European Environment Agency

The European biomass puzzle

Challenges, opportunities and trade-offs around biomass production and use in the EU

EEA Report 08/2023

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Luxembourg: Publications Office of the European Union, 2023

ISBN 978-92-9480-604-8
DOI 10.2800/834565

Cover design: © EEA
Cover image: © EEA; Images generated by Adobe Firefly, composition by EEA.
Layout: Formato Verde/EEA

Contents

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The following EEA staff members are acknowledged for their support in framing, writing and reviewing of the report based on their sectoral expertise: Annemarie Bastrup-Birk (forests), Markus Erhard (ecosystems), Ricardo Fernández (greenhouse gas inventories; energy), Hans-Martin Füssel (climate change impacts and adaptation); Andrea Hagyo (agriculture); Ybele Hoogeveen (ecosystems; circular economy); William Keeling (climate change mitigation); Gorka Mendiguren (digitalisation; climate change monitoring), Tobias Nielsen (circular economy); Christiana Photiadou (climate change impacts and adaptation); Dario Piselli (health and environment); Stephane Quefelec (building construction); Almut Reichel (waste, circular economy); Nicolas Robert (bioeconomy and forests); Friedrich Scherzinger (agriculture); Stephanie Schilling (transport); Tommaso Selleri (transport, aviation); Mihai Tomescu (renewable energy).

The EEA would like to acknowledge the work of external experts who contributed to the writing of Chapters 1, 2, 3 and 4 of the report: Lara Álvarez, Blandine Arvis and Adam Pitchard (Rambøll).

The EEA would like to thank the experts and stakeholders who provided comments on the draft versions of this report during the external consultation process. These include representatives of the European Commission, the Eionet national focal points from Belgium, Croatia, Denmark, Estonia, Finland, France, Germany, Hungary, Ireland, Latvia, Poland, Portugal, Slovakia, Slovenia, Spain, Sweden, and Türkiye.

Executive summary

Biomass is key to achieve the objectives of the European Green Deal. It is defined as vegetation that forms ecosystems, sequesters carbon, and provides food and feedstocks for a wide range of biobased materials in use in sectors such as construction, energy, transport, furniture and textile industries. There is strong competition for biomass because the same type of biomass can have multiple end-uses, including protecting it (non-use) for nature and biodiversity. The European Green Deal foresees biomass fulfilling several roles in relation to food and energy security, nature conservation, pollution reduction, and climate change mitigation and adaptation. However, scientific research indicates that not enough EU-sourced biomass will be available to fulfil all these envisaged roles in the future. This report highlights the challenges, co-benefits and trade-offs that must be understood and quantified so that biomass can help reach — and not hamper — the European Green Deal's objectives.

How is biomass used?

In the EU, we used 1.2 billion tonnes of biomass in dry matter in 2017. Of this, 50% was used for food, feed and bedding for livestock, 22% for bioenergy and 28% for materials. The bioenergy sector uses biomass either via direct combustion or for the production of biofuels. Biomass use in this sector has been growing since 2005 because of policy incentives and in 2021 biomass made up 56% of renewable energy consumed in the EU. Woody biomass is also used in construction, furniture manufacturing, paper production and packaging, and a diverse range of other industries that need biobased materials to operate.

Biomass is delivered by ecosystems. Its production and extraction can have positive or negative impacts on biodiversity, the condition of ecosystems, and their capacity to sequester carbon dioxide (CO_2) from the atmosphere. Therefore, the use of biomass needs to be balanced with ecosystem conservation needs.

How does policymaking impact biomass production and consumption?

EU policy has a fundamental role to play in how we use and manage biomass. It influences demand for biomass as a resource in different sectors and strengthens competition for it. Our analysis of policies under the European Green Deal shows that policy targets demand that biomass fulfils specific roles, which can be conflicting. This may increase the gap between biomass demand and supply by the EU's agricultural and forestry lands in the future if the appropriate policy incentives are not put in place. Ambitious greenhouse gas (GHG) emission reduction targets set under the EU's Fit for 55 package are connected to many sectoral policies. Using biomass as a substitute for fossil fuels and other carbon-intensive materials can support the decarbonisation process in the energy, transport and building sectors, for example. Yet, these policies can increase demand for biomass, which in turn can drive land use change and reduce stocks of the remaining, unharvested biomass left in ecosystems.

On the contrary, policies focusing on reducing the impacts of biomass production on biodiversity and ecosystems (e.g., the farm-to-fork strategy, the forest and biodiversity strategies, and the Nature Restoration Law) should benefit the quality and quantity of biomass left in nature. This may lead to a decrease in biomass supply for the bioeconomy and other purposes. Targets to increase and maintain carbon removals in the land use, land use change and forestry (LULUCF) sector combine nature and soil conservation (increased carbon stocks in living biomass and soils) and biomass harvesting, ideally for long-term storage in wood products.

Biomass, therefore, becomes a critical raw material. While it can support achieving short-term climate policy targets for 2030, long-term biomass supply as well as biodiversity and nature should not be threatened by increased biomass use.

Biomass for climate change mitigation

The role of biomass in climate change mitigation is complex. In recent decades, there has been an increased, policy-driven focus on biobased products as substitutes for fossil fuels and mineral-based carbon intensive materials. This is because substitution leads to lower emissions if biomass is grown, harvested and used in a sustainable manner.

Biomass used for energy generation is seen as carbon neutral because plants and trees can regrow and sequester CO_2 from the atmosphere. However, the process of regrowth can take several decades, while the use of biomass in energy via combustion releases significant amounts of CO_2 and other pollutants into the atmosphere over the short term. Data on biomass combustion for energy purposes, as reported in national GHG inventories, show an increase in CO_2 emissions of more than 250% between 1990 and 2020. This increased biomass combustion has helped to reduce fossil fuel consumption. However, there is a trade-off between reducing fossil fuel consumption and increasing air pollution due to higher emissions of particulate matter and volatile organic compounds. The data show that the use of solid biomass for bioenergy is very country specific and there are large differences between countries and how they use woody biomass, in particular.

Vegetation and soils are among the planet's major carbon sinks, meaning they are responsible for more carbon removals than emissions. Their contribution within the LULUCF sector has been recognised in EU climate policy. For the last 30 years, the EU's LULUCF sector has been a net sink, but this sink is decreasing because of various factors. These include the current state of the EU's forests and their age structure, the impacts of climate change, land use changes, the increased harvesting of wood for economic use – which includes bioenergy – and adaptation of the forest sector to climate change. Forest land and harvested wood products account for significant carbon removals, while cropland, grassland, wetlands, settlements and other lands contribute to net emissions and, therefore, require stronger actions to reduce related GHG emissions.

Different landscape types such as forest areas, intensive farmlands, semi-natural farmlands, and wetlands require different management solutions to reduce GHG emissions and increase carbon sequestration. Many of the management solutions have benefits for biodiversity, but they may have a negative impact on the amount of biomass available for extraction. For example, wetlands store large amounts of carbon in soils, and therefore are important to protect despite their low biomass productivity. If increasing biomass demand increases productivity within wetland areas or results in land use change, a significant amount of GHGs (methane) may be released. The size and geographical location of the area under production, the amount of harvest, and the intensity of production will determine how these different types of landscape deliver on various objectives.

Other challenges to consider related to biomass management

There are several other challenges related to biomass management to be considered by European society and policymakers in the context of the competition for biomass.

The availability of biomass is a significant challenge. Although the majority of biomass is produced in the EU, there are substantial regional differences in the balance between agricultural and forestry production in terms of both economic output and the products each country specialises in or can produce. These differences have implications for biomass supply and demand, flows and internal trade between EU Member States. In addition, more frequent and intense climate change impacts such as high summer temperatures, droughts, late frosts, storms, etc., threaten biomass production and the health and condition of ecosystems. In agriculture, this often results in a reduction in crop yields and deficits in soil moisture. In forests, climate change impacts on forest productivity and soil result in biomass and carbon losses. Evidence is growing that mono-species forests resulting from past management choices are more vulnerable to climate change impacts than diverse forests (in structure, composition and age).

These regional differences and the changing climate in the EU mean that biomass production in southern and central Europe will be more limited for some types of biomass, while other parts of Europe might experience increased production opportunities.

Another challenge is linked to the nature of biomass as a renewable resource, because it regrows although it is not an infinite resource. Its supply depends on natural growth rates, which vary between agricultural crops, grassland and trees. Therefore, it is critical to maintain biomass for ecosystem structure, functioning and biodiversity where needed, and to produce it sustainably and harvest it for use at a sustainable rate that allows for regeneration. Producing and harvesting biomass also potentially has impacts on surrounding habitats and biodiversity depending on the land use type, soil and management practices on both forestry and agricultural land. This means that environmental sustainability often requires limitations on the use of chemical inputs such as agricultural fertilisers or a reduction in livestock grazing density per hectare of grassland.

Academic papers on the potential of biomass production and use often point to land limitations in terms of biophysical boundaries. Increasing demand for food and biomass for other economic sectors heighten the risk of land use changes required to produce enough biomass. Expanding one type of biomass production for a particular use can lead to land use changes and additional pressure on ecosystems and their condition, including the amount of organic matter in the soil. Competition will also come from urban and other artificial land development, which leads to a decline in agricultural and forestry land around cities. This may result in trade-offs between long-term carbon removal and other ecosystem services, such as delivering biomass. This could have further impacts on ecosystems in countries exporting biomass to the EU. The global impact of EU biomass demand will depend on the types and volume of commodities that are traded, and where and how they are produced.

The way forward

The EU must decide how to prioritise biomass and for which purposes due to the different roles foreseen for biomass and the potential shortage of biomass supply in the future. Policy incentives need to strike a balance between using biomass to reach the 2030 European Green Deal targets while keeping ecosystems in good condition and maintaining their capacity to deliver biomass and carbon sequestration in the long term. What biomass feedstocks/products are to be prioritised and for which purposes needs to be evaluated against the economic and societal costs, and in relation to the following biomass functions highlighted in this report:

- remove CO_2 from the atmosphere by increasing carbon sequestration in Europe's ecosystems and ensuring long-term carbon storage both in living biomass and biomass products.
- reduce the climate change and environmental impacts of biomass production and consumption within and outside the EU and make biomass production systems more resilient to those impacts.
- replace fossil- and mineral-based materials in the European economy with bio-based materials and products to reduce GHG intensity/emissions.
- restore nature and biodiversity to maintain the diversity of European landscapes.
- re-use and recycle to make the best use of bio-based materials and products.

Decisions on biomass management are urgent. This is because the conditions of ecosystems that deliver biomass are, in general, not good and declining, and the forest carbon sink on which we rely so much to meet 2030 and 2050 climate targets has been on a declining trend in recent years. In addition, primary production sectors like agriculture and forestry are already experiencing climate change impacts that threaten carbon sinks and biomass production even more. Policy interventions on land use and land management, especially those affecting forests and agriculture, will deliver results over the next decades. When planning for 2030, 2050 and beyond, decisions are already needed today.

Significant knowledge gaps still exist, and they need to be addressed in order to understand how to manage and prioritise biomass. Better data on the quantities and types of biomass used for energy purposes and the impacts of biomass production on various environmental and climate aspects at the national level would provide more granular knowledge for policymakers. There is a significant amount of unreported wood in biomass flows, about which knowledge is required. Similarly, the lack of specific data on how we use 20% of agricultural biomass and the fact that plants can be used partly for bioenergy and partly for feed make it difficult to assess the exact quantity of crops and crop residues used for bioenergy. In addition, there are methodological challenges in projecting future climate change impacts on crops and forests. Available knowledge on the absolute impacts of climate change on specific crops or on forest productivity at the EU and Member State levels is inconclusive.

There are several policy responses needed to start addressing the biomass puzzle:

- Biodiversity enhancement and conservation objectives are needed to maintain a variety of European landscapes. Policies implementing EU-wide targets in the farm to fork, biodiversity and forest strategies should ideally specify which areas/ ecosystems contribute to these targets, and to what extent nature management and strict protection rules would allow for human interventions for biomass production and extraction.

- Policymakers need to ensure that the increasing demand for biomass for different uses does not lead to unsustainable practices in the EU and abroad.

- Using wood as a biobased material or using it as a source of energy does not deliver the same benefits. Once wood is burned it is not available for other uses. Policy incentives for a more cascading and circular use of wood could improve the climate benefits of harvested wood and increase wood supply, even though in the short term, this could reduce the amount of wood available for energy.

This report highlights several synergies and trade-offs in relation to land use, land management and biomass. A benefit for one stakeholder might be perceived as a disservice by another given the various stakeholders involved in or benefiting from land management and biomass. This means that the role of biomass in the European Green Deal is like a puzzle, where several challenges, co-benefits and trade-offs on biomass production and its intended uses need to be brought together. Opinions on the possible solutions to the European biomass puzzle differ between societal, economic and political stakeholders — not least those who are producing and consuming biomass. This report aims to contribute to the debate by providing facts and analysis that can be used to facilitate discussion between those different stakeholders.

1 Introduction

1.1 Why produce a report on the 'biomass puzzle'?

Biomass is a core element of many environmental and climate policies in the EU and is set to play a key role in the transition to a sustainable, climate-neutral economy. This assessment looks at the ways human society interacts with ecosystems that provide biomass, how biomass can help us reach our climate and environmental objectives, and how climate change might affect the EU's biomass production potential. The report also discusses key synergies and trade-offs in our use of biomass for different policy objectives. In this report, biomass is defined as all vegetation in ecosystems (including soil organic matter) and the biomass cycling through the economy as food and wood products, liquid and solid biofuels, biomaterials and biodegradable waste, and via other economic processes. Since most biomass is supplied by the agriculture and forestry sectors (respectively 68% and 27% of total EU biomass volume by dry weight in 2017 (Gurria et al., 2022; Avitabile et al., 2023)), these land use types are the key focus of the analysis in this report.

Box 1.1

Defining biomass

What is biomass?

Biomass refers to the biodegradable fraction of products, waste and residues of biological origin. It comes from agriculture, including vegetal and animal substances; forestry and related industries; fisheries and aquaculture; and the biodegradable fraction of industrial and municipal waste (EU, 2009). Biomass is produced in ecosystems through biological processes, with or without human intervention.

Carbon cycle and biomass

Plants use sunlight to convert nutrients into sugars and carbohydrates through the process of photosynthesis (Gough, 2011). Carbon dioxide (CO_2) also happens to be one of the nutrients essential for building plant elements such as leaves, roots and stems (Gorte, 2009). All parts of a plant contain carbon, but how it is distributed across a plant varies depending on species, age and growth pattern. The more photosynthesis takes place, the more CO_2 is converted into biomass. This leads to the plant absorbing more CO_2 from the atmosphere and sequestering it in plant tissues (vegetation) above and below ground (Gorte, 2009).

Carbon is also naturally released into the atmosphere by plants. This happens through plant respiration (where oxygen is taken in by plants at the same time as they release CO_2 via their tissues above and below ground) and the decomposition of dead organic matter (such as fallen trees or leaves) or other events (e.g. fires). The carbon cycle can therefore be summarised as the flow of carbon through plants, including carbon accumulation via sequestration, vegetative growth and the release of carbon when that vegetation breathes and dies (Gorte, 2009). Additionally, a substantial proportion of carbon is stored as dead biomass in soils, especially under anoxic conditions such as in wetlands and peatlands.

Humans have used biomass for energy, food and other purposes for thousands of years. Through harvesting biomass for these purposes, humans have changed European ecosystems by modifying original forest cover and creating semi-natural ecosystems (such as grasslands and heathlands) or highly modified ecosystems (such as urban areas). The use of fossil fuels, the invention of artificial nitrogen fertiliser and pesticides, and the adoption of industrial methods across manufacturing and much of farming have fundamentally changed our relationship with ecosystems and the way we use biomass over the last 150 years. This change in industrial methods across society has enabled increased production and more stable food supplies. However, it has also led to severe environmental problems, including climate change, soil and water pollution, and a substantial loss of biodiversity. As a consequence, many forest, grassland and heathland are now among the most threatened ecosystem types in the EU (EEA, 2022b).

The Industrial Revolution and the technological changes it spurred led to the use of materials other than biomass (e.g. fossil fuels, iron, steel) and deprioritised woody biomass, in particular for energy needs. This reduced demand, abandonment of farmland and targeted afforestation programmes contributed to increased forest cover across European landscapes in the 20th century. However, today the situation is reversing. As we try to wean our society off using fossil fuels and other carbon-intensive materials, we are increasing the use of biomass for many economic activities, including energy once again. The problem is that the intensity of this use is at a level that may threaten European ecosystems. Although biomass holds great potential to help us follow a more sustainable path, it must be used appropriately — or else we could damage the very resources that we hope will help us find our way out of the climate and biodiversity crisis.

In response to the climate and biodiversity crisis, the EU proposed a long-term strategy called the European Green Deal in 2019. It aims to reduce the EU's dependency on fossil fuels and enable it to become climate neutral by 2050 and beyond, while also supporting the development of more sustainable pathways for many economic sectors by moderating land use intensity, and protecting biodiversity, natural resources and human health. It combines various policy targets in a comprehensive and integrated manner; yet, how the policy targets will ultimately reinforce or compete with each other is still to be determined. By collecting facts about biomass origins and flows, this report increases awareness of the numerous roles and functions of biomass. In addition, it helps us understand related trade-offs and synergies and place them in the context of humanity's relationship with ecosystems and biomass use.

1.2 Land use, biomass and ecosystems

Natural ecosystems (such as undisturbed forests and peat bogs) are very rich in biodiversity and store carbon. However, human use of land has created additional types of ecosystems in Europe, mainly via different types of livestock grazing and biomass harvesting (for fodder, fuel, timber, etc.). Extensive traditional farming practices (and some types of forestry) created species-rich semi-natural ecosystems. However, because of the intensification of farming and forestry practices, nature-friendly farming and forestry represent only a small portion of land use today. Figure 1.1 shows the approximate share of land in Europe the various uses of land account for.

Figure 1.1 Current composition of land use and land cover in Europe

Source: FOREST: Top image © Juan Carlos Farias Pardo, Environment & Me/EEA and bottom © Brian Hennessy, Nature@work/EEA; SEMI-NATURAL and EXTENSIVE: © Ybele Hoogeveen; INTENSIVE: Top left, © Lee Scott, Nature@work/EEA, top right © Giulia Ballabio, Nature@work/EEA, bottom left © Alfred Albers, WaterPIX/EEA and bottom right © Katarzyna Kowalczewska; URBAN: © Blerta Meta, Environment & Me/EEA.

The illustration shows that, on the majority of current farm and forest land, land use has become so intense that substantial biodiversity loss has occurred. If humans apply measures such as fertilisation, drainage, irrigation and reduction of crop or tree species diversity to improve the productivity of land for economic reasons and to obtain more biomass for extraction, only a few species can survive (Kleijn et al., 2008).

The next dimension to consider is the type of ecosystem that is under human land use and that we want to extract biomass from. Different ecosystem types react differently to human influence, depending on whether they occur naturally or have been created via thousands of years of human intervention. There is hardly any area in Europe where ecosystems have not been influenced or even transformed by human land use (apart from some remote areas, e.g. in high mountains or the arctic). This means that nearly all main ecosystem types have different degrees of 'naturalness', or levels of human influence. The level of ecosystem transformation by land use (or other human impacts, such as pollution) is therefore a key factor to consider when assessing how biomass extraction impacts each ecosystem. Three different ecosystem groups can be distinguished: (1) natural ecosystems, (2) semi-natural ecosystems and (3) intensively managed ecosystems (anthropogenicecosystems). Their characteristics are described in Table 1.1.

Table 1.1 Review of ecosystem groups

Ecosystem group	Definition
Natural ecosystems	Natural ecosystems are those that existed before farming was introduced to Europe. These include natural forests, peat bogs, high mountain habitats, oceans, lakes and rivers. Unless strongly impacted by past human land use or fragmentation via infrastructure, drainage, pollution, fishing or other factors, they are generally rich in biodiversity and benefit from a reduction in or even total cessation of human intervention. This means that biomass extraction should be kept to a minimum or even stopped completely in such ecosystems.
Semi-natural ecosystems	Semi-natural ecosystems have been created by human land use over the last 10,000 years or so, mainly via different types of livestock grazing and biomass harvesting. They are nearly all linked to extensive farming practices but also include managed forest types, which are shaped by human interventions. Nearly all semi-natural ecosystems depend on a continuation of non-intensive land use; in other words, they require biomass extraction to exist if they are not to lose their species richness and semi-natural character.
Intensively managed ecosystems (anthropogenic)	Intensively managed ecosystems are those substantially transformed by human activity, e.g. wetland drainage, intensive cultivation and fertilisation. Key examples of such ecosystems include urban areas, intensively used farmland areas and some forest plantations, such as eucalyptus or mono-species conifer stands. They are generally species poor but well-adjusted to intensive biomass harvesting. They are also more susceptible to pest damage and other extreme events (e.g. forest fires).

Table 1.1 shows that interactions between land use and biodiversity are complex and vary between different ecosystem groups. The environmental impacts of different types of produced and extracted biomass also vary between the ecosystem groups. The size and location of the area affected by production and extraction and the intensity of biomass harvesting (in terms of the share of total biomass stock extracted and the method used) will determine how the different ecosystems are impacted. While this report does not fully explore the multitude of the various potential interactions, there are some general relationships that hold true in nearly all cases. The report uses four different landscape types for illustration: forests, intensive agricultural landscapes, semi-natural landscapes and wetlands. These landscapes were chosen because they are most relevant to agriculture and forestry land use, which are the focus of the analysis in this report. The four landscapes are characterised and discussed further in terms of land use intensity and biomass sourcing in Chapter 5.

1.3 Other environmental constraints related to biomass

While the previous section discussed the effects of different land use intensities on ecosystem types, this section briefly reviews other significant environmental limits related to biomass production and use. It focuses on land limitations, biomass growth rates, and impacts from climate change and global land use.

1.3.1 Limits on land supply

Academic papers on the potential of biomass production and use often point to land limitations in terms of biophysical boundaries (Muscat et al., 2020). One parcel of land cannot indefinitely satisfy competing demands such as increasing carbon storage and simultaneously increasing biomass harvest. This is particularly important considering the growing global demand for bioenergy, food and other uses of biomass, driven by an increasing world population (EC, 2019; Material Economics, 2021a). Expanding one type of biomass production for different uses can lead to land use changes and additional pressure on ecosystems and their condition, including soil organic matter. Competition will also come from urban and other artificial land development, which may lead to a decline in agricultural and forestry land around cities. This may result in trade-offs between long-term carbon removal and other ecosystem services, such as delivering biomass.

1.3.2 Ecosystem limits — vegetation growth rates

Biomass is a renewable resource, but it is not infinite. Its supply depends on natural growth rates, which vary between agricultural crops, grassland and forestry. In the case of forests in particular, biomass regrowth requires several years and is not guaranteed, especially under a changing climate. This means that the biomass supply is functionally finite; therefore, it is critical to harvest it at a sustainable rate that allows for regeneration (IEEP, 2021). Biomass harvesting should not exceed the natural growth rate needed to maintain biodiversity and ecosystem structure, functioning and productivity (Camia et al., 2018).

Producing and harvesting biomass also potentially impacts surrounding habitats and biodiversity, depending on the land use type, soil, and management practices on both forestry and agricultural land. Examples include intensive versus extensive farming and grazing, or disturbance of the landscape structure (e.g. from building road infrastructure or housing) (Gaudreault et al., 2016; Jager and Kreig, 2018). Examples of land management practices that take into account environmental sustainability include reducing the use of chemical inputs and fertilization as well as reducing livestock grazing density per hectares of grassland.

1.3.3 Climate limits — impacts on ecosystem productivity

Agriculture and forestry production depend on climate conditions, which are now in flux (Muscat et al., 2020). Changing weather conditions related to average temperatures, precipitation, extreme weather and climate events (e.g. droughts, floods, frost) are already influencing crop yields in many European regions (EEA, 2019) and lead to severe forest damage (Patacca et al., 2023). It is uncertain how climate change will impact future global biomass production and how the impact will be distributed. Intergovernmental Panel on Climate Change scenario modelling points to a significant global reduction in biomass production throughout the coming decades in some European regions (see Kovats et al., 2014; Chapter 4 of this report). This raises questions about whether the EU can sustain current levels of biomass production under more challenging climate conditions.

1.3.4 *Global limits — EU biomass demand impacts global land use and ecosystem change*

Increasing demand for food and biomass in the EU could generate changes in land use in order to produce enough biomass. This could further impact ecosystems in the EU and in countries exporting biomass to the EU. The global impact of EU biomass demand will depend on the types and volume of commodities that are traded, and where and how they are produced. The higher the demand from the EU for agricultural commodities in particular, the higher the risk of negative environmental impacts from land use change in other continents (Barreiro Hurle et al., 2021).

1.4 Biomass and climate change mitigation in the EU

This section explains the role biomass plays in reaching future climate change mitigation targets in the EU.

The European Green Deal strategy sets a pathway for a transition towards a climate-neutral and fossil fuel-free economy. The European Climate Law (EU, 2021) has turned the EU's objective of becoming climate neutral by 2050 into a legal commitment and set a new target of a decrease in greenhouse gas (GHG) emissions of at least 55% by 2030, compared with 1990 levels. To meet the EU climate commitment, the European Commission proposed a legislative package under the title 'Fit for 55' (EC, 2021), which is a set of proposals to revise and update the EU legislation accordingly. To reach the net GHG emissions target of 55%, reductions need to take place in the following areas:

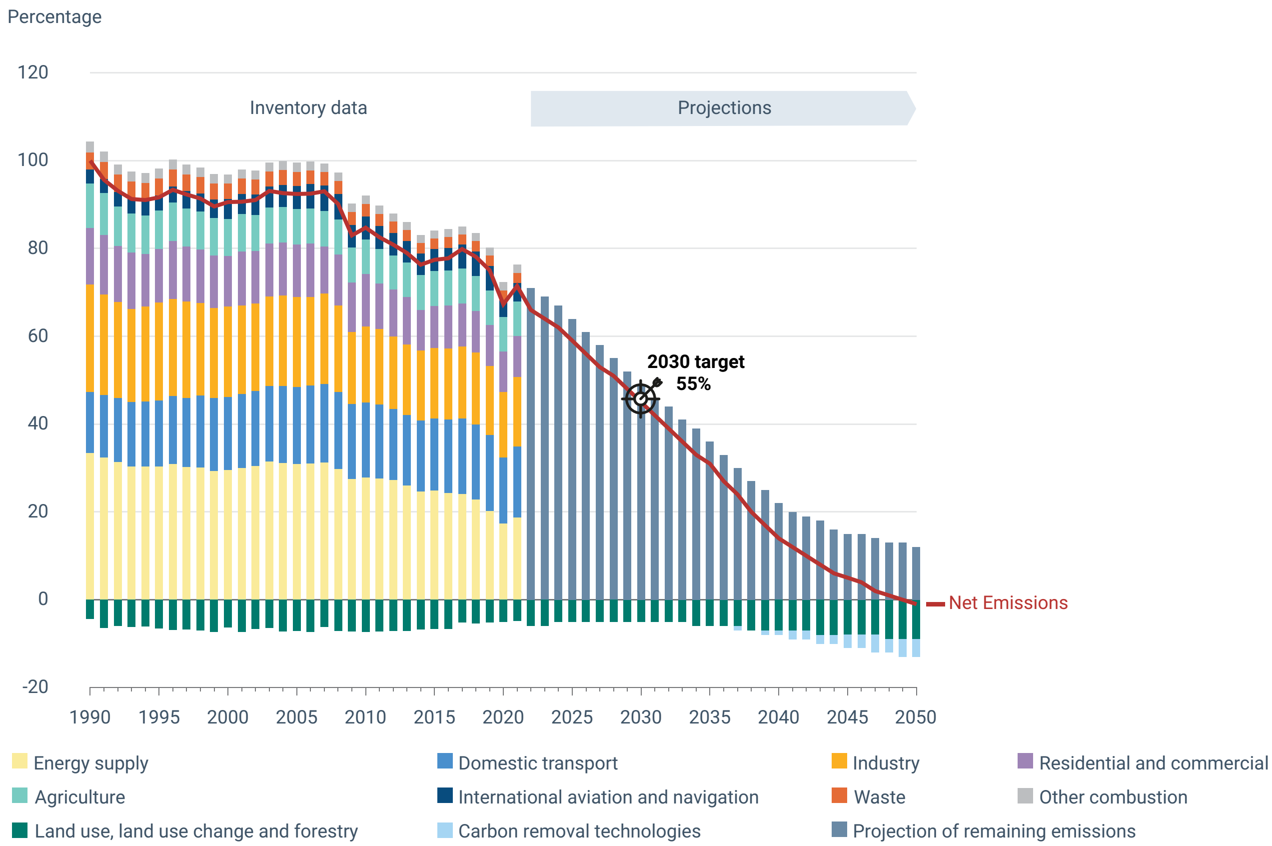
- the EU Emissions Trading System for energy-intensive industries (EU ETS);
- the transport, buildings, agriculture and waste sectors, as regulated by the Effort Sharing Regulation (EU, 2018), with a target of a 40% reduction in emissions by 2030, compared with 2005. The Effort Sharing Regulation amended by the Fit for 55 package sets new and binding 2030 targets for each Member State and defines annual national emission limits that progressively lead to achieving 2030 targets.

In addition, the LULUCF sector has a role to generate carbon removals through carbon sequestration in terrestrial ecosystems. The net carbon removal target of -310MtCO_2e for the entire EU (meaning the total sum of GHG emissions and carbon removals) has been set to contribute to the EU's overall 2030 climate target.

As illustrated in Figure 1.2, meeting the 2030 and 2050 targets requires significantly reducing present-day GHG emissions across many economic sectors. In addition, carbon removals in the LULUCF sector need to increase to compensate for emissions that cannot be further mitigated, mainly in the agriculture and industry sectors. Here, biomass may play a key role.

The total contribution of biomass to climate mitigation depends on the amount of carbon sequestered in ecosystems over time, the size of the carbon sink, the amount of carbon stored in wood products, the GHG emissions avoided by using biomass products instead of fossil fuels, and low-emission biomass production.

