing extraction of forest products and intensified forestry practices will also have diverse impacts on the various habitats and species protected under the EU's nature Directives.[8]

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[8] Birds Directive and Habitats Directive

4.2 Key biodiversity dimensions of forests

Although trees dominate forest landscapes, we sometimes tend to forget that they are not the only actors. Behind these remarkable protagonists, many other living organisms enter the scene more discreetly but with roles that are no less important. Indeed, the forest is a complex ecosystem, governed by interactions between many organisms. Forests are the types of habitats that host the largest number of living species (several thousand species in a single forest). Plants, animals, fungi and single-celled organisms act together to form and make these ecosystems work.

The diversity of species constitutes one level of 'biodiversity'. The term 'biodiversity' encompasses life's diversity in all its forms: species diversity (taxonomic diversity), diversity within a species at the level of one or more populations (genetic diversity), and ecosystem diversity. It also includes functional diversity, considering the variety of functions performed by the different groups of species within the ecosystem.

The complexity of biological interactions in forests makes it difficult to understand all the dynamics that influence biodiversity. Many scientists are working to understand the relationships that link the species richness of a forest to the characteristics of the associated environments (notably, open, rocky, aquatic). The ecological requirements of forest species are very varied, sometimes even completely contrasting. However, structural and compositional heterogeneity within forest stands offers many different habitats, which multiplies the chances of satisfying these varied requirements.

Forest management aims at harvesting trees when they have reached their exploitable age or diameter, defined as an economic optimum suitable for the supply chains of the moment, and considering the productivity and profitability of silvicultural operations. Since a tree's exploitable age is generally situated during this economically optimal phase – in the first third of the stand's life and well below the species' longevity potential – a very large part of the biological development of the trees is curtailed in the silvicultural cycle. The major differences between the foresters' silvicultural cycle and the natural silvigenetic cycle are a drastic shortening of the regeneration phase, the absence of the decline and terminal phases, and also the simplification of the composition of forests, in favour of 'production' species, which are often selected among the 'dryads' or post-pioneer species.

Box 7: Good forest ecosystem condition

A comprehensive approach to preserve and restore the biodiversity of an ecosystem must consider its structural, compositional and functional characteristics. The favourable conservation status of forest habitats at a local level is often characterised by different parameters, such as habitat extent, parcelling and fragmentation, the integrity of tree species composition (e.g. absence of invasive species), forest dynamics (number of large living trees; living trees with microhabitats and renewal processes), vertical vegetation structure that allows the multiplication of habitats for a wide diversity of species, the matter cycle (volume of dead wood) and absence of deterioration (e.g. soil damage - compaction, hydrological disturbances).

Emberger, Larrieu and Gonin (2019) suggest that forest management for both wood production and high taxonomic biodiversity could be guided by three key principles:

- Increase the number of living environments: promoting structural and compositional heterogeneity (in terms of species and ages of forest stands and stages of decomposition of dead wood) will in turn promote a varied range of habitats, which will increase the chances of meeting the varied ecological requirements of forest species;
- Maintain continuity in space: i.e. ensure diversity of species and structures are present in all plots, or in sufficient number and in a relatively balanced distribution. The habitats linked to trees are dynamic and temporary: they change over time and eventually disappear once the dead wood has decomposed. The need for species to have a habitat is continuous, although very few are able to remain on standby until the opportunity of a favourable environment presents itself (take, for example, the case of seeds which can remain dormant for many years). Most species must thus move regularly and the distances that they can cover are sometimes quite limited. Such a network of habitats also allows populations that are numerous enough to be viable.
- Maintain continuity over time: ensure the continuity of living environments over time, through their renewal as the populations evolve, to allow the long-term maintenance of populations. For example, take care to maintain old trees, which will become the dead wood of tomorrow.

A practical solution to ensure both continuity of biodiversity and continuity of diverse living environments may be to let a part of the forest stand complete the entire silvigenetic cycle (i.e. enabling the full life cycle of the trees, through reproduction to succession).

Box 8: Key types of species for forest biodiversity

The main forest biodiversity issues involve species and populations that are found only in forests or that are particularly sensitive to management, or that are threatened.

Gosselin and Paillet (2010), in their report focusing on French forest management, state that priority attention should be given to:

- species that are only found in forests or in typical forest microhabitats (dead wood, humus, crowns, tree cavities);
- species that depend on the forest for all or part of their habitat or their life cycle;
- and forest trees, keystone species which form the structure of the forest environment and which are the direct object of management.

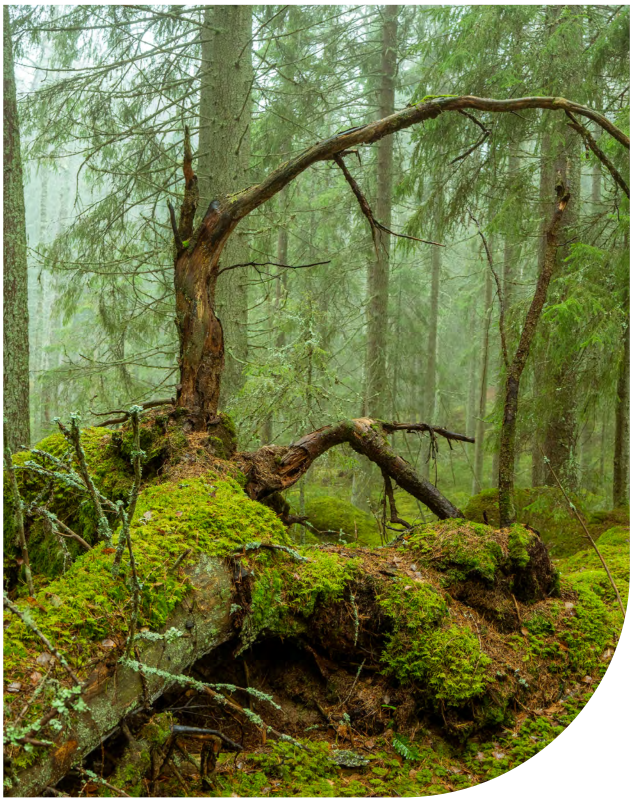
Source: Gosselin and Paillet, 2010.

4.2.1 Microhabitats: dead wood, tree cavities and very large trees

Dead wood is another important proxy for biodiversity, representing the substrate (material base) for a large number of animal and plant species (Maes *et al.*, 2020). Certain forest species – for example, some fungi, mosses and insects – are dependent on the presence of dead wood in a forest; dead wood serves as a living environment for several thousand species. In Europe, it has been estimated that 20-40% of forest species are dependent on dead or dying wood, at some point in their life cycle (Bauhus, Baber and Müller, 2019). These are known as 'saproxylic' species. Dead wood also contributes to the structural stability of soils, carbon sequestration, nutrient supply and water retention (Lachat *et al.*, 2013). The volume of deadwood in intensively managed forests is under 10% of that in comparable types of natural forests (Stokland *et al.*, 2012). Forest-dependent insects, mammals, non-vascular plants and breeding birds are heavily affected by an excessive removal of dead and old trees or the reduction of old-growth forests.

Very large, very old trees are understood to have characteristics that provide favourable habitat for a large number of species, and more potential for the formation of microhabitats. A large part of the complexity of the forest ecosystem is linked to the heterogeneity provided by living trees with cavities. They provide refuges, breeding, hibernation and feeding places for many species, such as roosts and nesting holes for insectivorous bats and birds.

Ycke natural reserve is an old conifer forest in Sweden,
©Getty images, public domain



Old primeval forest with nice lights and shadows,
©Getty images, public domain

4.2.2 Forest structure and composition and diversity of tree species

Due to their control over the surrounding microclimate – light, moisture, temperature – the tree species present within an ecosystem to a great extent also control the diversity of other dependent forest species, with multi-tree-species forests typically being more diverse than single-species forests (Forest Europe, 2016). While resource production may benefit from promoting tree species that produce high timber yields (EEA, 2016b), this can affect the overall diversity and functioning of the ecosystem. In functionally integrated forests (combining biodiversity conservation and production), tree species richness is positively related to the provision of multiple ecosystem services, including tree biomass, berry and game production, soil carbon storage, and other proxies for biodiversity. No single tree species can promote all ecosystem services, indicating that monoculture practices will reduce ecosystem service provision and highlighting the value of including multiple tree species within multi-functional forests (Gamfeldt *et al.*, 2013). Species-rich communities thrive within forests that are diverse in structure – for example, bird diversity has been shown to be strongly influenced by the vertical heterogeneity of forest stands; tree communities with differing bark characteristics can support high biodiversity by providing numerous different microhabitats; and saproxylic organisms (which depend on decaying wood) prefer environments with differing volumes and decay classes of deadwood (Storch, Dormann and Bauhus, 2018). A variety of layers of vertical vegetation (co-existing on the same square meterage) allows the multiplication of habitats for a wide diversity of species.

Forest stands composed of native trees can be very important for biodiversity. This is because the species composition defines the type of wood present in the forest, and therefore the structure and decomposition of this wood (and the microhabitats that are possible), which will have knock-on impacts on a cascade of other forest-dwelling species. Trees also play the indispensable role of structuring the whole ecosystem; each species of tree is accompanied by a specific cohort of species.

Monoculture of spruces, ©Wikipedia Commons CC BY-SA 2.0

4.2.3 Forest continuity or ’ancientness’

Forest continuity refers to the maintenance of the forest cover over time, regardless of stand maturity or management system. The measure of ‘ancientness’ distinguishes ancient forests, which have been forested continuously for centuries, from recent forests (also called post-agricultural forests), which result from spontaneous or man-made reforestation of former agricultural land. The threshold date after which a forest may be considered ancient differs between countries due to the often-complex land-use history and the availability of reliable maps of historical land use or other sources (Hermy and Verheyen, 2007).

A key part of forest biodiversity, closely linked to this state of ancientness is soil biodiversity – soil biota can be particularly sensitive to soil changes. Therefore, forest continuity can be seen as a complementary factor to forest maturity in identifying high conservation value forests.

Box 9: Index of Biodiversity Potential (IBP)

The IBP is a biodiversity evaluation tool created to help forest managers easily take taxonomic biodiversity into account in their daily working routine.

It focuses on biodiversity at the stand scale since this is the typical scale used by forest managers in their daily activities. The IBP is a standardised methodology combining ten historical, structural and compositional key factors for forest-dwelling species which are easily and directly measurable in the field by forest managers with no specialised taxonomic skills (other than knowledge of tree species).

By comparing threshold values with field observations recorded along a standardised route inside the stand, a scoring system awards a score per factor.

Seven factors (A to G) directly concern the stand and its current management: they assess vegetation (two factors), deadwood items (two factors), very large trees, tree-related microhabitat-bearing trees – called ‘habitat trees’, following Bütler *et al.* (2013) – and open areas.

Three supplementary factors (H, I and J) concern site history and context: temporal continuity of wooded state and presence of wetland rocky macrohabitats. Table 2 below outlines the list of factors.

Categories	Type of factor	Factor	Succinct definition
Stand and its current management	compositional	**A:** Tree richness	Number of autochthonous tree general (dead or living trees)
	structural	**B:** Vertical structure	Number of vegetation layers (max 4 layers)
		C: Standing deadwood	Number of snags (dbh ≥ 40 cm)
		D: Lying deadwood	Number of logs (diameter at the larger end ≥ 40 cm)
		E: Very large trees (VLT)	Number of tree with dbh ≥ 70 cm
		F: Habitat trees (HT)	Number of live trees with at least one tree-related microhabitat (reference list of tree-microhabitats to observe)
		G: Openness	% per ha of open areas (clearings, edges and other areas with a well-developed herb layer composed of flowering plants)
Context	historical	**H:** Temporal continuity of the woody state	Presence of the stand on an ancient map (19th c.)
	structural	**I:** Wet macrohabitats	Number of wet-habitat types (reference list of macrohabitats to observe)
		J: Rocky macrohabitats	Number of rocky-habitat types (reference list of macrohabitats to observe)

Table 2: Definitions of the ten factors that constitute the Index of Biodiversity Potential (IBP) and scoring system. Source: Gosselin and Larrieu, 2020; Larrieu and Gonin, 2008.

4.2.4 Species indicators

One of the most easily recognisable measures of biodiversity decline is species loss (although this metric can suffer from focusing more on species presence than on population sizes and other metrics; Zuidema, Sayer and Dijkman, 1996).

Abundance of forest birds can be used as an indicator for biodiversity in forests. Short-term trends since 2010 suggest an improvement in the abundance of forest birds in the EU-28, although the long-term trend is stagnating – or possibly declining (Maes *et al.*, 2020). However, a regional analysis reveals that in Norway, Sweden and Finland, a significant downtrend was found in the period 1980-2016 (Maes *et al.*, 2020).

While some introduced species may be better able to weather future (warming) climates, the introduction of non-indigenous and exotic species can threaten ecosystem functionality (Selva *et al.*, 2020). Invasive species can eliminate native species or endanger them by introducing diseases. They can “drive populations of rare species to extinction, [and] are currently considered one of the biggest threats to biodiversity” (Krumm and Vitkova, 2016). As human activity has become increasingly global and both land use and climactic change has accelerated, the rate of introductions and invasions of such species has increased, requiring adaptive management approaches and actions tailored to suit local conditions and infrastructure (ibid). Some data indicates that invasive alien species are present in around 44% of EU-28 forests (Maes *et al.*, 2020).

Great spotted woodpecker, ©Getty Images, public domain

Box 10: Cascades, migrations, and tipping points

Loss of biodiversity can shift forest ecosystems "closer to a tipping point beyond which they will no longer be able to fulfil their vital functions" (UN, 2010), and increase the risk of 'extinction cascades' – where initial species loss leads to a "domino effect" of further extinctions (University of Exeter, 2018). In addition, climate change may force tree species to 'migrate' to new areas (in search of suitable climatic conditions (moisture and/or cooler environments) at higher speeds than ever before; for example, temperate-zone July isotherms (lines connecting points on a map, which have the same temperature) are predicted to move northward by up to 6 kilometres annually, an order of magnitude greater than historic rates (Solomon, 1997). While tree migration can help preserve an individual species, in some cases (depending on the species) it may destabilise the species' ecosystem and threaten its resilience and sustainability (Cimons, 2018).

4.2.5 Naturalness and regeneration

Naturalness describes the disparity between a forest's current and potential 'natural' states. Examples of forest naturalness comprise primary forests (untouched by human activity), semi-natural forests (with some natural characteristics), and plantations (species communities with artificial dynamics). In the EU28, most forests are 'semi-natural' (89%: Maes *et al.*, 2020), whereas only 2-4% are primary forests. Naturalness does not always positively correlate with biodiversity; for example, intervening to help a particular species regenerate can help a community's overall diversity and resilience (Forest Europe, 2016).

Poloniny - Beech forest virgin area. ©Wikipedia Commons CC BY-SA 4.0

Box 11: Close-to-nature forestry

Forest management comprises a broad array of activities – from salvaging dying trees to shifting service production to producing timber to restoring damaged ecosystems – and can produce a wider range of ecosystem services and benefits than in an unmanaged forest (O'Hara, 2015). While forestry has traditionally focused on the production of one resource, namely wood, it has evolved towards sustaining forest ecosystems and their services and biodiversity. One example of this is 'close-to-nature' forestry, which aims to maintain biodiversity by taking an approach to forest management that relies upon natural processes (Pro Silva, 2012).

Close to nature forestry originated in central Europe in small farm or community mountain forests in the nineteenth century and has been widely applied in Central Europe and partly in Southern Europe. Close-to-nature silviculture seeks to use indigenous tree species, enhance structural diversity through forest tending and regeneration, allow for standing and dead trees, protect special forest biotopes, and regulate unsustainable populations (for example, over-grazing herbivores; ibid).

However, near-nature approaches differ according to ecosystem, and worldwide a number of such approaches are developed and tested: e.g.:

- Close-to-nature forest management,
- Continuous Cover Forestry,
- Retention Forestry,
- Reduced Impact Logging,
- Mimicking Natural Disturbance,
- Emulating Natural Processes,
- Ecosystem Management,
- Ecological Forestry and others (Puettmann *et al.*, 2015)

While such "near-natural approaches have the potential to develop complex and sustainable forests that are adapted to our changing world", says O'Hara (2016), they must be founded on a true understanding of forest science – an understanding of the best way to conserve biodiversity through forestry, rather than focusing on insubstantial 'green' labels or failing to "emulate the dynamism of [present-day] ecological systems" (e.g. the dynamics of disturbance, climate change, invasive species, or the effects of pollution).

Mixed forest NE-Germany, ©Wikipedia Commons CC BY-SA 3.0

Research indicates that primary forests are richer in biodiversity than regenerating (secondary) forests and must therefore remain a conservation priority (Lennox *et al.*, 2018). Old trees are especially valuable for some species of bat and other small mammals.

The EU's Biodiversity Strategy for 2030 supports and recognises this, and aims to "define, map, monitor and strictly protect all the EU's remaining primary and old-growth forests" (European Commission, 2020b). Primary forests hold biodiversity value in terms of their "wilderness and uniqueness" (Duelli and Chumak, 2005). Secondary forests can also deliver various valuable ecosystem services (including habitat provision for diverse species) if left to naturally regenerate; however, since secondary forests are frequently managed, ensuring a good potential to deliver goods and benefits in space and time usually requires targeted landscape management and planning towards conservation objectives. (Lennox *et al.*, 2018).

A number of the features of pristine natural forests disappear or reduce in managed forests. Old-growth features such as large, old trees, both living, dying, and in the form of debris and fallen logs, disappear, as do burned wood, open glades, deciduous trees, and diverse tree populations (in terms of both species and age). Many species that are dependent upon these habitats – hollow or decaying trees, for instance – therefore suffer under unsustainable forest management and quite a few are red listed. When it comes to deadwood habitats, climate change-driven extreme weather instances can both increase (via storms) and reduce (via wildfire) deadwood volume in forests (Forest Europe, 2016).

4.3 Biodiversity protection in forests: connecting the dots

Europe's network of protected areas is expanding, playing a crucial role in conserving biodiversity. Levels of protection range from strict to multi-functional, and concern ecological processes, the spiritual, recreational, educational, and other uses of an area, as well as resource management and extraction. The EU's Natura 2000 network is one of the world's largest networks of protected areas, spanning over 18% of the EU's land area and nearly 25% of its forest area (with more than 27,000 protected areas; Hermoso *et al.*, 2019). The Natura 2000 network is a core part of EU biodiversity conservation policy and aims to achieve biodiversity conservation and to combine it with the sustainable development of land and natural resources (Sotirov, 2018). Currently, around 23% of EU-28 forests fall within Natura 2000 sites (Maes *et al.*, 2020).

To be most effective, protection must consider connectivity between patches of forest, rather than creating fragmented islands of forest that lack connectivity (Selva *et al.*, 2020). Some forest-dependent species struggle to move between areas of fragmented habitat as they adapt to our changing climate (EEA, 2015).

Fragmentation can affect biodiversity by reducing the size of the forested region and creating a greater degree of isolation between species communities, reducing forage and shelter ranges, and increasing the impact of edge effects (changes in population or community structure that occur at the boundaries of contrasting habitats). In the short term since 2010, and also in the longer term, the percentage of forest fragmentation in the EU-28 seems to be staying approximately the same (Maes *et al.*, 2020). Some greater connectivity could be achieved via multifaceted approaches, which propose creating protected conservation-oriented hotspots within production-oriented forests. Combining functional integration and separation, these would retain reservoirs of species and habitat within larger areas.

Some researchers have called for intermediate-sized conservation areas rather than small fragments or extremely large areas, arguing that these would instead be the most efficient option for biodiversity conservation (Zuidema, Sayer and Dijkman, 1996). However, there have been more recent, more ambitious calls for vaster areas to be protected in order to allow for large-scale dynamics and create the connectivity needed to avoid an extinction crisis – up to 50% of land area globally, by 2050 (Baillie and Zhang, 2018).

4.4 Challenges for EU forest biodiversity

Forest biodiversity in managed forests is particularly affected by the removal of dead and dying trees, as well as by the clear-cutting removal of all trees (which is a particular pressure on breeding birds), and the conversion to monocultures or other forest types (EEA, 2020c; Maes *et al.*, 2020; see Figure 9 below).

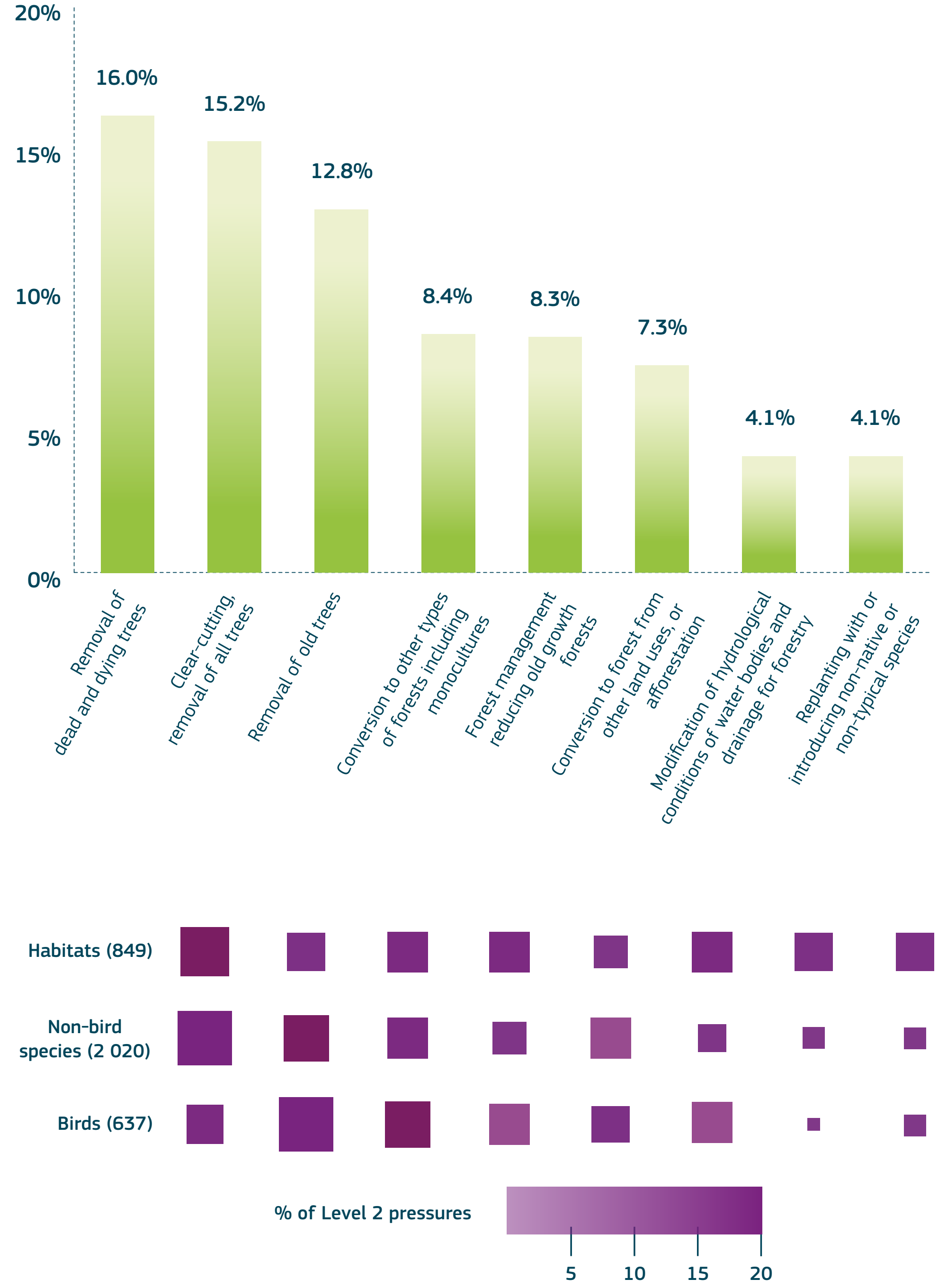


Figure 9: Distribution of the most relevant forest pressures for habitats and species. Notes: Level 2 pressures are individual, detailed pressures/threats/activities for both habitats and species, under the Article 12 and 17 reporting. The size of the squares and their shade reflect the percentage of pressures for each group: bigger darker squares indicate higher percentages. Total number of reports is given in parentheses. Source: From Article 12 and Article 17 Member States' reports and assessments in EEA, 2020c.

Biodiversity monitoring is challenging and expensive; animal species have large home ranges, highly specific characteristics, and may appear only seasonally. Approaches based on endangered or 'indicator' species (species that flag the health of an ecosystem and its value and relevance for conservation) also struggle to provide a comprehensive picture of the occurrence and abundance of other species in a habitat. Remote sensing monitoring often use observable parameters (e.g. tree cover change seen by satellite) as a proxy for forest change, which can be inaccurate and omits knowledge of, for example, natural regeneration or floor-level deadwood.

Overall, the goals of i) protecting biodiversity and ii) providing livelihoods, goods and services for people across Europe can be in conflict (Secretariat of the Convention on Biological Diversity, 2009). While these can be aligned, the growing need for timber products – such as industrial roundwood, demand for which is forecast to increase by 50% by 2050 (ibid) – is a strong driver for forest management that prioritises production and yield over biodiversity (see Chapter 5.2).