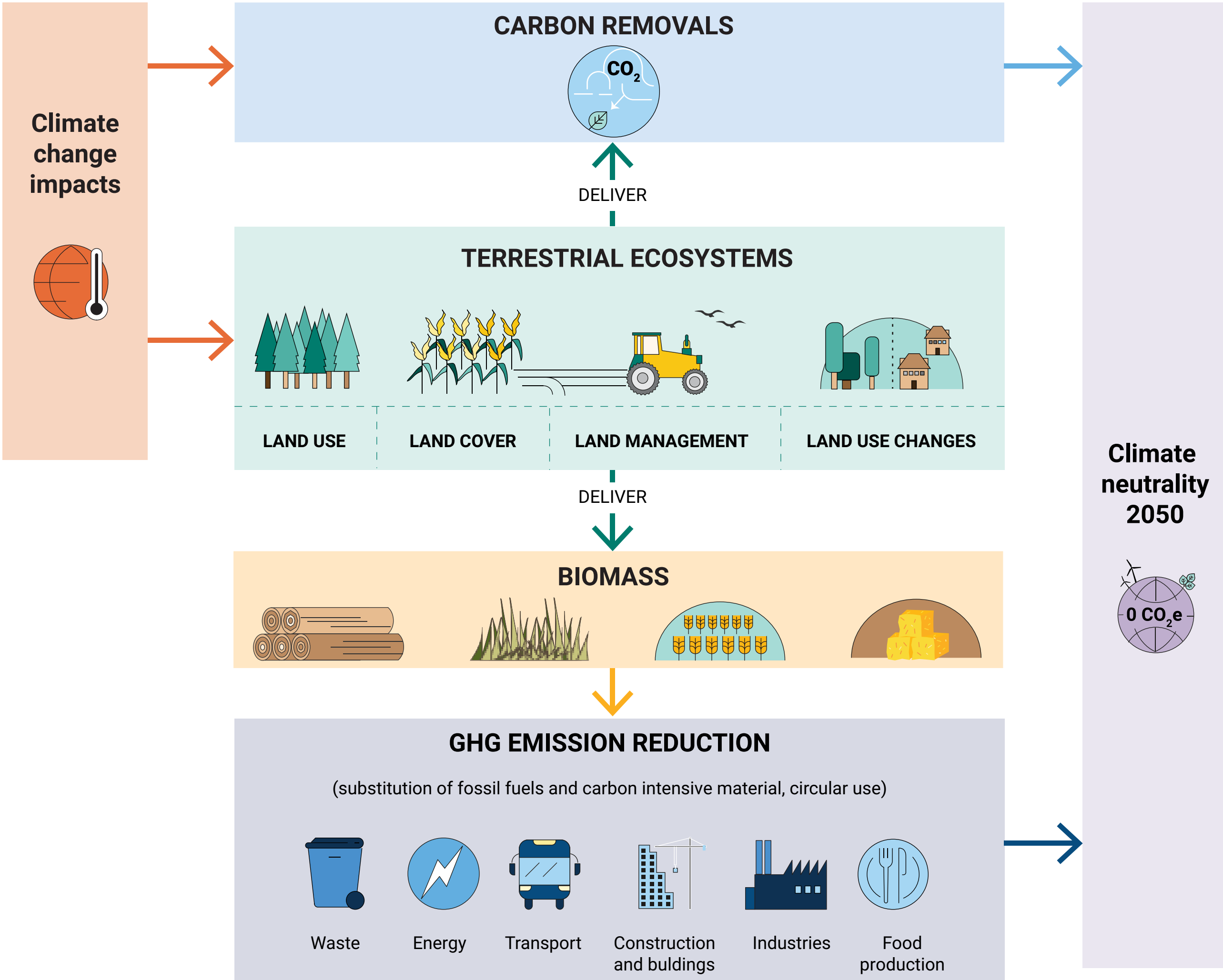
Figure 1.2 The pathway to climate neutrality



Source: EEA (2022c); EC (2020b).

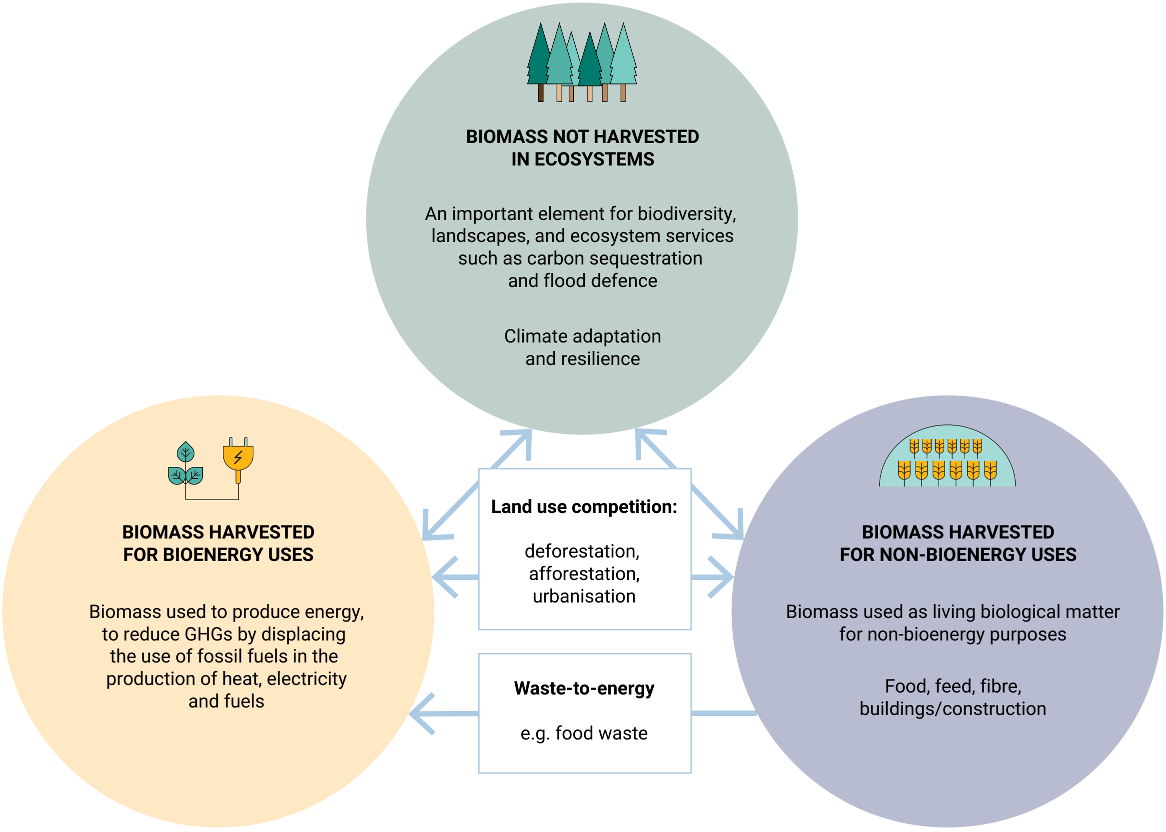
Figure 1.3 illustrates the complexity of the relationship between terrestrial ecosystems, biomass, and climate change mitigation. Since the same biomass resource can have multiple and often competing uses (EEA, 2013; Material Economics, 2021a), choices will need to be made about which types of biomass should be considered for what purpose; consideration will also need to be given to the impacts of such choices on GHG emissions. At the same time, biomass use can be a driver of land management, land use, and land use change, which has consequences for biodiversity and nature. In addition, climate conditions and climate change impacts determine which type of biomass can be grown and where. This requires land management to increase ecosystem resilience and protect against biomass losses. All of these land operations impact the amount of carbon that can be sequestered over time and the size (in terms of number of hectares) of a carbon sink.

Figure 1.3 **Biomass, climate change mitigation, and ecosystem dependencies**



Source: EEA.

Figure 1.4 Types of biomass uses



Source: EEA.

There are several different types of biomass use that are relevant for this report (Figure 1.4). Ecosystem biomass refers to plants and soils, which are the two largest terrestrial stores of carbon on land. Plants and trees represent a major carbon pool in terrestrial ecosystems: they have significant capacity to both accumulate and release carbon directly and also via their interaction with the soil. Soils store significantly more carbon than vegetation. To mitigate climate change, keeping and increasing biomass in some types of ecosystems is beneficial, as more carbon can be stored in vegetation and soils. In natural and anthropogenic ecosystem types (e.g. forests, intensive agricultural landscapes and wetlands) this also creates co-benefits for biodiversity. Wetlands store the largest amount of carbon per unit area, followed by forests (EEA, 2022a). Hence, carbon removals that can be achieved by the LULUCF sector have received significant attention, and their role in contributing to 2030 and 2050 climate targets is critical (as shown in Figure 1.2).

Non-bioenergy biomass is defined in this report as biomass for food and animal feed or biomass for material or industrial uses. Food and feed biomass products are almost entirely produced by the domestic (EU) agriculture sector. The agriculture and forestry sectors also produce many biomass materials for industrial uses, such as pulp and paper, timber and other fibre-based products, and straw for animal bedding. Wood-based materials are used for construction and furniture, particularly for solid wood products. In the construction sector wood products can replace more GHG-intensive materials such as cement and steel, and also plastics in packaging and building insulation (IEEP, 2021; Material Economics, 2021a). New biomass material uses are also expected to increase, such as textiles from human-made cellulosic fibres created from dissolved pulp, chemicals produced using biomass or biogenic CO_2 as a feedstock, and new bio-based materials created from fibres (IEEP, 2021).

Biomass is also used for bioenergy. Agricultural feedstocks are used for biofuels and biogas production. Biomass of woody origin is highly suited to energy production because of its high carbon content and relatively low water content, which makes it burnable. As a result, woody biomass is widely used to produce energy for power, heating and cooling. Since 2000, bioenergy use has increased by 150% in the EU (Material Economics, 2021a). This has largely been driven by policy incentives and commitments towards increasing renewable energy use across EU and Member States.

Biomass accounted for 56% (i.e. 125 million tonnes of oil equivalent (Mtoe)) of the overall EU's renewable gross final energy consumption in 2021. This share is not expected to decline very soon, because bioenergy is heavily relied upon for the EU's climate neutrality transition (EC, 2018a; EC, Joint Research Centre, 2019; Smith et al., 2021). This may put pressure on the agriculture and forestry sectors to scale up biomass production considerably. Scaling up the EU's overall renewable energy contribution will require a considerable amount of new bioenergy stock (demand) — perhaps doubling and potentially even tripling current biomass stock by 2050, according to some sources (EC, 2020a; Material Economics, 2021a).

Although using biomass as a source of energy and fuel can mitigate GHG emissions, its net effect will depend on the carbon intensity of the fuels displaced (e.g. fossil fuels) and broader decisions about its sourcing, production, transport, use and waste management (Giuntoli et al., 2022). In addition, EU legislation includes sustainability criteria for biofuels, aiming to reduce the risks of negative effects on the environment and climate (EC, 2018b). It also includes monitoring, reporting and verification mechanisms (MRVs) for the LULUCF sector for assessing how the sector is performing when it comes to delivering carbon removals and whether land resources are being used in a sustainable manner. These mechanisms are constantly revised and reinforced. Despite these criteria, data have shown that the LULUCF sink continues to decrease in the EU and bioenergy use is increasing. This triggers a debate about the extent to which biomass extraction for human use is sustainable, efficient biomass use, and the sustainability of biomass raw materials.

1.5 Motivation for and outline of the report

This report is a response to questions from the European Environment Agency's network and own staff on the increasing role of biomass in the European Green Deal. The motivation to write this report was related to one of a frequently asked questions: **can EU Member States sustainably produce (or source through trade) enough biomass for food, feed, energy, construction, and other purposes — while increasing their land capacity to sequester and store more carbon and maintaining or enhancing biodiversity?** Broader societal considerations are key to answer these questions, as they influence decisions around biomass production and biomass consumption.

As explained in this chapter, biomass is a key resource: vegetation that forms ecosystems, food, and feedstocks for biofuels and wide range of bio-based materials in use. There is a strong competition for biomass because the same biomass can have multiple end-uses, including non-use for nature and biodiversity. The European Green Deal foresees biomass to fulfil several roles in relation to food and energy security, nature protection and restoration, pollution reduction, and climate change mitigation and adaptation. In addition, the ecosystems delivering biomass are also affected by day-to-day management choices made by farmers and foresters responding to societal, economic and political trends as well as climate change. Ultimately, all of this means that the best way to deal with biomass is to treat it like a puzzle. This report does not solve the European biomass puzzle, but it highlights challenges, co-benefits and trade-offs that need to be understood and quantified so that biomass can help — not hamper — reaching objectives of the European Green Deal. What is known about many elements is summarised in answers to the following key questions (answers presented in chapter 6 of this report):

- How much biomass is estimated to be needed for the EU's economy in 2030 and 2050, and for which purposes?
- How does climate change currently impact total biomass production in the EU, and what is expected in the future?
- What are the ecological limits to increasing biomass use, and how can we limit the environmental impacts of biomass production?
- How do we make sure that the transition to a climate-neutral and circular economy remains sustainable over time?
- What are the expected environmental and climate co-benefits and trade-offs of biomass production and consumption?

The report consists of six chapters that address the following:

- Chapter 1 reviews key relationships between land use and biodiversity in the EU, describes how biomass is defined for the purpose of this report and reviews the role biomass plays in the context of climate targets.
- Chapter 2 provides key facts about biomass production and use in the EU, with a focus on the agriculture and forestry sectors.
- Chapter 3 discusses expectations placed on biomass in Europe, based on a review of current projections of future biomass supply and demand. It describes a selection of EU policies and targets, and potential complementary or conflicting impacts on biomass supply and demand.
- Chapter 4 discusses how climate change is likely to impact total EU biomass production.
- Chapter 5 discusses the role of terrestrial ecosystems in carbon sequestration. In addition, it illustrates how extracted biomass is a substitute for fossil fuel and contributes to reducing GHG emissions across different economic sectors.
- Chapter 6 presents conclusions of this report.

2 Biomass production and use in the EU

Key messages

- The majority of the EU's biomass supply is produced within the EU, and intra-EU trade plays a major role in this supply.
- The EU export of agricultural products was higher than import in terms of economic value in 2021. However, the agriculture sector is heavily dependent on soybean and soybean meal imports, in particular for animal feed.
- The main EU crops are cereal crops, such as wheat, maize, barley and oats, and non-cereal crops such as rape and sunflower. Production trends look stable and have increased for rapeseed and turnip rapeseed in the last 20 years.
- Agricultural biomass is used for animal feed and bedding (57%), plant-based food (13%) and biofuels (1.7%). Its use for producing fibres and other materials is increasing but is still minor. The use of 19% of supplied agricultural biomass is unknown or is partially lost.
- The use of woody biomass in the energy sector has increased as a result of policy incentives established to develop renewable energy. In 2017, direct and indirect energy uses accounted for almost 60% of all harvested woody biomass (according to the latest available biomass flows data set). In some Member States, the energy sector depends on wood products imported from other Member States and the rest of the world.
- Significant knowledge gaps remain, and there is a lack of available data from recent years on the origin and use of biomass. The use of 20% of all biomass is unknown, lost or discarded. Moreover, the quantity of unreported roundwood in the last years is increasing. These factors hinder proper analysis of biomass uses and their footprints.
- Over the past 5 years, the increase in roundwood production in some Member States can be attributed to natural disturbances (e.g. bark beetle infestations) that required large-scale salvage logging. As a result some country-level statistics showed a temporary increase in harvesting (e.g. Czechia and Slovenia in 2019-2020).

This chapter presents the state of knowledge on current and historical production, and current uses of land-based biomass in the EU. In addition, it provides an overview of the key environmental and climate impacts of biomass production. Furthermore, this chapter explores both agricultural and forestry biomass uses, and presents key categories of crops and forest products, supplemented by information boxes. Lastly, this chapter includes an overview of historical trade patterns of agricultural and forestry products.

In this chapter, the time series and most recent year of data presented depend on the timing and frequency of reporting obligations of statistical and other data reported by Member States, and the methodological settings of some data sets. This means that, for some elements, data from 2021 or 2022 were available; for others, the latest available data were a few years old.

Member States' capacity to produce land-based biomass depends on the amount of land available for production, the soil characteristics (e.g. richness, suitability) and the climatic conditions (including water availability, sunlight and temperature). It also depends on the crops or vegetation that grow (naturally or planted), the management techniques applied and other socio-economic factors (e.g. available labour force in rural areas). Agricultural/forestry productivity is also driven by economic conditions such as labour costs, machinery availability and incentives, which in turn are influenced by the overall economic structure. This results in a varying degree of agricultural and forestry development and competitiveness within the EU. Therefore, there are substantial regional differences between agricultural and forestry production, in terms of both economic output and the products each country specialises in or can produce. These regional differences in agriculture and forestry have ramifications for biomass supply, demand and flows.

2.1 Distribution and trends

2.1.1 Agricultural biomass in the EU: distribution and trends

European utilised agricultural area and output

In 2020, 157 million hectares (38% of total EU land area) were used for agricultural production by EU farms (Eurostat, 2023f). Approximately half (58.3%) of these were specialist crop farms, while around one quarter (21.6%) were specialist livestock farms. 19.3% were mixed farming systems (combining various crops and livestock) (Eurostat, 2023a).

In 2019, six countries held 69% of the EU's utilised agricultural area (UAA) (Eurostat, 2021c) and produced 70% of the 702.5 million tonnes (Mt) of dry matter produced in the EU: France, Germany, Italy, Spain, Poland and Romania (Gurria et al., 2022). These countries also contribute a similar proportion to the agricultural industry's value. Member States' agricultural output contributions vary widely because of differences in volumes, products and services offered, and prices received. France, Germany, Italy and Spain contributed over half (58.7%) of the EU-27's EUR 415 billion agriculture sector output value in 2020 (Eurostat, 2023c). Adding the output value from Romania and Poland, these six countries produced 69.1% of the total agricultural industry output value in 2020.

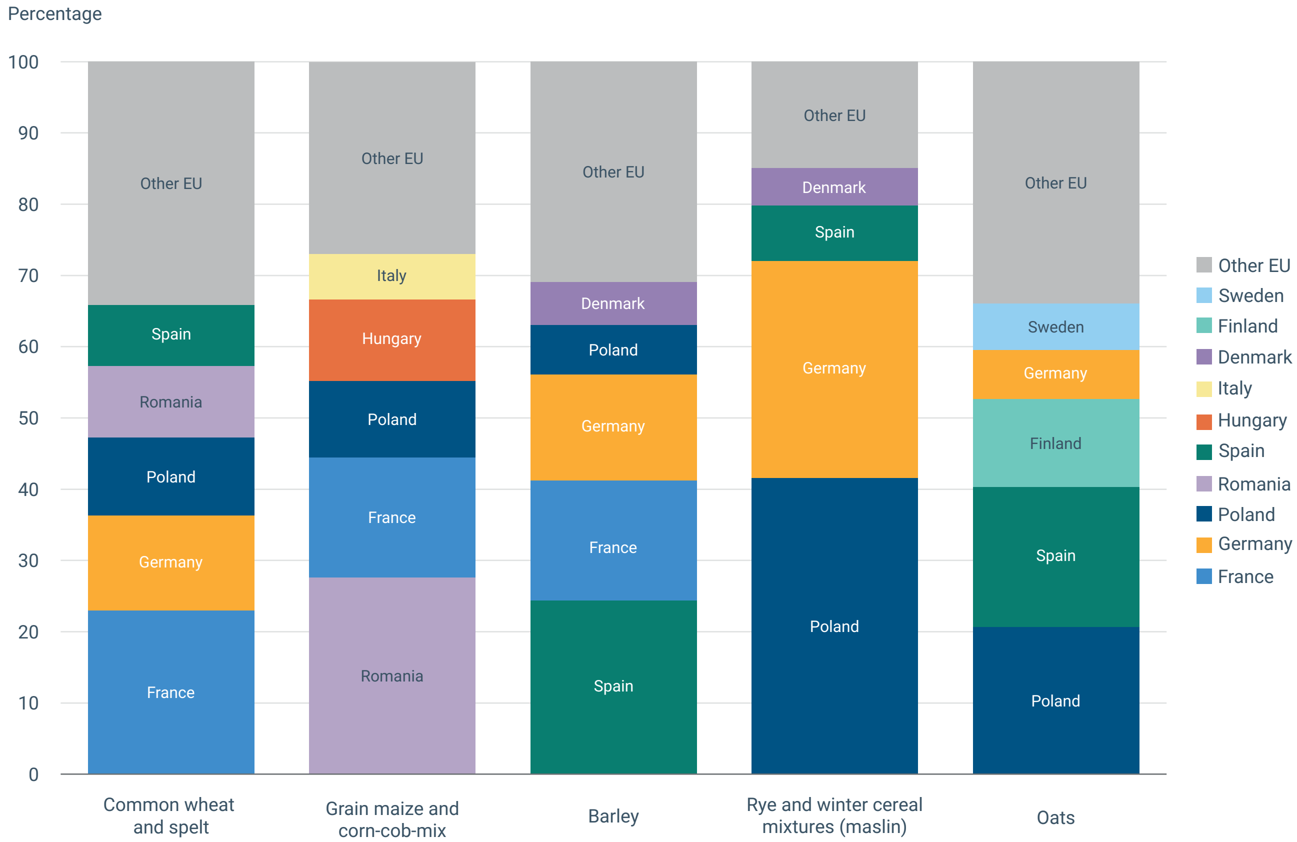
The gross output of EU agriculture has been growing since 2005, in both value (EUR billion at basic prices) and output volume (Eurostat, 2021b). The number of farms declined by approximately 37% between 2005 and 2020 (primarily due to the loss of farms under 5 hectares and an increase in farms over 100 hectares) (Eurostat, 2022e); however, the UAA remained relatively stable (+0.3%) (Eurostat, 2021c).

This growth in output can be attributed to increasing productivity and efficiency gains on larger farms, an increase in the economic value of agricultural products and technical progress, rather than an increase in total UAA. However, while overall agricultural output has increased, production trends for individual crops have experienced some annual variability. These trends are explored in more detail below.

Cereal crops

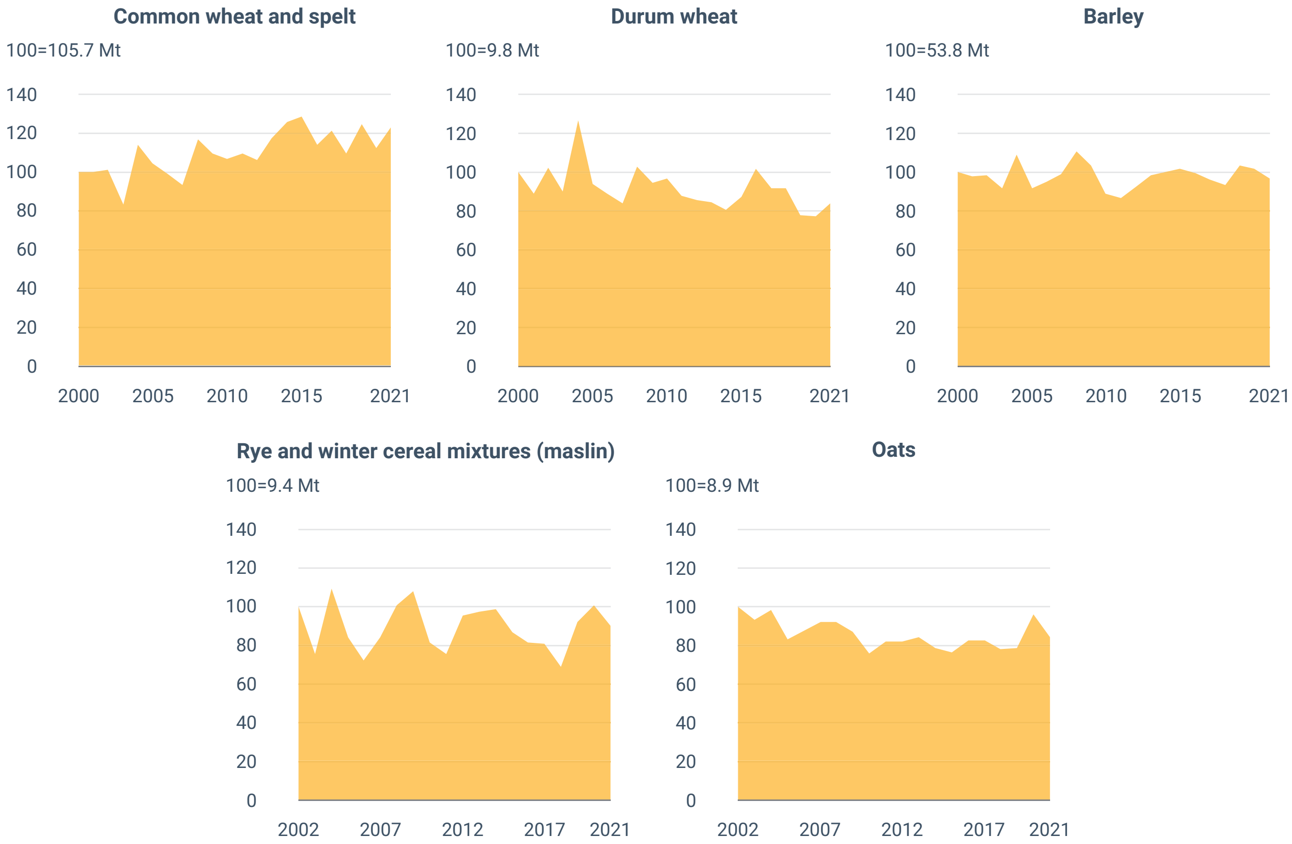
The main cereal crops are common wheat and spelt, grain maize and corn-cob mix, barley, oats, and rye and maslin (Table 2.1). Production of these crops is concentrated in relatively few Member States, including France, Germany, Poland, Romania and Spain (see Figure 2.1) (Eurostat, 2022a). The production trends between 2000 and 2020 for several of these crops were stable (Figure 2.2). A slight overall increase is shown for common wheat and spelt, while moderate decreases are shown for rye and maslin, and durum wheat, respectively. European drought years, or years with severe soil moisture deficits (EEA, 2021a), appear to have had little influence on overall production trends. However, annual variability can be seen for some crops due to various reasons, including droughts.

Figure 2.1 Cereal production by main Member State producers, 2021 (% share of EU-27 totals)



Source: Eurostat (2022a); online data code: apro_cpnh1.

Figure 2.2 **Cereal crop production developments in the EU-27 (2000=100 based on tonnage, EU, 2000-2020**



Source: Eurostat (2021b).

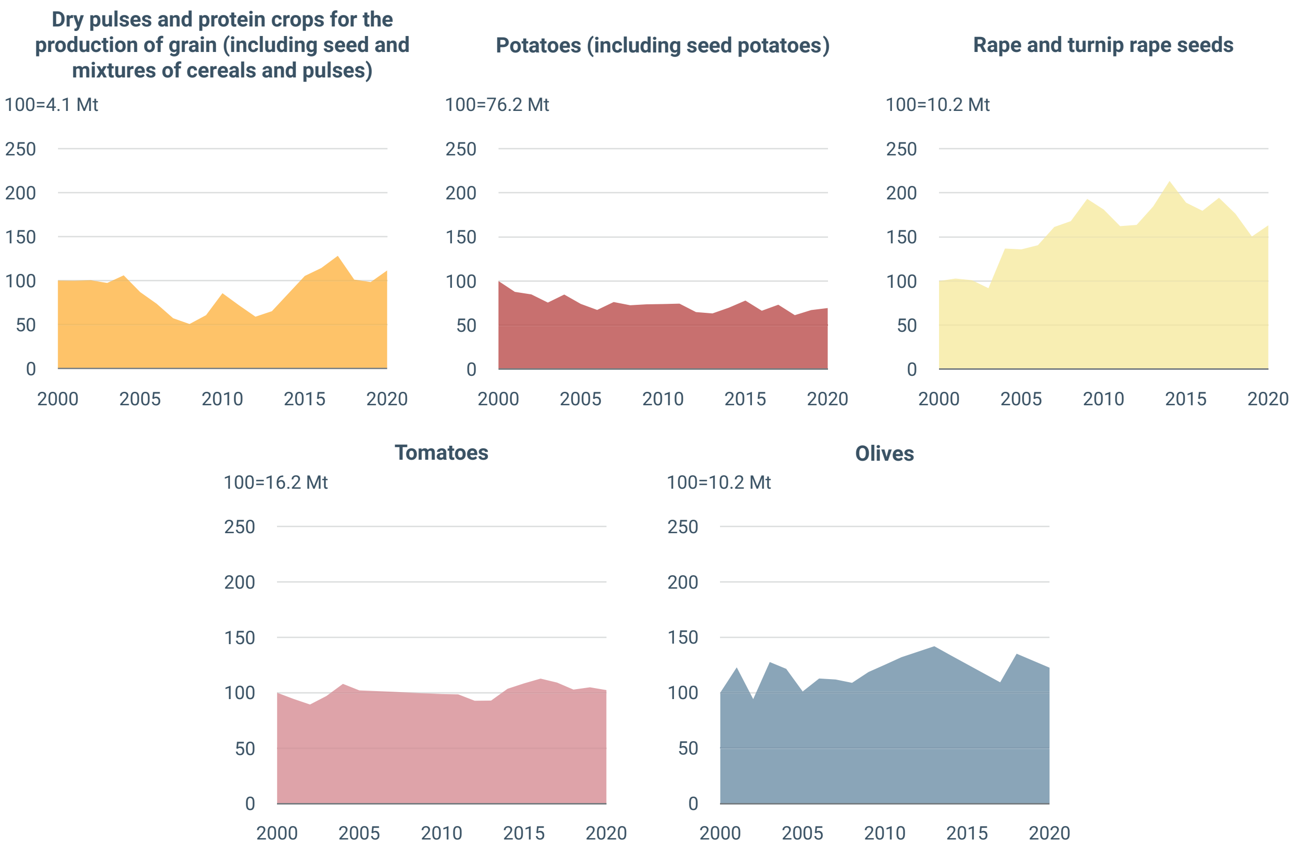
Non-cereal crops

The three main non-cereal crops produced in the EU are oilseeds — particularly rapeseed, but also sunflower, soya beans and linseed (Table 2.1). These crops were grown across 10.7 million hectares in 2021, mainly in France, Poland, Germany and Romania (Eurostat, 2022a).

Other crops grown on a significant scale in the EU are root crops, namely sugar beet (grown on 1.5 million hectares UAA in 2021) and potatoes (grown on 1.4 million hectares in 2021) (Eurostat, 2022a). Other root crops, such as fodder beet, fodder kale, fodder carrots and turnips, are grown on an estimated 0.1 million hectares (Eurostat, 2022a). Listed by production in tonnes, the top producers in 2019 of sugar beet and potatoes combined were France, Germany, Poland and the Netherlands (Eurostat, 2022a). Other specialist crops, such as fruits, remain concentrated in the southern region, in Member States including Spain, Italy and Greece (Eurostat, 2022a).