5. Forests and climate change mitigation

In recent years, the pressing need to address climate change has resulted in greater emphasis on forests' ability to mitigate climate change by absorbing and storing carbon. At the same time, the current policy framework supports the bioeconomy and the production of bioenergy, which increases demand for biomass – and notably forest biomass.

There are several ways in which forests can contribute to climate change mitigation. They can remove carbon dioxide from the atmosphere via photosynthesis, and store carbon in biomass and soil. Carbon can also be stored in wood products, delaying its release from harvested wood into the atmosphere. The use of wood instead of fossil-based materials (cement, steel or plastic, for example) can also play a role in reducing carbon emissions: carbon is being stored in the wood used as material.

The use of wood-based bioenergy has also been proposed to contribute to climate mitigation by substituting and lessening our reliance on fossil fuels. Burning biomass releases carbon (and other air pollutants); however, it can be assumed that this CO2 was previously absorbed by photosynthesis, making wood-based bioenergy theoretically carbon neutral. However, the theoretical carbon neutrality of biomass is true only if forests grow at least as fast as woody biomass is burnt to produce energy: carbon dioxide emitted can only be 'recaptured' after several years to several decades. The Land Use, Land Use Change and Forestry (LULUCF) Regulation (EU 2018/841) binds Member States to ensure that emissions from land use, land use change and forestry are at least entirely compensated by equivalent CO2 removals in the same sector (the 'no debt rule'). The reporting under the LULUCF Regulation therefore measures the evolution of carbon sinks. This is why the energy policy framework (and the Emissions Trading System, ETS) consider bioenergy as "zero-rated", in order to avoid double counting (since the emissions should have already been compensated for). Figure 10 below shows that the EU's reported emissions and removals for 2013-2018 produced an average sink of -396 Mt CO2 (a net removal). The reported net removals decreased from -440 Mt CO2 eq. to -319 Mt CO2 eq. from 2013 to 2018. Applying the specific accounting rules for the Kyoto Protocol, the EU's 'accounted' balance for 2013-2018 produced an average annual sink (or credit) of -114.1 Mt CO2 eq. The accounted net credits decreased from -150.3 to -79.3 Mt CO2 eq. from 2013 to 2017 and slightly recovered to -94.6 in 2018 (European Commission, 2020).[9]

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[9] Report from the Commission to the European Parliament and the Council, Preparing the ground for raising long-term ambition. EU Climate Action Progress Report 2019, SWD(2019)396. At: Progress made in cutting emissions | Climate Action (europa.eu)

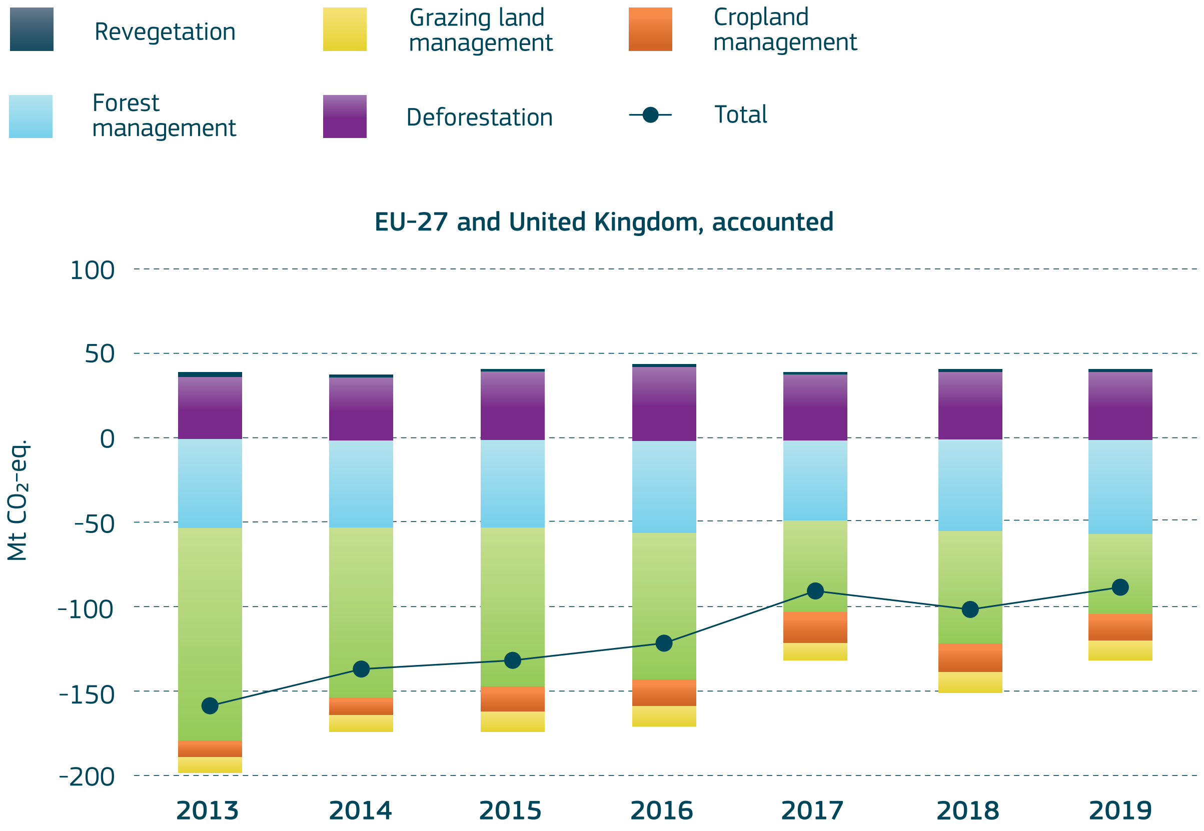


Figure 10: Preliminary accounted emissions and removals for activities reported under the Kyoto Protocol, second commitment period, EU-28. Source: European Commission, 2019.

The EU has identified that European forestry is expected to play a major role in supplying services and feedstock for the development of a sustainable bioeconomy (Freer-Smith *et al.*, 2019). And this seems a viable prospect since the decrease in demand for traditional forest-based products such as paper, is providing an innovation window for the development of new wood-based products that can provide more effective carbon storage and play a role in the bioeconomy (Toppinen *et al.*, 2017). There is also a need to consider how best to manage mitigation options so they can be synergistic with the other interconnected forest-based roles such as biodiversity support, ecological resilience, and economic and social benefits.

This chapter will summarise the different pathways of forest-based climate change mitigation and the trade-offs and synergies between them. It will also address the scientific uncertainty and debate that surrounds attempts to quantify their individual contribution to greenhouse gas (GHG) balances at an EU and global level (Rüter *et al.*, 2016).

5.1 Forests' role in climate change

Land is both a source and a sink of CO2; global models estimate net CO2 emissions from land use and land use change during 2007-2016 at 5.2 +/- 2.6 GtCO2 yr-1. These net emissions are mostly due to deforestation, although this is partly offset by afforestation/reforestation (IPCC, 2019). In Europe, forests are currently a net carbon sink because they absorb more carbon dioxide than they emit. Forest growth – both the incremental growth of trees in diameter and reforestation and afforestation via tree planting or natural means can lead to increased carbon sequestration. However forests are not pure sinks and also release carbon through respiration, decomposition, fires or harvesting (G. J. Nabuurs *et al.*, 2008). The rate of carbon sequestration also speeds up as the trees grow and then gradually slows down as the trees mature – meaning that the 'demography' of particular forests is also important in understanding various forests' contribution to carbon storage (Pugh *et al.*, 2019); on a small scale, this role may even shift from year to year, depending on disturbances and harvesting. Globally, for 1990 to 2007, the total forest sink was estimated as 2.4 +/- 0.4 petagrams of carbon per year, and the net global forest sink was 1.1 +/- 0.8 petagrams of carbon/year (Pan *et al.*, 2011).

Changes can produce complex climate impacts for example a shift in density or type of tree cover can alter the ability to reflect heat back into the atmosphere (albedo) which in turn contributes to climate warming (Luyssaert *et al.*, 2018). The conversion of deciduous forests into coniferous forests, results in changes to the canopy and albedo, generating a warming effect. Deciduous forests have an albedo (which is a measure of solar reflectiveness – see Box 12) in the range of 0.15–0.18, while coniferous forests can have an albedo as low as 0.08.

Volunteers: Young couple planting new little pine trees. ©Getty images, public domain

Box 12: Which aspects of a forest mediate its climate change mitigation potential?

Forest stock preservation: the growing stock is the volume of all living trees in a given area of forest that have more than a certain diameter at breast height, but carbon stock is also stored in living biomass within the soil and in dead wood and litter. Preserving this stock will help to preserve the amount of carbon that has been sequestered from the atmosphere.

Growth: both the incremental growth of trees (growth in diameter) and reforestation or afforestation via tree planting or natural means can lead to increased carbon sequestration.

Albedo: Albedo describes the amount of solar energy reflected by a surface. A reduction or increase in albedo due to reforestation or a change of species mix could increase the amount of solar energy absorbed by the earth's surface, increasing or reducing warming.

Canopy: The density of forest canopy, (the highest layer of the forest which represents the interface between leaf and light), has been positively correlated with forest carbon stocks.

Evapotranspiration: Higher rates of transpiration cool down the earth's surface, as well as regulating cloud cover and precipitation.

Roughness length: The roughness length describes the protrusions of a surface. Tall forests therefore have a much larger roughness length than a flat terrain. Roughness length influences wind speed and evapotranspiration. Removal of trees shortens the roughness length and causes a reduction in outgoing heat flux, leading to warming.

Sources: Favero *et al.*, 2018; Longobardi *et al.*, 2016; Xu *et al.*, 2018.

5.1.1 Capacity of forest ecosystems as a store and sink of carbon

A substantial pool of carbon is stored in forests: as much as 45% of all land carbon (Pan *et al.*, 2011). In all forests, tropical, temperate and boreal together, approximately 31% of the carbon is stored in the biomass (roots, trunks and branches) and 69% in the soil (IPCC 2000). Soil organic carbon is the largest carbon stock on terrestrial sphere, second only to oceans: in 2011 the carbon stock in global forested soil was estimated at 383 +/- 30 petagrams (ibid.). The length of time for which carbon is stored in forests can range from short-term to long-term, depending on age and type of forest, location and surrounding environment.

The amount of carbon stored in forests is subject to a variety of influences, both natural and caused by humans. For example, carbon can be removed and emitted when wood is harvested, when forest land is cleared for agriculture or development, or as a result of harmful events such as storms, wildfire, insects, and disease. Increased storage of carbon can result from natural reforestation of land that has previously been cleared for agriculture and active planting of trees and management practices that lead to an increased rate of growth.

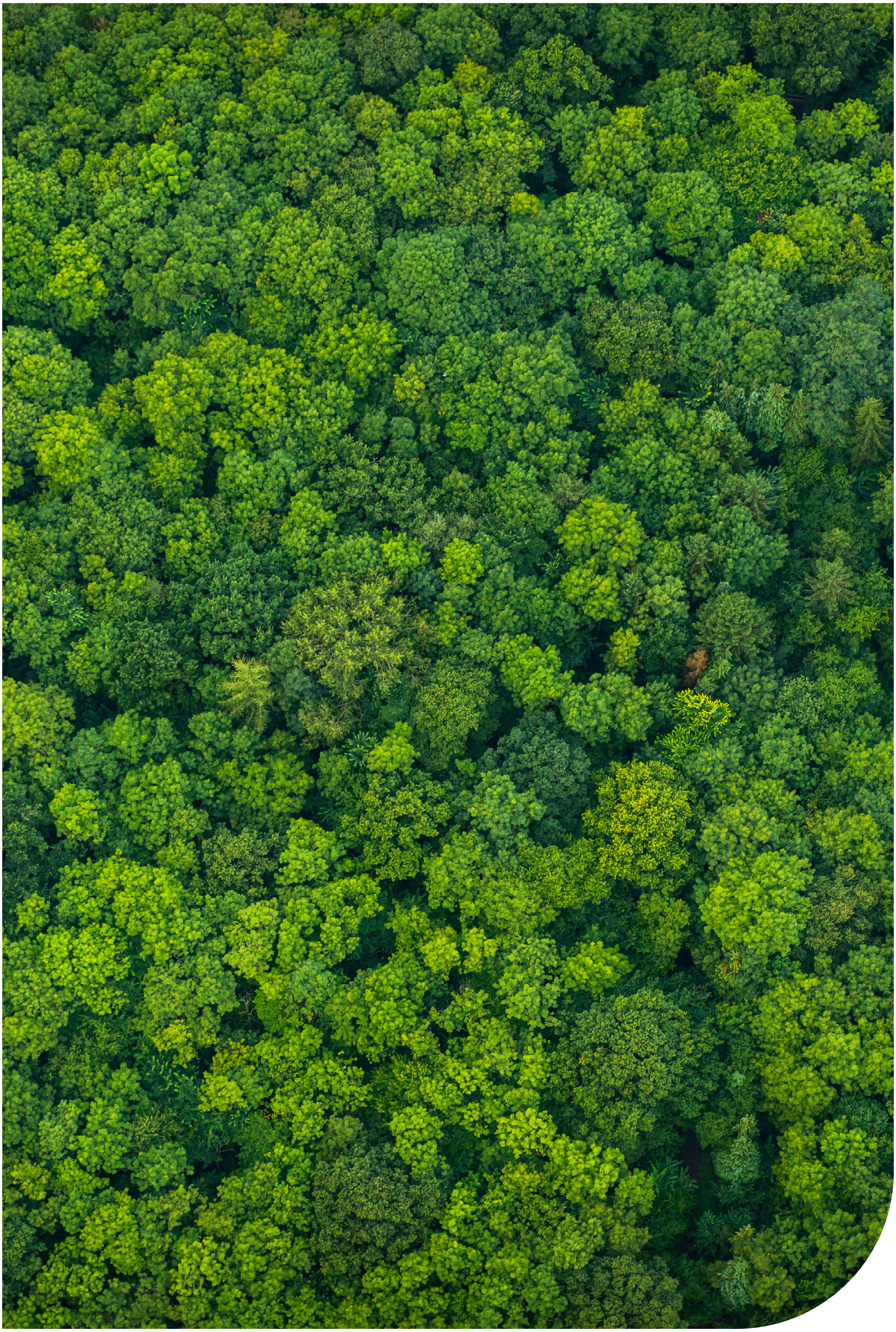
The contributions of land use, land use change and forestry in the EU to net CO2 emissions was reported to be -396 Mt CO2 eq. for 2013-2018 (average), which represents a net carbon sink (i.e. more carbon is stored away from the atmosphere than is emitted) (European Commission, 2020c;). From 2013 to 2017, there was a decrease in the sink overall – mainly resulting in the emissions resulting from an increase in harvesting rates, for example in Croatia, Czech Republic, Denmark, France, Lithuania, Luxembourg and Slovenia. Over this time period, forest disturbances also increased emissions rates. For example, bark beetle significantly affected forests in Czech Republic, causing a marked increase in salvage logging, and wildfires in Cyprus in 2016 and Italy and Portugal in 2017 resulted in net emissions for those years.

The IPCC has suggested that forests could provide an additional mitigation role of 90–180 Mt CO2 / year (IPCC, 2007) through reforestation and woodland creation, extending and protecting existing forests. The EEA and the IPCC both warn that, without action, Europe’s overall land use, land use change and forestry net carbon sink is likely to shrink considerably by 2030 (-25% to 140%) (EEA 2020b’ Kovats, 2014). The potential for forests to act as a carbon sink is also vulnerable to climate change, producing a complex interdependent relationship. A large amount of uncertainty surrounds the future evolution of the forest sink under climate change and its interaction with management practices (Valade *et al.*, 2017). Although this uncertainty is somewhat inevitable, the consideration of the multifunctionality of forests and their particular roles and demographies could help provide a more holistic approach with potentially fewer surprises (Pugh *et al.*, 2019; Winkel, 2017).

5.1.2 Carbon capture through regeneration, reforestation and afforestation

A recent study (Bastin *et al.*, 2019) that maps the potential tree canopy coverage across the world has indicated that there is room for an extra 0.9 billion hectares of tree canopy cover across the world (see Figure 11). This is in areas that are not agricultural or urban and could naturally support forests. It should be noted that tree canopy cover is different from forest area in that it refers to the layer of leaves, branches, and tree stems that cover the ground and is considered more relevant than ground area when discussing benefits provided by forests.

Furthermore, the study estimated that if the restored woodlands and forests were allowed to mature to a similar state as ecosystems found in protected areas, they could store up to 205 Gt of carbon (GtC). This places afforestation/reforestation as a major potential contributor to climate change mitigation, representing a considerable proportion of the IPCC estimate of the global anthropogenic carbon burden which is about 300 GtC to date (Masson-Delmotte *et al.*, 2019).



Green forest foliage, ©Getty Image, public domain

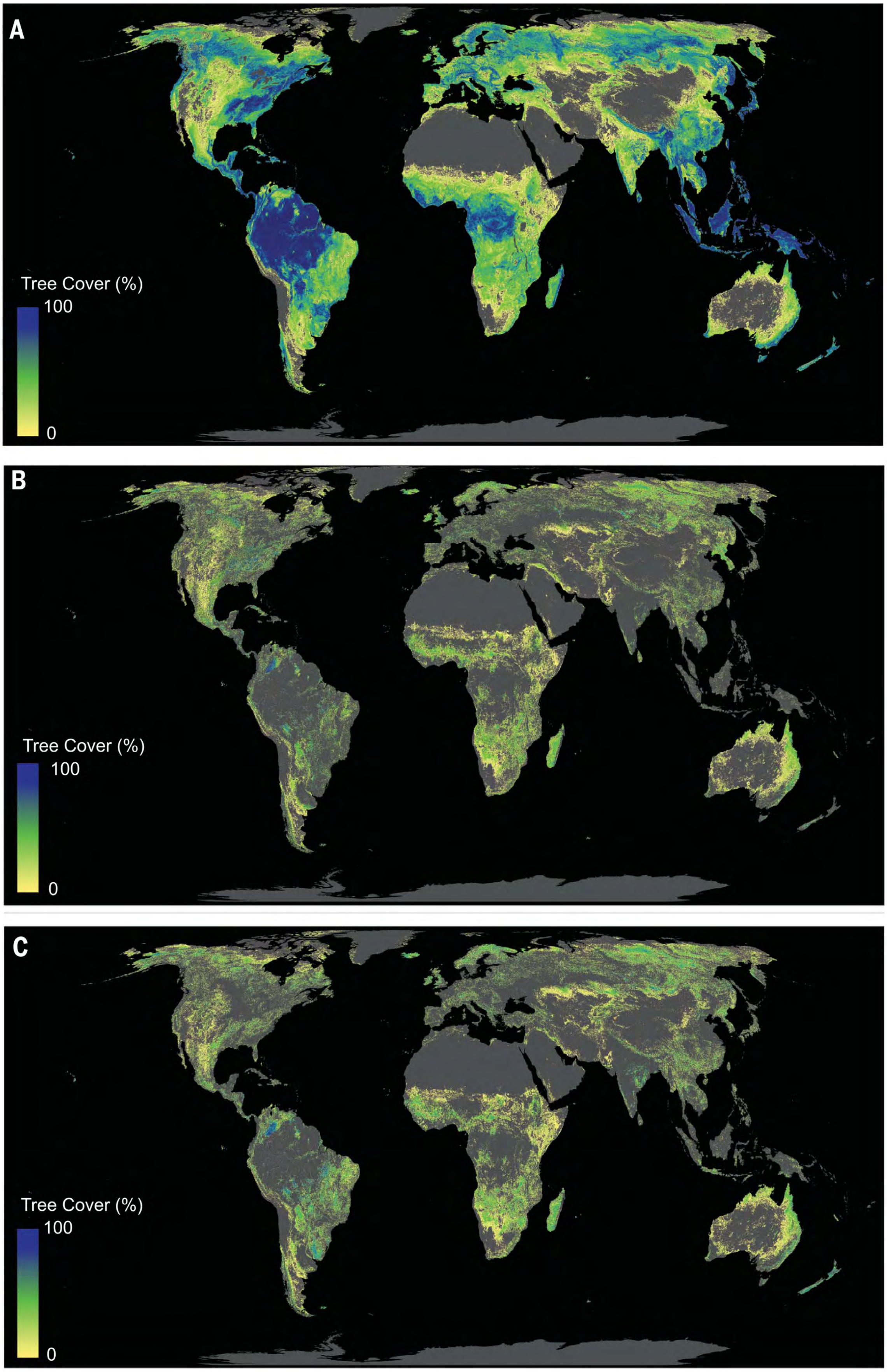


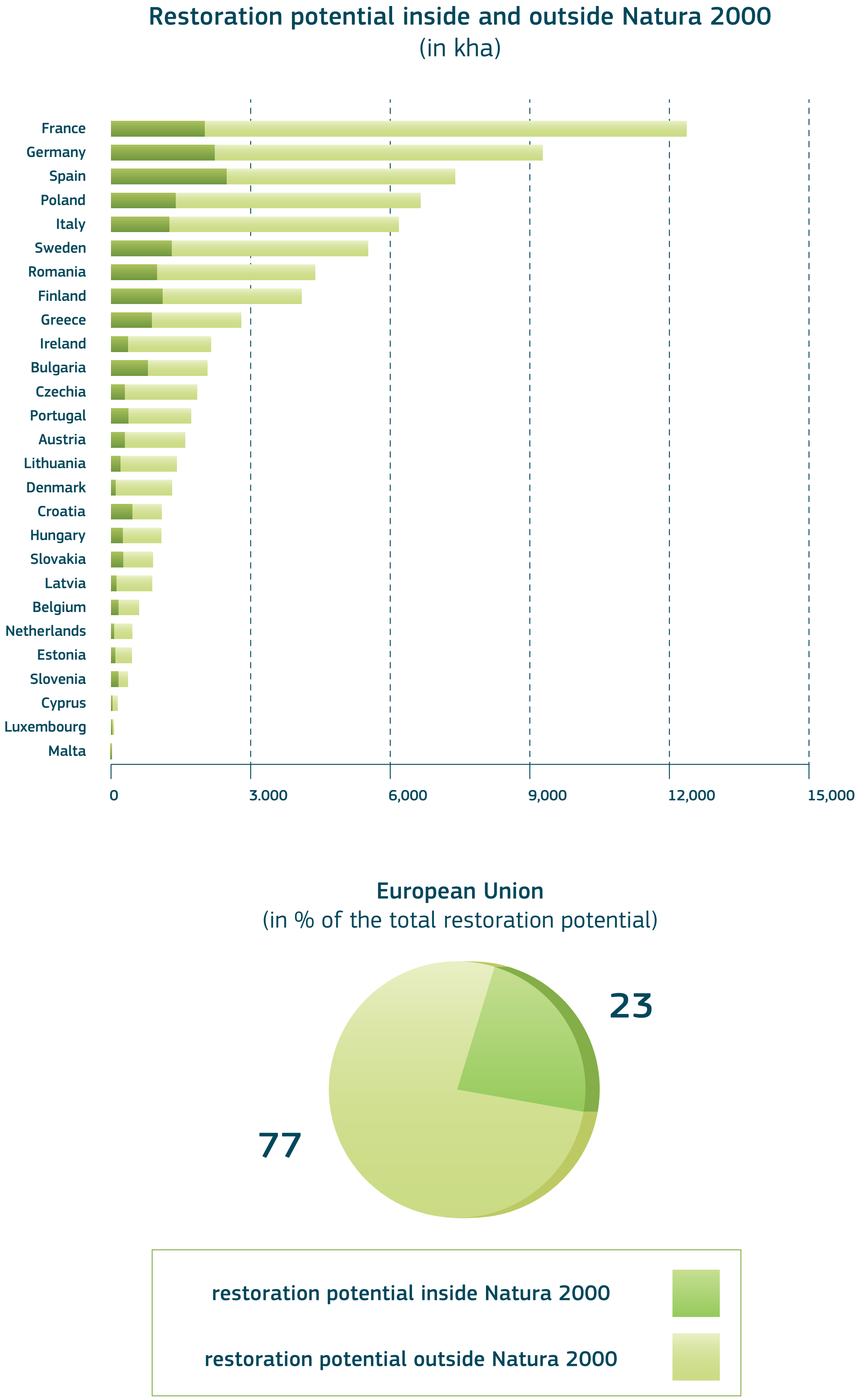
Figure 11: The natural tree cover potential of the planet Earth, based on bio-physical conditions only.
Source: Bastin *et al.*, 2019.

This estimate has generated a lot of discussion between researchers with many believing the figure of 205 Gt to be an overestimate. It has been suggested that assumptions around the gains in carbon storage in soil from increased tree cover are not realistic and that too much depends on afforesting grasslands and savannahs (which would have knock-on impacts on grassland species and ecology and possibly fire risk) (Veldman *et al.*, 2019) Critics have also argued that it does not take into account the albedo and respiration effects of increased tree cover, which could negatively affect climate mitigation and that it is possible that afforesting northern latitudes could have a warming impact via the increased absorption of solar energy by the dark surface area of the trees (snow, bare ground and grasses are, in comparison, more reflective). (Friedlingstein *et al.*, 2019; Veldman *et al.*, 2019).