Production trends in non-cereal crops between 2000 and 2020 (Figure 2.3) show that the most significant increase was in rapeseed and turnip rapeseed. This has been attributed by Ortega-Ramos et al. (2022) to the introduction of EU Directive 2003/30/EC promoting biofuels (EU, 2003). Potato production fell by almost one third (Figure 2.3; Eurostat, 2022a).

Figure 2.3 **Non-cereal crop production developments in the EU-27 (2000=100 based on tonnage), EU, 2000-2020**



Source: Eurostat (2021b).

Table 2.1 Key crops produced in the EU-27 and their production statistics

Crop type	Land allocated to cultivation in 2021 (Mha)	Tonnage produced in 2021 (Mt)	Average yields in 2021 (t/ha)	Primary producers in the EU
Wheat (soft wheat and durum wheat)	24.0	138.1	6.0 for soft wheat 3.6 for durum wheat	France, Germany, Poland
Maize	9.2	73.5	7.9	Romania, France, Hungary, Poland
Barley	10.3	51.9	5.1	Spain, France, Germany
Oats	2.6	7.5	2.9	Poland, Spain, Finland
Rye and other winter sown cereals (triticale, sorghum)	4.7	20.4	4.1 for rye, 4.4 for triticale, 5.4 for sorghum	Poland, Germany, Spain
Oilseeds (rapeseed, sunflower, soya beans)	10.6	30.1	2.8	France, Poland, Germany
Root crops (sugar beet, potato)	2.9	167.8	57.9	France, Germany, Poland
Permanent crops for human consumption (all fruit trees, including citrus trees, nut trees, berry plantations except strawberries, vineyards and olive trees)	11.7	75.5	6.4	Spain, Italy, Poland
Fresh vegetables (including melons) and strawberries	2.1	66.8	31.8	Italy, Spain, Netherlands

Notes: Potatoes, permanent crops for human consumption and fresh vegetables are not included in the EC's short-term outlook statistics. For this reason, UAA and production (tonnage) data have been taken directly from the Eurostat data tables (Eurostat, 2022a), using the most recent date that incorporated the whole of the EU-27. Yields were calculated using the tonnage of crops divided by the UAA.

Mha, million hectares.

Mt, million tonnes.

t/ha, tonnes per hectare.

Sources: EC (2022); Eurostat (2022a).

Livestock and animal products

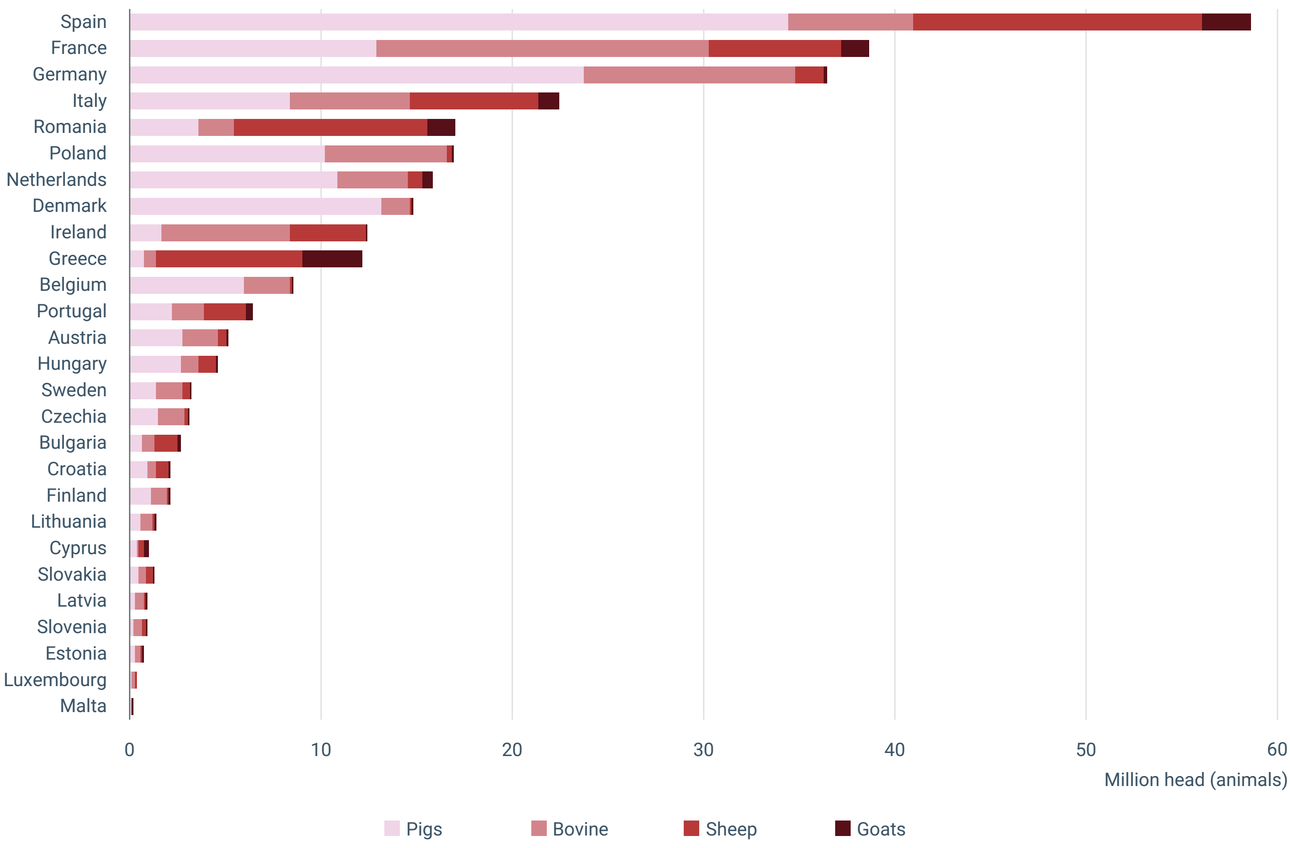
Approximately 297 million head of livestock were reared in the EU in 2020, split across pigs (146 million, producing 23.0Mt of pig meat carcasses), bovine animals such as cattle (76 million, 6.8Mt), and sheep and goats (75 million, 0.5Mt) (Eurostat, 2022b). Most livestock production is concentrated in just a few Member States, namely Spain, France and Germany (Eurostat, 2022b). A significant volume of poultry production is not included in these figures, but it is important to note.

The EU produced an estimated 13.6Mt of poultry meat in 2020, which was a new high, during the period from 2004-2020, there was a rapid and relatively uniform increase in the production of poultry meat, with EU production rising overall by 45.6%. (Eurostat, 2021b; Eurostat, 2022b). Poland, France, Spain and Germany accounted for the majority of poultry meat production (Eurostat, 2023g).

Specialisation in livestock production is apparent across the EU, with several smaller nations having significant specific herds. For example, Ireland accounted for 8.5% of the EU's bovine animals in 2020 (comparable with Spain, Italy or Poland's cattle herds) and Denmark accounted for almost as much of the EU's pig population as France, at around 9% each (Eurostat, 2022b). Additionally, Member States located further south contributed far more to the EU-27's sheep and goat herds. For example, Romania and Greece accounted for a significant volume of the EU's sheep population, despite rearing relatively low numbers of other livestock, and Greece has a disproportionally large share of the EU's goat herd (Eurostat, 2022b).

Figure 2.4 and Map 2.1 present an overview of livestock populations across the EU-27 and their densities. Livestock density measures the number of animals per hectare in a UAA (Eurostat, 2023e) and indicates the level of pressure livestock farming exerts on the environment. In other words, the higher the density, the more pressure on the environment.

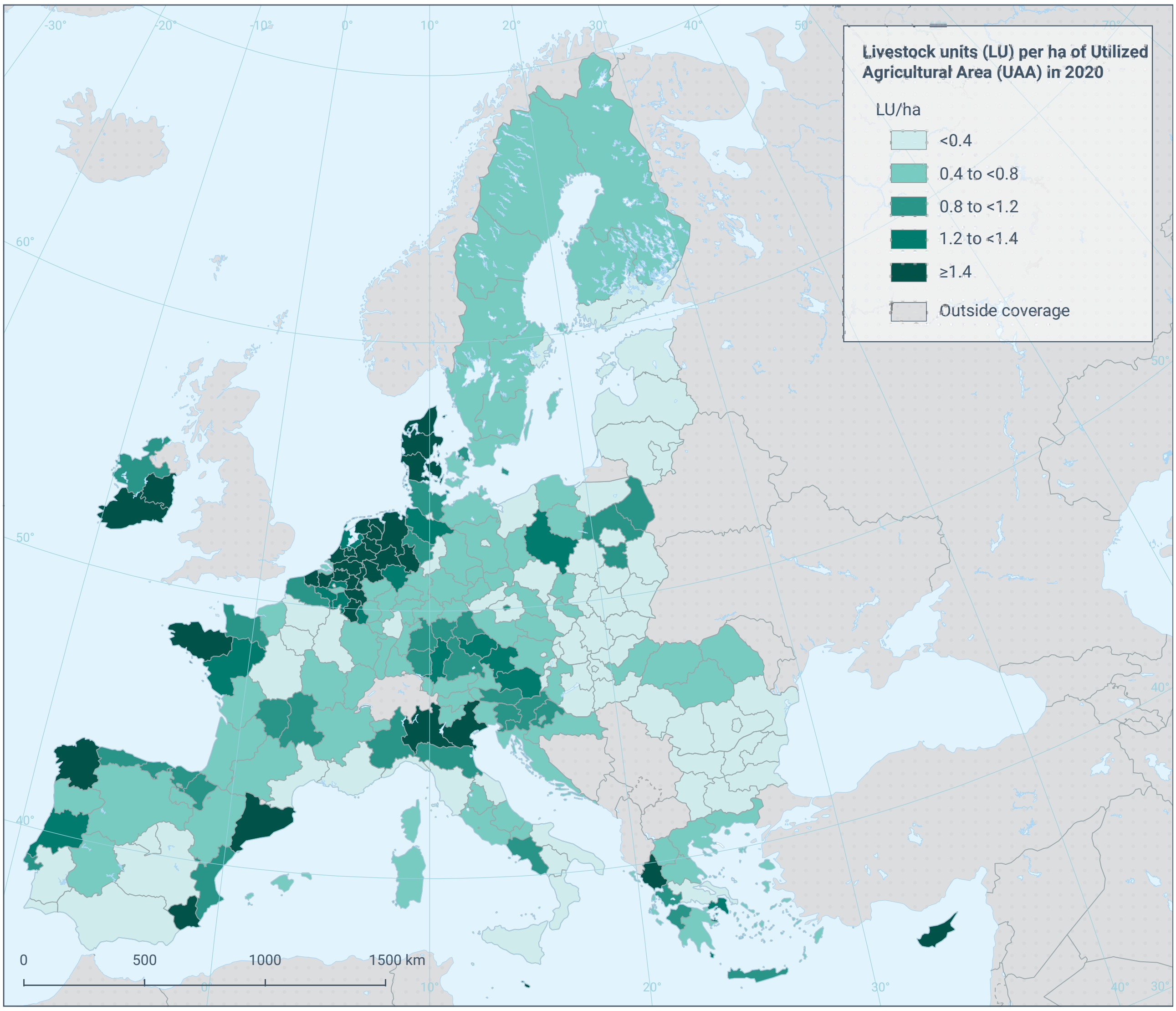
Figure 2.4 European livestock populations (million head, 2021)



Note: Includes estimates and provisional data, and 2019 data for sheep and goats where 2020 and 2021 data are unavailable.

Source: Eurostat (2022b); online data codes: apro_mt_lscatl, apro_mt_lspig, apro_mt_lssheep, apro_mt_lsgoat.

Map 2.1 Livestock density in 2020



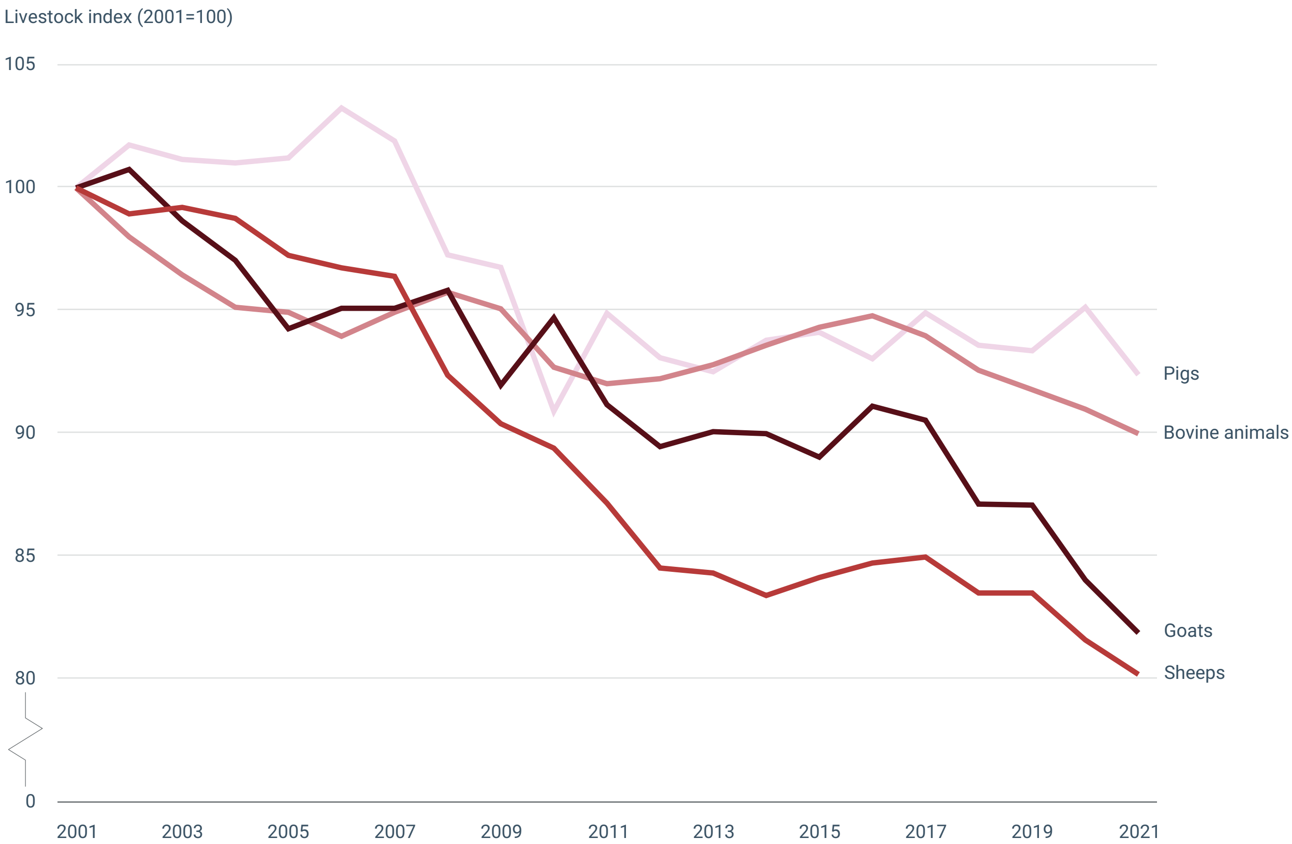
Reference data: © EuroGeographics, © FAO (UN), © TurkStat Source: European Commission – Eurostat/GISCO

Note: Livestock units per hectare of utilised agricultural area in 2020, EU NUTS 2.

Source: Eurostat (2020); online data codes: ef_lsk_main, ef_lus_main.

In the past 20 years, the EU's livestock population declined overall (Eurostat 2020, Figure 2.5). This decline applied to all major livestock populations but was most pronounced for the sheep population. In contrast, the fall in pig numbers was relatively modest, and numbers actually increased by 2.2% across the EU from 2019 to 2020 (Eurostat, 2020).

Figure 2.5 **Livestock population development in the EU-27 (2001=100 based on head of animals)**



Source: Eurostat (2020).

The EU's recent decline in livestock populations has not translated into reduced meat production and consumption. Excluding sheep and goat meat, which have exhibited downward trends (Eurostat 2020), EU meat production has remained either stable or has been on an upward trajectory since 2000. This has been driven by greater efficiencies in livestock farming methods and improvements in food and feed quality, according to Eurostat (2020). Poultry meat accounted for the biggest increase in the quantity of meat production. Similar increasing trends are seen for milk and other animal products (Eurostat, 2022f). Data on per capita meat consumption in EU countries between 2015 and 2022 shows an increase in meat consumption for many Member States (e.g. Italy, Germany, France, Poland) (Statista Research Department, 2021). Box 2.1 includes additional information on manure which is a by-product of the livestock sector.

Box 2.1

Manure and other organic fertilisers

Manure is defined by the Animal by-products Regulation (Regulation (EC) No 1069/2009) as 'any excrement and/or urine of farmed animals other than farmed fish, with or without litter', (EU, 2009) and by the Nitrates Directive (Directive 91/676/EEC) as 'waste products excreted by livestock: or a mixture of litter and waste products excreted by livestock, even in processed form' (EU, 1991; Köninger et al., 2021). Depending on the definition followed, approximately 1.42 billion tonnes of manure from farmed animals (primarily cattle) were produced annually from 2016-2019 in the EU-27 and UK. Ninety per cent of this was directly re-applied to soils as organic fertiliser. Excluding the United Kingdom, this amounts to 1.28 billion tonnes across the EU-27 (Köninger et al., 2021).

Manure and other organic fertilisers are widely used in agriculture, acting as valuable alternatives or supplements to mineral or inorganic fertilisers. In this role they promote plant growth, provide important nutrition to soil organisms, add genetic and functional diversity to soils and improve the chemical and physical soil properties, particularly through the important addition of nitrogen and phosphorus (Köninger et al., 2021). Mineral phosphorous fertilisers are particularly crucial to the agriculture sector, which accounts for approximately 80% of the mineral phosphorus used overall in the EU (Eurostat, 2022c). Its primary source is the non-renewable resource phosphate rock, which is concentrated in a few countries, none of them EU Member States. For this reason, phosphorous is on the list of critical raw materials for the EU (EC, 2014).

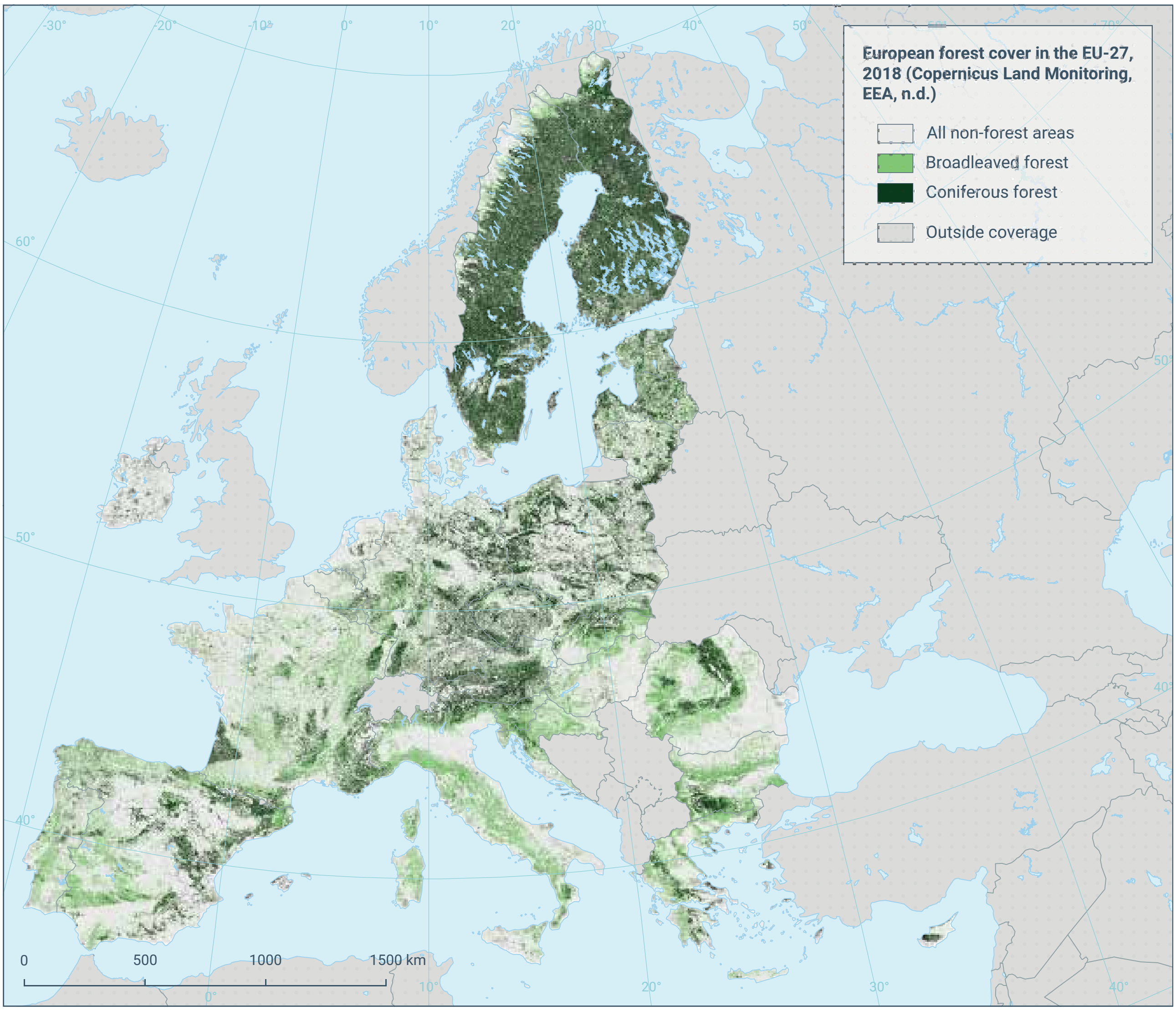
Despite many positive roles, excess application of manure on agricultural land can damage soils and cause eutrophication (due to high levels of nitrogen and phosphorus), which harms aquatic ecosystems (Singh, 2018; Zhang & Wang, 2020; (EEA, 2022a). Over-fertilisation with phosphorus can damage soils, leading to significant pollution even with limited new fertiliser inputs (Köninger et al., 2021; Geng et al., 2019). In Europe, there are episodes of eutrophication in seas and inland waters due to over-fertilisation (e.g. in Brittany (France) or Murcia (Spain)) with negative consequences for local ecosystems. Incorrectly used, manure can also introduce other toxic elements such as heavy metals, antibiotics and pathogens to both soils and water bodies via run-off, and can contribute to nutrient losses and damage soil microorganism biodiversity (Köninger et al., 2021). For this reason, the appropriate application of nutrient inputs from fertiliser or organic manure is crucial (EEA, 2022a). Limits on both appropriate timing and maximum loading is included under multiple pieces of EU legislation and policy such as the European Green Deal and its associated farm-to-fork strategy, the Nitrates Directive, the Water Framework Directive and the Common Agricultural Policy (EC, 2023d).

2.1.2 Forest biomass and its distribution across the EU

European forest cover

Forests covered approximately 39% (~159 million hectares) of EU land area in 2020 (Map 2.2; Eurostat, 2021a). The countries with the largest forested areas are Sweden, Finland, Spain, France, Germany and Italy, which account for over two thirds of total EU forest area (Eurostat, 2021a). In 2020, the growing stock of EU-27 forests available for wood supply was 27.2 billion m^3 (stemwood only and over bark) (Eurostat, 2021d). Germany, Sweden, France, Poland and Finland accounted for the largest share (Eurostat, 2021a; Hetemäki and Kangas, 2022).

Map 2.2 European forest cover in the EU-27, 2018



Reference data: © EuroGeographics, © FAO (UN), © TurkStat Source: European Commission – Eurostat/GISCO

Source: Copernicus Land Monitoring Service (EEA, 2023c).

Forest area has increased by approximately 10% in the EU since 1990 (Eurostat, 2021a). The change in forest area was positive in almost all Member States, with particularly strong increases in Spain, France and Italy (Map 2.3; Eurostat, 2021a). This change results from the afforestation of abandoned agricultural land and the change from other wooded land to forest and planting.

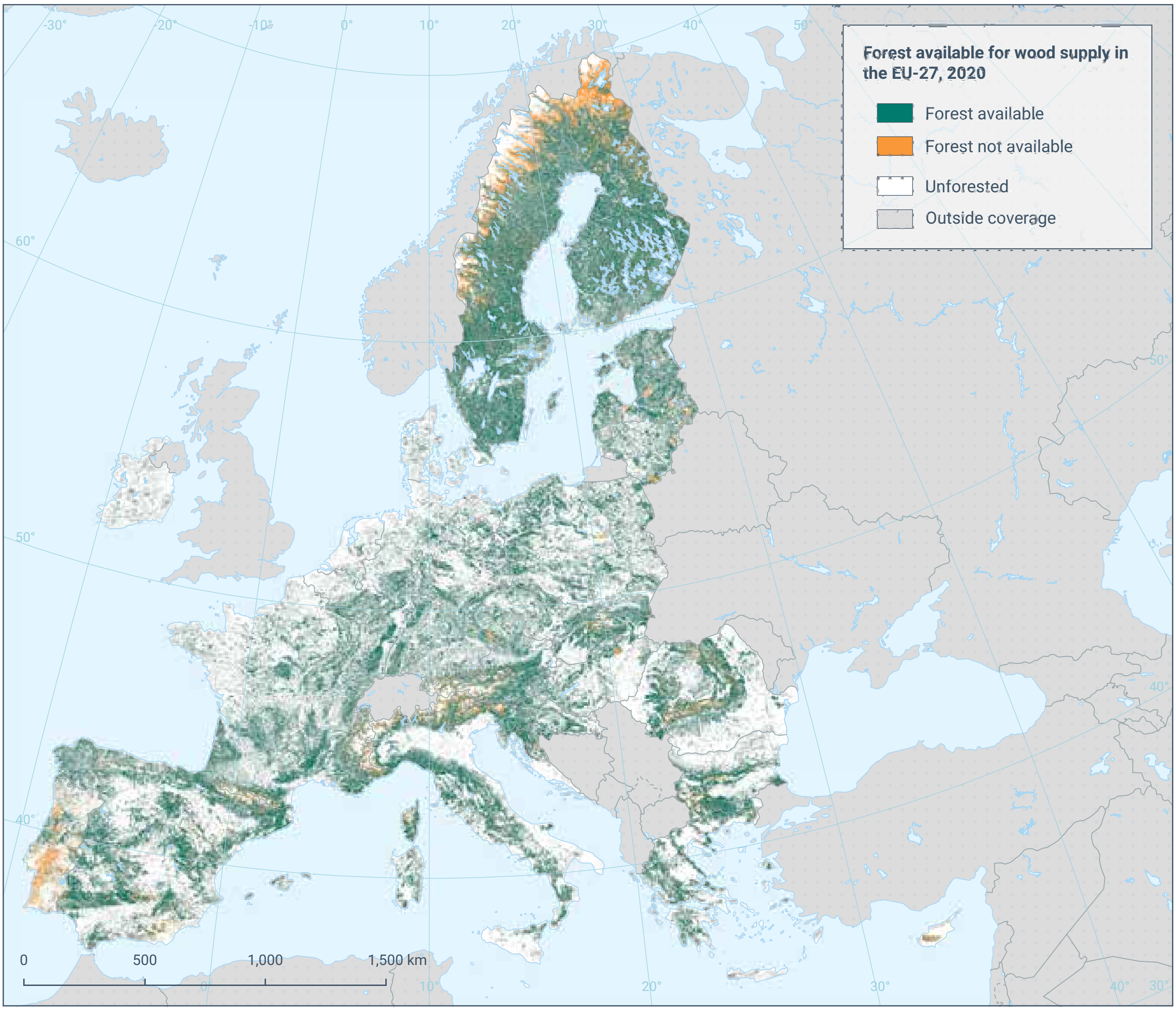
The volume of growing stock (indication of living trees) in EU forests increased by about 1% ([1]) per year between 2000 and 2020 (Eurostat, 2021a). This is the result of not only the increase in EU forest area, but also the proportion of ageing forest in many EU countries, as the volume of growing stock in old-growth forests is higher than that in young forests.

Forestry production and wood availability

Forestry as an economic activity incorporates the management, production and supply of wood and non-wood forest products and other ecosystem services from forests. Large northern European and mountainous Member States have an advantage because of the sheer area of woodland they possess. Forests cover more than two thirds of the land in Sweden (69%) and Finland (74%). In contrast, Ireland and the Netherlands have just 11% forest cover, and Malta just 1.5% (Eurostat, 2021a). However, other factors (besides forested area) also influence roundwood production, in particular land productivity and forest availability for wood supply. About 89% of EU-27 forest areas are considered available for wood supply (Avitabile et al., 2023). The remaining percentage is unavailable for harvest because of economic, environmental and social restrictions (Avitabile et al., 2020). The main restrictions to wood availability are economic, such as low profitability (particularly in northern and southern Europe), low accessibility and excessive slope of terrain. In terms of environmental restrictions, protected areas, habitats and species are the main factors that restrict biomass supply. Among social restrictions, recreational factors have the greatest influence on supply (Avitabile et al., 2020).

([1]) This value is conservative. There were breaks in the times series in some countries during the period. Moreover, for missing data, the imputation approach differed between countries. Therefore, national trends are not always known precisely.