The ongoing debate illustrates the difficulty in estimating the climate change mitigation potential of increasing forest area. What is agreed is the uncertainty in future effects of climate change on natural ecosystems and the complex interdependent relationships this creates; these involve potential feedbacks where elevated levels of CO2 concentrations may in fact enhance tree growth and where tree growth may not produce carbon sink effects due to increased albedo (Bastin *et al.*, 2019). The baseline carbon levels are central to these estimates since carbon currently existing in potential restoration areas must be subtracted to produce the estimates of the extra carbon storage potential. (Masson-Delmotte *et al.*, 2019), creating another layer of uncertainty.

Applying the same approach as Bastin *et al.* (2019) using EU-specific data, a more recent report looking specifically at Europe's capacity to restore its ecosystems through tree restoration (i.e., natural regeneration, not active afforestation) found that an additional total area of 77 million hectares could be covered by trees in Europe (Bastin *et al.*, 2020). This represents 19% of the total EU area of 402 million hectares; the five countries with the most restoration potential in the EU are France, Germany, Spain, Poland and Italy. In general, the natural canopy regeneration potential is greater outside of Natura 2000 protected areas than inside: of these 77 million hectares, 59 million hectares is available for restoration outside of Natura 2000 sites (an area larger than France). However, Sweden and Finland are two notable exceptions, where ecosystems outside Natura 2000 areas are closer to ecosystem maturity than those inside: the researchers suggest the reasons for this should be further investigated (ibid.).

Beeches (Ehrenbach, Germany), ©Wikipedia Commons CC BY-SA 4.0



Restoration potential inside and outside Natura 2000
(in kha)

European Union
(in % of the total restoration potential)

Figure 12: Canopy restoration potential inside and outside Natura 2000 protected areas (kha).
Source: Bastin *et al*., 2020.

Abandoned areas currently cover 43 million hectares in the EU (14% of the land outside Natura 2000 protected areas). Since these lands are often in remote locations, have low biodiversity value, and are not well suited for agriculture, they represent an important option for ecosystem recovery, particularly tree restoration. Following a projection that 15 million hectares of farmland will be abandoned by 2030, and using particular tree species that achieve stem wood growth of about 8 m3/ha/year, it has been estimated that the expansion of forests into this area could provide an additional sink of about 64 Mt CO2/year (Nabuurs *et al.*, 2017).

At a country level there is variation in the level of commitment to restoration with some appearing to over-reach their potential for restoration and others seeming to under-reach. Approximately 10% of countries globally have committed to restoring an area of land to forestry that is much greater than the land area actually available for restoration. However, 43% of the countries have gone in the other direction and committed to restore an area that makes up less than half that could potentially be restored. These results reinforce the need for better understanding of country-level accounting of land-use and the potential for reforestation for carbon storage gain, which is critical for developing effective management and restoration strategies (Bastin *et al.*, 2019).

It is, however, important to clarify that not all forest regeneration policies are equal in terms of climate mitigation. Lewis *et al.* (2019) argue that, on average, natural forests are, in terms of carbon storage, six times better than agroforestry and 40 times better than plantations. However, under the Bonn Challenge, only 34% of the total afforestation area was devoted to natural regeneration, with 45% devoted to monocultures and 21% to agroforestry.

5.1.3 Carbon storage through protecting forests?

Around 23% of EU-28 forests fall within Natura 2000 sites (Maes *et al.*, 2020). This means that half of the Natura 2000 Network is made up of forests, albeit with significant differences between countries: for example, the area of forests under Natura 2000 varies from 6.4% in the United Kingdom to 53.1% in Bulgaria. The reasons for inclusion in the network revolve around protecting species and their habitats with the ultimate goal of promoting biodiversity, but protection also has a significant impact on forests' capacity to store carbon. Forest habitats in Natura 2000 contain the highest carbon values of all habitats, ranging between €318 and 610 billion in 2010 (ECE - European Commission Environment, 2015).

The IPCC, as well as a number of charities and NGOs have proposed that more forests become protected, aiming for a goal of 10% of EU forests to be set aside as strict reserves. If even a 7% share of EU forests were set-aside as reserves by 2050, an additional CO2 sequestration of about 64 Mt CO2/year could be achieved on roughly 120,000 km2 (Gert Jan Nabuurs *et al.*, 2017). For reference, the area of Bulgaria is approximately 109 000 km2, whereas Greece is approximately 129 000 km2. Protection can take a number of forms. As well as increasing the number and size of reserves it can involve changing the legal definition of how land may be used so it cannot be converted to agriculture, or encouraging companies to commit to not clearing restored natural forests (Lewis *et al.*, 2019).

Protection of intact forests can typically secure very high environmental values with often relatively low implementation and opportunity costs. As such it has been proposed that forest protection should be better recognised in global environmental accords as a means to mitigate climate change. Maintaining and, where possible, restoring the integrity of intact forests can help address the biodiversity crisis, slow climate change and achieve sustainability goals (Watson *et al.*, 2018; Maes *et al.*, 2020).

However, most of Europe's forests are not protected (Maes *et al.*, 2020; Forest Europe, 2020). While strict protection is important, to preserve and increase the carbon stock in existing forests, non-protected areas can also have a role to play in providing harvests to substitute for other materials: increasing their carbon sinks and providing biomass and timber for longer-term uses. The trade-offs between these options – between increasing the carbon stocks of forest pools and making more wood available for the bioeconomy and other options – have not yet been fully explored in the scientific literature; however, in the short term at least, more harvest means less forest sink (Grassi *et al.*, 2021).

5.1.4 Impact of harmful events on carbon storage

Forest threats such as storms and forest fires on average cause emissions of 18 Mt CO2 per year (Gert Jan Nabuurs *et al.*, 2017).The success of afforesting and reforesting large areas to help mitigate against climate change is dependent on the forest remaining unburned.

Forest management and improved protection of forest areas in Europe can potentially reduce the emissions from fires, for example by creating fire-breaks with areas of either forest or different species. In Portugal, over 20% of the forest area consists of eucalypt plantations, and in a comparison between mixed hardwoods, mixed softwoods and eucalypts, a higher proportion of hardwoods decreased fire probability – and a small decrease was also noted for increased tree density (this may be related to a lower amount of shrub biomass, which increases fire risk) (Garcia-Gonzalo *et al.*, 2012). There is also evidence that the age of trees affects fire risk: the level of canopy damage from fire in conifer plantations reaches its maximum when the trees are 15-25 years old, but then declines as the trees mature (Thompson, Spies and Olsen, 2011). Average annual direct emissions to the atmosphere due to the burning of biomass and dead organic matter were equal to 5.27 Mt CO2 per year between 2000 and 2012 (Pilli *et al.*, 2016).

The projected increase of storms under climate change is another challenge for sequestering carbon in forests. The impact of storms on the biomass carbon stock is 5–10 times greater than fires, but while storms cause only indirect emissions (i.e., a transfer of carbon from living biomass to dead organic matter), fires cause both direct and indirect emissions (Pilli *et al.*, 2016). Valade *et al.* (2017) highlight the way that climate change increases vulnerability of forest carbon storage under changing climate conditions and the need to use forest management and other approaches to safeguard the stability of the current sink for the future. For storms, it has been suggested that carefully planned thinning and felling regimes could minimise the length of exposed edges to wind, alongside choosing species that produce more stability in the communities of forests (Nabuurs *et al.*, 2008) (e.g. choosing broadleaf trees that shed their leaves thereby reducing wind exposure during the stormy season instead of conifers). Multi-aged stands contain a range of tree sizes, as well as developing trees that can replace trees lost to any disturbances; this can increase forest resilience through the ability to return more quickly to a pre-disturbance state (O'Hara, 2006).

When salvage logging (where dead, damaged or disturbed trees are removed from the forest after a harmful event, often for commercial use) is employed, the impact of natural disturbances is often not easily distinguishable from the impact of harvest. This controversial practice has ecological effects that can interfere with natural processes of ecosystem recovery and biodiversity, as well as reduce resilience to future fires, spread invasive species, alter plant composition and damage fire-associated animal species. The removal of decaying biological matter – along with the resulting micro-habitats – can have long-lasting effects. These may be even stronger than in conventional logging because, after major disturbance, forest stands and soils can be particularly vulnerable to cumulative effects (Fernández, Fontúrbel and Vega, 2021).

5.1.5 Increasing the carbon store through improved forest management and land use

The stability of forests against external influences, natural and man-made, is crucial for protecting carbon storage and to enable trees and forest ecosystems to 'sink' more carbon. However, there is a rising intensity and frequency of disturbances, mainly due to the changing climate and long history of human activity in the forests (Camia *et al*., 2021). Stability, (in terms of both resistance and resilience to threats) can, to a large extent, be influenced by forest management. The use of site-adapted and climate-adaptable species and provenances in stands with rich variation in species, size and age can often make the most stable forests; correspondingly, single-species and even-aged plantations show in general low resistance and resilience to external stresses including climate change (Larsen, 1995).

Some conventional practices for forest management can have damaging effects. Camia *et al*. (2021) identify several 'lose-lose pathways; these include removing coarse, woody debris from the forest, removing low stumps and converting primary or natural forest into plantations. Conventional characteristics of forest management often involve establishing young plantations with single-species coniferous trees – although there has recently been a decrease in forest area dominated by a single tree species, and an increased preference for broadleaved species. The area covered by non-native species has increased steadily in most parts of Europe between 1990 and 2015. There are large differences in harvesting between countries, with some countries using mainly mechanical means, and others using mainly manual labour. Clear-cutting is the dominant harvest system in Europe (although it has been forbidden by law in Slovenia since 1947), but other more close-to-nature methods include 'shelterwood' cutting (where some trees are left to allow seedlings to establish naturally), group regeneration and continuous cover forestry or coppice stands. Most coppice forests in Europe are to a large extent abandoned (Verkerk and Lindner, 2020).

More frequent cuttings, and shorter rotation lengths lead to lower standing wood stocks in the forests: keeping cuttings at the under the level of demand could allow more volume to build up. However, postponing the thinning of plantation trees is also perceived to reduce timber quality and increase the risk of damage due to wind and pests (Härkönen *et al*., 2019).

Forests can be managed for either production of volume or profit, and decisions can also be influenced by growing conditions. For volume-oriented German forests, selected trees are allowed to stand for longer, whereas in Swedish forests, trees are harvested younger, allowed more space to grow early on; in most parts of Sweden, growing conditions do not support the production of large sized trees within a reasonable timeframe. These latter tend to prioritise Norway spruce which reaches a valuable volume in relatively short time (Brukas and Weber, 2009). Under climate change, forest productivity is expected to increase in northern Europe, but decrease in the Mediterranean countries due to severe drought effects. (Härkönen *et al*., 2019)

Alternative approaches to forest management have the potential to unlock further capacity for sinking carbon storage into forests. The selection and combination of management options needs to depend on the type and nature of the forest. For example, a form of management practice that has been posited to improve carbon storage involves the thinning of communities of trees or stands to reduce the density and improve the quality and growth and therefore, possibly, the carbon capture of the remaining trees. (Nabuurs *et al*., 2017). However, since there is evidence that, in some cases, increased stand density increases resilience against fires, and this doesn't consider the impact of carbon capture via soils, these factors need to be taken into account and balanced.

The Horizon 2020-funded ALTERFOR project looked critically at traditional forest management models and explored the potential to optimise forest management models currently in use in Europe. The project has compiled examples of alternative forest management models, such as biodiversity-centred management, bog restoration, non-clear cutting, adaptive rotation, even-aged mixed, uneven-aged mixed and stand edge management – with opportunities and challenges listed for each alternative.[10] They also compared different case study areas and models in terms of their carbon sequestration potentials.

The researchers found that above-ground and below-ground carbon storage pools are very closely related and that carbon sequestration generally increases as the level of harvest decreases. Those countries and areas with a high level of harvest (such as Germany and Ireland) showed a lower total carbon sequestration rate; in contrast, case study areas with a high biomass stock and low level of harvest (such as Netherlands) showed a higher carbon sequestration rate. (The study did not consider the effects of forest fires or forest soils/litter in this part of the model.) The study showed that carbon sequestration is generally higher in management models with a higher share of broadleaf trees, possibly due to lower levels of harvest in these areas. In the Augsburg Western Forests (Germany), the production-oriented alternative management models showed ca. 4 times lower forest carbon sequestration, compared to multifunctional and nature conservation alternative management models (Biber *et al.*, 2020).

Another part of the ALTERFOR study looked at carbon sequestration through harvested wood products. This clearly showed that the carbon sequestration of wood products increased where more wood was diverted into the sawn wood category. Harvests that are diverted into paper or bioenergy production result in lower carbon sequestration. It was apparent from the results that forest-based sequestration, and wood product utilisation both contribute to total carbon sinks, but they also suggest that overall carbon sequestration may be maximised if sequestration in the forest is maximised (Biber *et al.*, 2020).

For European forests to supply the circular, bio-based economy, research, policies and strategies need to be coordinated across the entire value chain from plantation establishment and management through to delivery of products and services. (Freer-Smith *et al.*, 2019). Innovation and increased production of wood-based products in construction, textiles, biochemicals have the potential of not only realising these economic benefits but also of providing another form of carbon storage within the products themselves, depending on the length of their lifetime. The value of this is usually estimated by substitution or replacement factor which compares the carbon storage of wood-based products to a more commonly used product performing the same function: this is discussed in the next Chapter.

Monti Aurunci Natural Park (Lazio, Italy), ©Wikipedia Commons CC-BY-3.0

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[10] For a full list of cases see: https://alterfor-project.eu/files/alterfor/download/Results/D1.2._Alternative%20Forest%20Management%20Models%20for%20ten%20Case%20Study%20Areas%20in%20Europe.pdf

5.2 Substituting materials for wood products

The carbon contained in wood that is harvested from the forests is not immediately released back into the atmosphere – except when it is burned to produce bioenergy. The carbon can instead be stored in wood products and released at a decay rate that depends on how long the products remain in use. Furthermore, if the harvested wood is used to replace a fossil fuel-intensive material or energy source, a 'substitution effect' may also come into play and this is covered in Chapter 5 (Leskinen *et al.*, 2018). However, as mentioned in Chapter 5.1.3., the trade-offs between increasing the wood available for wood products and increasing the carbon stocks in existing forests have not yet been fully explored (Grassi *et al.*, 2021) – and this is a crucial balance to get right.

5.2.1 Storing carbon in permanent structures and materials

Traditional industries for sawnwood and panel production are on the increase: the output of sawnwood across the EU-27 increased by approximately 12% from 2000 to 2019, reaching 108 million m3 in 2019 (Eurostat, 2020b). EU production of roundwood (which can be used as sawnwood, veneer and composite panels, pulp and paper or fuelwood) was 24% higher in 2019 than in 2000 (although 23% of this was used as fuelwood).

Up until 2016, the traditional forest industry markets of paper or pulp had been stagnating or declining (Johnston 2016) and, as such, they looked to expand their scope. After several years of decline, since 2016, employment in wood-based industries compared with total manufacturing has picked up again (Eurostat, 2020b). Innovation is playing an important role as new wood-based products emerge (Hurmekoski *et al.*, 2018) including promising markets for textiles, construction, biochemicals and packaging and plastic substitution.

Most studies on carbon storage in wood products focus on the use in construction. Significantly less information exists for other product types such as textiles and there is very limited research on the carbon storage potential for biochemicals, which are considered an important product in the future bioeconomy (Leskinen *et al.*, 2018).

Geographically, most available studies focus on North America and the Nordic countries in Europe, and there is less research regarding on south or east Europe (Leskinen *et al.*, 2018). It is expected that the use of wood will increase in the future, especially as new products are developed and marketed.

5.2.2 Wood-based products and materials in construction

In the last two decades innovation in engineered wood products has allowed them to directly compete with steel and concrete due to their more predictable and consistent technical properties (Hurmekoski *et al.*, 2018).) There are some buildings that can be termed carbon-neutral or even carbon negative (Amiri *et al.*, 2020) (meaning the wood from trees used in the production of these buildings makes the building a net store of CO2 emissions).

It has been estimated that, under the right support mechanism, the European building sector could achieve the potential for net carbon storage of about 46 million tonnes CO2-eqv. Per year in 2030 (Hildebrandt *et al.*, 2017). Without these support mechanisms in place, it is likely that innovation uptake and the resulting productivity growth of wood will be fairly low. In the EU there would need to be a much higher use of wood in construction for it to make a meaningful contribution to lowering GHG emissions (Leskinen *et al.*, 2018).

Amiri *et al*. (2020) find that the carbon storage capacity of buildings is not significantly influenced by the type of building, the type of wood or the size of the building but instead by the number and the volume of wooden elements used in the structural and non-structural components of the building. Construction companies tend to have less experience in the technical details and construction methods for higher-rise wooden buildings than for single-family dwellings. Local regulations and conditions also affect the amount of wood used. For example, strict fire regulations may result in the use of thicker or extra layers of wood, and in earthquake-prone areas such as Japan, greater amounts of wood are used in building structures. The researchers find that there are a lack of plans and incentives for buildings that capture carbon (most voluntary schemes, like focus on producing fewer emissions, rather than capturing carbon). One option could be to introduce performance-based construction standards that reflect sustainability of materials (Rüter *et al.*, 2016)

5.2.3 Wood-based materials in textiles

Currently the textile market is dominated by synthetic oil-based fibres. There is extensive use of natural fibres, notably cotton (25–30% of the textile fibre market) and man-made cellulosic fibres derived from plants make up about 7%, for example viscose and modal.

Generally there is an increasing demand for textiles and, although the production of cotton is slightly increasing, its relative share is decreasing (Hammerle, 2011), suggesting, there is an opportunity for wood-based textile fibres to become a growing market (Hurmekoski *et al.*, 2018).

Man-made, or regenerated cellulose fibre is dominated by wood-based viscose, which, until recently, involved harmful chemicals. New processes based on alternative solvents are currently being developed to overcome this environmental burden, for example Lyocell fibres are produced in a closed-loop process and harmful chemicals are not released into the environment, while the company Spinnova have replaced chemicals with mechanical processing, using the same pulp that could be used for paper.

Two existing studies (Rüter *et al.*, 2016; Shen *et al.*, 2010) in this area report that the production of wood-based fibres such as viscose, lyocell and modal results in lower levels of CO2 emissions than the production of cotton or synthetic fibres (Leskinen *et al.*, 2018).

5.2.4 Wood-based biochemicals and products of the future

Biochemicals tend to be 'platform chemicals' that are used to produce a large variety of other chemicals and end-use products. For example, in future new wood-based applications for the organic compound furfural, it could be converted into more than 80 usable chemicals and substitute industrial chemicals from petrochemical sources.

Currently there is very little research on these emerging product categories (Leskinen *et al.*, 2018) and the markets remain largely unchartered which is at least partly due to their complexity and different options for optimisation in terms of feedstock and processing (Hurmekoski *et al.*, 2018).

Toivo & Ignatius (2019) project that policy efforts across a wide spectrum of spheres are needed to promote innovation in this emerging technology field. There will also need to be an increase in public/private investment in R&D for innovative and carbon-efficient uses for wood products and for wood promotion as part of an overall climate change mitigation strategy (Rüter *et al.*, 2016).

5.2.5 Material substitution potentials, projections and effects on climate mitigation

Consideration of the physical storage of carbon in wood products is only part of the picture. There has been increasing debate around the value of wood products in providing a less carbon-intensive alternative to traditional products. In this context a substitution factor (or displacement factor) typically describes how much greenhouse gas emissions would be avoided if a wood-based product is used instead of another product to provide the same function (Leskinen *et al.*, 2018).

Calculation of the substitution factor should include emissions from across the life cycle of the product including raw material extraction, processing, transportation, manufacturing, distribution, use, re-use, maintenance, recycling and final disposal (see Figure 13 below). Substitution factors strongly affect the final results but are characterised by a high level of uncertainty (Grassi *et al.*, 2021).

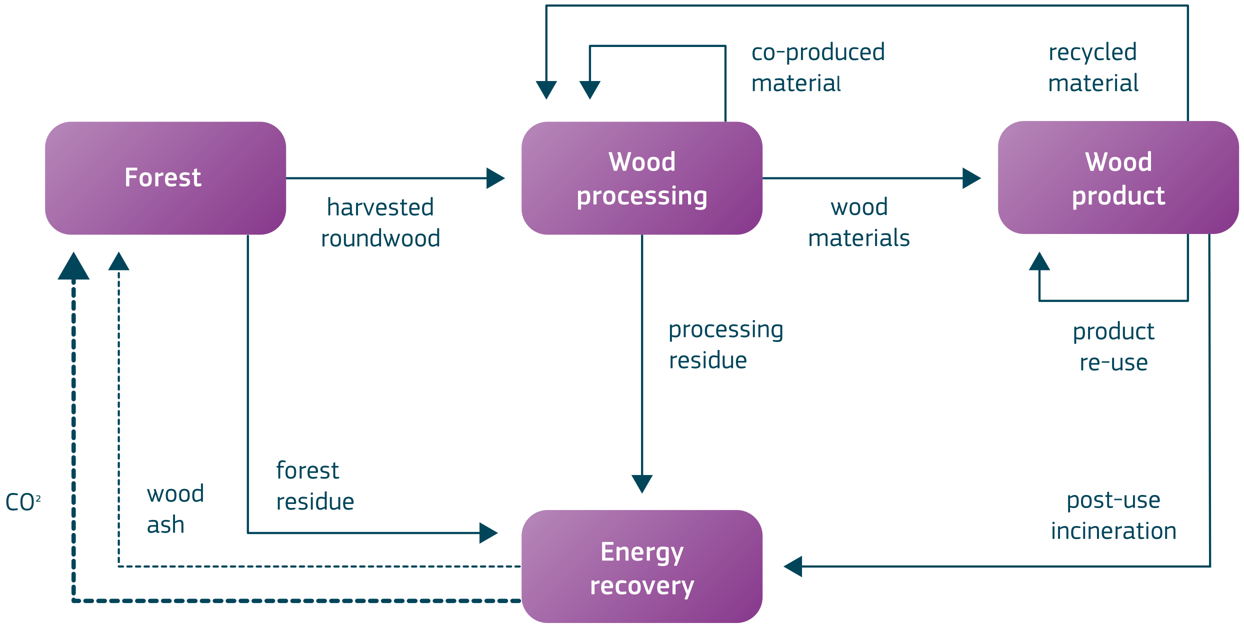

Figure 13: System-wide integrated material flows of wood products causing GHG emissions; authors argue these should be taken into account in the calculation of substitution factors. Source: redrawn from Leskinen *et al.*, 2018.

Currently, nations reporting greenhouse gas emissions to the United Nations Framework Convention on Climate Change (UNFCCC) and related processes do not report substitution benefits under a 'forest sector' category – nor are they reported as part of the land use sector; rather, these appear under manufacturing and construction (Leskinen *et al.*, 2018).

There are many assumptions used when calculating the climate mitigation effects of wood products, but some researchers have attempted to give estimates. According to a recent study (Jonsson *et al.*, 2021), the additional mitigation effect of wood products could range between 28 and 35 Mt CO2/yr in 2030. Although Leskinen *et al.* (2018) highlight the high uncertainty of the substitution factors applied to estimate these values, the range of values here is representative of the main values proposed by recent studies. At EU level, Nabuurs *et al.* (2017) estimate a possible material substitution potential equal to 43 Mt CO2/yr in 2050. Results from some recent studies are summarised in Table 3 below, which illustrates the range of possible estimates.

Source	Year	Value (Mt CO2e/yr)	Time horizon	Key assumptions
Nabuurs *et al.*	2017	-43	2050	One quarter of sawn wood ends up in structural longer-term use, displacing other materials
Rüter *et al.*	2016	-34	2021-2030	Business-as-usual scenario achieving EU energy and climate targets for 2020
		-18		A general shift from energy to material use, plus cascade uses lead to additional -18 Mt CO2e/yr
Jonsson *et al.*	2021	-28	2030	Additional mitigation potential when assuming increased wood-based construction
		-2		Additional mitigation potential assuming the demand for biochemicals and biofuels increases
		-35		Additional mitigation potential when combining previous assumptions

Table 3: Climate change mitigation benefit of using wood to replace other materials in the EU, based on specific studies. Source: Grassi *et al.*, 2021.

Wood and wood-based products are often associated with lower emissions both from the processes involved in production and from the use of products when compared to non-wood products – although feasibility studies are needed in this area. Overall it is estimated that for each kilogram of carbon in wood products that substitute non-wood products, there is an average reduction of 1.2 kg of carbon (Leskinen *et al.*, 2018). However, the storage of carbon in wood products needs to be balanced with the store in the trees themselves – and their capacity to sink further carbon. Jonsson *et al.* 2020 suggest that, within a short-term time horizon to 2030, the positive EU climate-change mitigation effects of increased carbon storage in harvested wood products and material substitution from increased wood construction will be more than offset by reduced net forests carbon sinks by 2030, due to increased EU harvests. This is reinforced by Grassi *et al.* (2021) whose assessment of the trade-offs concludes that it is necessary to significantly increase the net volume of trees (net annual increment) to reverse the current trend of declining forest sinks, and if we want to maintain or slightly increase the current harvest levels.