Map 2.3 Forest available for wood supply in the EU-27, 2020

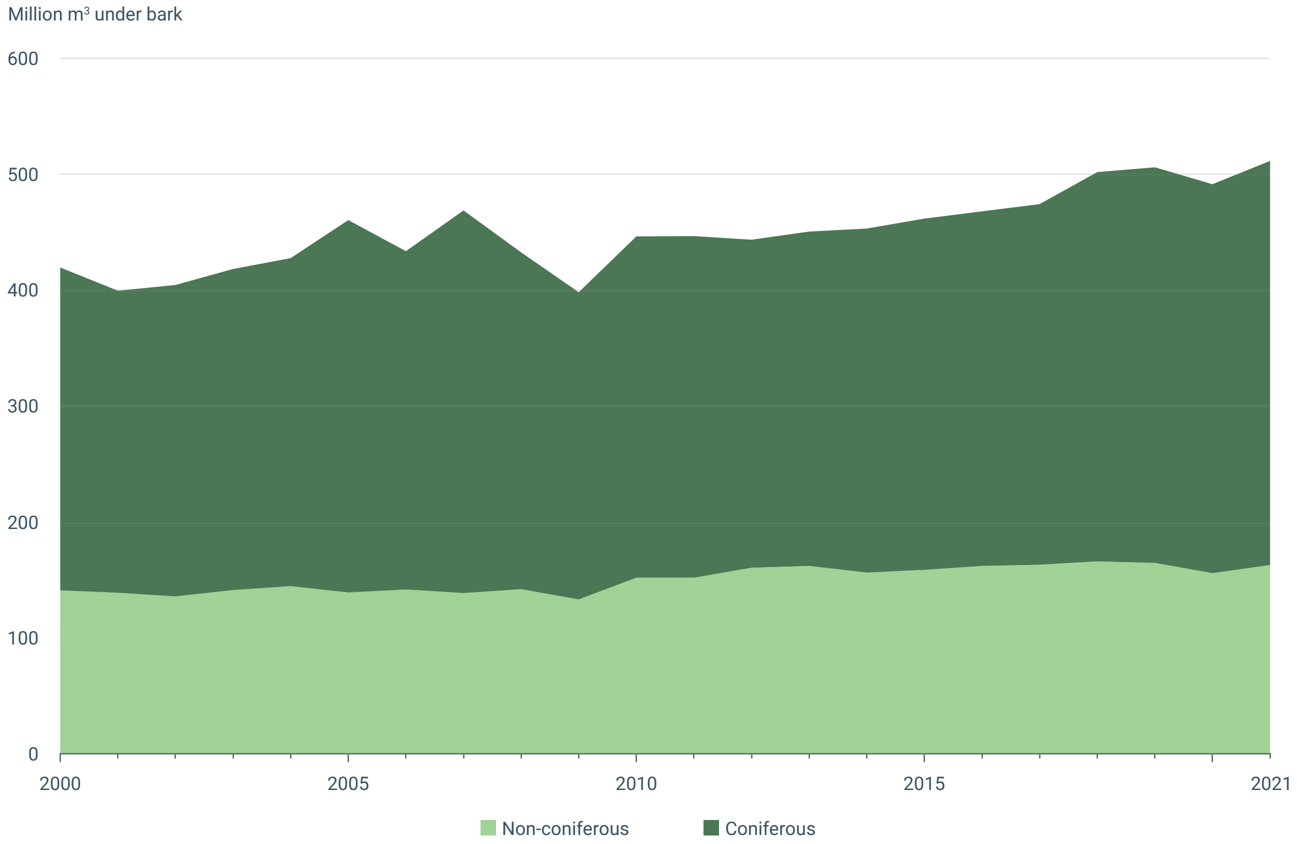


Reference data: © EuroGeographics, © FAO (UN), © TurkStat Source: European Commission – Eurostat/GISCO

Source: EEA adapted from Avitabile et al. (2023).

Roundwood production (507.2 million m^3 under bark in 2021 in the EU) is split into fuelwood (118.4 million m^3) and industrial roundwood (388.7 million m^3) (Eurostat, 2023h). Fuelwood includes wood harvested from main stems, branches and other parts of trees (that is normally of lower quality than roundwood used for industrial purposes) and wood that will be used directly as fuel, e.g. charcoal (in pit kilns and portable ovens), wood pellets and wood chips that are made directly (i.e. in the forest) from roundwood (Camia et al., 2021). The reported roundwood production in the EU increased by 25.6% from 2000 to 2021 (Eurostat, 2022g); for all species and by 27.5% for coniferous species. In 2021, coniferous species represented 69% of total roundwood production; the remainder was broadleaved species (see Figure 2.6).

Figure 2.6 **Annual roundwood production in the EU-27 (m³ under bark)**



Source: Eurostat (2022g); data code: for_remov.

Most of the coniferous wood is first used as industrial roundwood (90%). For broadleaved species, approximately 50% is used directly as wood fuel and 50% as industrial roundwood (FAOSTAT, 2023). These differences in use are mainly due to the trees' technical characteristics. Coniferous species, with their straight form and smaller branches, are easier to process in industrial systems compared with most broadleaved species. Lower quality pieces of softwood are also often used to produce pulp and boards because of their long fibres, whereas lower quality hardwood has fewer industrial uses.

Over the past 3 years, the increase in roundwood production in some Member States has been related to natural disturbances, such as storms, wildfires, droughts and bark beetle outbreaks. These have required large-scale salvage logging. This led to a temporary increase in harvesting at the country level (e.g. in Czechia and Slovenia in 2019-2020).

2.1.3 Biomass production impacts on the environment and climate

This section elaborates the environmental impacts of biomass production. An overview of the environmental impacts of ready-for-use materials derived from EU-27 consumption by impact category shows that biomass (particularly from agricultural production) is responsible for a large share of potential impacts such as acidification, eutrophication (freshwater and terrestrial), land use, water use and ecotoxicity (An Vercalsteren et al., 2023). Therefore, this section identifies these key environmental impacts of biomass production and presents a brief overview in the table 2.2.


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Table 2.2 The main environmental and climate-related pressures from EU agricultural production (cont.)

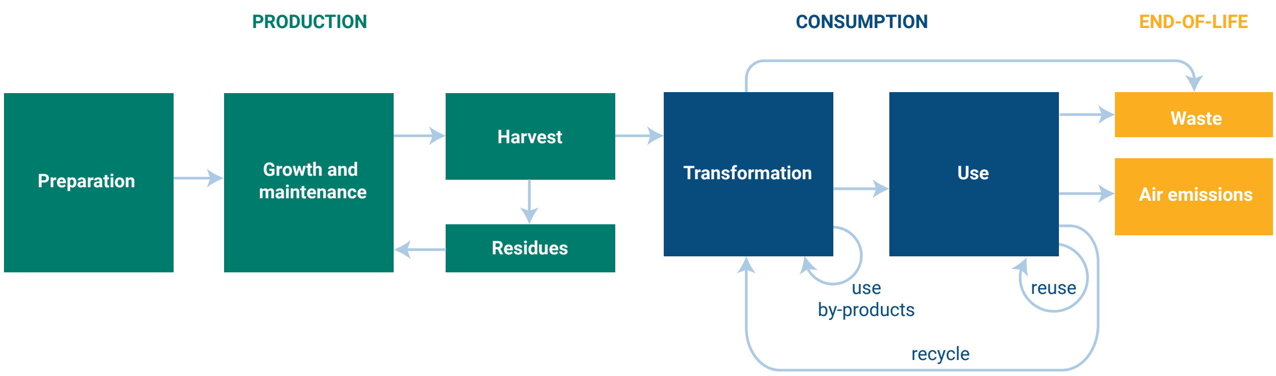
Environmental compartment	Pressures	Description
Atmosphere — climate	Greenhouse gas emissions	Emissions from agriculture account for about 11% of total emissions from the EU-27. These emissions include methane (CH_4) and nitrous oxide (N_2O) that are covered by the Effort Sharing Regulation (EU, 2018b). Agricultural emissions in 2019 and 2020 were about the same as in 2005; more notable reductions in this sector occurred before 2005 (EEA, 2022b). Agricultural emissions in the EU-27 were recorded at 382Mt of carbon dioxide equivalent ($MtCO_2e$) in 2020, driven by methane from enteric fermentation and manure management (circa 53% of the total agricultural emissions) and nitrous oxide from agricultural soils and manure management (circa 43% of the total agricultural emissions) (EEA, 2022b). In addition, agriculture emissions of CO_2 from land use and land use change from croplands and grasslands are reported under the LULUCF Regulation (EU, 2018a) (explored in Chapter 5 of this report).
Atmosphere — air quality	Emissions, land use change/ vegetation loss	Air quality is adversely impacted by ammonia emissions from livestock farming and the use of fertilisers containing nitrogen, which can pose serious threats to human health. In the EU, 95% of ammonia emissions are produced by farmed animals (EEA, 2023b; Allen et al., 2018). In addition, the combustion of wood, especially in the residential sector as well as in animal farming, releases significant amounts of particulate matter emissions (EEA, 2023a). Conversely, increased vegetation cover has been associated with improved air quality (Trenčiansky et al., 2021).
Biodiversity and ecosystems	Habitat loss, degradation and fragmentation; exploitation; over-harvesting; climate change; pollution; invasive alien species	Most reported pressures affecting both species and habitats stem from agricultural activities (EEA, 2021b). The loss, fragmentation and degradation of natural and semi-natural ecosystems caused by agricultural intensification are the main drivers of biodiversity loss in Europe. Additional pressures arise from over-harvesting, alien species, pollution and nutrient enrichment (EEA, 2020; Maes et al., 2020). Similarly, most species groups are negatively impacted by agricultural activities, including reptiles, molluscs, amphibians, arthropods, vascular plants and breeding birds. The main agricultural pressures are the abandonment of grassland management, the use of plant protection chemicals, intensive grazing or over-grazing by livestock, and the conversion from one type of agricultural land use to another (EEA, 2020).
Soil	Erosion and degradation	Land degradation is often caused by a combination of factors, including poor land management, unsustainable agricultural practices, pollution, hedge removal and deforestation. It can lead to soil erosion and loss of organic matter, the latter harming soil structure (Allen et al., 2018). Furthermore, agricultural soil sealing can occur because of urban expansion. Conversely, vegetation cover and responsible agricultural land management practices can improve soil structure, and reduce erosion and degradation (Trenčiansky et al., 2021).
	Pollution	The impact of agricultural inputs (nutrients and pesticides) in the EU remains high (Maes et al., 2020). Trace elements from fertilisers (e.g. cadmium from mineral fertilisers) and some fungicides (mainly copper), as well as pesticide residues, are all contaminants of major concern in agricultural soils. A land use and land cover (LUCAS) survey found that 80% of agricultural soils contain pesticide residues, and only 17% are free of pesticides (EEA, 2018).
Water	Water use	Agriculture is the largest net water user in the EU, accounting for up to 60% of water use (EEA, 2021c). Irrigation of crops uses a considerable amount of water. This is especially the case in southern Member States, where irrigation accounts for almost all agricultural water use and where over-abstraction remains an issue (Allen et al., 2018). However, vegetation cover benefits water use. Both forest cover and responsible agricultural land management can influence not only rates of surface water run-off, but also water quality (Trenčiansky et al., 2021).
	Water pollution	Pollution of both groundwater and surface water can occur via fertiliser use (nitrogen and phosphorus), manure management and pesticide contamination (Allen et al., 2018). Agricultural nitrogen surpluses remain unsustainable over large areas of Europe despite some improvements. Over the past 10 years, pesticide use at the EU level has not been reduced (EEA, 2020). Some agricultural practices and also forest cover can improve water quality and reduce water use (Trenčiansky et al., 2021).

2.2 Biomass uses in the EU

In this report, biomass uses are presented using Sankey diagrams produced using the most recent data sets of EU biomass flows from the Joint Research Centre of the European Commission (JRC) (Gurria et al., 2022). All quantities are expressed in dry weight: Mt or thousand tonnes (kt) of dry matter, unless stated otherwise. In diagrams, data are presented for 2019 (for crops) and 2017 (for forestry), as these are the most recent years for which comprehensive data are available within the JRC datasets.

Understanding how biomass is sourced and used in the economy requires considering entire biomass life cycles: primary production (e.g. growth, harvest, harvest residues remaining in the ecosystems), transformation (processing and transformation in products and by-products), use, reuse, recycling, cascading use and disposal. In this report, the term 'biomass flow' means the transfer of biomass from the environment to the primary sectors, and biomass transfers between economic agents and back to the environment (see Figure 2.7).

Figure 2.7 Simplified diagram showing the biomass flows



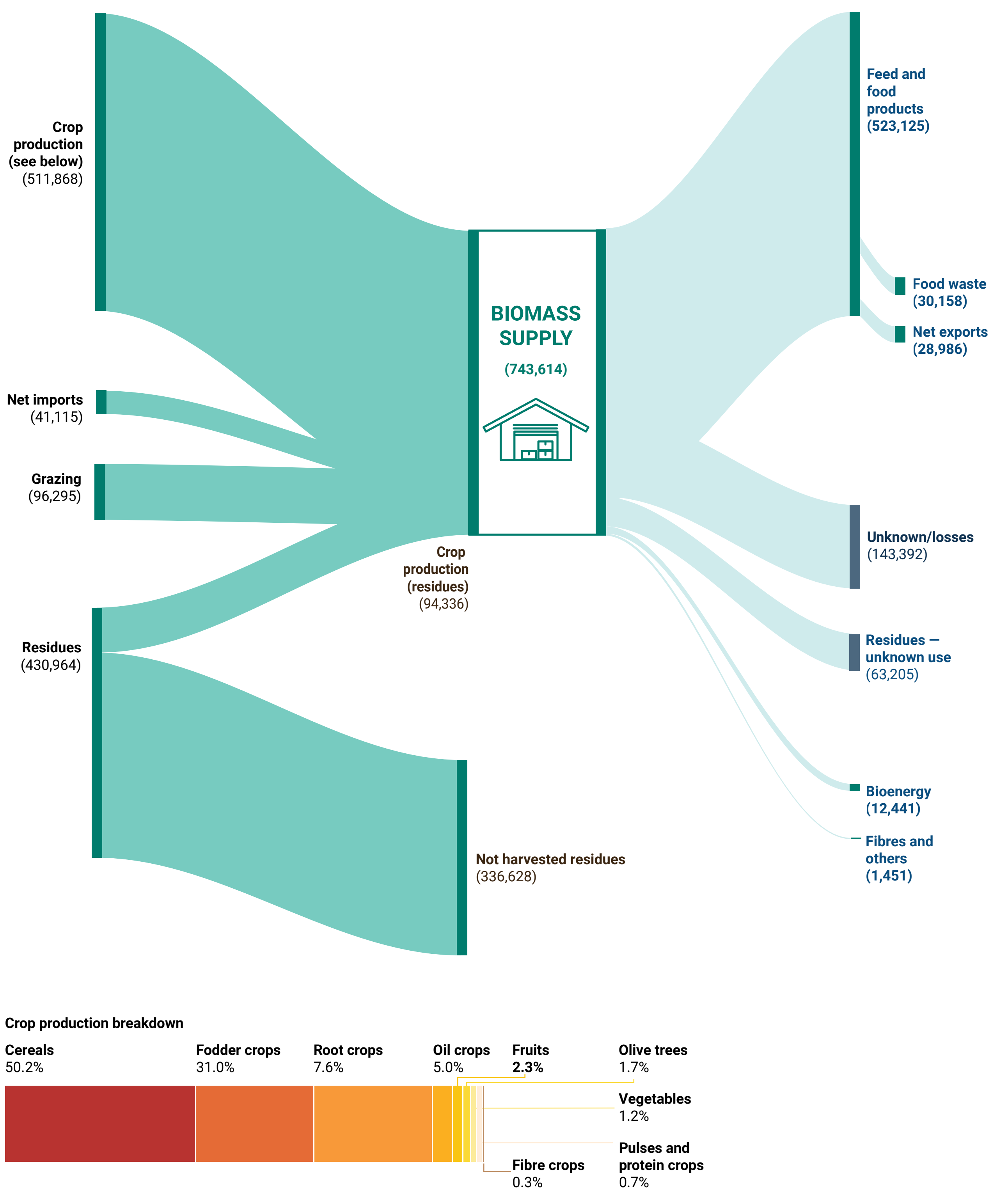
Source: EEA.

Biomass flows are driven by the balance of supply and demand and are influenced by numerous drivers. These include economic and market forces; technological development; environmental and climate drivers; population growth; consumer behaviour; trade; and the broader geopolitical, policy and regulatory landscape. Biomass waste recycling and management, including waste-to-energy, organic fertiliser use and nutrient cycling, are not included in any of the figures and have not been explored in this report.

The EU produced domestically (including net imports) around 1 billion tonnes of biomass in dry matter (tdm) while in use was 1.2 billion tdm of biomass in 2017 (Avitabile et al., 2023). The additional biomass in use was due to recovery of waste from industry and households. 50% of biomass was used for food, feed, and bedding for livestock, 22% went to bioenergy and 28% was used as material in industrial processes (Avitabile et al., 2023).

2.2.1 Agricultural biomass flows

Figure 2.8 Agricultural biomass flows in the EU-27 in 2019



Note: Unit is in kilo tonnes of dry matter including net trade.

Source: Gurria et al., 2022 (JRC).

The agriculture sector supplies food, animal feed and bedding, biofuels and bio-based materials.

Domestic EU production represented 95% of total EU biomass supply from agriculture in 2019 (in dry matter weight and considering net trade; EC, Joint Research Centre, n.d.). The domestic biomass supply consisted of harvested crops (68%), grazed biomass (12.8%) and collected residues (12.7%). Net imports of agricultural products represented around 5% of the total supply and consisted of plant-based food (52%), processed food products (28,7%) and plant products (19,7%).

The Sankey diagrams developed by Gurria et al. (2022) show that, in 2019, nearly 57% of the EU's agricultural biomass supply was used as animal feed and bedding, while 13% was used for plant-based food. The use of more than one quarter of the total supply was unknown (although it was probably used partly for energy and partly by industries) or was simply lost. The knowledge gap around the use of this significant proportion of agricultural biomass hinders proper analysis of the footprint made by its different uses.

The agricultural biomass (both crops and their residues) used for biofuels corresponds to 1.7% (in dry matter weight) of the total supply of agricultural biomass (see Figure 2.8). Based on calculations of the total biofuel consumption and trade, it was estimated that 7.4 million hectares of land was required to produce biofuels consumed in the EU in 2018, out of which 3.4 million hectares was located in the EU (3% of the total EU cropland) (EC, 2020). The total biomass produced on agricultural land used for bioenergy is higher, since crop residues are also used for bioenergy or converted into biogas. However, the lack of specific data and the fact that plants can be used partly for bioenergy and partly as feed make it difficult to assess the exact quantity of crops and crop residues used for bioenergy.

Cereal consumption for animal feed (56% of the total consumption in 2019) is much higher than for human food and industrial consumption (40%) and bioenergy (4%) (EC, 2021b). The importance of European cereal crops to the animal feed industry is summarised in Table 2.3 and explored further in Box 2.2.

Table 2.3 Overview of cereal crop end uses in the EU-27 in 2019

	Percentage (%) allocated to end use		
Cereal crop	Energy	Feed	Food and industrial
Wheat	3.2	38.6	58.2
Barley	0.9	78.4	20.7
Maize	7.9	80.4	11.8

Sources: EC, Joint Research Centre (2023b); medium-term outlook commodity flows.

Box 2.2

The animal feed sector in the EU-27

Animal feed in the EU used more than 1,208 million tonnes of feed products in 2020-2021 (EC, 2023c). It consisted of grass (52% in mass), silage maize (20%), cereals (13%), fodder legumes (7%) and co-products (6%, including oilseed, soya bean, rapeseed and sunflower meals). More than 95% of this biomass was produced in the EU, but some critical products had to be imported, such as soya meal (a major source of proteins in animal feed).

The animal feed sector is the largest consumer of cereal crops produced in Europe, accounting for 61% of Europe's total cereal production in 2019-2020. This means that it also has a larger arable land footprint than the human, non-animal food sector (FEFAC, 2021). In addition to competing with the human food sector, animal feed production sometimes competes with bioenergy and other industrial sectors such as the (bio)chemical industry. (However, it has to be taken into consideration that some co-products from the biofuel production process, such as dried distillers' grains with solubles from maize or rapeseed and soya meal, are used for animal feed.) These sectors are interested not only in the same primary agricultural crops as the feed sector but also in the agricultural residues stemming from their cultivation. This competition may result in higher pressure on land and an increase in price levels and price volatility in the EU and beyond (Scarlat et al., 2015).

Three cereal crops are of particular importance to the animal feed sector in the EU — maize, barley and wheat. The EU cereal balance sheets (EC, 2023a) show that, for the year 2020/2021, 79% of maize, 80% of barley and 41% of common wheat in the EU-27 was used as animal feed (by total weight at EU standard humidity). The latest available Eurostat data show that the total cultivation area under these crops (specifically common wheat and spelt, maize and barley) in the EU-27 is around 43.4 million hectares (Eurostat, 2023b). This constitutes around 82.8% of the total area dedicated to cereal production (52.4 million hectares) and 44% of the EU-27's total arable land (98.3 million hectares) (Eurostat, 2023b).

The European animal feed sector also relies heavily on oilseeds and oilseed meals that contain a high share of proteins, in particular soya beans and rapeseed, and co-products. There is increasing concern about soya beans and soya meal because they are not produced in significant volumes in the EU-27. In fact, EU production corresponds to only about 3% of what is consumed in the EU; the rest is imported from countries where soya bean production contributes to deforestation (see Box 2.3). The top three EU soya-producing countries (Italy, Romania and France) together accounted for 78% of EU soya production in 2018 (IDH, 2020).

Germany, France, Spain, Italy and Poland are the EU's five largest feed producers, responsible for 55% of total EU feed production (FEFAC, 2021); these countries are also the top EU producers of livestock (cattle, poultry and pigs). Studies show that more than half of feed produced is directly used by farmers to feed their animals. The rest is processed further by the industrial compound feed industry (FEFAC, 2021).

Total EU feed consumption is split fairly evenly among the different main livestock types. Poultry consumes 33.2% of all animal feed, followed by pigs (31.3%) and then cattle (29.7%) (FEFAC, 2021). Poultry feed is mainly produced by France, Poland, Germany, Italy and Spain, while pig feed is produced primarily in Spain, Germany, the Netherlands and France (FEFAC, 2021). More than half of all cattle feed is produced in Spain, Germany and France (FEFAC, 2021).

Biomass flows related to animal products are also available from JRC as medium-term outlook commodity flows (Gurria et al., 2022). These show agricultural commodities produced, expressed in total tonnage of product weight (e.g. milk is expressed in tonnes of milk equivalent). For consistency of data presentation with the JRC data set related to biomass flows, we keep 2019 as a reference year for agricultural commodities and we present data only for milk and meat. In 2019, EU farms produced 152Mt of cow's milk, with 94% delivered to dairies and 6% used on farm and sold directly. Of the raw milk delivered to dairies (with an added 2.3Mt of imports), 106Mt went to consumption in the EU (this includes manufactured and fresh dairy products). 21Mt of manufactured dairy products were exported outside the EU and 17Mt were used for 'other dairy products' (EC, 2023b).

The major meats produced in the EU in 2019 were, by order of carcass weight equivalent (c.w.e.), pork (52%), poultry (29%), beef and veal (15%), and sheep and goat (4%). The EU produced 44.5 thousand tonnes c.w.e. and imported 1.5 thousand tonnes of meat and 8 thousand tonnes of live animals. Domestic use of meat was 38.3 thousand tonnes and 7.6 thousand tonnes was exported, with volumes expressed in carcass weight equivalent.

2.2.2 Forestry biomass flows

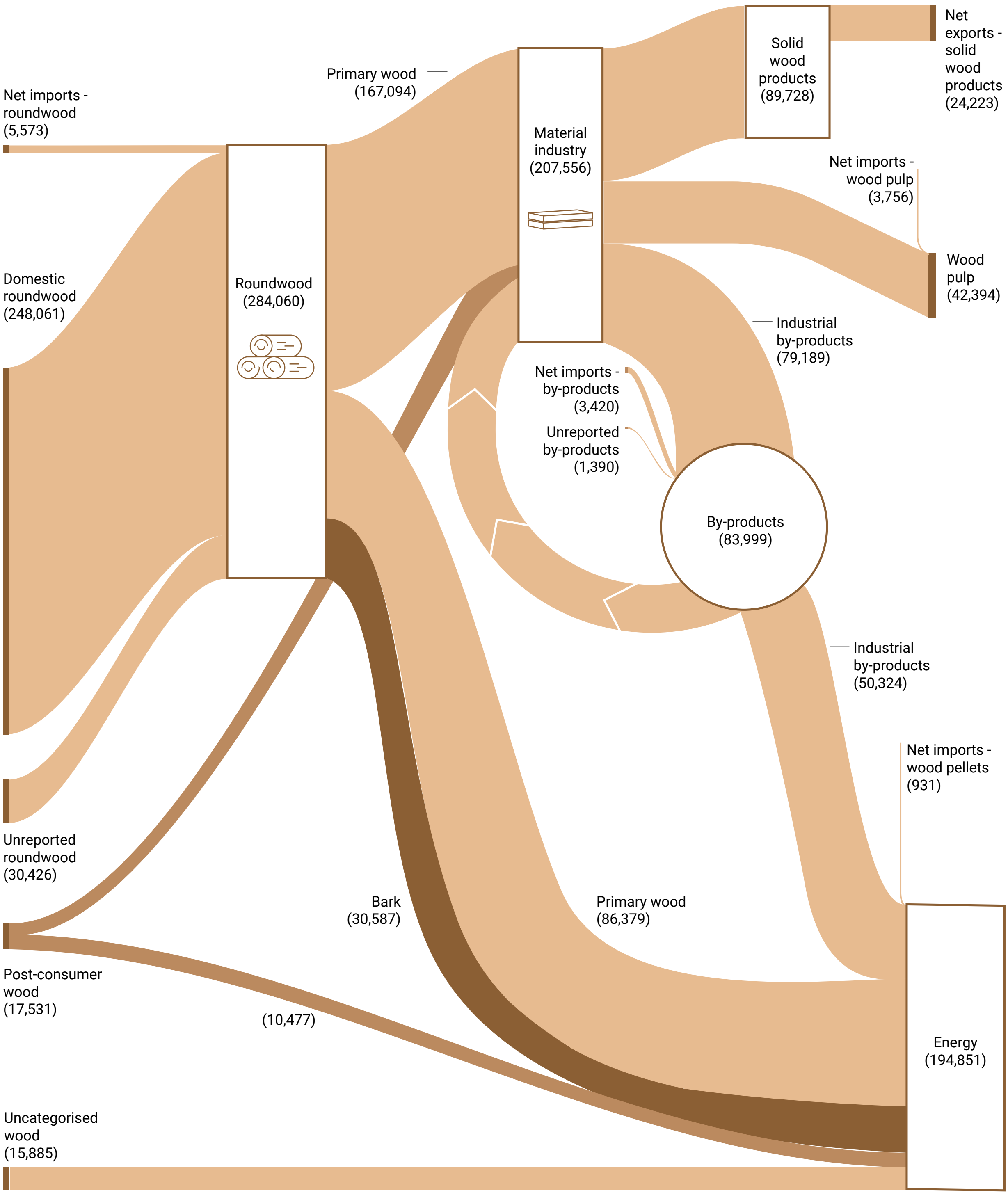
Forest biomass is used for construction, furniture and other wood products; for paper and packaging; and as a source of energy. In 2017, domestic roundwood ([2]) production accounted for the vast majority of the EU's roundwood supply (85% in dry matter weight), while just 2.2% of the supply came from net imports of roundwood (Avitabile et al., 2023). The remaining 12.3% of roundwood was unreported, meaning that its origins from where the wood was removed or imported were unknown and not included in the official Joint Forest Sector Questionnaire that was used to collect data on the use of woody biomass in energy sector.

In the EU, 80% of the biomass from felled trees is removed from the forest during harvesting operations; the remainder is left on the ground as primary logging residues (Camia et al., 2021). The harvesting process leaves dead wood in the forests, which plays various roles in soil maintenance and biodiversity preservation (especially coarse woody debris), and contributes to carbon flows (Camia et al., 2021).

Roundwood was used in the material industry (59%), and in energy sector (30% primary wood and 11% bark) (primary wood meaning woody biomass extracted directly from either forests or outside forests without further treatments or conversion). In 2017, 38% of roundwood from the material industry became by-products. These by-products were either reintegrated into the material industry to produce wood-based materials such as particleboard (40%) or were used for energy generation (60%).

([2]) Wood felled or otherwise harvested and removed from the forest.

Figure 2.9 **Woody biomass flows in the forest-based sector in the EU, 2017**



Note: Unit is in kilo tonnes of dry matter including net trade.

Source: Gurria et al., 2022 (JRC).

The recycling of post-consumer wood is often referred to as cascading use and it adds to the wood supply beyond primary wood (EC et al., 2016). In 2017, it added 17, 531 kt of dry matter of woody biomass to the total woody biomass supply.

Direct and indirect energy uses accounted for almost 60% of the total roundwood production in 2017. This 60% included primary wood, bark, and by-products from material industry as presented in figure 2.9. In 2017, woody biomass combusted for energy purposes was: primary wood directly used for combustion (44%), industrial by-products (26%), bark (16%), post-consumer wood (5%), 8% came from uncategorised woody biomass, and the remaining was net imports of wood pellets (Avitabile et al., 2023). According to Camia et al. (2021), the uncategorised woody biomass used for energy (heating and power generation) is more likely to come from primary wood (straight from the forest without treatments or conversion); it was reported by the official datasets but not categorised, therefore is not attributed to any specific flow. In addition, Camia et al. (2021) estimated, based on the data between 2009-2015, that roughly 47% of primary wood used for energy is made of stemwood while the remaining 53% of other wood components (treetops, branches, etc.).

Solid-wood products for construction, furniture and other wood products account for the second-largest share of forestry biomass end use at 29%, ahead of wood pulp (primarily used for paper), which constitutes 14%. Both solid-wood products and wood pulp are fed primarily by the EU's domestic material industry, although small volumes of imports also contribute to the wood pulp sector.

2.3 Biomass trade trends for the period 2000-2020

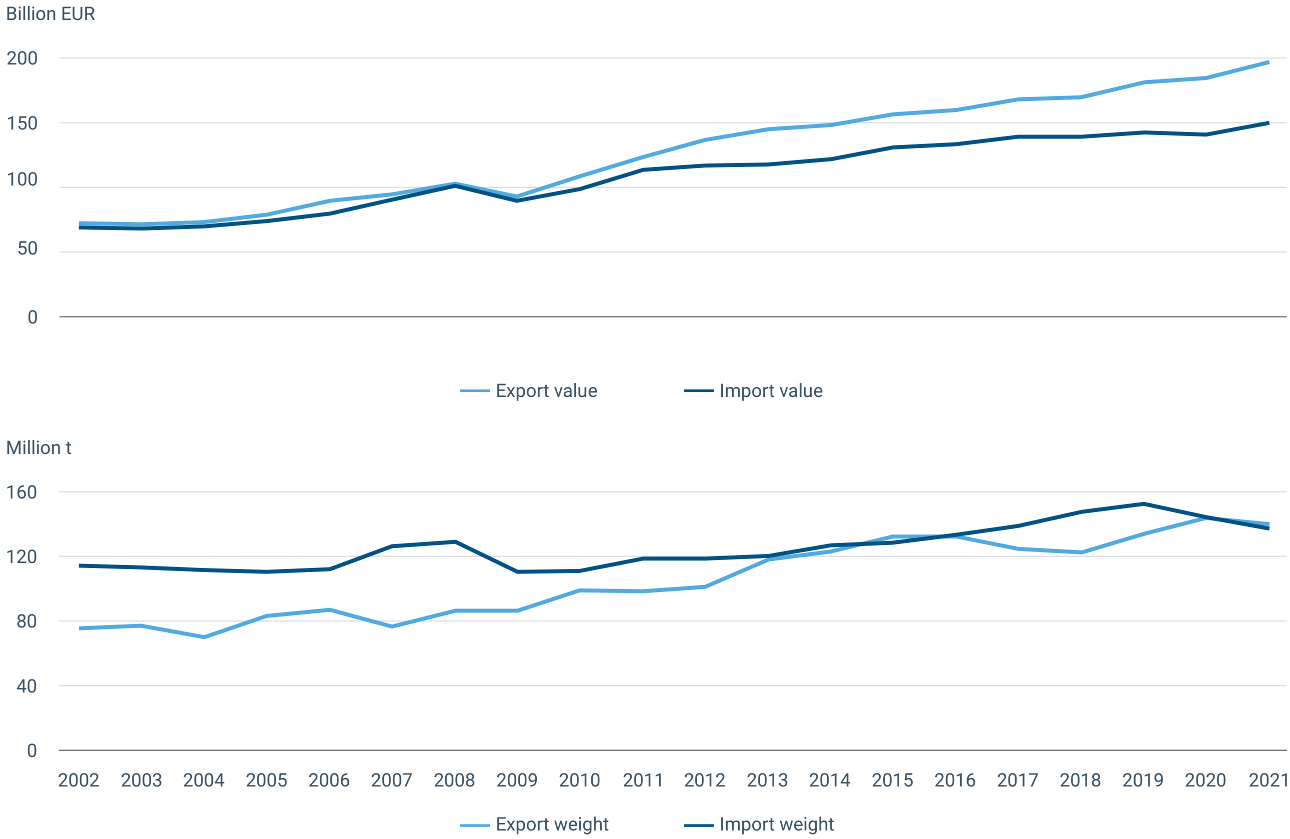
While the vast majority of EU biomass supply comes from domestic resources (90% expressed in dry matter), net imports of agricultural and forestry products from non-EU countries provide around 5% (in dry matter) of total biomass supply (the origin of the remaining 5% is unknown) (Avitabile et al., 2023). Although this is a small percentage, some of the imported products, such as coffee, soya, palm oil, cotton or exotic tree species, have a noticeable environmental and social impact outside the EU. However, the EU provides food to other parts of the world as a major exporter of cereal preparations and milling products as well as cereals, meat and dairy products. To understand the role, dependency on and responsibility of the EU globally, biomass trade import and export trends must be fully analysed.

The following section explores trade trends in EU agricultural and forestry products, looking at the period 2000-2020/2021 in terms of quantity of traded products and in monetary terms, using the latest Eurostat data. Data for the agriculture sector are structured slightly differently from previous sections to take account of Eurostat's sub-division of agricultural products into four main groups: animal products, vegetable products, oils and fats, and foodstuffs (Eurostat, 2022d).

2.3.1 EU trade in agricultural products

Since 2000, both the import and export of agricultural products have increased in the EU in quantity and value (Eurostat, 2022d; Figure 2.10). The increase in the quantity of exported products has been faster than that of the imports, leading to a reduction in the quantity of net imports, and even a positive balance in 2015 and 2021. The value of the exported products did not increase as fast as that of imported products. Nevertheless, the combination of changes in price and quantity led to a change in the monetary trade balance from almost neutral at the beginning of the period to largely positive after 2012. Overall, EU trade in agricultural products more than doubled from 2002 to 2021, equivalent to an average annual growth rate of 4.8% (Eurostat, 2022d).

Figure 2.10 Import and export of agriculture products between the EU and countries outside the EU



Source: Eurostat (2022d); online data code: DS-045.

European agricultural exports

Food products – in other words foodstuffs — (consisting of processed foods such as beverages, cereals, miscellaneous, and tobacco as presented in Figure 2.11) made up over half (54%) of EU exports in 2021, ahead of animal products (mainly meat and dairy products, 22%), vegetable products (20%), and fats and oils (4%) (Eurostat, 2022d). Beverages, spirits and vinegar represent a sub-sector where the EU has a trade surplus, with over EUR 35 billion in exports in 2021 compared with just over EUR 7 billion in imports (Eurostat, 2022d). This sector provides a high level of added value, particularly for luxury products such as wine.

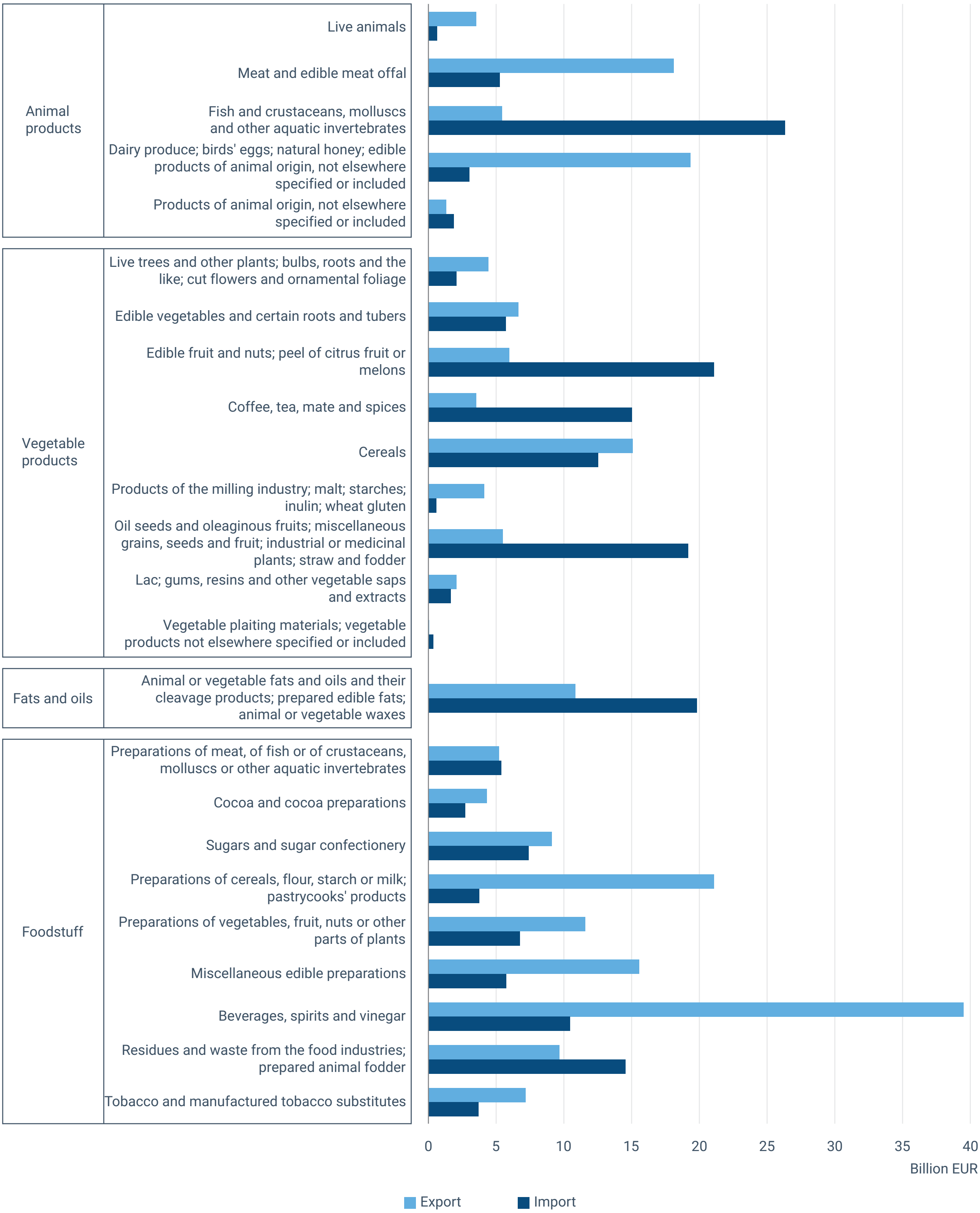
European agricultural imports

Vegetable products accounted for the highest share of European imports in 2021 at 39%, ahead of food products (32%), animal products (19%), and fats and oils (9%). The EU's largest trade deficits were in fish and crustaceans, molluscs and other aquatic invertebrates (~EUR 21 billion imports vs ~EUR 9 billion exports), edible fruits and nuts, peel of citrus fruits or melons (~EUR 20 billion imports vs ~EUR 6 billion exports), and oilseeds and oleaginous fruits (~EUR 14 billion imports vs ~EUR 5 billion exports) (Eurostat, 2022d). A full breakdown of the products forming each sub-division is provided in Figure 2.11 (Eurostat, 2022d).

Overall, the size of the European market, the continent's biogeographical diversity and the EU's positive agriculture sector trade balance mean that the EU has not historically been overly dependent on external agricultural imports. However, one product for which it does rely heavily on imports is protein crops, in particular soya bean (and its derivative soya meal) needed for animal feed. This is explored further in Box 2.3. Production of soya beans outside the EU often has negative environmental impacts. For example, Rajão et al., (2020) revealed that 20% of soya exports from Brazil to the EU may be associated with illegal deforestation.

This led to encouraging soya production in Europe, but mainly non-genetically modified (GM) varieties, since cultivation of GM soya beans is banned in the EU. GM soya products are authorised in the EU if imported. In 2020/2021, the EU produced less than 4% of the soya used as soya meal for domestic animal feed (35% of soya meal is produced from imported soya beans and 62% is directly imported as soya meal (EC DG AGRI, 2022).

Figure 2.11 **EU agricultural exports and imports by product categories, 2021 (Billion EUR)**



Source: Eurostat (2022d); data code: DS-045409.

Box 2.3

Increased demand in the EU for soya beans and soya meal

Plant protein, derived from protein-rich crops such as oilseeds, pulses and fodder legumes, is an essential part of the European agriculture sector in feeding livestock. In fact, there is a need for increased production in the EU (EC, 2018). Protein-rich crops have become critical to the animal feed sector; in addition to providing proteins, they supply important amino acids to livestock (EC, 2018). However, because of a variety of climatic and market conditions, domestic growth of these crops cannot satisfy EU demand. This means that the EU is dependent on imports of oilseed crops and meals, especially soya bean and soya meal (EC, 2018a). Soya bean is mostly a genetically modified crop, the cultivation of which is banned in the EU. Soya meal is the largest component of animal feed (roughly 64%) (EC, 2023c). 86% of EU soya beans, meal and oil imports came from Brazil, Argentina and the United States in 2020 (Kuepper and Stravens, 2022). The overall EU production of soya (i.e., varieties not genetically modified) remains minimal. It is being cultivated on an area of around 1 million hectares in the EU, and, in 2021, production of soya amounted to 2.6 million tonnes. By 2030, production is expected to increase by one third compared with 2018 production (EC, 2021a).

2.3.2 EU trade in wood products

Relatively few wood products are traded compared with their level of consumption. The EU has traditionally been a net importer of wood. However, in 2019, imports and exports were almost equal, and the EU became a net exporter in 2020/21. This is the result of not only an increase in demand from countries such as China but also a surge in the wood harvested from salvage logging that took place in Czechia and Germany, in particular because of bark beetle infestations.

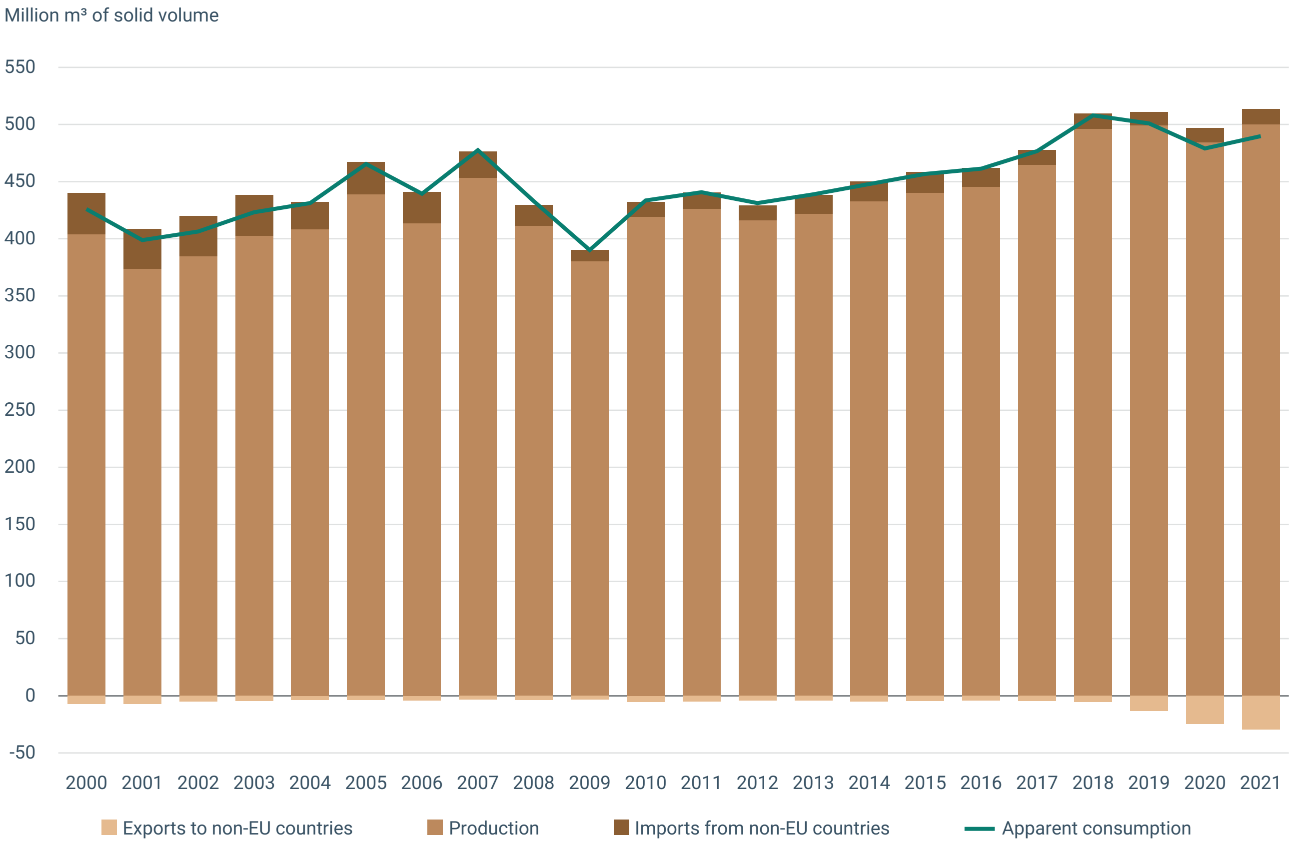
European roundwood trade

The EU-27 depends mainly on its own production for roundwood supply: only 3% of the roundwood consumed in the EU (in m^3) comes from outside the EU, a share that has been quite stable since 2010 (Eurostat, 2023h). Between 2000 and 2019, the EU annually exported about 1% of its roundwood outside its borders. Since then exports started increasing significantly and reached 6% in 2021 (Eurostat, 2023g) — reacting to an over-supply of wood on the EU internal market. Most of the increase in exports to non-EU countries came from Czechia, Germany, France, Belgium and Austria.

China is by far the main EU importer of roundwood from the EU. With a total value close to EUR 2 billion, the export of roundwood to China in 2021 represented 84% of the total value of roundwood exported outside the EU. Other partner countries include Vietnam, the United Kingdom, Norway, South Korea and Switzerland (Eurostat, 2023d).

The EU imports wood mainly from Russia, Brazil, Norway, Switzerland, the United States and central African countries (Congo, Central African Republic, Cameroon, etc.). However, EU trade has been affected in different ways by two recent crises (COVID-19 and the related lockdown periods, and Russia-Ukraine war). In 2019 and 2020, the effect of several lockdown periods slowed down the EU economy, leading to a temporary reduction in the supply (both production and import) and use of wood (+6% in volume in 2020 compared with 2018). This crisis was global, and impacted production and manufacturing levels around the world. Simultaneously, demand for finished wood products (in particular in construction) increased towards the end of the lockdown periods, leading to tensions on the market and high prices. The forest sector recovered to its pre-COVID-19 activity level in 2021, as did imports. In February 2022, Russia has invaded Ukraine. Russia was a major roundwood exporter to the EU until 2021, but restrictions on imports from Russia imposed by EU Member States in response to the war affected roundwood supply. Although this did not meaningfully affect total supply to the EU, it prompted a change in trading partner countries.

Figure 2.12 **Roundwood production, import and export from the EU (in million m³ of solid volume)**



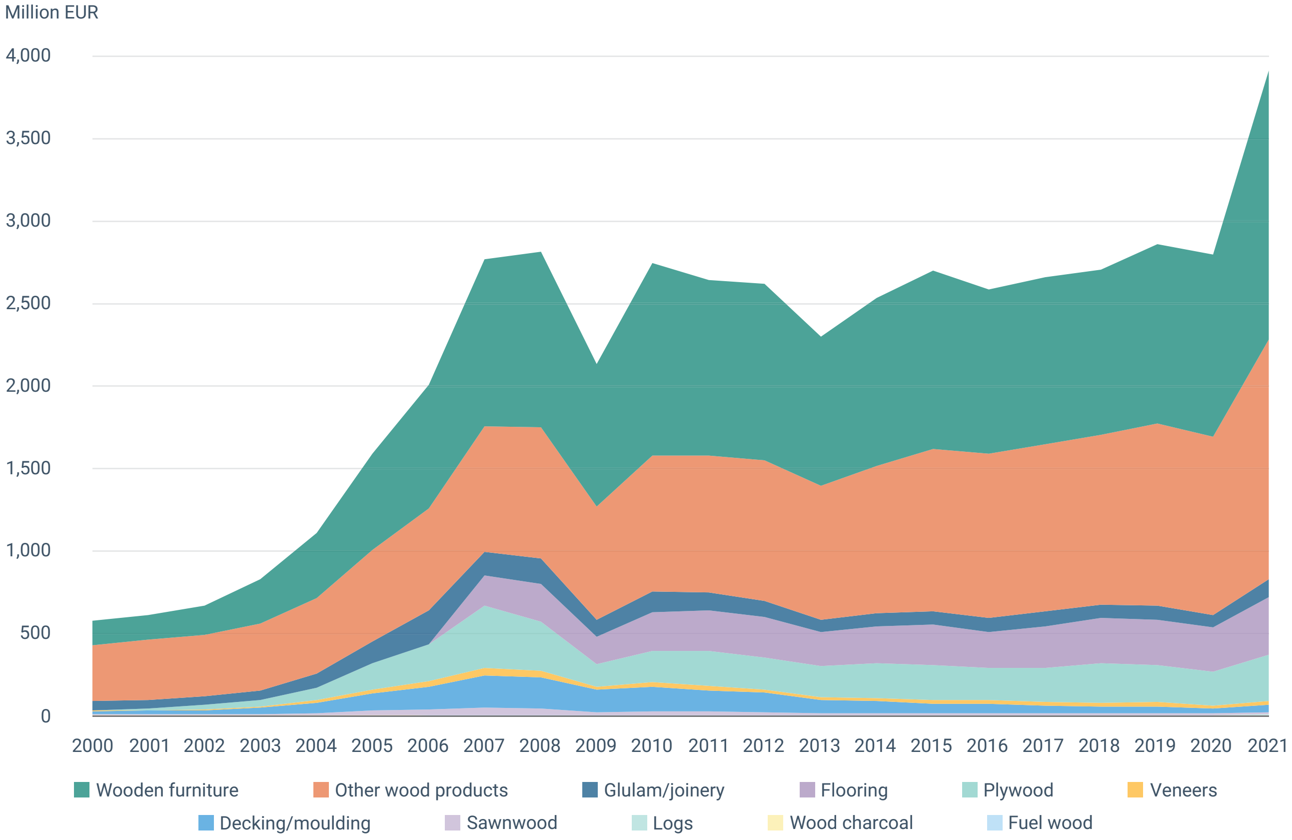
Note: Values for EU internal trade (export and import) are not included in the visualisation.

Source: Eurostat (2022g).

European manufactured wood product imports

Manufactured wood product imports from non-EU countries have been rising over the last two decades. The value of imports from China increased more than six-fold over this period (Figure 2.13; Eurostat, 2022g). China has become the largest exporter of wood-based products to the EU, particularly wooden furniture and other products such as wooden tableware and kitchenware, and wood marquetry and inlaid wood.

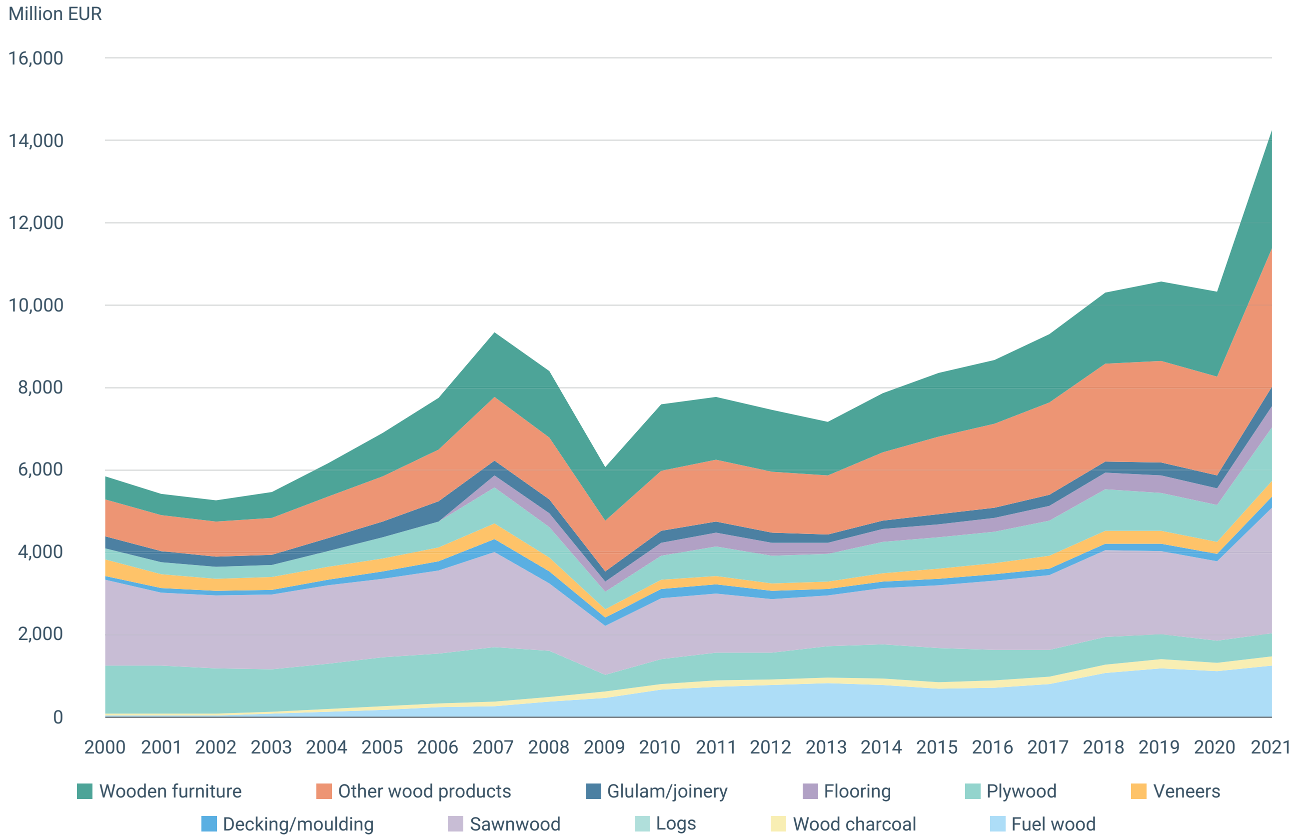
Figure 2.13 **Wood products imported to the EU from China**



Source: Eurostat (2022g).

Imports from countries other than China or tropical countries (see Figure 2.14) grew similarly for the same group of products, with the exception of sawn wood and, to a lesser extent, logs (Eurostat, 2022h).

Figure 2.14 **Wood products imported to the EU, excluding China and tropical countries**



Source: Eurostat (2022g).

3 Great expectations — EU policies and biomass

Key messages

- It is projected that there will be a growing gap between biomass demand and supply for bioenergy and bio-based materials between now and 2050. The size of the projected gap cannot be reliably assessed because of modelling uncertainties and difficulties in comparing across models.
- The scientific studies forecasting the demand for and supply of food and feed biomass in 2030 provide little or no quantitative estimates of anticipated shifts in biomass demand. They also use different values to estimate the amounts by which supply will reduce for some biomass types.
- Biomass is forecast to play various roles in society and policy in relation to nature conservation, food and energy security, pollution reduction, and climate mitigation and adaptation. This might magnify the risk of the gap between biomass demand and supply being further enhanced if the correct policy incentives are not in place.
- Within a complex policy and regulatory landscape, there are numerous policy targets and objectives relevant to terrestrial biomass. There is a clear need to better identify and quantify the co-benefits and trade-offs across the different policy lines and at national levels.
- Currently, biomass reporting requirements are heterogeneous and lead to incomplete knowledge because of data limitations. The knowledge base on biomass production and consumption will benefit from a more consistent biomass information system across all policy areas.

This chapter reviews EU policies relevant to biomass supply and demand in the context of the European Green Deal, its associated strategies and the regulatory frameworks supporting its implementation. In addition, this chapter explores how much biomass is forecast to be used and to be available according to EU and third-party estimations included in impact assessments, research projects and models.

3.1 What can we learn about future biomass demand and supply from the available scenarios?

This section presents an overview of current projections and knowledge on future biomass demand and supply based on a review of scientific and grey literature, including policy reviews, modelling exercises and impact assessments (IAs). Quantifying future biomass demand and biomass supply is complex and inconclusive, nevertheless, an overview of the forecast trends is provided.

To predict future trends in biomass demand and supply, the European Commission and research bodies utilise a wide range of models and assessments. Results range from qualitative, literature review-based findings focusing on either biomass demand or supply to detailed and quantitative partial or general equilibrium models that compute demand and supply simultaneously ([3]). Differences in model structure, scope, assumptions and policy considerations, units (e.g. million tonnes (Mt), million tonnes of oil equivalent (Mtoe), exajoules (EJ)) and sector classifications complicate comparisons across and within demand and supply studies. Therefore, conclusions drawn from their results must be treated with caution. In addition, historical data greatly outweigh future forecast data. Comparisons across future scenario analyses for both biomass demand and supply are not straightforward, especially in the context of geopolitical crises impacting food and energy supply.

Another challenge when comparing different biomass scenario analyses is their different policy focuses. Biomass-related policies tend to focus on specific biomass uses (e.g. bioenergy, bio-based materials, food, feed) or biomass quality (e.g. in relation to nature). Presenting a comprehensive overview of future biomass demand and supply therefore requires projecting impacts arising from often competing policies. As this is overly complex, scenario analyses also tend to focus on policy subsets targeting specific types of biomass or biomass use. The following sections thus look at two primary categories of biomass use individually: (1) bioenergy and bio-based materials and (2) food and feed.

3.1.1 Impacts of bioenergy and bio-based materials

This section reviews studies that project the demand and supply of biomass for bioenergy and material use through to 2050. An overview of their scopes and results is outlined in Tables A3.1 and A3.2 in the annex.

Demand-based projections

The share of biomass in the renewable gross final energy consumption in the EU-27 between 2005-2021 almost doubled (see also Figure 5.11 in Chapter 5), driven by a two-fold increase in the use of biomass for renewable electricity generation, and a 1.4 increase in the use of biomass for renewable heat generation (Eurostat, 2023a). The use of biodiesels in renewable transport between 2011-2021 increased by 2.4 times (Eurostat, 2023a).

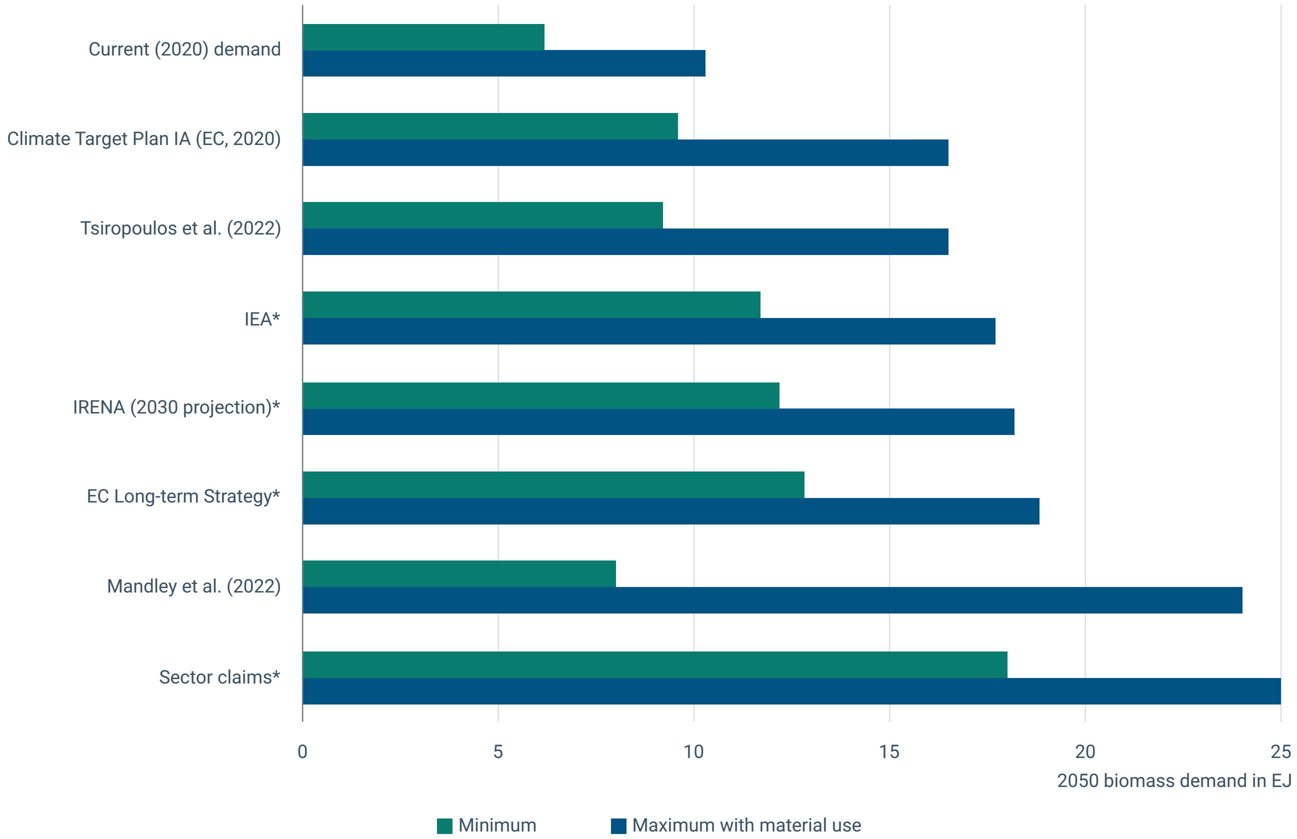
Several recent and publicly available studies, as well as national energy and climate plans, project sustained increases in demand for bioenergy and bio-based materials through to 2050 under different scenarios. Key among the European Commission's biomass projections is the impact assessment of the 2030 climate

([3]) Equilibrium models describe the allocation of resources and the distribution of incomes in a market economy as a result of the interaction of supply and demand, under the assumption that market forces will lead to an equilibrium between supply and demand and, consequently, to an equilibrium price. Equilibrium models integrate the behaviours of all market agents (consumers, producers, governments, etc.) in a systematic way. In the case of partial equilibrium models, only one market is considered at a time, ignoring potential interactions across markets. These models present a series of limitations, such as the assumption of general economic equilibrium (and that nothing happens — i.e. no decisions are made by economic agents and no transactions take place in the economy — until equilibrium is reached) may not be satisfied in practice, and the results are sensitive to the behavioural elasticities chosen, wider interactions among parts of the large economy, and constraints that apply to the various factors of production (e.g. labour, capital, land) and their movement across sectors.

target plan (EC, 2020a) ([4]), which outlines scenarios for the EU-27's bioenergy and biofuel demand and projects an upwards trend towards 230-250Mtoe (equivalent to 9.6-10.5EJ) in 2050 (EC, 2020a). Biomass demand for bioenergy and bio-based materials is now estimated at 6EJ and 4EJ, respectively. One EJ corresponds to approximately 55Mt of wood, or the harvesting of 5-7 million hectares of land for energy crops (Material Economics, 2021).