5.2.6 Challenges and opportunities in substituting materials for wood

Harmon (2019) suggests that substitution factors often overestimate the carbon benefits of wooden products and that more attention should be given to increasing the longevity of products and buildings. He also highlights that most studies assume a constant substitution effect into the future, whereas this value may change as the energy mix and manufacturing methods change. For example, the addition of fly-ash to concrete will reduce the carbon footprint of concrete, whereas creating more cross-laminated timbers suitable for constructing taller buildings would likely have a higher carbon footprint for these wood-based materials.

Future changes in market structure could significantly increase or decrease the substitution benefits of wood use, compared to current market scenarios. The variation of substitution factors with different structural changes in wood-using industries has been investigated in Finland (Hurmekoski *et al.*, 2020). The study showed that, between 2016 and 2056, shifting the use of kraft pulp and heat and power production towards textile, composite and wood-based panel production was more likely to achieve substitution benefits than increasing sawn wood production. The change with the biggest influence was an increased production of wood-plastic composites. This scenario created an extra saving of 8.1 Mt C (29.7 Mt 514 CO2 e.g. in substitution effects) for Finland, compared to current market structure. Grassi *et al.* (2021) also note that a shift to wood products with a higher service life, e.g. from paper to construction timber, would help conserve or increase the pool of carbon stored in harvested wood products, while maintaining a stable harvest over time.

A lifecycle approach for products is critical in assessing the climate mitigation benefits of the substitution of products with wood. However, the quantification of the lifecycle emissions also involves many uncertainties. Wood and non-wood products have different operating life spans as well as end-of-life management, and different uses for harvesting and processing residues. Analyses comparing lifecycle emissions can also be complicated by the use of integrated wood production systems, producing multiple products and interdependencies (for example, sawmilling residues serving as raw material for paper products) (Leskinen *et al.*, 2018). The established forest-based industries already provide a wide range of raw material and intermediate products such as sawnwood, pulp, and energy chips for burning (Hurmekoski *et al.* 2018). Estimating the future substitution carbon benefits is challenging because new production processes, technologies and markets will change the lifecycle impacts, and thereby, the climate mitigation benefits.

As wood-based substitution increases, sectoral boundaries and actors included in forest-based value chains will be increasingly challenging to define, as the diversity and complexity of the forest sector and its value-chains grows (Freer-Smith *et al.*, 2019). There is clearly more work to be done to account accurately for substitution effects and to define optimal wood-based strategies to mitigate climate change. (Nabuurs *et al.*, 2018).

5.3 Replacing fossil fuels through bioenergy production

There have been calls for wood to directly substitute fossil fuels, for example via burning, in order to help mitigate climate change. However, the picture is complex, and the climate mitigation potential of biofuels is the subject of much debate, since the burning of wood also emits carbon directly into the atmosphere, as well as other air pollutants. If the wood could have been kept in the forest, used for other purposes, or if it comes via unsustainable harvesting and transportation practices, the carbon benefits are not evident. Of all the wood used in the EU (both domestic and imported), 451 million m3 (63%) was used for bioenergy production in 2015. As shown in Figure 14, at least 37% of this came from primary wood sources – including forest residues.

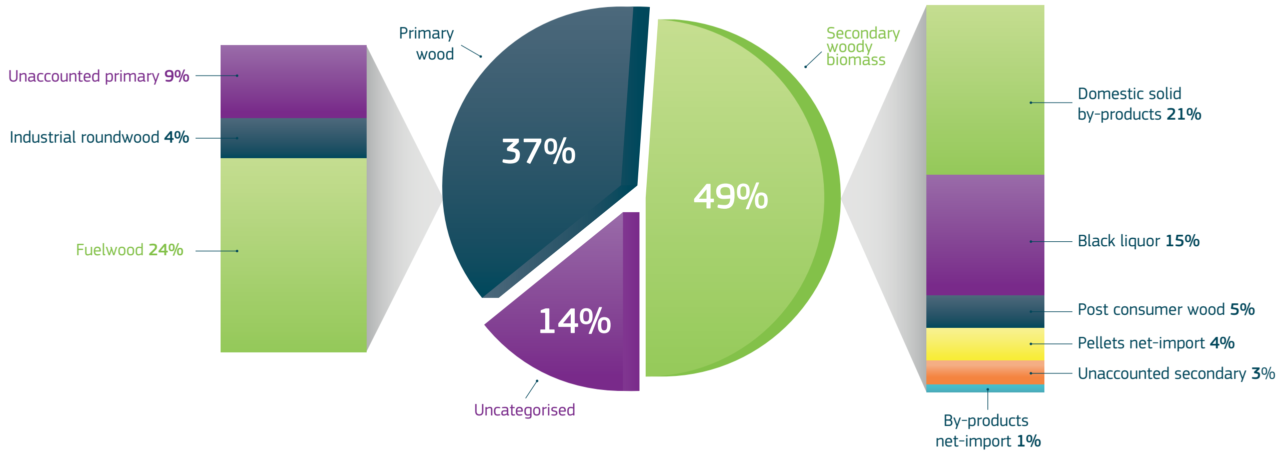

Figure 14: Origin of wood fibres used for bioenergy. Source: Camia *et al.*, 2021.

There have also been concerns that emissions and removals from bioenergy production will not be fully accounted for in international emissions accounting processes, and fears that undue under-accounting of bioenergy-related emissions could occur. As outlined in the introduction to Chapter 5, accounting for bioenergy emissions does not happen at the point of burning, under the ‘energy’ sector category (where these emissions are counted as 0 under the Emissions Trading Scheme), but under the ‘land-use and forestry’ sector instead. [11] As a result, it is possible to perceive the mitigation benefit of bioenergy to be a reduction in fossil fuel emissions, while ignoring the potential increased emissions or reduction of removals in the land sector. This, as well as the technically ‘renewable’ nature of trees, has led to some labelling bioenergy as ‘carbon neutral’ (Birdsey *et al.*, 2018). This is a misleading claim: bioenergy is rather categorised as ‘zero-rated’ in the accounting framework, to avoid double counting emissions that should have already been compensated by equivalent CO2 removals in the LULUCF sector. Many governments have factored this ’zero-rating’ of bioenergy into their mitigation targets and plans, without assessing in parallel the impacts on forest carbon sinks, for instance in National Energy and Climate Plans (NECPs). The validity of this partial approach continues to be questioned as some researchers posit that burning wood for fuel is likely to result in net CO2 emissions, and that the time taken for the carbon to build up again in new forest areas is too slow for the current climate crisis (EASAC, 2020; Schlesinger, 2018; Haberl *et al.*, 2012) (see ‘carbon debt payback time’, Chapter 5.3.1. below). In fact, the EU legal framework creates opposing incentives for different players: the LULUCF Regulation requires Member States to maintain or increase their sinks, while the Renewable Energy Directive incentivises foresters and bioenergy operators to harvest and burn forest biomass (Camia *et al.* 2020).

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[11] LULUCF Regulation EU 2018/841: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2018.156.01.0001.01.ENG

> **“…it is possible to perceive the mitigation benefit of bioenergy to be a reduction in fossil fuel emissions while ignoring the increased emissions in the land sector. This has led to bioenergy being labelled ‘carbon neutral’ because any emissions associated with biomass burning are reported in the land use sector”**
>
> (Birdsey *et al.*, 2018).

Research in Canada, Sweden and the US found no evidence that the rise in bioenergy demand over the past one to two decades has increased forest area (Giuntoli & Searle, 2019). The overall use of woody biomass for energy increased by about 34% between 2009 and 2015. Data from 2015 also indicates that bioenergy has a growing share of total wood uses (Camia *et al.*, 2020). Overall, the carbon sink related to forest management in Europe is projected to decline further substantially – partly due to the natural cycle of forests and partly due to increased harvest demand. Several Member States (e.g. Ireland, Estonia and Austria) expected forest management to change from being a sink to become a source by 2020 (European Commission, 2016). According to preliminary estimates using accounting rules under the Kyoto Protocol, for the period 2013-2020, Cyprus, Lithuania and the Netherlands were net emitters from their LULUCF sector (net emissions under 1 Mt Co2 eq. a year). Czech Republic, Latvia and Slovenia are expected to record debits (net emissions) of 1.5, 2.4 and 3.2 Mt Co2 eq. per year, respectively (European Commission, 2020c). As suggested above (Chapter 5.2), wood products that store carbon for longer periods of time can achieve substitution benefits, contrary to bioenergy (Birdsey *et al.*, 2018).

Primeval beech forest (Slovakia), ©Wikipedia Commons CC BY-SA 4.0

5.3.1 New approaches to carbon accounting of bioenergy

The temporal disconnection between CO2 emitted when wood is harvested or burnt and the sequestration of carbon in new biomass as forest areas grow, has been termed the 'carbon debt payback time'. The carbon debt payback time of bioenergy is increasingly seen as an indicator of the sustainability of bioenergy supply chains. Particularly for forest bioenergy supply chains, the time lapse between harvest and regrowth may be a significant factor for the modelled carbon debt.

Numerous studies on the carbon debt and payback time of the use of biomass for energy purposes have been published with diverging results. A meta-analysis (Bentsen, 2017) showed that a large part of the variability across different studies can be attributed to the applied modelling framework and underlying assumptions, rather than ecosystem and management assumptions.

There are, however, some general areas of agreement: that the cascading use of biomass is in general the best approach for climate and biodiversity (Camia at al., 2020); that the use of residual biomass (biomass as a by-product from other processes) is more beneficial (= shorter payback time) than using round wood and primary tree harvests; that using biomass to substitute coal is more beneficial than substituting oil or natural gas; and that harvest from productive and managed forest or from afforestation areas is more beneficial than harvest from natural forests. More detailed case studies (Madsen & Bentsen 2018, Nielsen *et al*. 2020) report payback times between 0 and 13 years for transitions from coal to forest biomass for heat and electricity production, and between 9 and 37 years for transitions from natural gas to forest biomass. These detailed studies corroborate the findings by Bentsen (2017) on the relative benefits of using residual biomass, on substituting coal, and on harvest in productive forests.

Another approach involves modelling the carbon stocks and fluxes throughout the lifecycle of bioenergy (Sterman *et al*., 2018). This has been done for substitution of wood for coal in power generation in eastern US and showed that because combustion and processing efficiencies for wood are lower than for coal, the immediate impact of using wood was an increase in atmospheric CO2, relative to using coal. The model estimated the payback time for this carbon debt to be between 44 and 104 years, depending on the forest type that was regrown. Critics of this model have suggested that assumptions about the management of the forest after harvesting for the biofuel understate the carbon performance of current forest management practices and that there is a need to adopt a 'landscape perspective' rather than one that centres around the stand or community of trees (Prisley *et al*., 2018).

It is clear from the science that bioenergy needs to be considered against the broader climate change context, to ensure that wood burning does not aggravate climate change. Broader possible climate change effects of using wood for bioenergy also include land-use change, impact of land-cover change on the climate, long-term impacts on soil productivity and changes in biodiversity (Birdsey *et al*., 2018). Giuntoli & Searle (2019) posit that, for bioenergy policies to provide any meaningful carbon benefit, the use of wood as energy must be coupled with specific measures to improve forest management to increase carbon stocks and biomass output simultaneously.

6. Combining forest biodiversity and resilience with climate change mitigation

The field of climate mitigation and forestry abounds with debate and uncertainty, whether it is around projecting the carbon storage capacity of forests, calculating the substitution factor for wood products or estimating when biofuels will payback their initial carbon emissions. Opinions are disparate and estimates vary. However, what these scientific discussions make clear is the need to embrace the interconnectedness and complexity of this area, both in scientific measurement and policy measures.

Although climate change mitigation may be the focus or goal of an approach, adaptation is crucial (only an adaptable (stable) forest is able to store carbon). Approaches must also consider the many other ecosystem services that forests provide since these are integral to their role in mitigation. Conserving biodiversity, and providing ecological resistance, resilience and adaptation to other threats must be part of any climate change mitigation plan for forests.

6.1 Resilience: climate change adaption

Alongside (and as a prerequisite for) providing a carbon sink to lessen the impact of climate change, forests must be able to adapt to the changing climate.

Due to climate change, forests will experience discrete disturbances such as fire and storms as well as slower, longer changes imposed by gradually shifts in climate. For a forest to maintain its functionality its must be able to withstand these two different cycles of disturbances, allowing it to keep recovering to a similar status (Buma & Wessman, 2013)

One main problem is that today's local adapted species might not be adapted to the future climate. Proposals for resilience-oriented management include the introduction and establishment adaptable non-native species and non-local provenances, thereby preserving the presence of a forest – although not necessarily the exact same forest. It has been proposed that this approach can consider disturbances as opportunities for more climatically adapted species to establish populations. Research in the US has investigated the impact of this via modelling and indicated that active, adaptation-oriented management could maintain forest structure and carbon stocks under most future climate projections, albeit at lower densities (Buma & Wessman, 2013). However, the introduction of non-local species must be done carefully; non-native species hold the potential to damage biodiversity and harm other species in an ecosystem, for example by competing with native species or modifying the physical condition of a site (EEA, 2016b). When protecting, restoring and possibly enhancing biodiversity and forest ecosystems, the European Commission does not allow the use or release of invasive alien species, and only allows the use of non-native species that a) use forest material to create favourable and appropriate ecosystem conditions (in terms of e.g. climate, soil, vegetation, fire resilience), and b) are only used in the case that current native species are no longer adapted to the projected conditions for the site in the future (EC, 2020c; supplement to EU 2020/852). The EU Adaptation Strategy (COM/2021/82 final) also prioritises local resilience as the 'bedrock' of adaptation – since climate adaptation challenges themselves are local and specific – and stresses the importance of biodiversity for a climate-resilient Europe.

The tools of restoration ecology, together with specific silvicultural techniques, can help to both plan and establish communities resilient to emerging conditions. Forests must not only become more resilient to the aforementioned discrete events such as storms and fires, but also more tolerant to longer-term shifts in temperature and precipitation, in order to gradually transition and assist in both carbon storage (climate mitigation) and shifts in biodiversity. Since climate change disrupts the link between climate and the local adaptation of forest tree populations it is likely that management techniques will have to adapt themselves as regimes change in the next century.

Box 13 – Assisted Migration and Suselect app

Assisted migration is a climate adaptation approach that facilitates the movement of species and populations (provenances) within and across their natural range to match the climatic conditions anticipated in the future. The Interreg Central Europe-funded project SUSTREE promotes climate adaption and the genetic diversity of forest ecosystems in Central Europe. It uses long-term data to develop transfer models for forest seed and seedlings and has integrated them into a decision support system to guide assisted migration. A practical outcome of the project has been the Suselect app, a smart approach that helps to find optimal seed sources under climate change for assisted migration. This combines species distribution models and seed transfer models to allow users to map the vulnerability of tree species under both the current climate and anticipated future changes and compare the vulnerability of different species. In this way the tool can help inform decision-making and location of the best planting material, thereby facilitating the movement of species and populations in order to establish a more adaptive forest landscape.

Figure 15: SusSelect: a decision tool to find optimal seed sources under climate change. Source: Chakraborty *et al.*, 2019.

6.2 The value and multifunctional role of older forests

There is a growing concern that the focus on forests as a means to mitigate climate change could jeopardise many of the functions provided by older existing forests. As seen in Chapter 3, retaining older forests has significant benefits for biodiversity and ecosystem health.

Some studies show that younger forests have more potential capacity to absorb carbon than older forest landscapes. For example, research modelling global carbon sequestration in forests over the period from 1981–2010 indicated that intact old-growth forests sequestered 65% less carbon than younger forests (those of under 140 years in age) (Pugh *et al.*, 2019). However, older trees have already stored a much greater amount of carbon, even if they do not grow as fast as younger trees.

There is also an argument that the carbon storage value of older forests has been underestimated, because old-growth forests steadily accumulate carbon for centuries and, if disturbed, will lose much of their carbon to the atmosphere. A review of previous literature suggests that the old-growth forests of the Northern Hemisphere (totalling 600 million hectares of trees between 15 and 400 years old) store about 1.3 +/- 0.5 gigatonnes of carbon per year (Luyssaert *et al.*, 2008).

Research on tree growth rates has also suggested that trees continue to gain mass at continually increasing rates as they age, rather than growth declining with age and size (Stephenson *et al.*, 2014). Thus, older trees may not act solely as senescent carbon reservoirs but actively fix large amounts of carbon across their lifetimes; at the extreme, a single larger, older tree could fix the same amount of carbon in one year as a mid-sized tree does in its lifetime. However, in disagreement with this suggestion, another study observed no evidence of continued carbon sequestration in an old-growth beech-dominated forest in Denmark over a 20-year period (Nord-Larsen, Vesterdal, Scott Bentsen, and Larsen, 2019), highlighting the uncertainty surrounding old-growth forests and their efficacy as carbon sinks. Another, more recent study explored the phenomenon where more mature trees appear to take up CO2, while not laying on accompanying growth. Over four years of growth in a carbon dioxide-enriched mature eucalyptus forest, they found that increased carbon in the atmosphere increased carbon uptake – but also that carbon was emitted back into the atmosphere via respiratory fluxes; increased soil respiration accounted for half the total re-emitted carbon (Jiang, Medlyn and Ellsworth, 2020).

Such studies demonstrate the issues around defining older-growth forests; more generally, it has been suggested that current climate policies lack science-based definitions that distinguish forest condition (Moomaw *et al.*, 2019) — and there is continuing debate on how best to do this. What is clear is that the value of older, intact forests cannot be dismissed and, alongside accounting for changes in carbon stock from strategies such as afforestation and reforestation in climate change policy, there is also a need to account more accurately for carbon changes that occur from simply leaving forests intact (Moomaw *et al.*, 2019).

Eucalyptus plantation in Spain,
©Wikipedia Commons CC BY-SA 3.0

Box 14: The challenge of 'green pledges' for forest restoration

Launched by the German government and International Union for the Conservation of Nature in 2011, the Bonn Challenge is a global goal to bring 350 million hectares of degraded and deforested land into restoration by 2030. The initiative implements an approach of 'forest landscape restoration' to restore the ecological integrity and functionality of a landscape, and aims for sustainability by: planting new trees, creating protected wildlife reserves, building agroforestry systems, maintaining ecological corridors, making and managing plantations, and more, with a focus on landscape- and location-specific approaches to strengthening ecosystem resilience (Bonn Challenge, 2020). Under the Bonn Challenge, 43 tropic and sub-tropical countries have committed nearly 300 million hectares of degraded land for restoration.

However, critique has been levelled at such 'green pledges'; one assessment of the Bonn Challenge's goals found that almost half of pledged land will be transformed into commercial tree plantations, which are far poorer at storing carbon than natural forests (Lewis, Wheeler, Mitchard and Koch, 2019). The issue is further complicated by the fact that commercial plantations do uptake some carbon, and can also liberate natural or old-growth forests from production pressure, aiding their preservation – however, the carbon uptake in commercial plantation is only temporary since most of the carbon harvested is returned to the atmosphere relatively quickly (Hudiburg et al., 2019).

This issue highlights the importance of considering not only the amount of 'restored forest area' but also the type, scale, and prevalence of ecosystem services provided by the restored landscape. Importantly, 'forest' is not a homogenous concept — forest can be tropical, temperate, or boreal; primary, second- or new-growth, natural, managed, or a combination; fragmented or intact; and considered at a stand or wider landscape context, among other properties. All types and structures have differing carbon sequestration abilities, and require different trade-offs between forest management and delivery of ecosystem services. For instance, primary (untouched) forests are havens for rare or endangered species, especially those sensitive to human disturbance (Sabatini *et al.*, 2018) — and this property should be accounted for along with carbon capture ability when considering forest management for climate mitigation and adaptation. Another example is forest 'intactness', which is a good indicator of a forest landscape's conservation value, integrity, and resilience to ongoing climate change (Potapov, 2017). Intactness can be reduced rapidly but is difficult to restore, and often arises due to expanding infrastructure (e.g. roads) and human activity (e.g. timber harvesting). Intact forests hold high carbon stocks, and therefore have great potential for climate mitigation strategies.

A modelling analysis by Lewis *et al.* (2019) estimates that, if the area targeted by the Bonn Challenge, 350 million hectares, were given over to natural tropical or subtropical forests, they would store an additional 42 petagrams (Pg) of carbon by 2100.[12] They estimate that the same area of (tropical/subtropical) plantations would sequester just 1 Pg of carbon (ibid).[13] In this analysis, the researchers found that biodiverse natural forests are six times better at carbon sequestration than agroforestry schemes — where crops and trees are grown together — and 40 times better than plantations (Lewis *et al.*, 2019).

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[12] Supplementary information for Lewis *et al.*'s (2019) methods of calculation can be found here: https://media.nature.com/original/magazine-assets/d41586-019-01026-8/16588506

[13] For comparison, about 1000 petagrames is locked in the Arctic permafrost (Bowen *et al.*, 2020)

Forest restoration and regrown several years after a wildfire. ©Getty images, public domain

6.3 The benefits of biodiversity for climate mitigation and adaptation

The maintenance and restoration of intact forests is proposed as important for global efforts to halt the ongoing biodiversity crisis, which in itself has implications for resilience and climate change mitigation. Biodiversity has both intrinsic and instrumental value in underpinning ecosystem functions such as tree productivity, nutrient cycling, seed dispersal, pollination, water uptake and pest resistance, all of which help maintain forests at a condition where they are able to provide carbon storage and remain resilient to climate change.

Given the evidence available on climate and biodiversity benefits, retaining the integrity of intact forest ecosystems as a central component of proactive global and national environmental strategies, seems to be of central importance, alongside current efforts aimed at halting deforestation and promoting reforestation.

Box 15: The role of herbivores in forestry

Degradation and fragmentation of natural forests are major causes of defaunation: the extinction of animal populations or species. Many large-bodied animals depend on large expanses of high-quality forest to sustain viable populations. As these animals become unable to flourish and survive there is also a significant decline in ecosystem services and functions. For example, large herbivores play an important role in seed dispersal, which allows natural regeneration of large-seeded hardwood plant species that are key to carbon storage (Watson *et al.*, 2018).

The EU project GrazeLIFE has shown that herbivores are key architects in a diverse and cost-effective range of benefits that forests can offer, including climate change mitigation. Extensive grazing by herbivores such as deer, bison and wild-living horses creates a mosaic of forests and grassy vegetation. This produces variation in habitat and boosts biodiversity but it also provides natural firebreaks, Coordinated by Rewilding Europe, the European Commission-funded GrazeLIFE project aims is to evaluate the benefits of various land management models involving domesticated and wild/semi-wild herbivores.

However, herbivores can be too effective as environmental architects. As European populations of ungulates (hoofed mammals, especially deer) continue to increase, issues arise around population management and wildlife-forestry conflict (Kuijper, 2011). Many such species lack a natural predator in managed forest systems, which also typically have lower ungulate carrying capacities and are more sensitive to the effects of ungulate browsing. However, predators play an important role in modifying and controlling how ungulates interact with plant species and help support a healthy balance of biodiversity and natural tree regeneration within an environment. Additionally, forest fragmentation causes ungulates to become concentrated in ‘pockets’ of forest, also concentrating their effects and increasing their impact on surrounding fauna and flora. Although human hunting may replicate some of the effects of carnivores — such as reduction in numbers — it does not replicate their indirect effects on a whole ecosystem. Adaptive forest management practices look to be an important tool in successfully navigating this burgeoning area of wildlife-forestry conflict.

6.4 Ensuring multiple benefits with forest management

The climate mitigation potential of a forest is driven by several aspects, including forest management (although not all management practices are purposeful for mitigation). There is a growing body of evidence indicating that responsible, sustainable forest management can allow forests to perform their climate change mitigation function whilst maintaining their other roles.

The concept of managing forests to optimise their natural functions is not new; many have advocated the use of **close-to-nature silviculture (CNS)** in forestry to cope with future climate change. A review of research in this area suggests that there are six main principles that can be applied in its use (Brang *et al.*, 2014). Several of these focus on increasing and maintaining richness and variety at a species level, at a genetic level, and at a structural level. Alongside this, recommended principles to guide management include increasing forest resistance to natural and human-induced stress, replacing high-risk tree communities with more adaptive species, and keeping the average density of growing stocks low.

Another related concept is '**retention forestry**', which aims to retain biological legacies (i.e. dead and living trees, intact patches of vegetation) throughout harvesting cycles and has been explored as an integrated biodiversity conservation approach in Europe (Gustafsson *et al.*, 2020). Retention forestry has a history of application to even-aged clearcutting systems but has been less applied to uneven-aged continuous-cover forestry (associated with temperate, broad-leaved forests, as are common in Europe). The approach highlights the importance of biological legacies in forest recovery, and in providing continuity for species populations and forest conditions (Gustafsson *et al.*, 2013).

Another emerging concept is **Climate-Smart Forestry (CSF)**, which aims to reduce and/or remove greenhouse gas emissions; adapt and build forest resilience to climate change; and sustainably increase forest productivity and incomes (G.-J. Nabuurs *et al.*, 2018). By considering the whole value chain from forest to wood products and energy, CSF takes a more holistic approach that aims to achieve multiple goals and create synergies between climate mitigation and the other services and needs associated with forests.

Many studies have considered the importance of multiple forest functions and assessed the best ways forward. A review of 40 land management practices to tackle prevalent challenges — including climate change mitigation and adaption, land degradation, food security, desertification and more — found that 10 practices had either a moderate or large mitigation potential without any adverse impacts on other land challenges, and that 16 had a large adaptation potential without adverse effects (Smith *et al.*, 2019). These practices include reduced deforestation and degradation, increased soil organic carbon content, agroforestry and agricultural diversification, restoration of landscapes known to effectively sequester carbon (e.g., wetlands) and improved, more sustainable forest management.

Such research focuses on the integrated co-delivery of benefits such as climate change mitigation and adaptation; however, other studies suggest that forest management could benefit from being more segregated by service at the landscape level, given the trade-offs between conflicting objectives (Duncker *et al.*, 2012). This approach posits that there is "no best single solution that combines all services", and that trade-offs require concerted management (e.g., balancing a strict nature reserve to protect biodiversity with a dedicated timber reserve for intensive production, to offset the productivity losses brought about by the reserve). Duncker *et al.* (2012) also highlight the benefits of silviculture operations integrating conservation measures in forest management approaches – for example retaining coarse woody debris or simulating natural disturbances in managed forests.

In Europe, the integration of conservation measures into forest management is highlighted by the cross-border Integrate Network, established via a collaboration between the Czech Minister of Agriculture and the German Federal Minister of Food and Agriculture, and supported by the European Commission in 2016. The Network aims to bring together stakeholders, identify and analyse best practice, encourage the sharing of knowledge, and derive appropriate recommendations for both policymakers and forest practitioners (Krumm, Schuck and Rigling, 2020). As of July 2021, the Network had 23 member organisations from 19 countries (both EU and non-EU).

Other research disagrees with the concept of segregated land management practices (as mentioned above). When synthesising a large analysis of how best to balance forestry and biodiversity conservation across Europe, Krumm *et al.*(2020) lay out nine considerations for the successful application of **integrative forest management**, which shows promise in meeting future societal demands and environmental change in a sustainable way. The researchers suggest that forest policy should be adapted to be relevant to different levels, from pan-European to regional to local, and should:

Consider targeted integrated forest management as a core approach supporting bioeconomy and biodiversity	Promote regional integrative forest management approaches across the continent via strong European forest policy	Use disturbances to accelerate climate change adaptation and improve biodiversity
Consider both production and biodiversity parameters in forest monitoring	Be coordinated at the landscape level across the sectors (integrated forest management)	Use the motivation, experience, and support of Europe’s forest owners, managers, and biodiversity experts to advance integrated forest management approaches
Involve diverse groups and listen to a broad spectrum of views to create the forests of the future	Invest in an open science-policy-practice interface to stimulate dialogue and mutual learning across interest groups	Promote pragmatic and courageous regional approaches

Adapted from Krumm *et al.* (2020)

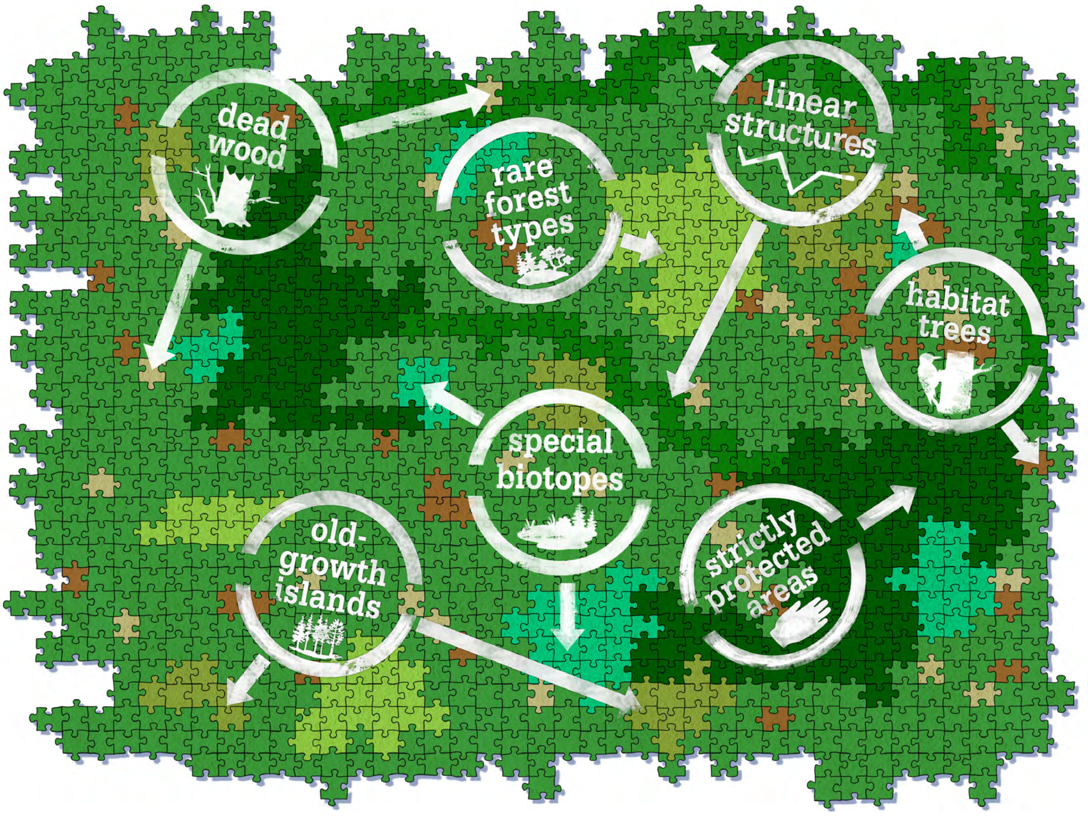

Figure 16: Model forest landscape with elements of a dual management strategy on different scales: several segregative elements, such as special biotopes, old-growth islands, linear structures, strict reserves, habitat trees, and deadwood, are embedded within a matrix of forest managed by close-to-nature principles. Source: Krumm *et al*., 2013.

There is of course variation in how and where differing forestry approaches are adopted depending on country, forest type, and more, but there are also some noted gaps in the implementation of some of the principles. In particular there are few examples of CNS in Europe that include management practices to replace those tree communities that are at high risk. Equally, there is a dearth of examples of CNS that maintain species richness and genetic variation, indicating a need for management to more closely consider how this principle may be incorporated in practice. Overall, there is a multitude of forest management approaches and techniques depending on the ecological conditions of a site, climate projections, historical and cultural development of a resource, and socio-economic context.

However, the overall objective of forest management is to enhance forest protection and reverse the degradation of ecosystems to reach good condition of habitats and species of the forests. This could be done by: reconnecting healthy and biodiverse forests; identifying and designating ecological corridors (including primary, old growth forests and other forest protected areas); restoring semi-natural forests as well as (by preserving stocks and increasing the carbon sinks in forests) their soils; and harvesting wood products in order to build resilience to threats such as climate change impacts on forests.

Box 16: Proforestation: functional segregation of forests

Proforestation, a recent term coined by William Moomaw, allows existing forest to grow, uninterrupted, to its ecological potential, which includes maximising water conservation, soil protection and climate-shaping parameters (Moomaw *et al*., 2019).

This represents strict protection, and functional segregation (setting forest completely aside for biodiversity conservation). Other benefits of proforestation include increasing biodiversity, improving water and air quality, providing flood and erosion control, and enhanced recreational value. While the substitution of materials cannot be also achieved from forests enjoying such strict protections, Jonsson *et al*. (2020) suggest that mitigation affects from material substitution will be more than offset by reduced net forest sinks by 2030, due to increased EU harvests.

Beech forest in Poloniny, ©Wikipedia Commons CC BY-SA 4.0

7. Better forests data, knowledge and understanding

Forest monitoring in Europe is not new, especially the practice of creating forest inventories. Since the 1980s, more attention has been paid to the declining health status of European forests. The main cause for concern in the 1980s was acid rain and the necessity of air pollution abatement policies to halt acidification. Under the Convention on Long-range Transboundary Air Pollution (UNECE), in 1985 the International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests (ICP Forests) was launched. The ICP Forests has since produced regular assessments on more than 6000 plots over 42 countries in Europe and beyond, measuring annual tree crown condition, soil condition and foliar nutrient status of trees.

However, new understandings of environmental problems – like climate change and biodiversity conservation – come with new data needs about forest status and the associated effects. At present, monitoring of forest biodiversity and climate change impacts in the EU is very patchy and complex, and there is no framework for holistic monitoring with high spatial and temporal granularity. This situation has developed in the absence of comprehensive mandatory requirements. The Forest Focus Regulation (2152/2003)[14] was in force during 2003-2007, and it contributed to the establishment of a scheme on monitoring of forests and environmental interactions to protect the European Community's forests. The scheme was built on the achievements of two previous Council regulations for monitoring the impacts of atmospheric pollution (Council Regulation (EEC)3528/86) and of fires (Council Regulation (EEC)2158/92) on forest ecosystems. A report on the implementation of the Forest Focus scheme is also available.[15]

Baseline data are needed to track changes in forest cover and condition on a European scale (EEA, 2016a), and data collected for forests must support various different sectors in collaborating and sharing insights pertaining to sustainable forest management (EEA, 2020a). While forests ecosystems often stretch across boundaries, forests are also seen as sovereign entities, and no consistent, transnational data-gathering approach has been fully developed for forests so far. Most of the European countries monitor forests within their national boundaries, producing National Forest Inventories. Although, together, EU Member States spend 50 million EUR annually on their national forest inventories (Maes *et al.*, 2020), often the information is unusable transnationally because countries cannot agree on definitions of parameters, the data are outdated or are too coarse (Nabuurs *et al.*, 2019). Winkel (2017) also found that forest monitoring would benefit from greater harmonisation and instruments that are comparable to those in other sectors.

In 2019 Nabuurs *et al*. argued that the existing raft of forest policies were based on "very little or out-dated information", and potentially created undesirable trade-offs. They called for a strong forest policy with goals and targets at a European scale, as well as a strongly improved information base that is novel, flexible and up to date. They recommend that forest information should be compiled from the latest digital data sources, supporting policymakers to make decisions in a transboundary way.

There have been several projects working to harmonise forests information in Europe, e.g. European National Forest Inventory Network (ENFIN) or the FUTMON project (2009-2011). Another positive example of forest data harmonisation is the European Atlas of Forest Tree Species, which provides valuable information and data on the presence / absence of forest and tree species across the EU. The Mapping and Assessment of Ecosystems and their Services (MAES) programme has also compiled data from across Europe to create an in-depth assessment of the most relevant pressures in EU-28 forests; however, in 2020 they found that there were still difficulties in using national forest inventories for pan-European assessments. They also found that there is an under-supply of forest information related to biodiversity and nature conservation, which could be filled by programmes that provide

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[14] https://ec.europa.eu/environment/archives/forests/ffocus.htm
[15] https://ec.europa.eu/environment/forests/pdf/final_report.pdf

seamless forests data on a European scale (e.g., Copernicus) (Maes *et al.*, 2020). Most recently, the Forest Information System for Europe has been set up as a single, seamless entry point for data, information and knowledge supporting forest-related policies in Europe (see Chapter 7.2 below).

The demand for information on biodiversity and nature conservation is greater than the supply from Member States – including, crucially, in the areas of water protection, amount of dead wood, harvested wood, and forest fires.[16] There is also an incomplete knowledge when considering the role of forests in biodiversity protection and climate change mitigation and adaptation. The effects of climate changes on forest dynamics are not fully understood, especially when the magnitude and frequency of pressure move beyond their background (historical) conditions (Maes *et al.*, 2020). The interdependent relationships between different forestry functions, overlaid with the uncertainty of climate change and its impact, makes this a challenging and non-linear area to navigate for both scientists and policymakers. Maes *et al*. (2020) also report that, within their assessment, strong spatial variability is common, with different biogeographical regions showing different trends and effects.

Maes *et al*. (2020) make clear that systemically collecting harmonised, spatio-temporal data from across the EU will be an important step towards tracking and preventing pressures at a pan-European level. Key data gaps identified in 2020 were in the following areas (Maes *et al.*, 2020).

Forest pressures:

- drought and heat-induced tree mortality;
- storm damage in forests;
- invasive alien species (including information on the presence of exotic tree species);
- forest pests, parasites and insect infestations;
- soil erosion;
- soil moisture (soil water deficit); and
- levels of over-harvesting.

Forest condition:

- defoliation;
- soil organic carbon;
- nutrient availability;
- land productivity dynamics;
- data on other forest species (not just common forest birds);
- structural information on forest stands.

There is also a deficit of mapped information and only poor-quality data on the amount of wood used as fuelwood and woody biomass used for energy. This has contributed to a difference being reported between volumes of sources of wood and volumes of wood used. For the EU-28 in 2013, there were some 98 million cubic metres of wood with a source that was 'missing' from reported data – something likely attributable to under-reported felling and wood removal (Camia *et al.*, 2018). A more recent report found that, despite the abundance of available datasets, there are still large data gaps on the sources and uses of woody biomass for energy, and that most datasets are incomplete or provide insufficient detail (Camia *et al.*, 2021). The report authors advise that deep cross-checking of statistics is required, due to inconsistent scope, assumptions and units, but also posit that data provided after 2023, under the Governance of the Energy Union Regulation, may improve the coherence of data in the area of woody biomass used for energy.

With a move towards more integrated approaches –ones that consider trade-offs and synergies in forest management alongside the increasing recognition of forests within the bioeconomy – the remainder of this chapter presents in further detail some calls for new approaches to collecting and reporting forest-based knowledge.

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[16] http://diabolo-project.eu/wp-content/uploads/2019/02/DIABOLO_WP1_Presentation_Koli-1.pdf

7.1 Forest indicators

Indicators are central tools to inform policy makers, forest managers and researchers on the status of forests and the impact of management approaches. There are shortcomings as regards the current availability of indicators and data for assessing and monitoring forest biodiversity, based on Forest Europe reports (which are de facto the only source of such data on EU forests overall). A report on the Goals for European Forests, published in 2015 by Forest Europe itself, acknowledges that data collected under these indicators are not sufficient to evaluate biodiversity loss, and that new or adapted indicators should be developed (Linser and Wolfslehner, 2015). Some Forest Europe indicators still lack a robust scientific consensus at the European level, for example regeneration (Chirici *et al.*, 2012), or only have partial agreement, e.g. forest naturalness (EEA, 2014; Winter, 2012), making harmonisation a challenge. For others there is already substantial academic agreement as to what is needed to achieve harmonisation, for example deadwood levels (Rondeux *et al.*, 2012) and tree-related compositional and structural indicators (Corona *et al.*, 2011).

For a number of indicators, the data reported at EU level are provide by Member States, and only available at national level (and the geographical and temporal differences in these data may be significant). This does not allow for an EU-wide analysis of certain indicators (e. g. deadwood has only been reported by 17 Member States to Forest Europe; abundance of common forest birds covers 25 Member States). Given that around 80% of EU forests are available for wood supply (i.e. not strictly protected), and 60% are privately owned, national forest policies are often influenced by the relevant forest industry interests in that country, which exacerbates patchy definitions of sustainable management and inconsistent data provision. Onida (2020) argues that, considering the crucial role of forests for biodiversity and climate, the instigation of common standards for sustainable management (such as threshold values) and new management criteria for climate and biodiversity, may be a next logical step.

Another major limitation on a horizontal level is the lack of data for the last two to three years, because of statistical procedures or lack of monitoring and reporting obligations, or availability of specific satellite products. Sometimes this delay is also caused by the lack of a reliable methodology for an EU-wide assessment (such as in the case of the impact of drought or bark beetle).

There has been a call to refresh the current sustainable forest management indicators in the light of the transition towards the bioeconomy (Winkel, 2017). This would incorporate new indicators that reflect a value-chain approach where forest products and ecosystem services are equally considered and provides more balance between economic, environmental and social aspects (see Figure 17).

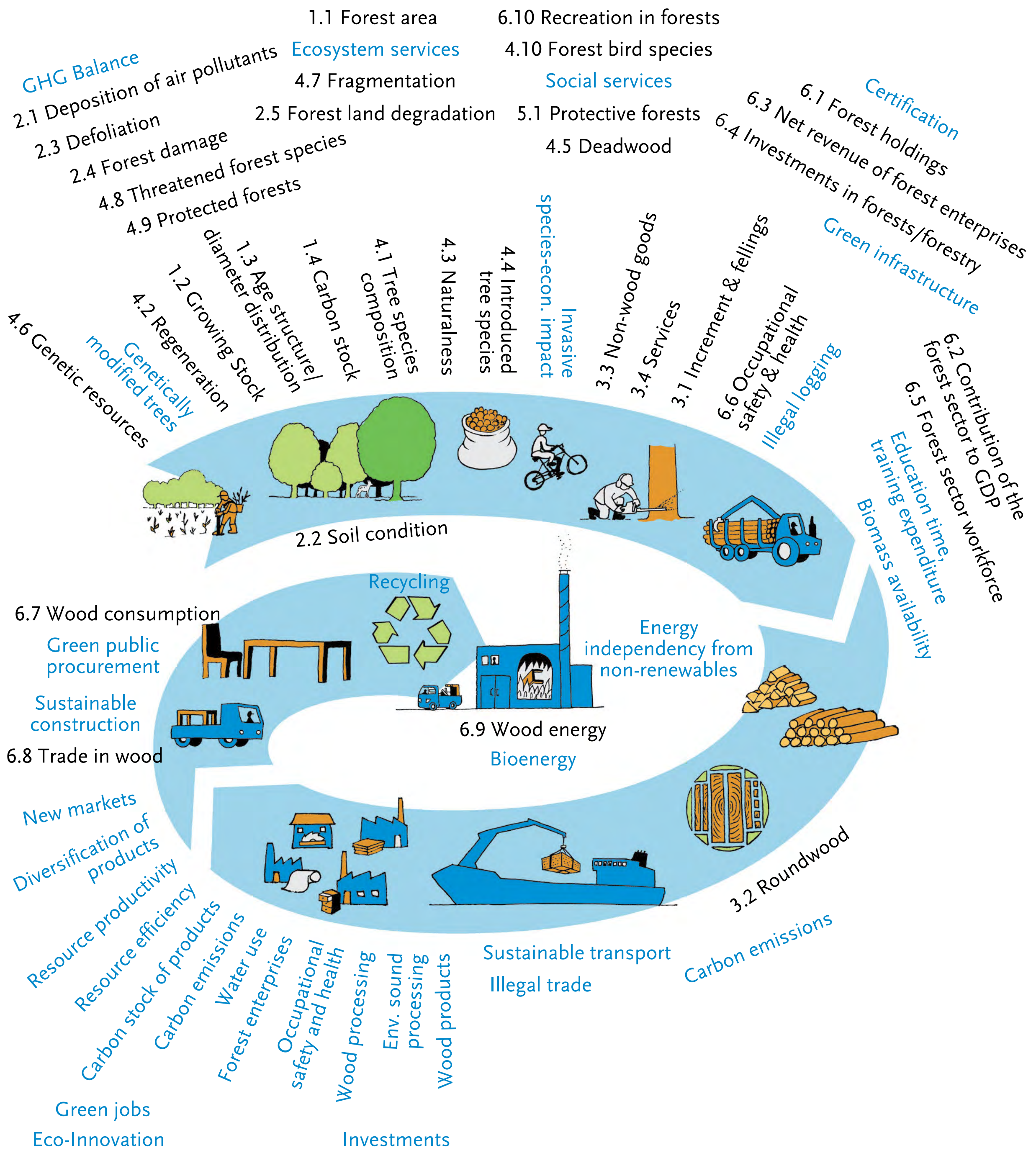

Figure 17: Current pan-European indicators for sustainable forest management and complementing additional indicators (in blue) along the forest-based sector value chain. Source: Wolfslehner *et al.*, 2016.

7.2 Towards a central knowledge base: the Forest Information System for Europe (FISE)

Understanding forests better requires the support of an adequate information system — one that provides accurate, integrated, harmonised and up-to-date data on Europe's forests, and elucidates the complex challenges facing these important ecosystems.

Developed and maintained by the European Commission and European Environment Agency (EEA) and launched in February 2020, the **Forest Information System for Europe (FISE)** is a centralised repository for all data, information and knowledge gathered or derived through key forest-related policy drivers in Europe (FISE, 2020). FISE aims to facilitate better sharing of harmonised data within the forest community on the state and development of Europe's forests. Under the EU Forest Strategy, FISE supports the objective of improving the knowledge base in terms of forest information, monitoring, research and innovation (San-Miguel-Ayanz, 2015). The System was referred to in the EU Biodiversity Strategy for 2030 as a way to "gain a better picture of the health of European forests" and "help produce up-to-date assessments of the condition of European forests and link all EU forest-data web-platforms" (EC, 2020).

FISE stores data from across Europe — including EEA member countries and the six cooperating countries from the West Balkan region — on forest land cover, density and use, and will progressively expand to cover the forest-focused priority areas of nature and biodiversity; climate change; health and resilience; and topics of relevance to the bioeconomy (for example, resource removal and forestry employment). The System also aims to become increasingly connected and integrated with other European information systems and sources of forest-related data.

FISE is heavily dependent on data and information provided by EU and EEA Member States (from national research institutes, governmental departments, universities, organisations, bureaus and more). A bottom-up process with Member States has been in place throughout the platform's development, to optimise knowledge exchange and coordination for key users (including policymakers, industry experts, forest owners, scientists and conservationists; EEA, 2020b).

Therefore, for FISE to completely meet its objectives, it will be important to build a stronger forest monitoring framework at EU level, reflecting all the priorities of the European Green Deal.

Box 17: Mapping ecosystem services: the MAES Initiative

In order to manage Europe's forest ecosystems, we first need to measure them. An essential part of the EU's approach to protecting and preserving its biodiversity and natural capital is the **MAES initiative (Mapping and Assessment of Ecosystems and their Services** – see also the introduction to this Chapter). MAES commits EU Member States to improving their knowledge and evidence base of European forest ecosystems, to support the collection and harmonisation of environmental information. The MAES indicator framework relies upon existing reporting streams (Maes, 2018); however, inconsistency remains in how methodologies are applied, the implementation of a common methodology, data quality (incl. spatial and temporal resolution) and gaps, and choice of metrics for indicator-based assessment, highlighting the need for "pan-European completeness" (ibid) and integration of new or improved data flows.

7.3 Big data solutions for forests

The call for better data from broader sources has also led to development of new innovative approaches to collection and compilation. For example, Smartelo is a free computer application to manage Forest Marking Classrooms, which are marked forest plots within which all the tree species have been characterised, measured, numbered and spatially located. The main objectives of Smartelo are to facilitate decision-making in forest marking and support teaching in this field through the organisation and processing of forest data. It enables the evaluation of different scenarios and alternatives, as well as obtaining numerical and graphical results which can be economic or ecological. Smartelo is constantly updated and is already being used by companies in the forestry sector.

The Suselect app is another example of smart approach to data which incorporates the modelling of species distribution and seed transfer to inform decisions around adaptive migration to enhance the resilience and reduce the vulnerability of European tree species (see Box 13). Digital projects have also been developed to help fight illegal logging. One of these is Digital Dryads, [17] which has produced the Wood Watcher tool, an application that measures stacks of wood (e.g. on the ground or on a truck) with high precision. The platform collects this data and also allows users to produce interactive maps of deforestation in the EU.

By harnessing the ever-increasing capacity to collect, model and analyse big data it is possible to consider forests in more encompassing frameworks and with all the vibrancy and complexity of the connections between their functions. This will help inform, implement and evaluate more multifaceted actions and polices that can bring together conventional sectors, markets and communities in new ways.

Continuous Cover Forestry in the Lake District, Cumbria, England. ©Wikipedia Commons CC BY-SA 3.0

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[17] https://digital-dryads.eu

7.4 Remote Sensing

Remote sensing – using technologies such as satellites and unmanned aerial vehicles – can be used to provide timely and reliable forest information and monitor different types of forest disturbances efficiently. Remote sensing can be used for increasingly diverse applications – from mapping the distribution of forest ecosystems, to characterising the three-dimensional structure of forests (Lechner, Foody and Boyd, 2020). Different sensors mounted on different platforms enable different maps and information products to be created, in different levels of detail. For forests, it is especially important to be able to detect disturbances or potential disturbances in a timely way, but also to be able to monitor forest condition and recovery immediately after disturbances or over a longer time period.

In their study on the Monitoring of Forests through Remote Sensing, Atzberger *et al*. (2020) critically assessed the potential contribution of remote sensing to the Forest Information System for Europe (FISE). They found that Copernicus (the European Union’s Earth observation programme, based on a fleet of satellites) already provides services that can be used for forest monitoring via land cover data. The Copernicus products that do exist are high quality; however, efforts are needed to expand the range of data products available, to support the recent forest-relevant policies more fully. Such products could include hazard maps showing information about events and their impacts, risk maps specifying exposure and vulnerability, and products that are specifically tailored to support reporting under LULUCF processes. The authors also showed that better spatial detail and higher update frequencies were needed, as well as a further harmonisation of approaches between Member States.