Other demand-based studies include qualitative reviews of published scientific literature (Material Economics, 2021; Giuntoli et al., 2022; Mandley et al., 2022; Tsiropoulos et al., 2022). The Material Economics (2021) study presents demand estimates from several European industry associations, all of which propose considerable increases for individual sectors, for example 4-5EJ for road and other forms of transport (including aviation and maritime), 5-6EJ for biogas, 7EJ for power generation and 4EJ for chemicals. When the use of biomass for bio-based materials is included (an estimated 1-2EJ of extra demand per year until 2050), even the more conservative scenarios forecast an increase in biomass demand of up to 20EJ, which is double today's use (Material Economics, 2021).

Figure 3.1 **Projections of biomass demand for bioenergy and bio-based material use in 2050**



Notes: Current (2020) demand is shown for reference (multiple sources).

(*) source interpreted by Material Economics (2021). Minimum indicates minimum projected biomass use demand in the studies; maximum indicates maximum projected biomass use demand in the studies.

Source: EEA based on multiple sources.

([4]) Since publication of the climate target plan, other IAs have also been published for the Fit for 55 proposals, including for the Renewable Energy Directive (RED) (https://eur-lex.europa.eu/resource.html?uri=cellar:0f87c682-e576-11eb-a1a5-01aa75ed71a1.0001.02/DOC_1&format=PDF) and the Land Use, Land Use Change and Forestry (LULUCF) Regulation. The RED IA is based on the climate target plan modelling and is generally in line with its scenarios but provides additional insight into biomass waste use and the various end-use sectors. The LULUCF Regulation IA provides only very high-level data on impacts and does not provide more detailed, additional insights on the projected development of EU biomass supply.

Overall, the considerable variation between studies — from approximately 16EJ to 25EJ — indicates a high degree of uncertainty around projected biomass demand in 2050. The variation equates to the difference between requiring an extra 50% or 150% biomass in addition to what is currently used. While there are differences in scope between studies that account for some of the discrepancy, this uncertainty nevertheless raises important questions about how biomass supply will be structured (i.e. where this additional biomass will come from) in 2050, and its climate and environmental consequences.

Crucially, assumptions about biomass supply vary widely across all demand-based models. Some studies point to a potential dependency on imports to meet demand, projecting an increase in biomass imports of between 4% and 60% (Mandley et al., 2022). Other studies (e.g. Tsiropoulos et al., 2022; EC, 2020) assume that this increase in demand will be covered by domestic land use change prioritising the growth of advanced, high-energy lignocellulosic crops (assumed to replace current food and feed crops used for biofuel production post 2030). According to the climate target plan IA study (EC, 2020), most of this land will be taken from cropland previously dedicated to producing conventional feedstocks for biofuels. However, some land is anticipated to be redirected from other land uses such as food and feed cropland, as well as lands where biomass is not currently extracted for use (EC, 2020a) (EC, 2020) ([5]) ([6]). Competition between non-food-based bioenergy production and food crops, and how this impacts land use, land use change and forestry (LULUCF) greenhouse gas (GHG) emissions/removals, food security and food prices, is not explored in any great detail in the literature reviewed for this report.

Supply-based projections

As with biomass demand, considerable uncertainty exists when predicting future trends for biomass supply. A key driver of uncertainty in supply-based studies is the requirement to model future land productivity and capacity, with studies covering various drivers of change in biomass supply (see Table A3.4 in the annex). As a result, projections vary widely and ultimately create unrealistic scenarios (Giuntoli et al., 2022).

Projecting how biomass supply patterns will shift in response to developments on the demand side requires independent analysis of potential biomass supply, since demand-based models such as the climate target plan IA (EC, 2020) assume that supply will shift to achieve an equilibrium. Biomass-for-bioenergy supply data presented in this section were therefore extracted from recent, publicly available, scientific supply-based EU-level modelling, and from global literature on biomass categories relevant to bioenergy and biofuels (presented in Table A3.3 in the annex).

Supply-based projections include the ENSPRESO database developed by the European Commission Joint Research Centre (JRC) and partners (Ruiz et al., 2019), CE Delft and RH DHV's 'Bio-Scope' study (CE Delft, 2019) and Material Economics's value curve model (Material Economics, 2021). Each of these studies forecasts potential increases in biomass supply under most scenarios considering a range of climatic, policy and demand-side or market shifts, with upper limits of projected 2050 biomass supply ranging from 13EJ in Material Economics's value curve model to 20EJ in the same study's literature review (Figure 3.2) (Material Economics, 2021).

([5]) The environmental impact of scenarios inducing such land use change is projected to be minimal. While energy crops replacing natural land leads to a decline in biodiversity metrics, their replacement of cropland is seen as positive because energy crops are permanent crops with a lesser impact on biodiversity than the annual crops they replace, such as rapeseed currently used for the production of biodiesel.

([6]) While ambitious, the European Commission's comparison between baseline and policy scenarios still achieves only a 60% decline in GHG emissions compared with 1990 emissions, suggesting more action is required to achieve the 2050 net-zero goals of the European Green Deal.

Figure 3.2 Projections of biomass supply in 2050

Notes: Current supply is shown for reference (multiple sources).
Minimum indicates minimum projected biomass supply; maximum indicates maximum projected biomass supply.

Source: EEA based on multiple sources.

As with biomass demand studies, considerable variations in technical scope and uncertainty lead to significant differences within supply-based studies. For example, the projected supply in the CE Delft (2019) study ranges from 5.5EJ to 18.7EJ (320-1,100Mt dry matter). This difference is due to the study's distinction between 'sustainable potential' and 'technical sustainable potential', the former incorporating materials- and energy-related EU policies and thus representing a far more realistic projection of future biomass supply. In contrast, 'technical sustainable potential' ignores such policies and provides a much higher volume of biomass supply that could 'technically' be achieved.

The variation across supply-driven models can also be partly explained by the different shares of forestry and agricultural biomass supply growth projected in these studies. For example, Ruiz et al. (2019) project an equal contribution to additional bioenergy supply from forestry and agriculture. CE Delft (2019), however, projects an increase in agricultural biomass supply that is almost double that of forestry under its 'technical sustainable potential' scenario. Nonetheless, as with many demand-based studies, neither Ruiz et al. (2019) nor CE Delft (2019) explore in any detail the potential impacts or trade-offs associated with an increase in biomass production (e.g. competition with food crops, nature protection and restoration, carbon sinks and stocks, and other land use changes).

Supply-demand gap

When supply data are assessed in the context of increasing demand, potential gaps emerge between projected supply and demand. However, the extent of this gap is uncertain and cannot be reliably predicted based on current evidence.

One study that has sought to quantify the extent of the gap between future biomass supply and demand is that by Material Economics (2021), which references several scenario projections and estimates a minimum 40-70% shortfall in biomass supply for materials and energy in 2050 compared with projected demand. Stating that these predictions are conservative, the study concludes that increasing available supply to the level required to meet demand would result in major trade-offs with key environmental objectives. It cites difficulties relating to the import of significantly higher volumes of biomass for energy and materials, and the fact that forests, and waste and residue streams are projected to offer only a modest, at most 10-15%, increase in supply. At this level, the amount of forestry/cropland that would be required is unrealistic. It would require a complete remodelling of Europe's agricultural and forest landscape, with significant social, economic, environmental and climate-related consequences (Material Economics, 2021).

3.1.2 Impacts on food and feed biomass

This section reviews studies that project the demand and supply of food and feed biomass up to 2030, developed in the context of the policies and supporting strategies of the European Green Deal. The scenarios reviewed (for supply-based projections only) were developed in the context of the EU farm-to-fork and biodiversity strategies and the proposed common agricultural policy (CAP) reform (see annex, Table A3.1). They have been further informed by scientific literature.

Projections of demand for food and feed

Recent decades have seen the European food system change from predominantly supply-driven to more demand-driven value chains, focused on providing food at the lowest possible prices (EC, 2016). While there is significant uncertainty about how demand has influenced agricultural change across Europe during this period, some insights can be drawn from production and trade trends outlined in previous sections of this report. Gross EU agricultural output has seen an upwards trend since 2005, both in value (EUR billion at basic prices) and in volume (Eurostat, 2021b). This growth is probably driven, at least partially, by population growth (Eurostat, 2021; EC, 2021; van Dijk et al., 2021).

Eurostat projections estimate that the EU population will continue to grow slowly up to 2026 and start declining thereafter. Changes to living standards are more difficult to predict, with inflationary pressures and the risk of recession on the horizon across many Member States (Eurostat, 2021a). These factors increase the pressure on energy and food commodity prices and erode households' purchasing power (EC, 2022b), with subsequent impacts on the diets of EU consumers. In this context, predicting the success of policies to reduce food waste and loss and to encourage dietary shifts towards a lower intake of animal products and calories is difficult.

Preventing food loss and food waste requires a complex set of policies targeting a range of interventions across the whole supply chain, including changes in consumer behaviour (Rust et al., 2020). In the EU, up to 10% of all food supplied to consumers is wasted, which resulted in 57Mt of food waste in 2020 (Eurostat, 2023b). Food waste is one of the largest sources of inefficiency in the agri-food chain and depletes limited natural resources, such as land, water and biodiversity, on which the food system depends. In addition, 8-10% of global GHG emissions are associated with food that is not consumed (UNEP, 2021). The scale of the problem is still widely debated, as well as the food waste figures themselves. For example, Feedback EU (2022) estimates that 153.5Mt of agricultural products are wasted each year, worth in excess of EUR 143 billion per year, whereas Stenmarck et al., (2016) a widely cited source, estimated 88Mt of food waste per year. While Member States are obliged to report annually how much food waste they produce (EU, 2019), the lack of a harmonised definition of food waste and loss, and a consistent methodology to measure food losses and waste at the production stage, result in uncertainties around and differences in estimates (Stenmarck et al., 2016).

Similarly, while it is recognised that the shift towards more plant-based diets has the potential to reduce biomass demand and agricultural GHG emissions, the policies needed to address the health and environmental impacts of the food system cannot focus solely on consumer behaviour. Action is needed across the supply chain. There is little consensus on the scale at which the shift towards plant-based diets might take place, or in which direction, particularly in the absence of appropriate policy measures. In its in-depth analysis, the European Commission recognised this uncertainty and explored the GHG mitigation implications of five different diets (EC, 2020a). These ranged from a slight decrease in consumption of meat and dairy products, which resulted in a reduction in GHG emissions of just over 5MtCO_2e (Mt carbon dioxide equivalent) by 2030, to a more substantial decrease, which led to a reduction of more than 30MtCO_2e (EC, 2020a).

Based on the above, and in the absence of evidence on projected changes in food demand resulting from measures favouring one diet over another, no quantitative estimates of anticipated shifts in demand up to 2030 can be provided.

Projections of supply for agricultural biomass

Recent European agricultural production trends are well covered in Chapter 2 of this report. It describes the increase in the domestic production of numerous agricultural products during the period 2000 to 2020, both in value (EUR billion at basic prices) and in volume, and the EU trade surplus.

The European Green Deal's policies and associated strategies contain several targets and ambitions that complement the Common Agricultural Policy to shape the new policy landscape on agricultural production in the EU. These ambitions, which range from reducing the use of pesticides to increasing the area of EU-27 farmland under organic management, all have implications for the production of different types of agricultural biomass. Recent studies (policy reviews, modelling exercises and IAs) from both the European Commission and other organisations have sought to investigate how this new policy landscape will shape European agricultural production.

Within the studies done by the European Commission, they forecast a decrease in future agricultural biomass supply as a result of European Green Deal policies. Moreover, a modelled scenario from JRC (Barreiro Hurle et al., 2021) estimates that cereal crop production will decline by 13-15% and oilseed production by 12-15%, depending on the implemented CAP changes related to a reduction of the risk and use of pesticides, a reduction of nutrient losses, an increase of area under organic farming, and an increase of area for high-diversity landscape features.

For an overview of the main food and feed supply changes in 2030, see Table A3.3 in the annex.

Figure 3.3 **Different studies' quantitative impacts of European Green Deal policies on EU-27 cereal and oilseed production**

Sources: EEA based on multiple sources.

Overall, studies conclude that crop production will decline (as shown in Table A3.3 in the annex). However, the value ranges they provide (a supply reduction of between 8% and 40% for cereals and between 10% and 61% for oilseeds) must be treated with caution. These studies give some useful insights into the potential effects of combining various policies on food production; however, none can be considered conclusive because of limitations in the modelling exercises, scope and data. The studies also fail to account for mitigation measures that may reduce impacts on yield, such as integrated pest management or new plant breeding techniques. Moreover, they do not consider demand-side measures (e.g. dietary shifts or reduced consumer food waste) or impacts resulting from new or revised trade agreements. Lastly, although each study looks at the impacts of different sets of policy developments, none fully captures the wider range of policy initiatives and environmental, demographic, technological and economic drivers of change.

Supply-demand gap

There is a lack of understanding about the impact of policy changes on the supply of and demand for food and feed in the EU. Consequently, there is uncertainty about the potential gap between supply and demand that may arise as a result of implementing the European Green Deal and its supporting policies.

Particular challenges are posed by historical unfluctuating food demand (Beckman et al., 2020; Guyomard et al., 2020; Barreiro Hurle et al., 2021) (see Table A3.4 in the annex for an overview of the scope of all agricultural studies referenced in this section). Unlike bioenergy and bio-based materials, where substitute energy sources and materials exist, there is no alternative to food; should output fall, prices will increase. For this reason, while global projections of food demand towards 2050 exist (e.g. Islam and Karim, 2019; Fukase and Martin, 2020; Noleppa and Cartsburg, 2021, all of whom project increasing demand), future EU scenario forecasts tend to focus on how European policies will impact domestic agricultural production. These forecasts also predict demand shifts through price increases and trade patterns (Barreiro Hurle et al., 2021; Witzke, 2021). As a result, we may outsource agricultural production to countries with lower environmental standards compared to the EU; this may lead to GHG emissions, biodiversity loss, inefficient use of water and ecosystem degradation in those countries.

3.2 Policy landscaping for biomass

Biomass impacts and is impacted by a large range of EU policies, as well as market, technological, geopolitical and demographic developments and behavioural shifts. A complete analysis of the EU policy landscape would need to look at the different stages of the biomass value chain that appear in specific policies. These policies cover different land uses, biomass production in ecosystems, ways to convert biomass for use, the end use, and distribution of bio-based products and services (for an overview see Singh et al., 2021). These policies also try to limit the environmental and climate impact of biomass production and consumption.

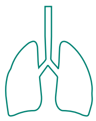
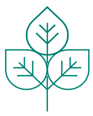
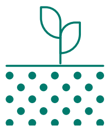
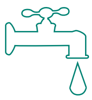
Since this report focuses on terrestrial ecosystems, we limited our policy analysis to regulatory instruments related to the following points:

- biomass production in terrestrial ecosystems and its impacts on biomass supply;
- end use by those economic activities that might need biomass to reach the 2030 climate GHG reduction targets set in the Fit for 55 package;
- how the policies and regulatory instruments identified generally deal with known climate and environmental impacts, and how this may affect biomass demand and supply.

3.2.1 Overview of the policy landscape

This section presents an overview of the EU policy that is anticipated to drive demand for and supply of biomass. It focuses on the elements that address the main environmental and climate-related pressures from biomass production and consumption, as shown in Table 3.1.

Table 3.1 General overview of environmental and climate-related pressures from biomass production and consumption and how existing policy might address these

Symbol	Environmental and climate-related pressures	Existing policy interventions
	Atmosphere: GHGs — climate change	• Reducing GHG emissions in the agriculture sector • Increasing carbon removals and long-term storage in terrestrial biomass • Reducing GHG emissions by substituting fossil fuels with bio-based products/materials in many economic sectors (e.g. construction, energy) • Improving resource efficiency (e.g. via circularity), leading to reduced biomass production and consumption needs • Employing land management practices that make forests, agricultural land and urban areas less vulnerable to climate change and protect against biomass losses
	Atmosphere: air pollution — air quality	• Reducing air pollutant emissions overall and in the agriculture sector • Employing land management practices that make forests, agricultural land and urban areas less vulnerable to air quality problems
	Nature: biodiversity loss and degradation, and fragmentation of ecosystems	• Halting the loss and degradation of ecosystems caused by land management practices such as agricultural intensification, overharvesting and nutrient enrichment • Halting the fragmentation of ecosystems from land planning • Employing nature restoration measures
	Soils: erosion, degradation and pollution	• Reducing land management choices and land management practices that increase soil erosion and lead to loss of soil organic matter • Employing land management practices that improve soil structure • Adding less nutrients and pesticides to soil and preventing soil contamination
	Water: use and pollution	• Using forest cover and responsible agricultural land management practices to improve water quality and limiting water use • Reducing nutrient and pesticide pollution of groundwater and surface waters
	Waste	• Reducing food waste • Reducing climate and environmental impacts from waste handling in landfills and waste incineration facilities • Using waste as a secondary material within the economy to increase resource efficiency

Under the European Green Deal, a large amount of thematic and horizontal legislation has recently been adopted or is under development that is relevant to biomass production and consumption. Figure 3.4 presents this legislation. How such legislation is impacting biomass production and consumption is discussed in more detail in Section 3.2.2.

Figure 3.4 EU policy relevant to biomass production and consumption

Source: EEA.

3.2.2 Policy impacts on biomass supply and demand

This section presents a qualitative analysis of the projected effects of a selected subset of policy targets, with expected impacts on biomass production (refer to the impact matrix approach in Table 3.2) by 2030. Based on the above-mentioned limitations and gaps in evidence, this analysis is not intended to predict the combined effects of achieving all the policy targets. The purpose is to highlight potential conflicts and trade-offs. The value of this exercise is in outlining the anticipated impacts/pressures of individual policies on the supply and demand of biomass (i.e. biomass extracted for bioenergy and non-bioenergy uses, and non-harvested biomass remaining in ecosystems).

The analysis is based on expert judgement and comprised the steps outlined in Table 3.2.

Table 3.2 Impact matrix approach for policy review

1 Scope definition	2 Impact mapping and assessment	3 Quality assurance
Policy targets were identified that were anticipated to lead to material impacts on biomass supply and/or demand, with a focus on European Green Deal-related targets and a selection of subsets.	A logic-chain approach facilitated a high-level review of key characteristics and pathways to reach each target (i.e. what potential pathways or mechanisms are in place/could be implemented to achieve the target). Results were informed by the expert judgement of EEA staff.	The resulting matrix was further reviewed and refined in a workshop setting with EEA experts/staff.

In populating the impact matrix, the following approach was taken:

- The analysis focused on the impact of achieving each policy target, taking into consideration its known or potential implementation mechanisms (to the extent that these have been defined or outlined). In that sense, each policy target was assumed to be met.

- Each policy target was assessed in isolation, without considering the dynamic nature of the baseline. Supply and demand will shift over the assessment period irrespective of the policy under consideration. The purpose of the analysis was not to identify the impact of the policy on underlying trends and its overall contribution to the dynamic baseline, but rather to identify the pressures on biomass supply and demand driven directly by the policy through its known or anticipated implementation mechanisms.

- Other policies may mitigate or counter these pressures. However, it is important to stress that maximising the synergies and co-benefits, and enhancing the impacts of different policies, are an essential part of the European Green Deal.

A glossary of terms for the policy matrix in Table 3.4 is presented in Table 3.3. It is important to note that the classifications based on end uses and their associated production areas are not necessarily mutually exclusive and can spatially overlap.

Table 3.3 Glossary of biomass classifications and terms

Term	Description
Agricultural and other non-harvested biomass	Agricultural biomass left in agricultural fields; stocks in nature/resources in agricultural or other land; other non-harvested biomass in agroecosystems, including landscape features (such as hedgerows and field margins), and in moorlands, peatlands, saltmarshes, natural grasslands and other ecosystems, except forests.
Forest biomass standing stocks (not harvested)	Includes strictly protected forest sites and forest maintained for carbon sequestration and storage objectives, regardless of their management regimes. Excludes forest residues that are used for other production purposes.
Agricultural biomass extracted for use (i.e. bioenergy and non-bioenergy)	Includes all harvested crops (e.g. short rotation/perennial crops) and biomass of livestock origin and from grazed pastures and grasslands, regardless of their management regime, and their residues extracted and used for bioenergy or other purposes (e.g. crop residues, manure).
Forestry biomass extracted for use (i.e. bioenergy and non-bioenergy)	Biomass from forests extracted for bioenergy or non-bioenergy uses (e.g. roundwood materials, fuelwood and tree residues), regardless of their management regime.
Waste	Biomass that is discarded and has become waste after use in the economy. Biomass is included in many different waste types. Some waste types as reported under the EU Waste Statistics Regulation can be assumed to consist mainly of biomass (e.g. animal and mixed food wastes, vegetal wastes). Others can contain both biomass-based materials and other materials, e.g. textiles or mixed household waste.

General considerations for assessing the policy matrix

- Table 3.4 includes only selected EU policy targets and is intended as an illustration rather than a detailed analysis of each target. Policy targets are grouped by EU strategy or other EU legislation.

- The time horizon of the analysis is the period up to 2030. This means that, for those strategies and regulations with 2050 targets, only the short-term, 2030 effects of their targets are considered. Long-term impacts are expected to differ from short-term impacts in some cases, as some policy targets are designed with long-term objectives in mind but may induce indirect, short-term impacts.

- The table intends to capture the main anticipated impacts of achieving the selected policy targets and the potential trade-offs related to biomass supply and demand. However, these will not necessarily always apply under all circumstances because habitat type, biophysical and climatic factors, and land management considerations will influence impacts at each individual location.

- The potential impacts of achieving each policy target on supply and demand of the following types of biomass were analysed:
    - **biomass extracted for use** – impacts were explored relative to anticipated changes in biomass demand and supply with the objective of highlighting whether the target would have a **direct effect** on biomass availability for extraction (**supply**) or on **demand** for biomass (driven by market or consumer needs), given that supply and demand are intrinsically connected in a market economy and any change in one of these two parameters will invariably trigger shifts in the other over time;
    - **biomass left in nature** (biomass in stock, in natural and semi-natural ecosystems);
    - **waste biomass** and whether it is available for recycling instead of being disposed of.

Table 3.4 Matrix of various European Green Deal policy targets and their impacts on different biomass uses and biomass stocks

↑	Biomass increase due to the policy target
↓	Biomass decrease due to the policy target
↑?	Possible biomass increase due to the policy target
↓?	Possible biomass decrease due to the policy target

European Green Deal/Fit for 55

	Anticipated impacts on biomass extracted for use in the economic system: • demand (coming from the markets, consumers, policy) • supply (production through the agriculture or forestry sectors)												Anticipated impacts on biomass in natural and semi-natural ecosystems	
	Bioenergy						Non-bioenergy						Agroecosystem and non-forest landscapes stock	Forestry stock
Policy target	Agriculture		Forestry		Waste		Agriculture		Forestry		Waste			
	D	S	D	S	D	S	D	S	D	S	D	S		
Increase current target from 32% to 42.5% share of renewable energy sources in final energy consumption by 2030 (RePowerEU Plan (EC, 2022a); Provisional deal on RED, (Council and Parliament of the EU, 2023).	↑?	-	↑	↑	↑	-	-	↓	-	↓	-	↓	↓	↓

An increase in the demand for biomass for bioenergy raises questions. Where is the biomass supply likely to come from and how much more is needed? Can we expect a reduced supply of biomass for non-bioenergy related uses? There is some uncertainty around exactly where the land required to grow more biomass is to come from. Moreover, would more demand for biomass lead to more intensive land management, or to increased imports of some biomass products from outside the EU? Achieving renewable energy targets includes biomass and other renewable energy sources, such as solar and wind, so biomass use can increase or decrease depending on other renewable energy developments.

Table 3.4 Matrix of various European Green Deal policy targets and their impacts on different biomass uses and biomass stocks (cont.)

European Green Deal/Fit for 55														
	Anticipated impacts on biomass extracted for use in the economic system: • demand (coming from the markets, consumers, policy) • supply (production through the agriculture or forestry sectors)												Anticipated impacts on biomass in natural and semi-natural ecosystems	
Policy target	Bioenergy						Non-bioenergy						Agroecosystem and non-forest landscapes stock	Forestry stock
	Agriculture		Forestry		Waste		Agriculture		Forestry		Waste			
	D	S	D	S	D	S	D	S	D	S	D	S		
40% reduction in GHG emissions in the Effort Sharing Regulation sectors by 2030 compared with 2005 (EU, 2018b)	↑?	↓	↑?	↓	-	↑	↑	↓	↑	↓	-	↑	↓	↑?

The Effort Sharing Regulation provides targets for national annual emissions at the Member State level that refer to all effort sharing sectors (such as agriculture, buildings, waste and transport). Each Member State decides individually on the pathway towards reaching this target. Therefore, at the EU level, it is very hard to estimate potential impacts on biomass demand and supply. In order to reduce emissions from the transport and building sectors, biomass demand may increase. Any increased biomass demand may negatively impact forest stock, as well as biomass supply for non-bioenergy, e.g. land left fallow for environmental reasons. The aim of reducing GHG emissions in the agriculture sector may lead to lowering inputs such as fertilisers and lowering yields. One could predict less waste going to landfill, so waste supply would increase, e.g. for recycling.

European Green Deal/LULUCF sector														
	Anticipated impacts on biomass extracted for use in the economic system: • demand (coming from the markets, consumers, policy) • supply (production through the agriculture or forestry sectors)												Anticipated impacts on biomass in natural and semi-natural ecosystems	
Policy target	Bioenergy						Non-bioenergy						Agroecosystem and non-forest landscapes stock	Forestry stock
	Agriculture		Forestry		Waste		Agriculture		Forestry		Waste			
	D	S	D	S	D	S	D	S	D	S	D	S		
310MtCO_2e of EU net GHG removal for the LULUCF sector in 2030 (LULUCF Regulation (EU) 2023/839)		↓		↓				↓	↑?	↓	-	↑	↑	↑

Setting a carbon sequestration target has consequences for forest ecosystems. It may mean taking some additional land out of production or lowering the intensity of wood extraction from forests to maintain the forest carbon sink. If less wood is extracted, there is less supply for bioenergy and non-bioenergy uses unless it is compensated for by imports. In addition, one of the potential question is whether afforestation will take place on high or low productive agricultural land. Since harvested wood products deliver to carbon removals in the scope of the LULUCF Regulation and are expected to increase under the forthcoming carbon removals certification framework, the demand for wood products (not used in bioenergy) may increase.

Table 3.4 Matrix of various European Green Deal policy targets and their impacts on different biomass uses and biomass stocks (cont.)

European Green Deal/LULUCF sector

Anticipated impacts on biomass extracted for use in the economic system:
- **demand (coming from the markets, consumers, policy)**
- **supply (production through the agriculture or forestry sectors)**

Anticipated impacts on biomass in natural and semi-natural ecosystems

Policy target	Bioenergy						Non-bioenergy						Agroecosystem and non-forest landscapes stock	Forestry stock
	Agriculture		Forestry		Waste		Agriculture		Forestry		Waste			
	D	S	D	S	D	S	D	S	D	S	D	S		
Cleaner maritime fuels, asking to cut ship emissions by 2% as of 2025 and by 80% as of 2050 (EU, 2023).	↑	-		-	↑	-	-	↓?	-	-	-	-	↓	-

FuelEU Maritime will demand a progressive reduction in the GHG emission intensity of the energy used on ships, starting from a baseline of 91.16gCO_2/MJ (year 2020). This will drive an increase in the demand for biofuels in this sector. Economic and technological aspects will drive the choice of the feedstock used. In the long term, this demand for biomass could be stabilised or even reduced by the uptake of advanced energy vectors such as ammonia or hydrogen, which are currently expensive or technically complex. A conceptually similar initiative is under discussion for the aviation sector as well, and this may have similar implications for biomass demand.