Via a survey of members of the EIONET National Reference Centres on Forests Atzberger *et al*. (2020) gathered information about forest remote sensing activities in the EEA countries. The results demonstrate that, for only five of six forest disturbances examined (wildfires, droughts, storm damages, illegal logging and phenology shifts), effective monitoring via remote sensing will be technically possible. For the sixth, pests and diseases, they predicted that effective monitoring will require near-real-time data, with high spatial and spectral resolution and extremely high revisit frequency, so detecting problems at an early enough stage to limit spread will be a problem: such sensors do not yet exist. The authors emphasise that significantly more research is needed in this area, as the problem of pests and diseases is severe and expected to increase with the changing climate.

Atzberger *et al*. (2020) also advise to integrate traditional inventory approaches with new remote-sensing capacity to create mutually beneficial synergies which are useful at a pan-European level. They recommend giving remote sensing a stronger role in the implementation of, specifically, the European Green Deal, the EU Forest Strategy, the EU Biodiversity Strategy, the EU Rural Development Programme and the Regulation for the Land Use, Land Use Change and Forestry sector. The rapid advancement of remote-sensing techniques, open data platforms and vast, global datasets, is also likely to result in greater democratisation to support forest management and conservation. Techniques from computer vision and machine learning (including deep learning) are starting to be applied to remote sensing, and cloud networks mean that the expensive computing and human resources required are reducing (Lechner, Foody and Boyd, 2020).

8. Summary

It is clear that the resistance, resilience and biodiversity of Europe's forests are fundamentally linked to our ability to thrive in a changing climate. Any of the enormous benefits of forests to humans – climate buffering, clean air and water, food and medicines, materials, fuel, economic development and jobs, and social and cultural wellbeing – are reliant on the maintenance and restoration of healthy, functioning, diverse, well-connected forest ecosystems.

Forest area in the EU has been increasing in recent years. However, the biodiversity and resilience of forests (and their possible adaptation) is under pressure by inadequate management practices and current and future climate changes. The conservation status of protected forest habitats in general has not improved or, in several cases, has even worsened in the past decades. Therefore, their protection, restoration and adequately adapted management is essential.

Forests hold a significant share of biodiversity in the EU. Forest biodiversity in managed forests is particularly affected by the removal of dead and dying trees, as well as by the clear-cutting removal of all trees, and the conversion to monocultures or other forest types – so a shift in forest management approaches has a large role to play in preserving and restoring forest biodiversity. There are still questions to be answered about the extent of functional separation (setting aside forest completely for biodiversity conservation) vs functional integration (combining conservation and production). However, given the extent of plantation area in Europe, it is clear that both strict protection and adaptive management will be crucial to achieve the goal of the Biodiversity Strategy for 2030 to improve the status of habitats and of the species dependent on them. Forests will also play an increasingly vital role in the mitigation of climate change – through sequestering carbon and storing it in trees, soil and other biomass as well as in wood products that replace the fossil fuel economy – and also play an important role in combatting erosion and desertification. To maintain these valuable aspects of forests, forest ecosystems themselves will need to be protected from the impacts of climate change. They will also need to adapt.

As shown in Chapter 2, forest area in Europe has remained fairly stable in the last 20 years, but Europe's forests are clearly under immense pressure. The harvesting of trees to meet the demand for wood products is increasing very fast, and there are projections that the expected reduction in forest carbon sinks will fully outweigh the carbon benefits gained through wood product harvesting.

Native, natural, old-growth forests have many benefits, and are a clear priority target for the stringent conservation and restoration ('proforestation') measures that allow for old growth to emerge and naturally adapt to climate change. Management approaches such as close-to-nature forestry, which rely on natural processes to maintain biodiversity, have the potential to allow adaptive, resilient forests to emerge and endure – if these are based on a true understanding of forest science. Furthermore, it is imperative to explore what will happen to forests under more sudden changes to our climate, and how forests – and the biodiverse species they host – can adapt and maintain their multi-functionality – by changing through natural processes or through human interventions, including assisted migration.

Scientific results and knowledge from various sectors and disciplines, which attempts to shed light on the various priorities for forests, are mostly not yet joined up. Different countries also use different parameters for forest data reporting, which increases the challenge of decision-making on a large enough scale.

A mixture of multi-benefit and context-specific approaches will need to be trialled, evaluated and implemented at scale to respond to the upcoming challenges. Improved forests data will provide the fulcrum of success throughout these efforts. New initiatives to bring the different threads of evidence of forests together, particularly the new Forest Information System for Europe, should make large steps towards balancing the large demands we will be making on forests over the coming years. Such inter-country platforms, if they are iteratively developed and kept up to date, could provide important strategic capacity for Member States to be able to share best practice and results from successful attempts to balance priorities. Coordination between Member States will be vital.

Given the highly complex mixture of local societal conditions, ecosystem characteristics, challenges in monitoring, and unaligned objectives surrounding Europe's forests, meeting biodiversity, climate and bioeconomy goals together will require an unprecedented level of cooperation between sectors. Meeting multiple goals, and achieving multiple benefits requires widespread discussion and open debate between conservation and ecosystems experts, governments, forest owners, managers, workers, industries, environmental groups, and, crucially, citizens. As well as accurate reporting, the scientific community should openly debate the implications of their work and engage with society about the issues it may raise.

This brief has pulled together some of the latest scientific evidence on how biodiversity, the bioeconomy and climate change mitigation are vitally underpinned by Europe's forests. As a crucial renewable resource under intense pressure, action must be taken now to ensure that the next steps for forests are sufficiently evidenced and considered. The science in this brief has pointed the way towards essential changes for forestry management practices that will help to ensure that biodiversity – a decisive factor in both forest resilience and climate change mitigation – is not left out of this equation.

9. References

- Alberdi, I.; Nunes, L.; Kovac, M.; Bonheme, I.; Cañellas, I.; Castro Rego, F.; Dias, S.; Duarte, I.; Notarangelo, M.; Rizzo, M.; and Gasparini, P. (2019) 'The conservation status assessment of Natura 2000 forest habitats in Europe: capabilities, potentials and challenges of national forest inventories data', Annals of Forest Science 76(2). https://doi.org/10.1007/s13595-019-0820-4.

- Amiri, A.; Ottelin, J.; Sorvari, J.; and Junnila, S. (2020) Cities as carbon sinks – classification of wooden buildings. Environ. Res. Lett. 15(2020): 094076.

- Baillie, J. and Zhang, Y.-P. (2018) Space for Nature. (Editorial) Science 361(64 7): 105

- Bastin, J.-F.; Finegold, Y.; Garcia, C.; Mollicone, D.; Rezende, M.; Routh, D.; Zohner, C. M.; and Crowther, T. W. (2019) The global tree restoration potential. Science 365. http://science.sciencemag.org/

- Barredo, J. I.; Brailescu, C.; Teller, A.; Sabatini, F.M.; Mauri, A.; and Janouskova, K. (2021) Mapping and assessment of primary and old-growth forests in Europe. JRC Science for Policy Report. Luxembourg: European Commission. https://publications.jrc.ec.europa.eu/repository/handle/JRC124671

- Bastin, J. F., Finegold, Y., Garcia, C., Gellie, N., Lowe, A., Mollicone, D., Rezende, M., Routh, D., Sacande, M., Sparrow, B., Zohner, C. M. and Crowther, T. W. (2019). Response to Comments on 'The global tree restoration potential.' Science 366(6463). https://doi.org/10.1126/science.aay8108

- Bastin, J.F.; de Haulleville, T.; Maniatis, D.; Marchi, G.; Massaccesi, E.; Mollicone, D.; and Pregagnoli, C. (2020) Tree restoration potential in the European Union. Preliminary assessment prepared by the FAO Climate, Biodiversity, Land and Water Department, produced under a contract with the European Commission. Study contract: 070202/2020/825508/ETU/ENV.D.l

- Bauhaus, J., Baber, K. and Müller, J. (2019) Dead Wood in Forest Ecosystems. Oxford Bibliographies. Ecology. Oxford Bibliographies. Article. DOI: 10.1093/OBO/9780199830060-0196

- Bengtsson, J.; Nilsson, S.G.; Franc, A.; and Menozzi, P. (2000) Biodiversity, disturbances, ecosystem function and management of European forests. Forest Ecology and Management 132(1): 39-50.

- Bentsen, N. S. (2017) Carbon debt and payback time – Lost in the forest? Renewable and Sustainable Energy Reviews (73): 1211-1217.

- Biber, P., Nieuwenhuis, M. and Nordström, E.-M. (2020) New FMMs in a landscape perspective: Innovation needs and gains in ES provisioning. Deliverable 3. 4 – Synthesis report. ALTERFOR, Swedish University of Agricultural Sciences, Uppsala.

- Birdsey, R.; Duffy, P.; Smyth, C.; Kurz, W. A.; Dugan, A. J.; and Houghton, R. (2018) Climate, economic, and environmental impacts of producing wood for bioenergy. Environmental Research Letters 13(5). https://doi.org/10.1088/1748-9326/aab9d5

- Boer, M.M., Resco de Dios, V. and Bradstock, R.A. (2020) Unprecedented burn area of Australian mega forest fires. Nature Climate Change 10(3): 171–172.

- Bolte, A.; Hilbrig, L.; Grundmann, B.; Kampf, F.; Brunet, J. and Roloff, A. (2010) Climate change impacts on stand structure and competitive interactions in a southern Swedish spruce–beech forest. European Journal of Forest Research 129: 261-276.

- Boncina, A. (2011) Conceptual approaches to integrate nature conservation into forest management: a Central European perspective. The International Forestry Review 13(1): 3-22.

- Booth, M. S. (2018) Not carbon neutral: Assessing the net emissions impact of residues burned for bioenergy. Environmental Research Letters 13(3). https://doi.org/10.1088/1748-9326/aaac88

- Bowd, E.J.; Banks, S.C.; Strong, C.L.; and Lindenmayer, D.B. (2019) Long-term impacts of wildfire and logging on forest soils. Nature Geoscience 12(2): 113–118.

- Bowen, J.C.; Ward, C.P.; Kling, G.W.; and Cory, R.M. (2020) Arctic Amplification of Global Warming Strengthened by Sunlight Oxidation of Permafrost Carbon to CO2. Geophysical Research Letters 47(12): e2020GL087085. https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2020GL087085z

- Brang, P.; Spathelf, P.; Larsen, J. B.; Bauhus, J.; Bončína, A.; Chauvin, C.; Drössler, L.; García-Güemes, C.; Heiri, C.; Kerr, G.; Lexer, M. J.; Mason, B.; Mohren, F.; Mühlethaler, U.; Nocentini, S.; and Svoboda, M. (2014) Suitability of close-to-nature silviculture for adapting temperate European forests to climate change. Forestry 87(4): 492–503. https://doi.org/10.1093/forestry/cpu018

- Brukas, V. and Weber, N. (2009) Forest management after the economic transition-at the crossroads between German and Scandinavian traditions. Forest Policy and Economics 11(8): 586–592. https://doi.org/10.1016/j.forpol.2009.08.009

- Buma, B. and Wessman, C. A. (2013) Forest resilience, climate change, and opportunities for adaptation: A specific case of a general problem. Forest Ecology and Management 306: 216–225. https://doi.org/10.1016/j.foreco.2013.06.044

- Buras, A. and Menzel, A. (2019) Projecting Tree Species Composition Changes of European Forests for 2061–2090 Under RCP 4.5 and RCP 8.5 Scenarios. Frontiers in Plant Science 9.

- Buras, A., Rammig, A. and Zang, C.S. (2020) Quantifying impacts of the 2018 drought on European ecosystems in comparison to 2003. Biogeosciences 17(6): 1655–1672.

- Bütler, R.; Lachat, T.; Larrieu, L. and Paillet, Y. (2013) Habitat trees: key elements for forest biodiversity in Kraus, D. and Krumm, F. (Eds.) Integrative approaches as an opportunity for the conservation of forest biodiversity, European Forest Institute (2013): 84-92

- Camia A.; Robert N.; Jonsson R.; Pilli R.; García-Condado S.; López-Lozano R.; van der Velde M.; Ronzon T.; Gurría P.; M'Barek R.; Tamosiunas S.; Fiore G.; Araujo R.; Hoepffner N.; Marelli L. and Giuntoli J. (2018) Biomass production, supply, uses and flows in the European Union: First results from an integrated assessment. European Commission, Joint Research Centre.
- Camia A.; Giuntoli, J.; Jonsson, R.; Robert, N.; Cazzaniga, N.E.; Jasinevičius, G.; Avitabile, V.; Grassi, G.; Barredo, J.I.; Mubareka, S. (2021) The use of woody biomass for energy purposes in the EU, EUR 30548 EN, Publications Office of the European Union, Luxembourg, ISBN 978-92-76-27867-2, doi:10.2760/831621, JRC122719 Cardellini, G.; Valada, T.; Cornillier, C.; Vial, E.; Dragoi, M.; Goudiaby, V.; Mues, V.; Lasserre, B.; Gruchala, A.; Rørstad, P.K.; Neumann, M.; Svoboda, M.; Sirgmets, R.; Näsärö, O.-P.; Mohren, F.; Achten, W.M.J.; Vranken, L.; Muys, B. (2018) EFO-LCI: A New Life Cycle Inventory Database of Forestry Operations in Europe. Environmental Management. DOI: 10.1007/s00267-018-1024-7.
- Cazzaniga N.E.; Jonsson R.; Palermo D.; Camia A. (2019) Sankey diagrams of woody biomass flows in the EU-28. EC Joint Research Centre. Publications Office of the European Union: Luxembourg. DOI:10.2760/227292.
- Ceccherini, G.; Duveiller, G.; Grassi, G.; Lemoine, G.; Avitabile, V.; Pilli, R. and Cescatti, A. (2020) Abrupt increase in harvested forest area over Europe after 2015. Nature 583(7814): 72–77.
- Chakraborty D.; Gaviria J.; Bednárová D.; Bolte A.; Bouissou C.; Buchacher R.; Hazarika, R.; Henning L.; Kowalczyk J.; Longauer R, Lstibůrek M.; Nagy L.; Schnabel G.; Stejskal J, Tomášková I.; Schueler S. (2019) Implementing assisted migration. SUSTREE Policy Brief No. 2, Output of the INTERREG CENTRAL EUROPE Programme 2014-2020. https://doi.org/10.3220/DATA20191016132031
- Chirici, G.; McRoberts, R.E.; Winter, S.; Bertini, R.; Brändli, U.-B.; Asensio, I. A.; Bastrup-Birk, A.; Rondeux, J.; Barsoum, N. and Marchetti, M. (2012) National forest inventory contributions to forest biodiversity monitoring. Forest Science 58(3): 257-268.
- Cimons, M. (2018) Trees Are Migrating West to Escape Climate Change. PopSci.com. https://www.popsci.com/trees-are-migrating-west-to-escape-climate-change/
- Cohn, A.S.; Bhattarai, N.; Campolo, J.; Crompton, O.; Dralle, D.; Duncan, J.; and Thompson, S. (2019) Forest loss in Brazil increases maximum temperatures within 50 km. Environmental Research Letters 14(8): 084047.
- Corona, P.; Chirici, G.; McRoberts, R.E.; and Winter, S. (2011) Contribution of large-scale forest inventories to biodiversity assessment and monitoring. Forest Ecology and Management 262(11): 2061-2069.
- Crowther, T.; Glick, H.; Covey, K.; Bettigole, C.; Maynard, D.S.; Thomas, S.M.; Smith, J.R.; Hintler, G.; Duguid, M.C.; Amatulli, G.; Tuanmu, M.-N.; Jetz, W.; Salas, C.; Stam, C.; Piotto, D.; Tavani, R.; Green, S.; Bruce, G.; Williams, S.J.; Wiser, S.K.; Huber, M.O.; Hengeveld, G.M.; Nabuurs, G.-J.; Tikhonova, E.; Borchardt, P.; Li, C.-F.; Powrie, L.W.; Fischer, M.; Hemp, A.; Homeier, J.; Cho, P.; Vibrans, A.C.; Umunay, P.M.; Piao, S.L.; Rowe, C.W.; Ashton, M.S.; Crane, P.R.; and Bradford, M.A. (2015) Mapping tree density at a global scale. Nature 525: 201–205. https://doi.org/10.1038/nature14967
- De Groot, M. and Nikica Ogris, N. (2019) Short-term forecasting of bark beetle outbreaks on two economically important conifer tree species. Forest Ecology and Management 450(15): 117495. DOI: 10.1016/j.foreco.2019.117495.
- De la Fuente, B., Saura, S. and Beck, P.S.A. (2018) Predicting the spread of an invasive tree pest: The pine wood nematode in Southern Europe. Journal of Applied Ecology 55(5): 2374-2385.
- De Rigo, D.; Libertà, G.; Houston Durrant, T.; Artés Vivancos, T. and San-Miguel-Ayanz, J. (2018) Forest fire danger extremes in Europe under climate change: variability and uncertainty, EUR 28926 EN, Publications Office of the European Union, Luxembourg.
- Duelli, P. and Chumak, V. (2005) The biodiversity values of European virgin forests. Forest Snow and Landscape Research 79(1): 91-99 (2005)/
- EASAC (2020) 'Emissions Trading System: Stop Perverse Climate Impact of Biomass by Radically Reforming CO2 Accounting Rules', Press Release and 'Comment on the Commission consultation on the ETS', Consultation comment. European Academies Science Advisory Council. https://easac.eu/media-room/press-releases/details/emissions-trading-system-stop-perverse-climate-impact-of-biomass-by-radically-reforming-co2-accounting-rules/ https://easac.eu/fileadmin/PDF_s/Press_Releases/EASAC_ETS_PR_Annex.pdf
- EC (2010) Forest soil and biodiversity monitoring in the EU. Luxembourg: Publications Office of the European Union. ISBN 978-92-79-14992-4.
- EC (2013) A new EU forest strategy: for forests and the forest-based sector. EC COM 2013. 659 final.
- EC (2014) Biomass. [online] Energy – European Commission. Available at: https://ec.europa.eu/energy/topics/property-fieldtopicparent/biomass_en [Accessed 15 May 2020].
- EC (2018) A sustainable bioeconomy for Europe: strengthening the connection between economy, society and the environment. Updated Bioeconomy Strategy.
- EC (2018b) Progress in the implementation of the EU Forest Strategy 'A new EU Forest Strategy: for forests and the forest sector' COM(2018) 811 final.
- EC (2018c) Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the Promotion of the Use of Energy from Renewable Sources (recast).
- EC (2019) The European Green Deal. COM(2019) 640 final.
- EC (2019a) Forest Fires – Forests – Environment – European Commission. [online] Available at: https://ec.europa.eu/environment/forests/fires.htm [Accessed 12 Aug. 2020].

- EC (2019b) European droughts in 2018: a warning of things to come. [online] EU Science Hub – European Commission. Available at: https://ec.europa.eu/jrc/en/news/european-droughts-2018-warning-things-come [Accessed 17 Aug. 2020].
- EC (2020) Forest fires: factsheet. Available from: https://ec.europa.eu/echo/what-we-do/civil-protection/forest-fires_en
- EC (2020a) EU Biodiversity Strategy for 2030: bringing nature back into our lives. Brussels. 20.5.2020 COM(2020) 380 final.
- EC (n.d.) Forestry explained. [online] Available at: https://ec.europa.eu/info/food-farming-fisheries/forestry/forestry-explained_en. [Accessed 12 May 2020]
- EC (n.d.a) 'Rural development measures: How measures are applied' European Commision website. [online] https://ec.europa.eu/info/food-farming-fisheries/key-policies/common-agricultural-policy/rural-development/measures_en
- EC (n.d.b) Forests – Environment – European Commission. [online] Available at: https://ec.europa.eu/environment/forests/index_en.htm [Accessed 15 May 2020].
- EC JRC (2015) A database of the recreational value of European forests: Design and implementation from recreational valuation studies.
- ECE and FAO (2019) ECE/FAO/Forest Europe Guidelines on the Promotion of Green Jobs in Forestry. https://unece.org/sites/default/files/2021-02/2006219_E_pdf_web.pdf
- Edwards, D. P.; Gilroy, J.J.; Woodcock, P.; Edwards, F.A.; Larsen, T.H.; Andrews, D.J.; Derhé, M.A.; Docherty, T.D.; Hsu, W.W.; and Mitchell, S.L. (2014) Land-sharing versus land-sparing logging: reconciling timber extraction with biodiversity conservation. Global ChangeBbiology 20:183-191.
- EEA (2014) Developing a forest naturalness indicator for Europe. Technical report No 13/2014.
- EEA (2015) State of nature in the EU: Results from reporting under the nature directives 2007 – 2012.
- EEA (2016a) European forest ecosystems: States and trends. EEA Report No. 5/2016. European Environment Agency.
- EEA (2016b) Biodiversity and forest ecosystems in Europe. https://www.eea.europa.eu/highlights/biodiversity-and-forest-ecosystems-in-europe-1
- EEA (2017a) Wind storms [online] Available at: https://www.eea.europa.eu/data-and-maps/indicators/storms-2/assessment [Accessed 17 Aug. 2020].
- EEA (2017b) Forest: growing stock, increment and fellings. [online] Available at: https://www.eea.europa.eu/data-and-maps/indicators/forest-growing-stock-increment-and-fellings-3/assessment [Accessed 15 May 2020].
- EEA (2018) Forest dynamics in Europe and their ecological consequences. [online] Available at: https://www.eea.europa.eu/themes/biodiversity/forests [Accessed 6 May 2020].
- EEA (2019a) Global and European temperature. [online] Available at: https://www.eea.europa.eu/data-and-maps/indicators/global-and-european-temperature-9/assessment.
- EEA (2019b) Forest fires — European Environment Agency. [online] Available at: https://www.eea.europa.eu/data-and-maps/indicators/forest-fire-danger-3/assessment [Accessed 12 Aug. 2020].
- EEA (2020a) A new EU Forest Strategy [online] https://www.eea.europa.eu/policy-documents/the-eu-forest-strategy-com
- EEA (2020b) EU launches new Forest Information System to improve knowledge on forests and woodlands. https://www.eea.europa.eu/highlights/eu-launches-new-forest-information
- EEA (2020c) State of nature in the EU. Results from reporting under the nature directives 2013-2018. European Environment Agency.
- EEA (2020d) Annual European Union greenhouse gas inventory 1990–2018 and inventory report 2020, submission to the UNFCCC Secretariat. 27 May 2020, http://unfccc.int/national_reports/items/1408.php.
- EEA (2020e) Abundance and distribution of selected European species (SEBI 001) European Environment Agency.
- ECE (2015) Natura 2000 and Forests. Part III - Case Studies. European Commission Environment https://doi.org/10.2779/699873
- EEA (n.d.) EFFIS data — European Environment Agency. [online] Available at: https://www.eea.europa.eu/data-and-maps/data/external/european -forest-fire-information-system/view [Accessed 12 Aug. 2020].
- EEA/EC (n.d.) Mid-term review of the EU biodiversity strategy to 2020: EU assessment of progress towards the targets and actions. Available from: https://ec.europa.eu/environment/nature/biodiversity/comm2006/pdf/mid_term_review_summary.pdf
- EFI (2000) Destructive Storms in European Forests: Past and Forthcoming Impacts
- EFFIS (n.d.) About EFFIS. [online] Available at: https://effis.jrc.ec.europa.eu/about-effis [Accessed 12 Aug. 2020].
- ESRI (2019) How Artificial Intelligence, Robots Enhance Forest Sustainability in Finland. https://www.esri.com/about/newsroom/blog/finland-enhances-forest-data-accuracy-for-automation/
- EUFORGEN (2016) Why active forest management is necessary. http://www.euforgen.org/about-us/news/news-detail/why-active-forest-management-is-necessary (n.d.) Article 17 web tool [online] Available at: https://nature-art17.eionet.europa.eu/article17/reports2012/ [Accessed 29 Apr. 2020].
- European Commission (2016) Commission staff working document: Impact assessment Accompanying the document Proposal for a Regulation of the European Parliament and of the Council on the inclusion of

greenhouse gas emissions and removals from land use, land use change and forestry into the 2030 climate and energy framework and amending Regulation No 525/2013 of the European Parliament and the Council on a mechanism for monitoring and reporting greenhouse gas emissions and other information relevant to climate change. SWD(2016 249 final/COM (2016) 479 final. Brussels. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52016SC0249&from=EN

- European Commission (2018) Study on progress in implementing the EU forest strategy. Final report. European Commission (2019) Preparing the ground for raising long-term ambition EU Climate Action Progress Report 2019. Report from the Commission to the European Parliament and the Council. SWD(2019) 396 final. https://ec.europa.eu/clima/system/files/2019-10/swd_2019_396_en.pdf

- European Commission (2020a) International Conference on Forests for Biodiversity and Climate. 4-5 February 2020, Belgium. https://ec.europa.eu/info/events/international-conference-forests-biodiversity-and-climate_en.

- European Commission (2020b) EU Biodiversity Strategy for 2030: Bringing nature back into our lives. https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1590574123338&uri=CELEX:52020DC0380

- European Commission (2020c) Kickstarting the journey towards a climate-neutral Europe by 2050: EU Climate Action Progress Report. November 2020. https://ec.europa.eu/clima/sites/clima/files/strategies/progress/docs/com_2020_777_en.pdf

European Commission (2021) New EU Forest Strategy for 2030. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Brussels 16.7.2021. COM(2021) 572 final.

- European Commission (2021b) COMMISSION STAFF WORKING DOCUMENT STAKEHOLDER CONSULTATION AND EVIDENCE BASE SWD(2021) 652 final Accompanying the document COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS New EU Forest Strategy for 2030 COM(2021) 572 final.

- European Commission (n.d.) Sustainable forest management. https://ec.europa.eu/growth/sectors/raw-materials/industries/forest-based/sustainable-forest-management_en

- European Parliament (2021) The European Union and forests | Fact Sheets on the European Union | European Parliament. Available at: https://www.europarl.europa.eu/factsheets/en/sheet/105/the-european-union-and-forests.

- Eurostat, 2017, Agriculture, forestry and fishery statistics: 2017 edition. Publications Office of the European Union, Luxembourg.

- Eurostat (2019) Agriculture, forestry and fishery statistics. 2019 edition. Publications Office of the European Union, Luxembourg.

- Eurostat (2020a) Roundwood, fuelwood and other basic products [online] Available at: https://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=for_basic&lang=en [Accessed 17 May 2020].

- Eurostat (2020b) 'Wood products – production and trade'. Eurostat: Statistics explained website. Data extracted in December 2020. https://ec.europa.eu/ uropa t/statistics-explained/index.php/Wood_products_-_production_and_trade#Primary_wood_products

- Eurostat (2021) Final report from phase II of the INCA project aiming to develop a pilot for an integrated system of ecosystem accounts.

- Eurostat (n.d.) Eurostat – Tables, Graphs and Maps Interface (TGM) table. [online] https://ec.europa.eu/ uropan/tgm/=tabledo?tab=table&plugin=1&language=en&pcode=tag00058 [Accessed 25 Oct. 2020].

- FAO (2015) Global Forest Resources Assessment. FAO, UN.

- FAO (2020) Sustainable forest management [online] http://www.fao.org/forestry/sfm/en/

- FAO and UNEP (2020) The State of the World's Forests 2020. Forests, biodiversity and people. FAO and UNEP. https://doi.org/10.4060/ca8642en

- Favero, A.; Sohngen, B.; Huang, Y.; and Jin, Y. (2018) Global cost estimates of forest climate mitigation with albedo: a new integrative policy approach. Environmental Research Letters 13(12): 25002.

- Fernández, C., Fontúrbel, T. and Vega, J. A. (2021) Cumulative effects of salvage logging and slash removal on erosion, soil functioning indicators and vegetation in a severely burned area in NW Spain. Geoderma 393. https://doi.org/10.1016/j.geoderma.2021.115004

- FISE (2020) About us: Forest Information System for Europe [online] https://forest.eea.europa.eu/about

- Forest Europe (2014) Green Economy and Social Aspects of Sustainable Forest Management. 29-30 April 2014, Spain. Workshop Report. https://www.foresteurope.org/documentos/report_workshop_green_economy.pdf

- Forest Europe (2015) State of Europe's Forests 2015. Report. Ministerial Conference on the Protection of Forests in Europe. https://www.foresteurope.org/docs/fullsoef2015.pdf

- Forest Europe (2016) SFM Criteria & Indicators. 07/10/2016 [online] https://foresteurope.org/sfm-criteria-indicators2/#1472655675267-8e6b009d-b722a184-c9ce5d80-64e0

- Forest Europe (2020) State of Europe's Forests 2020. 394. https://foresteurope.org/state-europes-forests-2020/

- Forest Europe (n.d.) Indicator 4.9: Protected forests. https://foresteurope.org/protected-forests/

- Freer-Smith, P.; Muys, B.; Leuven, K. U.; Drössler, L.; Farrelly, N.; Jactel, H.; Korhonen, J.; Minotta, G.; Nijnik, M.; and Orazio, C. (2019) Plantation forests in Europe: challenges and opportunities. https://doi.org/10.36333/fs09

- Freerk Wiersum, K., Elands, B. H. M. and Hoogstra, M. A. (2005) Small-scale forest ownership across Europe: Characteristics and future potential. Small-scale Forest Economics, Management and Policy 4: 1-19. https://link.springer.com/article/10.1007/s11842-005-0001-1

- Friedlingstein, P.; Allen, M.; Canadell, J. G.; Peters, G. P.; and Seneviratne, S. I. (2019) Comment on 'The global tree restoration potential.' Science 366(6463): 76–79. https://doi.org/10.1126/science.aay8060

- Garcia-Gonzalo, J.; Zubizarreta-Gerendiain, A.; Ricardo, A.; Marques, S.; Botequim, B.; Borges, J. G.; Oliveira, M. M.; Tomé, M.; and Pereira, J. M. C. (2012) Modelling wildfire risk in pure and mixed forest stands in Portugal. Allgemeine Forst- Und Jagdzeitung 183(11–12): 238–248.

- Gardiner, B.; Schuck, A.; Schelhaas, M-J.;Orazio, C.; Blennow, K. and Nicoll, B (2013) Living With Storm Damage To Forests. What Science Can Tell Us.

- Gauthier, S.; Bernier, P.; Kuuluvainen, T.; Shvidenko, A.; and Schepashenko, D. (2015) Boreal forest health and global change. Science 349(6250): 819-822. DOI: 10.1126/science.aaa9092.

- Giuntoli, J. and Searle, S. (2019) Does Bioenergy Demand Improve Forest Management? July, 48.

- Gosselin, F. and Larrieu, L. (2020) Developing and using statistical tools to estimate observer effect for ordered class data: The case of the IBP (Index of Biodiversity Potential). Ecological Indicators 110: 105884.

- Gosselin, M. and Paillet, Y. (2017) Mieux intégrer la biodiversité dans la gestion forestière. Nouvelle édition. Éditions Quae: Versailles.

- Grassi, G.; Fiorese, G.; Pilli, R.; Jonsson, K.; Blujdea, V.; Korosuo, A. and Vizzarri, M. (2021) 'Brief on the role of the forest-based bioeconomy in mitigating climate change through carbon storage and material substitution', in Sanchez Lopez, J., Jasinevičius, G. and Avraamides, M. (eds). European Commission, JRC124374.

- Haberl, H.; Sprinz, D.; Bonazountas, M.; Cocco, P.; Desaubies, Y.; Henze, M.; Hertel, O.; Johnson, R. K.; Kastrup, U.; Laconte, P.; Lange, E.; Novak, P.; Paavola, J.; Reenberg, A.; van den Hove, S.; Vermeire, T.; Wadhams, P.; and Searchinger, T. (2012) Correcting a fundamental error in greenhouse gas accounting related to bioenergy. Energy Policy 45: 18–23. https://doi.org/10.1016/j.enpol.2012.02.051

- Haines-Young, R. and Potschin, M (2013) Common International Classification of Ecosystem Services (CICES): Consultation on Version 4, August-December 2012, EEA Framework Contract No. EEA/IEA/09/003.

- Hammerle, F. M. (2011) The Cellulose gap (the future of cellulose fibers). Lenzinger Berichte 89.

- Hansen, A. J.; Spies, T. A.; Swanson, F. J.; and Ohmann, J. L. (1991) Conserving Biodiversity in Managed Forests. BioScience 41(6): 382-392. https://www.jstor.org/stable/1311745?seq=1https://www.jstor.org/stable/1311745?seq=1

- Härkönen, S.; Neumann, M.; Mues, V.; Berninger, F.; Bronisz, K.; Cardellini, G.; Chirici, G.; Hasenauer, H.; Koehl, M.; Lang, M.; Merganicova, K.; Mohren, F.; Moiseyev, A.; Moreno, A.; Mura, M.; Muys, B.; Olschofsky, K.; Del Perugia, B.; Rørstad, P. K.; Solberg, B.; Thivolle-Cazat, A.; Trotsiuk, V.; and Mäkelä, A. (2019) A climate-sensitive forest model for assessing impacts of forest management in Europe. Environmental Modelling and Software 115(February): 128–143. https://doi.org/10.1016/j.envsoft.2019.02.009

- Harmon, M. E. (2019) Have product substitution carbon benefits been overestimated? A sensitivity analysis of key assumptions. Environmental Research Letters 14(6). https://doi.org/10.1088/1748-9326/ab1e95

- Hemy, M. and Verheyen, K. (2007) Legacies of the past in the present-day forest biodiversity: A review of past land-use effects on forest plant species composition and diversity. Ecological Research 22(3): 361-371.

- Henttonen, H.M., Nöjd, P. and Mäkinen, H. (2017) Environment-induced growth changes in the Finnish forests during 1971–2010 – An analysis based on National Forest Inventory. Forest Ecology and Management 386 (15 February 2017): 22-36.

- Heräjärvi, H. (2019) Wooden buildings as carbon storages–Mitigation or oration? Wood Material Science and Engineering 14(5): 291–297. https://doi.org/10.1080/17480272.2019.1635205

- Hildebrandt, J., Hagemann, N. and Thrän, D. (2017) The contribution of wood-based construction materials for leveraging a low carbon building sector in Europe. Sustainable Cities and Society 34(June): 405–418. https://doi.org/10.1016/j.scs.2017.06.013

- Hlásny, T.; Krokene, P.; Liebhold, A.; Montagné-Huck, C.; Müller, J.; Qin, H.; Raffa, K.; Schelhaas, M-J.; Seidl, R.; Svoboda, M.; Viiri, H (2019) Living with bark beetles: impacts, outlook and management options. From Science to Policy 8. European Forest Institute.

- Hof, C.; Voskamp, A.; Biber, M. F.; Bohning-Gaese, K.; Engelhardt, E. K.; Niamir, A.; Willis, S. G.; and Hickler, T. (2018) Bioenergy cropland expansion may offset positive effects of climate change mitigation for global vertebrate diversity. PNAS 115(52): 13294-12399. https://www.pnas.org/content/115/52/13294

- Holling, C.S (1973) Resilience and stability of ecosystems. Ann. Rev. Ecol. Syst. 4: 1-23.

- Hudiburg, T. W.; Law, B. E.; Moomaw, W. R.; Harmon, M. E.; and Stenzel, J. E. (2019) Meeting GHG reduction targets requires accounting for all forest sector emissions. Environmental Research Letters 14(9): 095005.

- Humpenöder, F.; Popp, A.; Dietrich, J.P.; Klein, D.; Lotze-Campen, H.; Bonsch, M.; Bodirsky, B.L.; Weindl, I.; Stevanovic, M. and Müller, C. (2014) Investigating afforestation and bioenergy CCS as climate change mitigation strategies. Environmental Research Letters 9(6): 064029.

- Hurmekoski, E.; Jonsson, R.; Korhonen, J.; Jänis, J.; Mäkinen, M.; Leskinen, P.; and Hetemäki, L. (2018) Diversification of the forest industries: Role of new wood-based products. Canadian Journal of Forest Research 48(12); 1417–1432. https://doi.org/10.1139/cjfr-2018-0116

- Hurmekoski, E.; Myllyviita, T.; Seppälä, J.; Heinonen, T.; Kilpeläinen, A.; Pukkala, T.; Mattila, T.; Hetemäki, L.; Asikainen, A.; and Peltola, H. (2020) Impact of structural changes in wood-using industries on net carbon emissions in Finland. Journal of Industrial Ecology 24(4): 899–912. https://doi.org/10.1111/jiec.12981

- IPCC (2000) Land Use, Land-Use Change and Forestry – Special report in R.T. Watson, I. R. Noble, B. Bolin, N.H. Ravindranath, D.J. Verardo, D.J. Dokken (eds). Intergovernmental Panel on climate change, Meteorological Office: Bracknell, United Kingdom: 377.

- IPCC (2007) Intergovernmental Panel on Climate Change 4AR. Forestry. Chapter 9. in Metz, B.; Davidson, O.R.; Bosch, P.R.; Dave, R.; and Meyer, L.A. (2007) Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press: Cambridge, United Kingdom and New York, NY, USA.

- IPCC (2019) Summary for Policymakers. In: Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems in P.R. Shukla; J. Skea; E. Calvo Buendia; V. Masson-Delmotte; H.- O. Pörtner; D. C. Roberts; P. Zhai; R. Slade; S. Connors; R. van Diemen; M. Ferrat; E. Haughey; S. Luz; S. Neogi; M. Pathak; J. Petzold; J. Portugal Pereira; P. Vyas; E. Huntley; K. Kissick; M. Belkacemi; and J. Malley (eds). In press.

- IUCN (2004) Afforestation and Reforestation for Climate Change Mitigation: Potentials for Pan-European Action. IUCN.

- IUCN (2019a) Over half of Europe's endemic trees face extinction. IUCN News. 27/09/2019. https://www.iucn.org/news/species/201909/over-half-europes-endemic-trees-face-extinction

- IUCN (2019b) European Red List of trees. IUCN. Available from: https://portals.iucn.org/library/node/48512

- IUFRO (2009) Adaptation of Forests and People to Climate Change: A Global Assessment Report. IUFRO World Series Volume 22. 224.

- Jiang, M., Medlyn, B.E. and Ellsworth, D.S. (2020) the fate of cacrbon in a mature forest under carbon dioxide enrichment. Nature 580: 227-231.

- Jones, M. W.; Smith, A.; Betts, R.; Canadell, J. G, Prentice, I. C and Le Quéré, C. (2020) Climate change increases the risk of wildfires. Rapid Response Review, ScienceBrief.org. Available from: https://tyndall.ac.uk/sites/default/files/wildfires_briefing_note.pdf

- Jonsson, R.; Rinaldi, F.; Pilli, R.; Fiorese, G.; Hurmekoski, E.; Cazzaniga, N.; Robert, N.; and Camia, A. (2021) Boosting the EU forest-based bioeconomy: Market, climate, and employment impacts. Technological Forecasting and Social Change 163(June 2019): 120478. https://doi.org/10.1016/j.techfore.2020.120478

- Keenan, R.J. (2015) Climate change impacts and adaptation in forest management: a review. Annals of Forest Science 72(2): 145–167.

- Keenleyside, C. and Tucker, G. (2010) Farmland Abandonment in the EU: an Assessment of Trends and Prospects A report for WWF Netherlands by www.ieep.eu

- Klapwijk, M.J.; Hopkins, A.J.M.; Eriksson, L.; Pettersson, M.; Schroeder, M.; Lindelöw, Å.; Rönnberg, J.; Keskitalo, E.C.H.; and Kenis, M. (2016) Reducing the risk of invasive forest pests and pathogens: Combining legislation, targeted management and public awareness. Ambio 45(S2): 223–234.

- Khabarov, N.; Krasovskii, A.; Obersteiner, M.; Swart, R.; Dosio, A.; San-Miguel-Ayanz, J.; Durrant, T.; Camia, A.; and Migliavacca, M. (2014) Forest fires and adaptation options in Europe. Regional Environmental Change 16(1): 21–30.

- Knorr, W., Jiang, L. and Arneth, A. (2016) Climate, CO2 and human population impacts on global wildfire emissions. Biogeosciences 13(1): 267–282.

- Kovats, R.S.; Valentini, R.; Bouwer, L.M.; Georgopoulou, E.; Jacob, D.; Martin, E.; Rounsevell, M.; and Soussana. J.-F. (2014) 'Europe' in Barros, V.R.; C.B. Field, D.J. Dokken, M.D. Mastrandrea, K.J. Mach, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L.White (eds.) Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press: Cambridge, United Kingdom and New York, NY, USA: 1267-1326.

- Kremen, C. (2015) Reframing the land-sparing/land-sharing debate for biodiversity conservation. Annals of the New York Academy of Sciences 1355:52-76.

- Krumm, F., Schuck, A. and Kraus, D. (2013) Integrative management approaches: a synthesis in Kraus, D. and Krumm, F. (eds.) Integrative approaches as an opportunity for the conservation of forest biodiversity. European Forest Institute: 256–262.

- Krumm, F. and Vítková, L. (eds) (2016) Introduced tree species in European forests: opportunities and challenges. European Forest Institute.

- Krumm, F.; Rigling, A.; Bollman, K.; Brang, P.; Durr, C.; Gessler, A.; Schuck, A.; Schulz-Marty, T.; and Winkel, G. (2020) 'Synthesis: improving biodiversity conservation in European managed forests needs pragmatic, courageous and regionally-rooted mangement approaches' in Krumm, F., Schuck, A. and Rigling, A. (eds) How to balance forestry and biodiversity conservation - A view across Europe. European Forest Institute (EFI); Swiss Federal Institute for Forest, Snow and Landscape Research (WSL), Birmensdorf.

- Lachat, T.; Bouget, C.; Bütler, R.; and Müller, J. (2013) 2.2 'Deadwood: quantitative and qualitative requirements for the conservation of saproxylic biodiversity' in D. Kraus, and F. Krumm (Eds.), Integrative approaches as an opportunity for the conservation of forest biodiversity: European Forest Institute.

- La Porta, N.; Capretti, P.; Thomsen, I.; Kasanen, R.; Hietala, A. and Von Weissenberg, K. (2008) Forest pathogens with higher damage potential due to climate change in Europe. Canadian Journal of Plant Pathology 30(2): 177-195.
- Larrieu, L. and Gonin, P. (2008) L'Indice de Biodiversité Potentielle (IBP): une méthode simple et rapide pour évaluer la biodiversité potentielle des peuplements forestiers. Revue Forestière Française 60: 727-748.
- Larsen, J.B. (1995) Ecological stability of forests and sustainable silviculture. Forest Ecology and Management 73(1–3): 85–96.
- Larsen, J.B. (2009): Forestry between land use intensification and sustainable development: Improving landscape functions with forests and trees. Danish Journal of Geography 109: 191-195.
- Larsen, J.B. (n.d.) Integrating nature conservation in forest management – from global to local level [presentation, University of Copenhagen]: https://informar.eu/sites/default/files/pdf/rold/04Bo_Larsen_Integrating_nature_conservation__30-10-19.pdf
- Lennox, G.D.; Gardner, T.A.; Thomson, J.R.; Ferreira, J.; Berenguer, E.; Lees, A.C.; Nally, R.A.; Aragão, L.E.O.C.; Ferraz, S.F.B.; Louzada, J.; Moura, N.G.; Oliveira, V.H.F.; Pardini, R.; Solar, R.R.C.; Vaz-de Mello, F.Z.; Vieira, I.C.G.; and Barlow, J. (2018), Second rate or a second chance? Assessing biomass and biodiversity recovery in regenerating Amazonian forests. Global Change Biology 24(1): 5680-5694.
- Leskinen, P.; Cardellini, G.; González García, S.; Hurmekoski, E.; Sathre, R.; Seppälä, J.; Smyth, C. E.; Stern, T.; and Verkerk, H. (2018) Substitution effects of wood-based products in climate change mitigation. From Science to Policy, 7(November): 28. https://www.efi.int/publications-bank/substitution-effects-wood-based-products-climate-change-mitigation
- Lewis, S. L.; Wheeler, C. E.; Mitchard, E. T. A.; and Koch, A. (2019) Restoring natural forests is the best way to remove atmospheric carbon. Comment. Nature 568(7750): 25–28. https://doi.org/10.1038/d41586-019-01026-8
- Lindenmayer, D. B. and J. F. Franklin (2002) Conserving forest biodiversity: a comprehensive multi-scaled approach. Island Press.
- Lindner, M.; Green, T.; Woodall, C. W.; Perry, C. H.; Nabuurs, G. J.; and Sanz, M. J. (2008) Impacts of forest ecosystem management on greenhouse gas budgets. Forest Ecology and Management 256(3): 191–193. https://doi.org/10.1016/j.foreco.2008.04.005
- Lindner, M.; Maroschek, M.; Netherer, S.; Kremer, A.; Barbati, A.; Garcia-Gonzalo, J.; Seidl, R.; Delzon, S.; Corona, P.; Kolström, M.; Lexer, M.J. and Marchetti, M. (2010) Climate change impacts, adaptive capacity, and vulnerability of European forest ecosystems. Forest Ecology and Management 259(4): 698–709.
- Linser, S. and Wolfslehner, B. (2015) Meeting the Goals for European Forests and European 2020 Targets for Forests. Report on the Mid-term Evaluation of the Goals & Targets.
- Longobardi, P.; Montenegro, A.; Beltrami, H. and Eby, M. (2016) Deforestation Induced Climate Change: Effects of Spatial Scale. PLOS ONE 11(4): p.e0153357.
- Lopatka, J. (2019) Climate change to blame as bark beetles ravage central Europe's forests. [online] Available at: https://uk.reuters.com/article/uk-centraleurope-environment-barkbeetle/climate-change-to-blame-as-bark-beetles-ravage-central-europes-forests-idUKKCN1S21LE [Accessed 18 Aug. 2020].
- Luyssaert, S.; Marie, G.; Valade, A.; Chen, Y. Y.; Njakou Djomo, S.; Ryder, J.; Otto, J.; Naudts, K.; Lansø, A. S.; Ghattas, J.; and McGrath, M. J. (2018) Trade-offs in using European forests to meet climate objectives. Nature 562(7726): 259–262. https://doi.org/10.1038/s41586-018-0577-1
- Luyssaert, S.; Schulze, E. D.; Börner, A.; Knohl, A.; Hessenmöller, D.; Law, B. E.; Ciais, P.; and Grace, J. (2008) Old-growth forests as global carbon sinks. Nature 455(7210): 213–215. https://doi.org/10.1038/nature07276
- MackDicken, K.G. (2015) Global Forest Resources Assessment 2015: What, why and how? Forest Ecology and Management 352(7): 3-8.
- Madsen, K. and Bentsen, N. S. (2018) Carbon Debt Payback Time for a Biomass Fired CHP Plant—A Case Study from Northern Europe. Energies 11(4).
- Maes, J.; Teller, A.; Erhard, M.; Condé, S.; Vallecillo, S.; Barredo, J.I.; Paracchini, M.L.; Abdul Malak, D.; Trombetti, M.; Vigiak, O.; Zulian, G.; Addamo, A.M.; Grizzetti, B.; Somma, F.; Hagyo, A.; Vogt, P.; Polce, C.; Jones, A.; Marin, A.I.; Ivits, E.; Mauri, A.; Rega, C.; Czúcz, B.; Ceccherini, G.; Pisoni, E.; Ceglar, A.; De Palma, P.; Cerrani, I.; Meroni, M.; Caudullo, G.; Lugato, E.; Vogt, J.V.; Spinoni, J.; Cammalleri, C.; Bastrup-Birk, A.; San Miguel, J.; San Román, S.; Kristensen, P.; Christiansen, T.; Zal, N.; de Roo, A.; Cardoso, A.C.; Pistocchi, A.; Del Barrio Alvarellos, I.; Tsiamis, K.; Gervasini, E.; Deriu, I.; La Notte, A.; Abad Viñas, R.; Vizzarri, M.; Camia, A.; Robert, N.; Kakoulaki, G.; Garcia Bendito, E.; Panagos, P.; Ballabio, C.; Scarpa, S.; Montanarella, L.; Orgiazzi, A.; Fernandez Ugalde, O. and Santos-Martín, F. (2020) Mapping and Assessment of Ecosystems and their Services: An EU ecosystem assessment. EUR 30161 EN, Publications Office of the European Union. ISBN 978-92-76-17833-0, doi:10.2760/757183, JRC120383.
- Marquer, L.; Mazier, F.; Nielsen, A.B.; Sugita, S.; Trondman, A.-K.; and Leydet, M. (2018) Europe's lost forests: a pollen-based synthesis for the last 11,000 years. Nature Scientific Reports 8: 716. DOI:10.1038/s41598-017-18646-7
- Masson-Delmotte, V.; Zhai, P.; Pörtner, H.-O.; Roberts, D.; Skea, J.; Shukla, P. R.; Pirani, A.; Moufouma-Okia, W.; Péan, C.; Pidcock, R.; Connors, S.; Matthews, J. B. R.; Chen, Y.; Zhou, X.; Gomis, M. I.; Lonnoy, E.; Maycock, T.; Tignor, M.; and Waterfield, T. (eds) (2019) Global warming of 1.5°C An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. IPCC.