EU biodiversity strategy for 2030

Anticipated impacts on biomass extracted for use in the economic system:
- **demand (coming from the markets, consumers, policy)**
- **supply (production through the agriculture or forestry sectors)**

Anticipated impacts on biomass in natural and semi-natural ecosystems

Policy target	Bioenergy						Non-bioenergy						Agroecosystem and non-forest landscapes stock	Forestry stock
	Agriculture		Forestry		Waste		Agriculture		Forestry		Waste			
	D	S	D	S	D	S	D	S	D	S	D	S		
30% of land is protected, of which 10% is strictly protected	-	↓	-	-	↓	-	-	↓	-	↓	-	-	↑	↑

Despite the differences in forest management based on each forest's protection status, the overall trend in terms of both forest extent and the amount of forestry biomass left on site is expected to be positive and in line with the overall policy objective. Biomass supply from forestry is expected to decrease because of this policy target. The overall trend for extracted biomass is anticipated to be negative because some land is expected to be taken out of production also because of reduced intensity/non-biomass extraction from protected forests.

The trend for non-extracted agricultural and other non-forest biomass is less clear. Biomass in landscape features is expected to increase but biomass in some restored non-woody habitats is expected to reduce. This is due to restoration measures such as removing scrub encroachment or non-native plantations, rewetting peatlands and potential land conversion (e.g. from grassland to forest). There is uncertainty about the land use composition of new, protected land. However, it can be assumed that agricultural activities would be allowed at a lower intensity level and possibly in a reduced area. Therefore, a reduced supply of extracted biomass is expected.

Certain natural habitats (such as Mediterranean forests) need to be managed to avoid biomass build-up to reduce the risk of wildfires.

Policy target	Bioenergy Agriculture D	Bioenergy Agriculture S	Bioenergy Forestry D	Bioenergy Forestry S	Bioenergy Waste D	Bioenergy Waste S	Non-bioenergy Agriculture D	Non-bioenergy Agriculture S	Non-bioenergy Forestry D	Non-bioenergy Forestry S	Non-bioenergy Waste D	Non-bioenergy Waste S	Agroecosystem and non-forest landscapes stock	Forestry stock
10% of agricultural area under high-diversity landscape features	-	↓	-	-	-			↓	-	-	-	-	↑	-

An increase in high-diversity landscape features within agricultural areas is assumed to increase the quantity of biomass stock left on site. If more areas covered by woody landscape features are expected to be devoted from lower productivity land, agricultural biomass supply is expected to decrease slightly. Taking this into account, yield could become more stable as the presence of landscape features increases.

Table 3.4 Matrix of various European Green Deal policy targets and their impacts on different biomass uses and biomass stocks (cont.)

European soil strategy for 2030

Anticipated impacts on biomass extracted for use in the economic system:
- **demand (coming from the markets, consumers, policy)**
- **supply (production through the agriculture or forestry sectors)**

Anticipated impacts on biomass in natural and semi-natural ecosystems

Policy target	Bioenergy						Non-bioenergy						Agroecosystem and non-forest landscapes stock	Forestry stock
	Agriculture		Forestry		Waste		Agriculture		Forestry		Waste			
	D	S	D	S	D	S	D	S	D	S	D	S		
All EU soil ecosystems are in healthy condition in 2050	-	↓	-	↓	-	-	-	↓	-	↓	-	-	↑	↑
This target is assumed to benefit all biomass types thanks to improved soil condition. In 2050, with restored and healthy soils, yields are expected to benefit. However, short-term reductions in the production of many biomass types could be assumed because of the actions needed to fulfil this long-term aim (in particular, de-intensifying production). Since this table looks at the 2030 horizon, biomass supply from agriculture and forestry are assumed to be reduced. Some uncertainty arises because of the different expected outcomes depending on which habitats/ecosystems will be prioritised for improved soil conditions. However, this uncertainty is not robust enough to impact the directions of changes/arrows.														
Significant areas of degraded and carbon-rich ecosystems, including soils, are restored	-	↓?	-	↓?	-	-	-	↓?	-	↓?	-	-	↑	↑
The supply of biomass from agriculture and forestry is expected to reduce. However, this depends on land management actions (i.e. what habitats are restored, how and for what activities). For example, restoration is likely to yield positive benefits, but can also involve significant biomass or carbon removal on biomass stocks left on site/in nature (e.g. heathland restoration). Biomass extraction is likely to decrease over the short term. Long-term benefits are anticipated but depend on management actions.														

EU forest strategy for 2030

Anticipated impacts on biomass extracted for use in the economic system:
- **demand (coming from the markets, consumers, policy)**
- **supply (production through the agriculture or forestry sectors)**

Anticipated impacts on biomass in natural and semi-natural ecosystems

Policy target	Bioenergy						Non-bioenergy						Agroecosystem and non-forest landscapes stock	Forestry stock
	Agriculture		Forestry		Waste		Agriculture		Forestry		Waste			
	D	S	D	S	D	S	D	S	D	S	D	S		
All primary and old-growth forests will have to be strictly protected	-	-	-	↓?	-	-	-	-	-	↓?	-	-	-	↑
Forest stocks left in nature/on site are likely to benefit from this target, as will biodiversity. In principle, this should lead to sustained carbon sequestration. However, carbon sequestration also depends on the age of a tree. If all primary and old-growth forests are strictly protected by harvesting bans, this could intensify pressure on those forests from which wood can be extracted. Impacts on agriculture are unknown, as are impacts on non-extracted agricultural systems.														

Table 3.4 Matrix of various European Green Deal policy targets and their impacts on different biomass uses and biomass stocks (cont.)

EU forest strategy for 2030														
	Anticipated impacts on biomass extracted for use in the economic system: • demand (coming from the markets, consumers, policy) • supply (production through the agriculture or forestry sectors)												Anticipated impacts on biomass in natural and semi-natural ecosystems	
Policy target	Bioenergy						Non-bioenergy						Agroecosystem and non-forest landscapes stock	Forestry stock
	Agriculture		Forestry		Waste		Agriculture		Forestry		Waste			
	D	S	D	S	D	S	D	S	D	S	D	S		
Trade in legal and 'deforestation-free' commodities and products (EU, 2023)	-	-	↑?	↑?	-	-	↑?	-	↑?	↑?	-	-	-	?

It is highly uncertain how this policy target will impact biomass demand and supply in the EU. Since this target is primarily aimed at non-EU forests/trade, impacts are primarily related to reduced supply of non-EU wood and perhaps the resulting need for greater EU production. Impacts on domestic forestry biomass stock are unclear. The EU forestry stock may benefit from reduced illegal logging but may also be pressured by the need for increased production. Some food and feed agricultural production, such as cattle, cocoa, coffee, palm oil, soya and wood, may be affected. Currently, imports of soya bean, fruit and vegetables from outside the EU are quite significant. Therefore, reducing these imports in the event of reduced availability of certified deforestation-free stocks would imply an increase in demand for domestic supply for some products.

Farm-to-fork strategy														
	Anticipated impacts on biomass extracted for use in the economic system: • demand (coming from the markets, consumers, policy) • supply (production through the agriculture or forestry sectors)												Anticipated impacts on biomass in natural and semi-natural ecosystems	
Policy target	Bioenergy						Non-bioenergy						Agroecosystem and non-forest landscapes stock	Forestry stock
	Agriculture		Forestry		Waste		Agriculture		Forestry		Waste			
	D	S	D	S	D	S	D	S	D	S	D	S		
25% of agricultural land is under organic management	-	↓	-	-	-	-	↑?	↓	-	-	-	-	↑?	-
Yields are assumed to be lower in areas under organic production. However, a key question is whether EU agricultural land use is required to compensate for lower yields and increased land under organic cultivation. If so, how would this take place — through new agricultural areas, or a change from extensive to intensive farming in some areas? There are assumed benefits for non-extracted agricultural biomass stocks, but they are uncertain. Negative impacts on agricultural production for bioenergy are also assumed because of an increased area under organic production and are also uncertain. Another question remains: does the fact that more EU food is to be organic correspond with the EU demand for domestically produced organic food?														
50% reduction in the use and risk of chemical pesticides and use of most hazardous pesticides by 2030		↓		↓?				↓	-	↓?			↑?	↑?
The assumptions here are largely the same as for organic management, meaning that a reduction in agricultural yields can be expected. The IA within the proposed revision of Directive 2009/128/EC on the regulation of sustainable use of pesticides envisages a reduction in crop yields under the farm-to-fork targets. With this in mind, a decline in agricultural yields is more likely. It should be noted that the IA states that strong regulatory support and economic subsidies could help deploy and scale up the use of alternative plant protection methods without yield reductions. However, as previously noted, this policy is assessed independently of other instruments that may counter or reinforce the trend. No anticipated impacts for extracted forestry are assumed. In tandem, the impacts for the overall stock of non-extracted biomass are unknown (although the IA does forecast a positive impact on biodiversity and ecosystem resilience).														

Table 3.4 Matrix of various European Green Deal policy targets and their impacts on different biomass uses and biomass stocks (cont.)

Farm-to-fork strategy														
	Anticipated impacts on biomass extracted for use in the economic system: • demand (coming from the markets, consumers, policy) • supply (production through the agriculture or forestry sectors)												Anticipated impacts on biomass in natural and semi-natural ecosystems	
Policy target	Bioenergy						Non-bioenergy						Agroecosystem and non-forest landscapes stock	Forestry stock
	Agriculture		Forestry		Waste		Agriculture		Forestry		Waste			
	D	S	D	S	D	S	D	S	D	S	D	S		
20% reduction in use of fertilisers	-	↓?	-	-	-	-	-	↓?	-	-	-	-	↑?	↑?
Reducing fertiliser use may lead to a reduction in biomass supply in some locations because crops will receive lower inputs. However, some reduction in fertiliser use can be achieved by improving fertilisation/fertilisation planning. There are still large differences in fertiliser use among farmers.														
50% reduction in nutrient losses with no deterioration in soil fertility	-	-	-	-	-	-	-	-	-	-	-	-	↑?	-
Assuming that the target is reached by using integrated nutrient management, a reduction in nutrient losses would be reached without a change in yield. Non-extracted stocks would probably increase as well because of more buffer strips being used as a nature-based solution to reduce nutrient losses.														
50% reduction in food waste	-	-	-	-	-	↓?	↓	-	-	-	-	↓	↑?	↑?
Reduced food waste probably allows for more biomass left in nature, except if the land is used for other purposes. However, reduced food waste does not necessarily equate to reduced food demand or less need for other biomass from agriculture. If less food waste is generated, then less food waste will be available for anaerobic digestion (and thus energy generation) across the whole value chain. The purpose of the food waste reduction target is to reduce the demand for food and thereby reduce environmental impacts of food production upstream. However, reduced demand for food could simply lead to a higher share of food exported if production is kept at the same level.														
Transition to a more plant-based diet with less red and processed meat, and more fruits and vegetables ([a])	-	↑?	-	↑?	-	-	↓	↓	-	↑?	-	-	↑?	↑?
Reduced demand for biomass allocated to food and feed is assumed, with potential associated benefits as a result of more available land for biomass being left in nature. The target could potentially influence other sources of biomass because of freed-up space. However, the specific allocations are unknown. The extent to which EU producers will benefit from a growth in global demand by increasing exports of meat and meat products could also influence biomass allocation. However, current forecasts show that the production of beef and pig meat is likely to follow consumption trends and decline by 2031. The decline in beef production is expected to be particularly pronounced (EC, 2021a).														

Note: ([a]) Not a specific policy target and therefore does not come with a specific percentage target.

Table 3.4 Matrix of various European Green Deal policy targets and their impacts on different biomass uses and biomass stocks (cont.)

Waste Framework Directive (WFD) and Landfill Directive (LD)

Policy target	Anticipated impacts on biomass extracted for use in the economic system: • demand (coming from the markets, consumers, policy) • supply (production through the agriculture or forestry sectors)												Anticipated impacts on biomass in natural and semi-natural ecosystems	
	Bioenergy						Non-bioenergy						Agroecosystem and non-forest landscapes stock	Forestry stock
	Agriculture		Forestry		Waste		Agriculture		Forestry		Waste			
	D	S	D	S	D	S	D	S	D	S	D	S		
Municipal waste: 65% of generated municipal waste should be recycled (WFD target) and landfilling reduced to 10% maximum (LD target) by 2035 (EC, forthcoming), (EU, 2018a).	-	-	-	-	-	↑	-	-	-	-	-	↑	-	-
On average, biomass accounts for more than 37% of municipal waste (mostly food and garden waste from households and similar sources) (EEA, 2022). To meet these targets, it is crucial to collect biowaste separately and recycle it. More than half of all biowaste generated is currently landfilled or incinerated. Separately collected biowaste is either composted or digested in the fermentation process, creating biogas for energy purposes and generating organic fertilisers.														

Circular economy action plan (a building block of the European Green Deal)

Policy target	Anticipated impacts on biomass extracted for use in the economic system: • demand (coming from the markets, consumers, policy) • supply (production through the agriculture or forestry sectors)												Anticipated impacts on biomass in natural and semi-natural ecosystems	
	Bioenergy						Non-bioenergy						Agroecosystem and non-forest landscapes stock	Forestry stock
	Agriculture		Forestry		Waste		Agriculture		Forestry		Waste			
	D	S	D	S	D	S	D	S	D	S	D	S		
Doubling the circular material use rate by 2030, (EC, 2020b).	↓	↓?	↓	↓?	-	↓	↓	↓	↓	↓	↑	↓?	↑	↑
Achieving this target will require reducing material consumption in the economy (e.g. through extending the lifetime of products and more efficient production) and increasingly recycling discarded materials. The target's impact on biomass depends on the balance between these two strategies. The target is also directed at all materials, and biomass accounts for only about 25% of them. Therefore, if the focus is on increasing the circular use of non-biomass materials, the impact on biomass might be very low. However, if the circular use of biomass increases, this would mean less (primary) biomass used in the economy (and less extracted from agriculture and forestry) and more recycled biomass. If the focus of the target is on replacing mineral and fossil fuel materials with bio-based materials and increasing the cascading use of biomass supply, then the amount of waste biomass could increase.														

3.2.3 Policy matrix conclusions

Within the policies related to biomass production, there are many targets focusing on reducing the impacts of biomass production on biodiversity and ecosystems (e.g. the farm-to-fork strategy, the forest and biodiversity strategies and the proposed Nature Restoration Law). They call for using fewer external inputs, less intensive practices and less harmful chemical substances while focusing on nature-based solutions. Such solutions focus on ecosystem restoration, increasing the area under protection or strict protection, maintaining extensive production systems and increasing carbon sequestration in ecosystems. These policies are generally expected to benefit the quality and quantity of biomass stocks left in nature. However, they are also expected to lead to a reduction in net biomass production for use in the bioeconomy, potentially adding pressure to current stocks of biomass in nature in an effort to address the gap in biomass production (e.g. if fallow land is taken back into production to compensate for reduced crop yield). In this situation, some of the intended policy benefits for biodiversity and ecosystems could be accompanied by unintended negative effects.

In recognition of these trade-offs, the farm-to-fork strategy also includes less precise objectives targeting a reduction in the demand for food. They revolve around two main focus areas: (1) a shift in consumer demand towards healthier diets (in particular, consuming less animal-based food) and (2) a reduction in food loss and waste across the whole value chain. Given their aspirational nature and the complex set of changes and supporting policies already required across the food value chain, the success of these targets is unknown, as is how targets for organic farming and antimicrobial use will impact consumer demand. For example, it seems unlikely that substantial reductions in biomass demand through dietary shifts will be achieved through changes in societal preferences alone, without policy interventions. Based on a no-action baseline, the European Commission forecasts only a modest reduction in EU meat consumption by 2031, from 69.8kg to 67kg per capita (EC, 2021a). However, some additional benefits for biomass may also come from the parallel shift in the type of meat consumed (i.e. beef consumption is expected to decline, and pig meat will continue to be replaced by poultry meat) (EC, 2021a). In addition, regarding policy measures on food waste, the Commission is investigating setting binding targets on food waste reduction under the ongoing revision of the Waste Framework Directive.

Policies that promote ecosystem restoration and healthier soils are expected to benefit all biomass types over the long term. However, there might be trade-offs as a result of lower biomass production in the short term (e.g. on agricultural land when implementing practices related to improving soil quality).

A transition to a circular economy can also reduce demand for primary biomass materials and increase the availability of secondary biomass, for instance through recycling or recovering waste instead of landfilling it.

Box 3.1

The circular economy

One of the EU's objectives within the European Green Deal is a transition towards a circular economy. Circular economy actions target both production and consumption and can better balance the scales between biomass supply and demand. This can occur because of increased resource efficiency and enhanced biological cycles, whereby nutrients from biodegradable materials help regenerate nature by returning to Earth after use (EEA, 2018; Ellen MacArthur Foundation, 2023).

In a linear economy (take-make-waste), demand for natural resources, including biomass, continually increases as the economy grows. In contrast, in a circular (bio)economy the value of biomass-based products, materials and resources is maintained for as long as possible. This substantially reduces the demand for biomass and the negative impacts on the environment associated with its production.

In addition to resource efficiency, a circular economy aims to promote regenerative practices. This would improve biological cycles by promoting biomass extraction and production methods that enhance biodiversity and ecosystems. A recent study by the Finnish Innovation Fund Sitra (Forslund et al., 2022) argues that, through a broad range of circular economy measures, global biodiversity loss can be halted by 2035 and the global agriculture land area could be reduced by 640 million hectares.

Ambitious GHG emission reduction targets set under the Fit for 55 package are connected to many sectoral policies (such as transport, energy, buildings, agriculture and waste) and may add pressure on the demand for and supply of biomass. Although none of the targets implicitly calls for using more biomass, its use will support decarbonisation process of these sectors (e.g. biomass replacing carbon-intensive fossil fuels or construction materials). These policies increase demand for harvested biomass, which in turn could drive land use changes and reduce stocks of non-harvested biomass left in ecosystems. This is important given the potential of these policies to reduce or increase competition across the different biomass categories (i.e. system-level trade-offs between harvested biomass for use in the economic system and non-harvested biomass remaining in the ecosystem). At the same time, carbon removal targets related to the LULUCF Regulation (including the forestry strategy) recognise nature as a solution and call for enhanced carbon sequestration in forests and other land ecosystems. This carbon removal target may also impact biomass's availability for replacing carbon-intensive materials and products and impact the stocks of biomass left on site and not harvested. But this greatly depends on the type of forest in question; it is not always favourable to maintain or increase the amount of biomass that remains in the forest.

Unintended pressures on biodiversity, ecosystems and other nature-related objectives could also arise from climate-related policy targets (e.g. when widespread monoculture tree planting interferes with other non-harvested biomass stocks). Therefore, the LULUCF Regulation includes linkages with biodiversity strategy and the proposed Nature Restoration Law to limit these trade-offs.

The demand for biomass for use in the decarbonisation of the EU's economic and financial systems needs to be carefully balanced with supply constraints to ensure that carbon sequestration, biodiversity and conservation objectives are also met. In this context, EU action is needed to ensure that the increasing demand for biomass such as wood is not met by increased illegal logging in the EU and abroad or other unsustainable practices. In addition, over the medium to long term, there should be a clearer approach to bringing in biomass as a source of energy as a last step and prioritising other types of renewable energy sources that have lower impacts on climate, biodiversity and air pollution.

3.2.4 Policy requirements for biomass reporting

A coherent information infrastructure is a necessary condition for evidence-based policymaking and decision-making around biomass production and use. In 2023, a new process for climate and energy reporting in relation to biomass will begin with the national climate and energy progress reports, based on two implementing regulations (EU, 2020, 2022) under the Regulation on the governance of the energy union and climate action, (EU) 2018/1999 (EU, 2018c).

Member States are legally required to provide biomass data in relation to bioenergy use, including:

- total installed capacity and quantities of biomass used in various sectors (electricity generation, heating and cooling, transport, buildings);
- how biomass production impacts various factors (water use, biodiversity, soils, air quality, commodity prices, land use);
- technological developments and biofuel deployment;
- cases of fraud in biofuel, bioliquid and biomass fuel chains.

Additionally, data on biomass for energy use will provide more granular knowledge about its domestic production, import, export, stock changes, and net calorific value for specific forms of biomass per Member State. The biomass categories include forest biomass used for energy production, agricultural biomass and organic waste biomass. Beyond this, Member States are legally required to report on any policies and/or measures that relate to biomass and their associated impacts (GHG emission reductions, energy generation, energy savings), additional information on policies and measures focusing on energy subsidies (including for biomass), and progress towards reducing energy dependency from imported biofuels.

In addition, a framework on forest monitoring and strategic planning is also being developed under the EU forest strategy to improve policy coordination across legislative proposals and to support the development and coordination of strategies at national and regional levels. As part of this initiative, the Commission plans to put forward a harmonised EU forest observation, reporting and data collection to provide open access to detailed, accurate and timely information on the condition and management of EU forests. New initiatives regarding data collection must be consistent with existing reporting obligations for Member States.

The provision of all data, if reliably reported by EU Member States, may provide a broader understanding at Member State level about the supply, use and impacts of biomass — particularly biomass for energy use and associated GHG emissions. However, it is unknown to what extent new reporting requirements will help to fill data gaps on biomass supply and demand and improve our understanding of biomass use. In addition, it is unknown how reliable and complete the data submitted by Member States are going to be. Although data quality assurance is expected, Member States do not need to resubmit data once they have been quality checked.

4 Biomass production under a changing climate

Key messages

- Climate change has already been impacting the biomass supply from the European agriculture and forestry sectors in both positive and negative ways and this impact has regional differences.
- Studies looking at long-term climate trends on European crops have shown evidence of crop yield reductions for maize, wheat and other cereals (e.g. rapeseed and sorghum) in southern Europe due to increasing temperatures, decreasing precipitation and a shift in seasons. In other parts of Europe, changes in temperature and precipitation positively impact some crop species.
- Severe and frequent droughts occurring in the EU have negatively impacted forest growth and stability. Such events have caused habitat loss, local species migration and spread of invasive alien species, and contributed to forest fires. Particularly since 2018, as a result of the prolonged and severe drought events experienced in central Europe, forest tree health has deteriorated, which sparked a significant bark beetle infestation. As a result, widespread tree mortality was observed, and large amounts of preventive felling took place to mitigate further mortality.
- According to long-term model projections, southern Europe is expected to experience high crop yield losses, central Europe moderate losses and northern Europe increases in yield, particularly for maize and wheat.
- Studies projecting future climate change impacts on forests are inconclusive and show large variations per country/region and species. This is because a forest's response to climate change can be complex and multilayered. Typically, biodiverse forests are more resilient to the effects of climate change than monotypic forest stands.

This chapter aims to examine how total biomass production in the EU-27 will change by 2050 as a result of climate change. Therefore, it explores how climate change is impacting the quantity and quality of biomass that is grown in the EU (i.e. crops, grassland, forests) and how it may cause production losses or lead to opportunities.

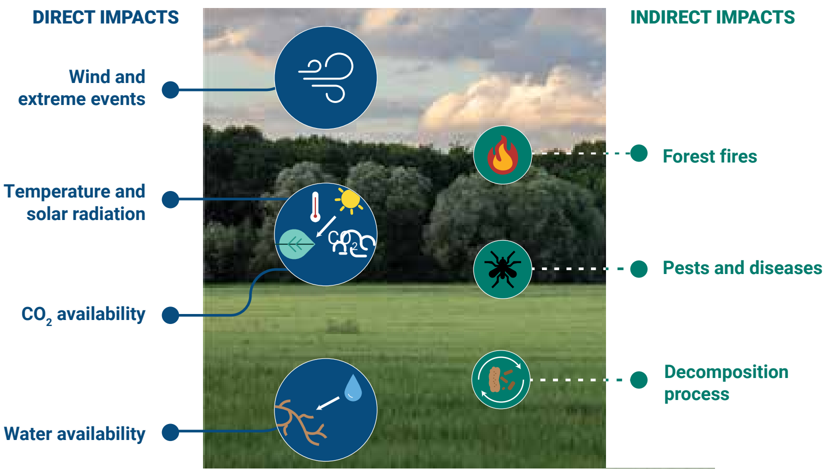
4.1 Links between climate change and biomass productivity

Biomass production in terrestrial ecosystems strongly depends on prevailing weather and climatic conditions. Changes in climate (specifically in temperature and precipitation) and extreme weather and climate events directly influence crop yields and forest productivity in many EU Member States. This section summarises the physical interactions between vegetation and the atmosphere, and it identifies the direct and indirect impacts of climate change on vegetation growth in the recent past (1960 onwards, in line with the literature review). Finally, this section introduces the concept of climatic zones and summarises how observed shifts in these zones have influenced biomass productivity.

4.1.1 Vegetation-climate interaction

Plant biomass growth is driven by photosynthesis and root absorption of water and nutrients. Photosynthesis as a biological process uses solar radiation, water and carbon dioxide (CO_2) to assimilate mass and build plant tissue. The availability of these resources and the intensity of extreme events that can physically damage plants are affected by climate change, in what we call direct climate impacts. Indirect climate impacts, meanwhile, are compound impacts of climate change that lead to many changes in ecosystems (due to, for example, the development of pests and diseases and faster soil decomposition). Figure 4.1 illustrates the main interactions between the atmosphere and vegetation through the main direct and indirect impacts, while Table 4.1 contextualises these by focusing on agriculture and forestry.

Figure 4.1 Direct and indirect climate change impacts on vegetation growth



Source: EEA.

Table 4.1 Direct and indirect climate-related impacts on agricultural and forestry biomass

<table>
<tr><th>Impact</th><th>Agriculture</th><th>Forestry</th></tr>
<tr><td colspan="3">Direct impacts</td></tr>
<tr><td>Impacts linked to temperature and solar radiation</td><td>A plant's development is tied to the cumulative temperature received over its lifetime, measured through indicators such as biologically effective degree-days ([a]) or growing season length. Rising temperatures and heat stress accelerate plant development. They can provoke earlier harvests and cut short stages of plant development and reproduction that are critical to yield, such as flowering and grain filling.

Heat stress in the growing season has multiple negative impacts, including a reduced photosynthesis rate, a reduced grain number and weight, and an accelerated senescence rate and plant mortality. Plant sensitivity to heat stress varies depending on its phenological stage. Therefore, even short periods of heat stress can significantly impact yield. Temperatures above 30°C damage most crops, and temperatures above 35°C damage even the heat-resistant maize crop.

Minimum temperatures also determine crop growth. Some crops are frost sensitive and require long frost-free periods, while others (winter crops, fruit crops, etc.) rely on vernalisation (the process of being exposed to cold temperatures) so they may flower at a suitable time (spring).</td><td>A moderate increase in temperature positively impacts forest productivity in temperate forests due to its positive impact on photosynthesis (Solberg et al., 2009). A longer growing season leads to increased growth, except where water or mineral limitations may occur. Under extreme temperatures, however, forests can also experience a decrease in gross primary production. Forests can also shift from being carbon sinks to net sources of CO_2 emissions due to these hot spells (Ciais et al., 2005; Duffy et al., 2021; Oddi et al., 2022). This is partly due to warmer climates increasing the forest soil decomposition and accelerating carbon losses from soils and litter (Stuble et al., 2019).</td></tr>
<tr><td rowspan="2">Impacts linked to water availability</td><td colspan="2">Low water availability is the greatest limiting factor for plant growth and yield worldwide (Oliver et al., 2009; EEA, 2019) with consecutive impacts. With a deficit in soil moisture, stomata close. This reduces photosynthesis because of low intercellular CO_2 concentration and thus leads to lower overall plant growth. Studies have shown that, when assessing soil moisture trends using the soil moisture index, drought conditions are expected to worsen in Europe, with substantial differences among regions. Eastern Europe and Mediterranean regions are expected to be most affected (Grillakis, 2019).</td></tr>
<tr><td>In some perennial crops (grape, olives, etc.), moderate heat and longer periods without water can improve fruit quality; this may also be true for sugar content in forage crops.

However, the timing of precipitation can be more important than the total amount of precipitation in driving vegetation growth and water availability and thus productivity (Ruiz-Pérez and Vico, 2020). Late-occurring rainfall (autumn or late summer) can also increase moisture in grains, affecting the yield and quality.

Crop yields in Mediterranean regions will be severely affected by reductions in soil moisture and increased frequency and intensity of droughts. To achieve high yields, irrigation is needed during the whole vegetative cycle (Katerji et al., 2008). Irrigation systems are a common component of agriculture in the Mediterranean basin (Aguilera et al., 2020). A combination of irrigation and growing demands for water from domestic industrial and tourism activities (mainly seasonal) pressurises and constrains the Mediterranean's water resources and availability, as well as many economic sectors (FAO and Plan Blue, 2018) . This will need to be taken into account in future agricultural production in this region (Ferreira et al., 2022).</td><td>There is evidence that drought stress due to excessively low soil moisture limits the regeneration success and growth of tree stands (Ruosteenoja et al., 2018). Several studies have reported increased tree mortality in response to droughts (Senf et al., 2020). However, the studies are selective because they have researched only one particular forest ecosystem or short time series, or effects of only one drought event. Senf et al. (2020) observed that a drought-related decrease in tree vitality is often related to an increase in harvest activity (i.e. sanitation logging) before large-scale dieback of trees can occur. Their study concluded that drought as an agent of tree mortality across Europe remains unclear (Senf et al., 2020).</td></tr>
</table>

([a]) The biologically effective degree days (°C) index is the sum of daily mean temperatures above 10°C and less than 30°C for a given period.

Table 4.1 Direct and indirect climate-related impacts on agricultural and forestry biomass (cont.)