- Mélin, J. (2019) Bark beetle infestation in Europe. [online] Available at: https://www.europarl.europa.eu/doceo/document/E-9-2019-004240_EN.html [Accessed 18 Aug. 2020].
- McDermott, C. L.; B. Cashore, and P. Kanowski. (2010) Global environmental forest policies: An international comparison. Earthscan: Oxon.
- McDowell, N.G. and Allen, C.D. (2015) Darcy's law predicts widespread forest mortality under climate warming. Nature Climate Change 5(7): 669–672.
- Mendelsohn, R.; Prentice, I.C.; Schmitz, O.; Stocker, B.; Buchkowski, R.; and Dawson, B. (2016) The Ecosystem Impacts of Severe Warming. American Economic Review 106(5): 612–614.
- Moomaw, W. R., Masino, S. A. and Faison, E. K. (2019) Intact Forests in the United States: Proforestation Mitigates Climate Change and Serves the Greatest Good. Frontiers. Forests and Global Change 2(June): 1–10. https://doi.org/10.3389/ffgc.2019.00027
- Moreno, A., Neumann, M. and Hasenauer, H. (2017) Forest structures across Europe. Geoscience Data Journal 4(1): 17–28.
- Nabuurs, G.-J.; Verkerk, Pieter Johannes Schelhaas, M.-J.; González Olabarria, José Ramón Trasobares, A.; and Cienciala, E. (2018) Climate-Smart Forestry: mitigation impacts in three European regions. In Efi.Int (Issue April). https://www.efi.int/sites/default/files/files/publication-bank/2018/efi_fstp_6_2018.pdf
- Nabuurs, G. J.; Thürig, E.; Heidema, N.; Armolaitis, K.; Biber, P.; Cienciala, E.; Kaufmann, E.; Mäkipää, R.; Nilsen, P.; Petritsch, R.; Pristova, T.; Rock, J.; Schelhaas, M. J.; Sievanen, R.; Somogyi, Z.; and Vallet, P. (2008) Hotspots of the European forests carbon cycle. Forest Ecology and Management 256(3): 194–200. https://doi.org/10.1016/j.foreco.2008.04.009
- Nabuurs, G.J.; Delacote, P.; Ellison, D.; Hanewinkel, M.; Hetemäki, L.; Lindner, M.; and Ollikainen, M. (2017) By 2050 the mitigation effects of EU forests could nearly double through climate smart forestry. Forests 8(12): 1–14. https://doi.org/10.3390/f8120484
- Naudts, K.; Chen, Y.; McGrath, M. J.; Ryder, J.; Valade, A.; Otto, J.; and Luyssaert, S. (2016) Europes forest management did not mitigate climate warming. Science 351(6273): 597–601.
- Nielsen, A. T., Bentsen, N. S., Nord-Larsen, T. (2020) CO2 emission mitigation through fuel transition on Danish CHP and district heat plants – Carbon debt and payback time of CHP and district heating plant's transition from fossil to biofuel. IGN Report, November 2020. Department of Geosciences and Natural Resource Management, University of Copenhagen: Frederiksberg.
- Norwegian Meteorological Institute (2013) Extreme Weather Events in Europe: preparing for climate change adaptation. Available at: www.dnva.no
- Nota, K. and Parducci, L (2020) Early Holocene presences of Norway spruce (Picea abies L. Karst.) at high latitudes in Norway and Sweden: the genetic story of up to 9550 year old spruce clones in the Scandinavian mountains, EGU General Assembly 2020, Online, 4–8 May 2020, EGU2020-21385, https://doi.org/10.5194/egusphere-egu2020-21385
- O'Hara, K. L. (2006) Multiaged forest stands for protection forests: Concepts and applications. Forest Snow and Landscape Research 80(1): 45–55.
- Onida, M. (2020) Forest and forestry policy between the EU and its Member States. Elni Review 2020. Environmental Law Network International: Bingen, Germany. ISSN 1618-2502
- Osuri, A.M.; Gopal, A.; Shankar Raman, T.R.; DeFries, R; Cook-Patton, S.C. and Naeem, S. (2020) Greater stability of carbon capture in species-rich natural forests compared to species-poor plantations. Environmental Research Letters 15(3). https://doi.org/10.1088/1748-9326/ab5f75
- Pan, Y.; Birdsey, R.A.; Fang, J.; Houghton, R.; Kauppi, P.E.; Kurz, W.A.; Phillips, O.L.; Shvidenko, A.; Lewis, S.L.; Canadell, J.G.; Ciais, P.; Jackson, R.B.; Pacala, S.W.; McGuire, A.D.; Piao, S.; Rautiainen, A.; Sitch, S.; and Hayes, D. (2011) A Large and Persistent Carbon Sink in the World's Forests. Science 333(6045): 988–993.
- Pawson, S. M.; Brin, A.; Brockerhoff, E. G.; Lamb, D.; Payn, T. W.; Paquette, A.; and Parrotta, J. A. (2013) Plantation forests, climate change and biodiversity. Biodiversity and Conservation 22(5): 1203–1227. https://doi.org/10.1007/s10531-013-0458-8
- Pearson, T.R.H.; Brown, S.; Murray, L. and Sidman, G. (2017) Greenhouse gas emissions from tropical forest degradation: an underestimated source. Carbon Balance and Management 12(1).
- Pilli, R.; Grassi, G.; Kurz, W.A.; Moris, J.v.; and Viñas, R.A. (2016) Modelling forest carbon stock changes as affected by harvest and natural disturbances. II. EU-level analysis. Carbon Balance and Management 11(20). DOI: 10.1186/s13021-016-0059-4
- Pretzsch, J. (2005) Forest related rural livelihood strategies in national and global development. Forests, Trees and Livelihoods 15 (2):115-127. https://doi.org/10.1080/14728028.2005.9752515
- Primmer, E. (2011) Analysis of institutional adaptation: integration of biodiversity conservation into forestry. Journal of Cleaner Production 19(16):1822-1832.
- Prisley, S. P.; Gaudreault, C.; Lamers, P.; Stewart, W.; Miner, R.; Junginger, H. M.; Oneil, E.; Malmsheimer, R.; and Volk, T. A. (2018) Comment on 'Does replacing coal with wood lower CO2 emissions? Dynamic lifecycle analysis of wood bioenergy.' Environmental Research Letters 13(12). https://doi.org/10.1088/1748-9326/aaf203
- Pro, Silva (2012) Pro Silva Principles. Pro Silva – Association of European Foresters Practicing Management which follows Natural Processes.
- Puettmann, K.J., Wilson, S.M., Baker, S.C.; Donoso, P.J.; Drössler, L.; Amente, G.; Harvey, B.D.; Knoke, T.; Lu, Y.; Nocentini, S.; Putz, F.E.; Yoshida, T.; and Bauhus, J. (2015) Silvicultural alternatives to conventional even-aged forest management – what limits global adoption? Forest Ecosystems 2(8) https://doi.org/10.1186/s40663-015-0031-x

- Pugh, T. A. M.; Lindeskog, M.; Smith, B.; Poulter, B.; Arneth, A.; Haverd, V.; and Calle, L. (2019) Role of forest regrowth in global carbon sink dynamics. Proceedings of the National Academy of Sciences of the United States of America 116(10): 4382–4387. https://doi.org/10.1073/pnas.1810512116

- Rädler, A.T.; Groenemeijer, P.H.; Faust, E.; Sausen, R. and Púčik, T. (2019) Frequency of severe thunderstorms across Europe expected to increase in the 21st century due to rising instability. NPJ Climate and Atmospheric Science 2(1).

- Roberts, N.; Fyfe, R.M.; Woodbridge, J.; Gaillard, M.-J.; Davis, B.A.S.; Kaplan, J.O.; Marquer, L.; Mazier, F.; Nielsen, A.B.; Sugita, S.; Trondman, A.-K.; and Leydet, M. (2018) Europe's lost forests: a pollen-based synthesis for the last 11,000 years. Nature Scientific Reports 8: 716. DOI:10.1038/s41598-017-18646-7

- Rondeux, J.; Bertini, R.; Bastrup-Birk, A.; and Corona, P. (2012) Assessing deadwood using harmonized national forest inventory data. Forest science 58(3): 269-283.

- Ronzon, T.; Piotrowski, S.; M'barek, R.; Carus, M.; and Tamošiūnas, S. (2018) Jobs and wealth in the EU bioeconomy / JRC – Bioeconomics. European Commission, Joint Research Centre (JRC) [Dataset: https://datam.jrc.ec.europa.eu/datam/mashup/BIOECONOMICS/index.html]

- Rouault, G.; Candau, J.-N.; Lieutier, F.; Nageleisen, L.-M.; Martin, J.-C.; and Warzée, N. (2006) Effects of drought and heat on forest insect populations in relation to the 2003 drought in Western Europe. Annals of Forest Science 63(6): 613–624.

- Rüter, S.; Werner, F.; Forsell, N.; Prins, C.; Vial, E.; and Levet, A. L. (2016) ClimWood2030 'Climate benefits of material substitution by forest biomass and harvested wood products: perspective 2030'. Final report. In Thunen Report (Vol. 42). https://doi.org/10.3220/REP1468328990000

- Sabatini, F.M.; Burrascano, S.; Keeton, W.S.; Levers, C.; Lindner, M.; Pötzschner, F.; Verkerk, P.J.; Bauhus, J.; Buchwald, E.; Chaskovsky, O.; Debaive, N.; Horváth, F.; Garbarino, M.; Grigoriadis, N.; Lombardi, F.; Marques Duarte, I.; Meyer, P.; Midteng, R.; Mikac, S.; Mikoláš, M.; Motta, R.; Mozgeris, G.; Nunes, L.; Panayotov, M.; Ódor, P.; Ruete, A.; Simovski, B.; Stillhard, J.; Svoboda, M.; Szwagrzyk, J.; Tikkanen, O.-P.; Volosyanchuk, R.; Vrska, T.; Zlatanov, T.; and Kuemmerle, T. (2018) Where are Europe's last primary forests? Diversity and Distributions 24(10): 1426–1439.

- Sabatini, F.M.; Keeton, W.S.; Lindner, M.; Svoboda, M.; Verkerk, P.J.; Bauhus, J.; Bruelheide, H.; Burrascano, S.; Debaive, N.; Duarte, I.; Garbarino, M.; Grigoriadis, N.; Lombardi, F.; Mikoláš, M.; Meyer, P.; Motta, R.; Mozgeris, G.; Nunes, L.; Ódor, P.; Panayotov, M.; Ruete, A.; Simovski, B.; Stillhard, J.; Svensson, J.; Szwagrzyk, J.; Tikkanen, O.; Vandekerkhove, K.; Volosyanchuk, R.; Vrska, T.; Zlatanov, T. and Kuemmerle, T. (2020) Protection gaps and restoration opportunities for primary forests in Europe. Diversity and Distributions 26(12):1646-1662.

- San-Miguel-Ayanz, J. (2015) The Forest Information System for Europe (FISE) https://www.unece.org/fileadmin/DAM/timber/meetings/20151102/ToS_Meeting/12-FISE-SANMIGUELAYANZ.pdf

- San-Miguel-Ayanz, J.; Durrant, T.; Boca, R.; Maianti, P.; Libertá, G.; Artés-Vivancos, T.; Oom, D.; Branco, A.; de Rigo, D.; Ferrari, D.; Pfeiffer, H.; Grecchi, R. and Nuijten, D. (2020) Advance EFFIS Report on Forest Fires in Europe, Middle East and North Africa 2019, EUR 30222 EN, Publications Office of the European Union.

- Santini, A.; Ghelardini, L.; De Pace, C.; Desprez-Loustau, M.L.; Capretti, P.; Chandelier, A.; Cech, T.; Chira, D.; Diamandis, S.; Gaitniekis, T.; Hantula, J.; Holdenrieder, O.; Jankovsky, L.; Jung, T.; Jurc, D.; Kirisits, T.; Kunca, A.; Lygis, V.; Malecka, M.; Marcais, B.; Schmitz, S.; Schumacher, J.; Solheim, H.; Solla, A.; Szabò, I.; Tsopelas, P.; Vannini, A.; Vettraino, A.M.; Webber, J.; Woodward, S. and Stenlid, J. (2012) Biogeographical patterns and determinants of invasion by forest pathogens in Europe. New Phytologist 197(1): 238–250.

- Sathre, R. and Gustavsson, L. (2009) Using wood products to mitigate climate change: External costs and structural change. Applied Energy 86(2): 251–257. https://doi.org/10.1016/j.apenergy.2008.04.007

- Sathre, R. and O'Connor, J. (2010) Meta-analysis of greenhouse gas displacement factors of wood product substitution. Environmental Science and Policy 13(2): 104–114. https://doi.org/10.1016/j.envsci.2009.12.005

- Schlesinger, W. (2018) Are wood pellets a green fuel? Science 359(6382): 1328-1329.

- Schuldt, B.; Buras, A.; Arend, M.; Vitasse, Y.; Beierkuhnlein, C.; Damm, A.; Gharun, M.; Grams, T.E.E.; Hauck, M.; Hajek, P.; Hartmann, H.; Hiltbrunner, E.; Hoch, G.; Holloway-Phillips, M.; Körner, C.; Larysch, E.; Lübbe, T.; Nelson, D.B.; Rammig, A.; Rigling, A.; Rose, L.; Ruehr, N.K.; Schumann, K.; Weiser, F.; Werner, C.; Wohlgemuth, T.; Zang, C.S. and Kahmen, A. (2020) A first assessment of the impact of the extreme 2018 summer drought on Central European forests. Basic and Applied Ecology 45: 86–103.

- Schulz, T.; Krumm, F.; Bücking, W.; Frank, G.; Kraus, D.; Lier, M.; Lovrić, M.; van der Maaten-Theunissen, M.; Paillet, Y.; Parviainen, J.; Vacchiano, G.; and Vandekerkhove, K. (2014) Comparison of integrative nature conservation in forest policy in Europe: a qualitative pilot study of institutional determinants. Biodiversity and Conservation 23(14): 3425–3450.

- Searchinger, T.D.; Beringer, T.; Holtsmark, B.; Kammen, D.M.; Lambin, E.F.; Lucht, W.; Raven, P.; and van Ypersele, J.-P. (2018) Europe's renewable energy directive poised to harm global forests. Nature Communications 9(1).

- Searchinger, T. D.; Wirsenius, S.; Beringer, T.; and Dumas, P. (2018) Assessing the efficiency of changes in land use for mitigating climate change. Nature 564(7735): 249–253. https://doi.org/10.1038/s41586-018-0757-z

- Secretariat of the Convention on Biological Diversity (2009) Sustainable Forest Management, Biodiversity and Livelihoods: A Good Practice Guide. Montreal.

- Seidl, R.; Klonner, G.; Rammer, W.; Essl, F.; Moreno, A.; Neumann, M. and Dullinger, S. (2018) Invasive alien pests threaten the carbon stored in Europe's forests. Nature Communications 9(1).

- Seidler, R. (2017) Patterns of Biodiversity Change in Anthropogenically Altered Forests. https://doi.org/10.1016/B978-0-12-809633-8.02186-5
- Selva, N.; Chylarecki, P.; Jonsson, B-G.; Ibisch, P. L. (2020) Misguided forest action in EU Biodiversity Strategy. Science Letters 368(6498): 1438-1439.
- Silva, J. S.; Rego, F.; Fernandes, P.; and Rigolot, E. (2010) Towards integrated fire management: outcomes of the European project fire paradox.European Forest Institute.
- Siitonen, J. (2001) Forest Management, Coarse Woody Debris and Saproxylic Organisms: Fennoscandian Boreal Forests as an Example. Ecological Bulletins 49(49): 11-41.
- Shen, L., Worrell, E. and Patel, M. K. (2010) Environmental impact assessment of man-made cellulose fibres. Resources, Conservation and Recycling 55(2): 260–274. https://doi.org/10.1016/j.resconrec.2010.10.001
- Sherwood, H. (2019) Getting back to nature: how forest bathing can make us feel better. [online] The Guardian. Available at: https://www.theguardian.com/environment/2019/jun/08/forest-bathing-japanese-practice-in-west-wellbeing. [Accessed 14 May 2020].
- Smith, P.; Calvin, K.; Nkem, J.; Campbell, D.; Cherubini, F.; Grassi, G.; Korotkov, V.; Le Hoang, A.; Lwasa, S.; McElwee, P.; Nkonya, E.; Saigusa, N.; Soussana, J.-F.; Taboada, M.A.; Manning, F.C.; Nampanzira, D.; Arias-Navarro, C.' Vizzarri, M.; House, J.; Roe, S.; Cowie, A.; Rounsevell, M.; and Arneth, A. (2019) Which practices co-deliver food security, climate change mitigation and adaptation, and combat land degradation and desertification? Global Change Biology 26(3): 1532-1575.
- Sotirov, M. (2017) Natura 2000 and Forests – Assessing the State of Implementation and Effectiveness. What Science Can Tell Us. European Forest Institute. ISBN 978-952-5980-38-7.
- Sterman, J. D., Siegel, L. and Rooney-Varga, J. N. (2018) Does replacing coal with wood lower CO 2 emissions? Dynamic lifecycle analysis of wood bioenergy. Environmental Research Letters 13(12). https://doi.org/10.1088/1748-9326/aaa512
- Stokland, J.N., Siitonen, J. and Jonsson, B.G. (2012) Biodiversity in dead wood. Cambridge: Cambridge University Press: 509 pages. DOI:10.1017/CBO9781139025843.
- Storch, F., Dormann, C. F. and Bauhus, J. (2018) Quantifying forest structural diversity based on large-scale inventory data: a new approach to support biodiversity monitoring. Forest Ecosystems 5(34).
- Sultanova, R. R.; Gabdrahimov, K. M.; Khayretdinov, A. F.; Konashova, S. I.; Konovalov, V. F.; Blonskaya, L. N.; Sabirzyanov, I. G.; Martynova, M. V.; Isyanyulova, R. R.; and Gabdelkhakov, A. K (2018) Evaluation of Ecological Potential of Forests. Journal of Engineering and Applied Sciences 13: 6590-6596.
- Talberth, J. and Yonavjak, L. (2011) Forests at work: a new model for local land protection. WRI Issue Brief 3. World Resources Institute.
- The Forest Bathing Institute. (n.d.) About. [online] Available at: https://tfb.institute/about/ [Accessed 14 May 2020].
- Thompson, I.; Mackey, B.; McNulty, S.; and Mosseler, A. (2009) Forest Resilience, Biodiversity, and Climate Change. A synthesis of the biodiversity/resilience/stability relationship in forest ecosystems. Secretariat of the Convention on Biological Diversity, Montreal. Technical Series no. 43: 67 pages.
- Thompson, J. R., Spies, T. A. and Olsen, K. A. (2011) Canopy damage to conifer plantations within a large mixed-severity wildfire varies with stand age. Forest Ecology and Management 262(3): 355–360. https://doi.org/10.1016/j.foreco.2011.04.001
- Toivo, H. and Ignatius, J. (2019) Wood-based biochemical innovation systems : challenges and opportunities. Masters Thesis.
- Toppinen, A.; Pätäri, S.; Tuppura, A.; and Jantunen, A. (2017) The European pulp and paper industry in transition to a bio-economy: A Delphi study. Futures 88: 1–14. https://doi.org/10.1016/j.futures.2017.02.002
- Turco, M.; Rosa-Cánovas, J.J.; Bedia, J.; Jerez, S.; Montávez, J.P.; Llasat, M.C. and Provenzale, A. (2018) Exacerbated fires in Mediterranean Europe due to anthropogenic warming projected with non-stationary climate-fire models. Nature Communications 9(1): 1–9.
- UN (2010) Biodiversity loss brings ecological systems closer to a tipping point, Ban says. UN News. https://news.un.org/en/story/2010/05/339392-biodiversity-loss-brings-ecological-systems-closer-tipping-point-ban-says
- UNECE and FAO (2020) Who owns our forests? Forest ownership in the ECE region. United Nations and the Food and Agriculture Organisation of the United Nations. https://unece.org/DAM/timber/publications/2008976E_lastWeb.pdf
- UNECE (n.d.) Sustainable forest management in a green economy: Key findings. https://www.unece.org/fileadmin/DAM/timber/meetings/Sustainable_forest_management_in_a_green_economy_Key_findings_of_SOEF_2011.pdf
- UNEP (2011) Towards a Green Economy: Pathways to Sustainable Development and Poverty Eradication.
- UNEP (2012) Green Economy in the European Union: Supporting Briefing. https://ieep.eu/uploads/articles/attachments/071ec7ac-3e08-4d92-8b26-45a2254489c3/KNOSSOS_Green_Economy_Supporting_Briefing.pdf?v=63664509783
- University of Exeter (2018) Biodiversity loss raises risk of 'extinction cascades'. http://www.exeter.ac.uk/news/featurednews/title_640529_en.html

- Valade, A.; Bellassen, V.; Magand, C.; and Luyssaert, S. (2017) Sustaining the sequestration efficiency of the European forest sector. Forest Ecology and Management 405: 44–55. https://doi.org/10.1016/j.foreco.2017.09.009

- Veldman, J. W.; Aleman, J. C.; Alvarado, S. T.; Michael Anderson, T.; Archibald, S.; Bond, W. J.; Boutton, T. W.; Buchmann, N.; Buisson, E.; Canadell, J. G.; De Sá Dechoum, M.; Diaz-Toribio, M. H.; Durigan, G.; Ewel, J. J.; Wilson Fernandes, G.; Fidelis, A.; Fleischman, F.; Good, S. P.; Griffith, D. M.; Hermann, J.M.; Hoffmann, W.A.; Le Stradic, S.; Lehmann, C.E.R.; Mahy, G.; Nerlekar, A.N.; Nippert, J.B.; Noss, R.F.; Osborne, C.P.; Overbeck, G.E.; Parr, C.L.; Pausas, J.G.; Pennington, R.T.; Perring, M.P.; Putz, F.E.; Ratnam, J.; Sankaran, M.; Schmid, I.B.; Schmitt, C.B.; Silveira, F.A.O.; Staver, A.C.; Stevens, N.; Still, C.J.; Strömberg,

- C.A.E.; Temperton, V.M.; Varner, J.M.; and Zaloumis, N.P. (2019) Comment on 'The global tree restoration potential.' Science 366(6463): 2020. https://doi.org/10.1126/science.aay7976

- Verkerk, H. and Lindner, M. (2020) (The atlas of) Forest Management Practices in Europe: Managing Forests in the 21st century. Presentation by the European Forest Institute, 3-5 March 2020, Potsdam. https://www.pik-potsdam.de/en/institute/departments/climate-resilience/projects/project-pages/formasam/meetings/4/VerkerkLindner_AtlasForestManagement_day2_ShareYes.pdf

- Vilén, T.; Gunia, K.; Verkerk, P.J.; Seidl, R.; Schelhaas, M.-J.; Lindner, M.; and Bellassen, V. (2012) Reconstructed forest age structure in Europe 1950–2010. Forest Ecology and Management 286: 203–218.

- Vose, J.M.; James Samuel Clark, Luce, C.H.; Toral Patel-Weynand and Service, F. (2016) Effects of drought on forests and rangelands in the United States: a comprehensive science synthesis. Washington, D.C.: United States Department Of Agriculture, Forest Service, January: 114–133.

- Wainhouse, D. and Inward, D. J. G. (2016) The influence of climate change on forest insects in Britain. Forestry Commission – Research Note. ISBN: 978-0-85538-940-6.

- Watson, J. E. M.; Evans, T.; Venter, O.; Williams, B.; Tulloch, A.; Stewart, C.; Thompson, I.; Ray, J. C.; Murray, K.; Salazar, A.; McAlpine, C.; Potapov, P.; Walston, J.; Robinson, J. G.; Painter, M.; Wilkie, D.; Filardi, C.; Laurance, W. F.; Houghton, R. A.; Maxwell, S.; Grantham, H.; Samper, C.; Wang, S.; Laestadius, L.; Runting, R.K.; Silva-Chávez, G.A.; Ervin, J.; and Lindenmayer, D. (2018) The exceptional value of intact forest ecosystems. Nature Ecology and Evolution 2(4): 599–610. https://doi.org/10.1038/s41559-018-0490-x

- Winkel, G. (ed.) (2017) Towards a sustainable European forest-based bioeconomy – assessment and the way forward. https://www.efi.int/publication-bank/towards-sustainable-european-forest-based-bioeconomy-assessment-and-way-forward

- Winter, S. (2012) Forest naturalness assessment as a component of biodiversity monitoring and conservation management. Forestry: An international Journal of Forest Research 85(2): 293-304.

- Wolfslehner, B.; Linser, S.; Pülzl, H.; Bastrup-Birk, A.; Camia, A.; and Marchetti, M. (2016) Forest bioeconomy – a new scope for sustainability indicators. From Science to Policy 4. European Forest Institute. https://doi.org/10.36333/fs04

- World Bank (2013) Sustaining Forests and Livelihoods in a Changing World. 29 January 2013. https://www.worldbank.org/en/news/feature/2013/01/29/sustaining-forests-livelihoods-changing-world

- World Weather Attribution (2018) Heatwave in northern Europe, summer 2018. [online] Available at: https://www.worldweatherattribution.org/attribution-of-the-2018-heat-in-northern-europe/ [Accessed 17 August 2020].

- Xu, L.; Shi, Y.; Fang, H.; Zhou, G.; Xu, X.; Zhou, Y.; Tao, J.; Ji, B.; Xu, J.; Li, C.; and Chen, L. (2018) Vegetation carbon stocks driven by canopy density and forest age in subtropical forest ecosystems. Science of the Total Environment 631–632: 619–626. https://doi.org/10.1016/j.scitotenv.2018.03.080

- Zomer, R.J.; Trabucco, A.; Bossio, D.A. and Verchot, L.V. (2008) Climate change mitigation: A spatial analysis of global land suitability for clean development mechanism afforestation and reforestation. Agriculture, Ecosystems & Environment 126(1–2): 67–80.

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