Impact	Agriculture	Forestry
Direct impacts		
Impacts linked to increased CO_2 levels	Vegetation growth entails CO_2 removal from the atmosphere for photosynthesis. Plants have evolved to follow two separate photosynthesis processes called C3 and C4 metabolism. Most plants and trees fall within the C3 category; and many important crops are C3 plants, such as rice, wheat and soya bean. C4 plants include maize, sugarcane, sorghum and some Euphorbia species (Young et al., 2020). The influence that atmospheric CO_2 has on plant growth (positive or negative and on what types of plants) is still debated (Degener, 2015). When CO_2 levels rise, C3 plants have a comparative advantage in biomass production and yield due to the increase in CO_2 levels and photosynthesis, compared with C4 plants. However, C4 plants benefit from rising global temperatures more than C3 plants (see Anwar et al., 2021). C4 photosynthesis is more efficient than C3 photosynthesis in warmer climates where yield potential is high (Cui, 2021). C4 plants are efficient in nitrogen and water use. Because climate change impacts plant photosynthesis and growth dynamics via increased CO_2 levels, this may lead to shifts not only in crop composition but also in weed community composition. This may alter crop-weed interactions and competition outcomes between plants at the expense of crops (Cui, 2021).	
	Extreme weather events (such as downpours, short-duration heat waves and floods) and extreme climate events (such as droughts and wildfires) have increased in frequency over the last few decades due to anthropogenic activities (IPCC, 2023). They inflict physical damage on plants and trees, causing harvest losses or plant/tree mortality.	
Impacts linked to extreme weather and climate events	Aside from impeding field operations during sowing or harvesting periods, heavy rainfall can cause mechanical damage to crops by washing out plantations, causing nutrient run-off or soil erosion. Waterlogged soils are also lethal to some crops with shallow root systems.	Although natural weather disturbances are an integral part of forest ecosystem dynamics, extreme weather and climate events impede forest stability and growth. They can disturb trees, particularly in recently burned forests; make plants more vulnerable to flooding; and make soils more vulnerable to erosion. In addition, more frequent high winds can stress tree stands (Kron et al., 2019) and significantly damage ecosystems. Prolonged conditions of higher temperature and lack of precipitation significantly lower soil water moisture and increase risks of wildfires. If they take place, biomass loss will occur.
Indirect impacts		
Impact linked to pests and diseases	Climate change impacts the population dynamics of many insect populations and pathogens (Burdon and Zhan, 2020). These impacts include range expansion, an increased chance of winter survival and an increased number of generations that can be reproduced each year. It intensifies the risk of plant and tree diseases. Due to pests and infestations, one can expect potential biomass losses (Seidl et al., 2017). For example, soya bean and wheat are largely grown in high-density monocultures and such high-density crops are more easily compromised by plant pathogens (Singh et al., 2023). The same situation may concern forests: monotypic forest stands, especially plantations, are more prone to infestations than biodiverse forests (Thompson et al., 2009). The benefits of yield gains due to other climate change impacts may therefore be tempered by the greater burden of crop protection due to increased disease and unfamiliar pathogens (Chaloner et al., 2021).	

Table 4.1 Direct and indirect climate-related impacts on agricultural and forestry biomass (cont.)

Impact	Agriculture	Forestry
Indirect impacts		
Impacts linked to soil decomposition	A changing climate may alter the composition of not only plants but also soil communities and the interactions between them (Pugnaire et al., 2019). Climate change affects soil decomposition, which in turn affects soil fertility and thus vegetation. Warming is likely to accelerate decomposition and mineralisation by stimulating microbial enzyme activity and altering microbe populations (Stuble et al., 2019). Increased mineralisation also leads to reduced organic carbon content; therefore warming may accelerate the loss of soil organic carbon to the atmosphere in a negative feedback loop (Hopkins et al., 2012). Forest ecosystems producing more biomass due to CO_2 fertilisation also produce more litter and fine roots. Trees that have increased growth require higher nutrient uptake. In unfertilised soils, this is met by an increase in the decomposition rate of soil organic carbon, thus causing an inverse relationship with soil organic carbon content (Terrer et al., 2021). However, the ways in which decomposition and mineralisation may be affected by a changing climate (i.e. warming, elevated CO_2 concentration, nitrogen deposition, changes in precipitation), alter soil organic matter and influence the carbon cycle remain uncertain and need further examination (You et al., 2021).	
Impacts of forest fires		Higher temperatures in conjunction with low soil water moisture will cause an increase in forest fire risk in the future. Forests will be impacted by more severe periods of droughts and widespread forest fires that can negatively affect biomass growth. The Fire Weather Index is used to predict the future risk of forest fires.

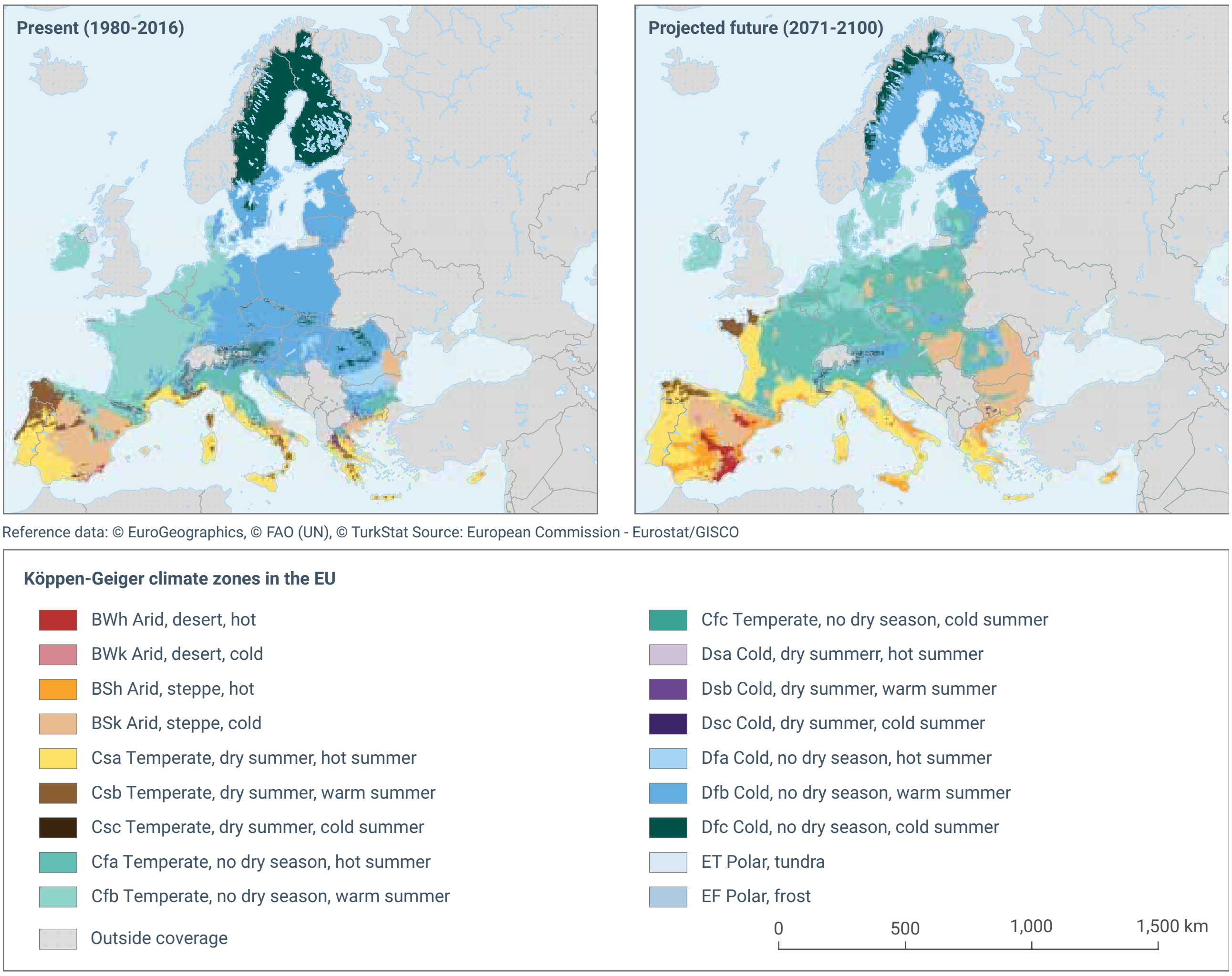
4.1.2 Shifting climate zones

Climate zones are areas with distinct climates that allow us to understand the conditions required for biomass growth. The Köppen-Geiger classification system (Beck et al., 2018) summarises information on prevailing temperature and precipitation conditions, and the vegetation types existing within each climate zone. There is evidence of shifts in climate zones in Europe taking place over the past 40 years (EEA, 2019). Projecting climate zones into the future can provide a cursory overview of how ecosystems and vegetation types may shift under a changing climate.

Map 4.1 illustrates the projected poleward shift of the major climate zones in Europe. Mediterranean-type climates, with dry and hot summers, may expand to parts of western Europe by 2070, while snowy climates all but disappear in the Alps and other central European mountain ranges. A warm temperate climate with hot summers extends to large swathes of central Europe. In northern Europe, snowy climates are partly replaced by temperate ones, and warm summers become hotter. These changes are likely to lead to shifts in many of the high-potential agricultural and forestry areas of Europe.

An in-depth analysis of past and future climate hazards in Europe can be found in the EEA's report *Europe's changing climate hazards* (EEA, 2021a).

Map 4.1 Köppen-Geiger climate zones for the present (1980-2016) (left) and for the future (2071-2100) (right) under Representative Concentration Pathway (RCP) 8.5



Reference data: © EuroGeographics, © FAO (UN), © TurkStat Source: European Commission - Eurostat/GISCO

Source: Reproduced from Beck et al. (2018), licensed under CC BY 4.0.

4.2 Past impacts of climate change

This section explains how climate change has already affected biomass growth in crops, grassland and forests.

4.2.1 Evidence of past impacts on crops and grassland

Climate change is increasingly influencing crop production, through both a northward shift in climatic zones and changes in the growing season (Bednar-Friedl et al., 2022), and the increasing frequency and severity of extreme events. Evidence shows that negative impacts linked to drought and extreme heat have tripled in the last 50 years and have led to reduced cereal and non-cereal yields in some locations in Europe (Brás et al., 2021). In addition, losses from a conjunction of meteorological extremes were up to 30% higher in the past decade relative to predicted trends (Bednar-Friedl et al., 2022).

However, when attempting to identify how climate change impacts crop production, proper attribution to both climate and non-climate factors is key. This is because factors other than the climate can drive trends in yields, such as advances in production techniques and new crop varieties. These can also be seen as part of the adaptation process.

Several studies have analysed the long-term trends in crop yields in relation to climate change for the recent past (1960 onwards) ([7]), concluding that climate change has already impacted crop yields in Europe through warming and changes in precipitation and extreme events. However, fewer studies have provided exact percentages of losses or gains per crop type in a country/region, and this was of particular interest in this report. The findings for some crop type produced in Europe are presented below:

- Studies have found that warming and precipitation changes have mostly negatively impacted maize yield in Europe (Ray et al., 2019), while the negative effect of climate change on maize yields is even stronger in southern Europe (Moore and Lobell, 2015). Estimates of the magnitude of this effect range from 0.3% for all of Europe (Moore and Lobell, 2015) to -24.5% for eastern and northern Europe (Ray et al., 2019).

- For wheat, the impact on the yield trend has been negative for many countries, with, for example, values ranging from -7% in Spain to -30% in Germany, as presented in Agnolucci and De Lipsis (2020).

- For other cereal crops like barley, sorghum and soya bean, impacts were slightly but unanimously negative (Ray et al., 2019). Average production-weighted, continent-wide barley yields reduced by 3.8% (Moore and Lobell, 2015).

- For rapeseed, temperatures and precipitation changes negatively impacted yield in western and southern Europe, and positively impacted eastern and northern Europe (Ray et al., 2019).

- For sugar beet, impacts were mixed, although pronouncedly negative in southern Europe. In central Europe, recent warming (especially the increase in minimum temperature) was found to have positive long-term impacts on field-grown vegetable yield; in parallel, yield stability decreased, possibly due to high-temperature episodes (Potopová et al., 2017).

- For grassland, several studies simulating the impact of climate change on modelled grassland productivity in Europe show productivity increases (e.g. by 29%) (Gómara et al., 2020). An increase in the potential annual production of grassland (over 3% per decade) was found from 1961 to 2010 (Chang et al., 2015). In other modelling work, however, the net primary productivity of grassland in Europe was found to decrease from 1981 to 2010 (Gang et al., 2015). Because managed grassland can be used for foraging or grazing, figures for grassland production are estimates rather than statistics, complicating the process of assessing impacts on production.

([7]) Depending on the literature source, the trends were studied for different periods. Moore and Lobell (2015) studied the period 1960-2009; Ray et al. (2019) studied the period 1974-2008; Agnolucci and De Lipsis (2020) studied the period 1961-2014; Potopová et al. (2017) studied the period 1961-2014; and Chang et al. (2015) studied the period 1961-2010.

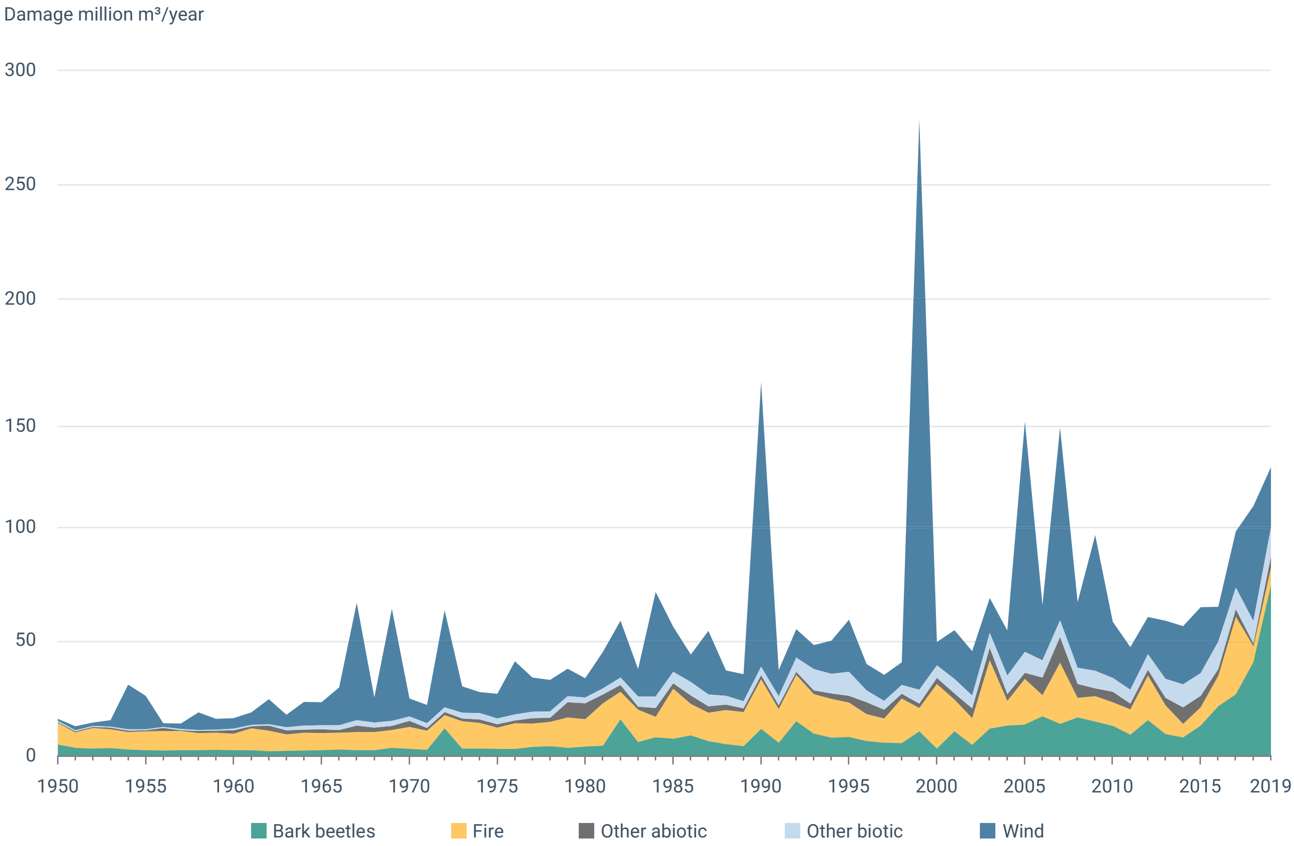
4.2.2 Evidence of past impacts on forests

Climate change is already affecting forest growth and stability in Europe, both directly through extreme weather events and indirectly through changes in the composition and diversity of plant communities due to new climatic conditions, which can alter tree productivity (Morin et al., 2018) (Figure 4.2). In recent decades, European forests have experienced intense droughts, which have resulted in widespread wildfires and amplified natural biotic disturbances, such as pest (e.g. bark beetle) and disease outbreaks (Buras et al., 2020; Hlásny et al., 2019; Seidl et al., 2017). These biotic and abiotic factors can reduce the benefits of increased growth resulting from increased temperature.

Forest growth is impacted by several factors resulting from climate disturbances. Studies have shown that changes in forest growth over the 20th century have mainly originated from changes in nitrogen deposition, with only limited contribution from carbon fertilisation or climate change. Trends in forest productivity were generally positive, except for sites where low water availability, low air temperature and/or low nitrogen deposition levels limited growth (e.g. Mediterranean or boreal regions) (Boisvenue and Running, 2006; Kahle, 2008). However, since 2000, scholars have documented how observed forest growth is linked to climate warming, the extended growing season and CO_2 fertilisation due to human activities (Pretzsch et al., 2014). There is evidence that increased forest growth takes place mainly in higher latitudes (Henttonen et al., 2017) and higher altitudes in mountainous regions (Sedmáková et al., 2019). This is because, although those regions tend to have shorter growing seasons in colder climates, temperatures seem to have increased more at high latitudes, benefiting growth in these regions.

Nonetheless, the interplay between the different climate variables is important for explaining forest productivity changes in general. The combined impact of these variables can mitigate any positive impact from global warming on forest ecosystems. For example, soil moisture remains essential for tree development, and, during 2000-2019, the growing season soil moisture content in many EU-27 countries fell below critical levels several times (EEA, 2021). Particularly strong decreasing trends took place in the northern continental region; hence, drought pressure intensity increased in these areas (EEA, 2021). These trends, accentuated by preventive felling to combat the spread of pest species (Buras et al., 2020), led to the widespread mortality of many tree species. This has also caused species distribution shifts, particularly in the Mediterranean region (Dorado-Liñán et al., 2019).

Figure 4.2 Reported damage caused by natural disturbances in Europe



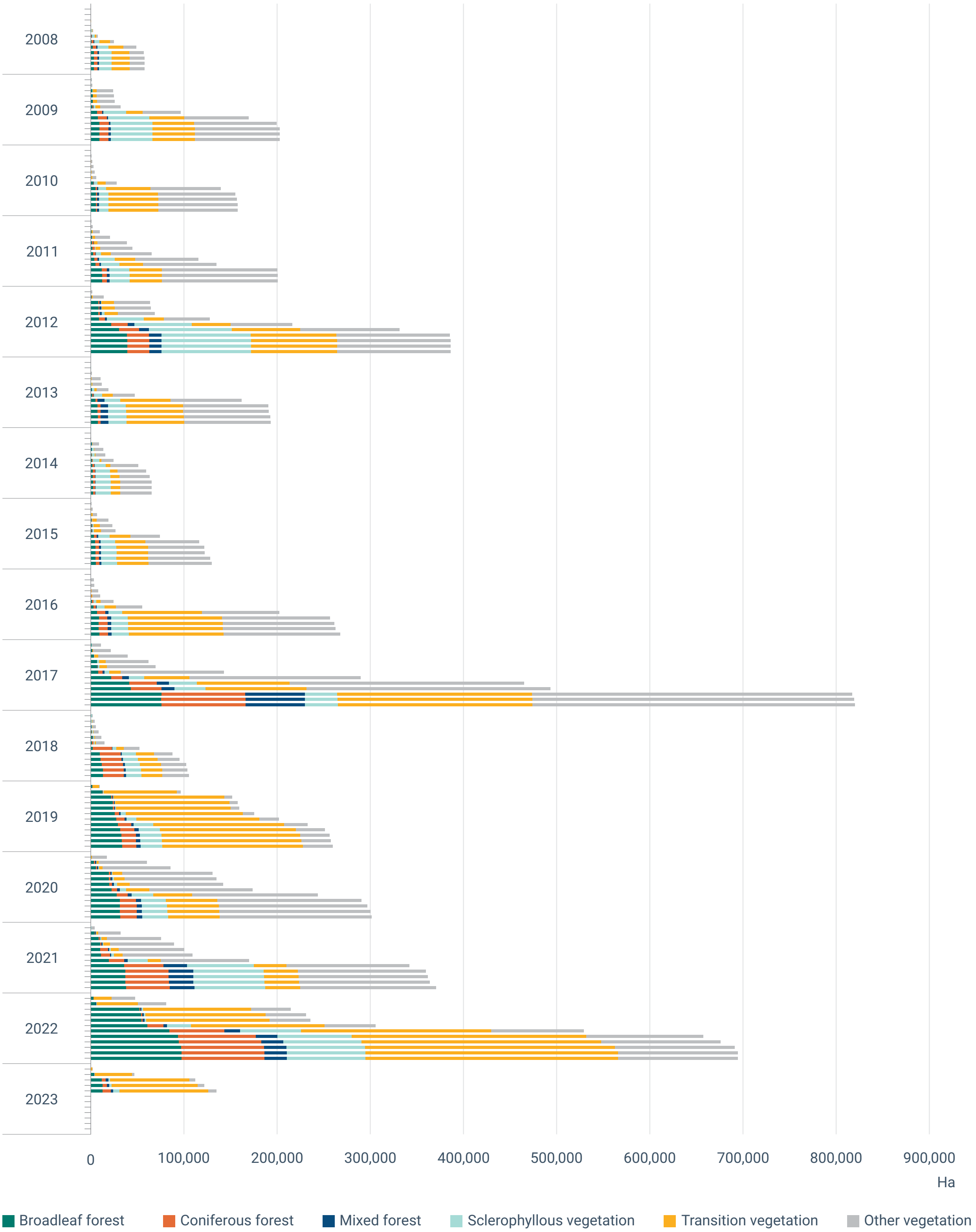
Source: Reproduced from Patacca et al. (2023); licensed under CC BY-NC-ND 4.0.

More than other disturbances, wildfire risks and damage to European forests keep increasing as an indirect impact of climate change. Fires can have negative long-term impacts on forest soils — in turn impacting ecosystem function and forest productivity — and evidence is growing that mono-species forests are more susceptible to spreading fires (Senf et al., 2019; Afreen et al., 2011), especially when the tree species burn very easily, such as eucalyptus and pine trees (Doerr et al., 1998). Megafires are also becoming more numerous and difficult to contain each year, with 2022 being unprecedented in terms of the number of fires.

Figure 4.3 illustrates that the burned areas have accumulated in each year since 2008 until 2022. The area of forests burned during the early spring months has increased in recent years, as has the number of fires that disproportionately affect broadleaved and coniferous forests.

Here, it must be noted that climate change affects forest ecosystems and individual species. However, the degree of impact may not always be clear: almost all forests in the EU are under management, and so the aftermath of forest management is difficult to separate from climate change impacts. Moreover, not all studies find a clear association between climate change and impacts to forests. This is partly because there are time lags between changes to the climate and how quickly trees are able to migrate to new regions in response (Renwick and Rocca, 2015). Clear challenges are the regional disparities of direct and indirect climate impacts.

Figure 4.3 **Monthly accumulated burned areas of forest**



Note: Transition vegetation means transitional bushy and herbaceous vegetation with occasional scattered trees where fully grown trees covers <30% of area; sclerophyllous vegetation means bushy sclerophyllous vegetation in a climax stage of development, including maquis, matorral and garrigue.

Burned area mapped using Sentinel-2/MODIS images.

Source: https://effis.jrc.ec.europa.eu/apps/data.request.form

4.3 Future impacts of climate change

This section explains how climate change is expected to impact crop yields, the productivity of grassland and forests. In addition, it provides insights into climate change impacts on biomass for two countries: France and Finland. The respective case studies are included in Boxes 4.1 and 4.2.

4.3.1 Crop yields

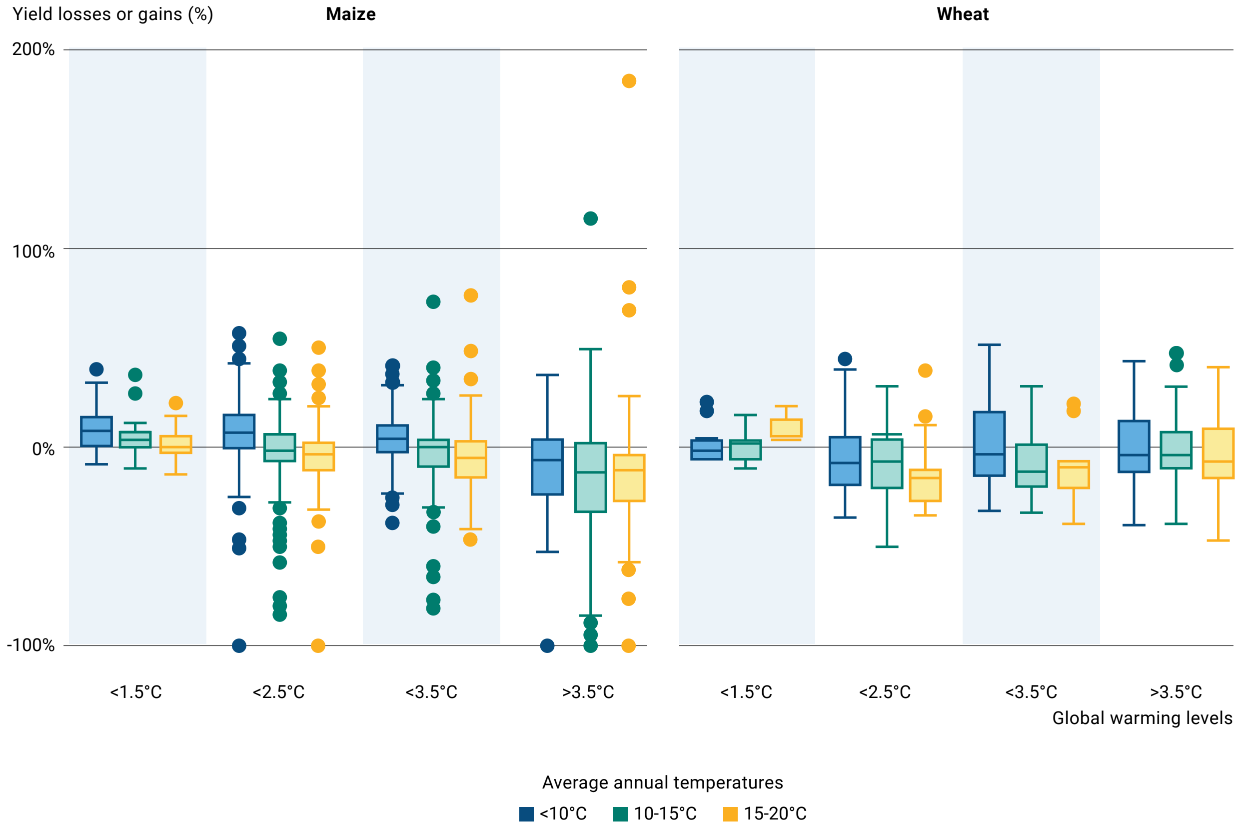
Four major cereal crops — wheat, maize, soya bean and rice — have been the subject of extensive research on yield projections. Further evidence is lacking for other cereals or oil crops, and is sparse for others such as fruits, vegetables and tubers.

In a systematic literature review conducted for the International Panel on Climate Change's Sixth Assessment Report (Hasegawa et al., 2021), 20 peer-reviewed papers contained results for simulated yields for wheat and maize in Europe. The results from these papers are displayed in Figure 4.4. Their results show that beyond 1.5°C of global warming, the likelihood of yield losses increases for both maize and wheat. When breaking down simulated yield results by current average annual temperature of the country the data are from (Figure 4.4), heterogeneous responses to climate change emerge. Yield impacts are more positive when annual average temperatures are low (below 10°C); however, negative impacts can be seen with higher average temperatures and higher global warming levels. This translates to significant impacts on crop yields in southern Europe, variable impacts in central Europe and possible yield increases in northern Europe until extreme global warming levels are reached (beyond 3.5°C).

When assessing the results, it is important to note that the range of results (with and without outliers) expands at higher warming levels, which translates into increasing levels of uncertainty. This is partly because such temperatures are typically reached further into the future, where multiple sources of uncertainty and complexity combine (different Representative Concentration Pathway (RCP) scenarios, models and parameters).

Maize is considered more vulnerable to climate change than wheat, despite its higher heat tolerance. This is due to its high water needs and C4 metabolism, which does not seem to benefit from increased CO_2 levels (as explained in Section 4.1.1). Maize is widely cultivated in southern Europe, a region projected to be heavily impacted by climate change in the future and experience losses in yields.

Figure 4.4 **Yield losses for maize and wheat due to climate change impacts for different global warming levels and depending on annual average temperatures**



Source: EEA based on data from Hasegawa et al. (2021).

As mentioned earlier (see Section 4.2.1), fewer studies relying on yield projections are available for other cereals and oil crops. These show negative climate impacts for barley and sunflower, largely positive impacts for rapeseed and slightly positive impacts for sugar beet. There are very few studies on soya bean in Europe since the cultivation area of the crop in the EU-27 is small.

For non-grain crops (e.g. vegetables, tubers, perennials), projecting how climate change will impact yield is highly complex. For instance, studies assessing how climate change impacts vegetables often focus on changes in pathogen distribution or irrigation requirements. The impacts of temperature on quality (nitrogen or amino acid content, digestibility, sugar concentration, etc.) is also a crucial field of study for vegetables, pastures and perennials. Overall, estimates of yield losses are rarely available, yet these 'other' agricultural products also significantly contribute to total biomass output and need to be considered. Table 4.2 shows the expected climate impacts on pasture and grassland only in terms of production volume or value due to the scope of this report. These climate impacts may be manifest as changes in productivity or quality. For pastures, productivity is expected to increase in northern and western Europe and in alpine regions where overall annual precipitation is expected to increase.

Table 4.2 Anticipated climate change impacts in Europe on pasture and grassland, based on the literature review

Region	Description of impact	Climate change impact	Source
Pasture or grassland			
Whole of Europe	Under increased temperature and decreased water availability, changes in above ground dry weight (AGDW) are around -6% (credible interval of -20% to +10%); when increased CO_2 concentrations are taken into account, the change is smaller (mean change around -3%). Under increased temperature and increased water availability, AGDW is likely to increase (mean change +30%, credible interval -30% to +140%). Under reduced water availability, plant AGDW will decrease across Europe. Values for mean change range from -15% (Atlantic) to -45% (continental region). Shrubs and legumes are most susceptible to reduced water availability, and graminoids and forbs are affected to a lesser degree.	?	Dellar et al., 2018
	Higher temperatures can cause an increase in non-digestible factors and lignin content (reducing digestibility of forage) (negative impact for extensive systems). However, high CO_2 concentrations may cause a strong increase in soluble sugar, resulting in higher energy values and ensilage potential (positive impact for intensive forage-based systems).	?	Virkajärvi et al., 2016
	Reductions in forage nitrogen concentration (negatively affecting forage quality) are likely under increased temperature and CO_2 concentration, regardless of water availability.	↓	Dellar et al., 2018
	Increases in grassland productivity due to rising CO_2 concentrations.	↑	Chang et al., 2017
Northern and central Europe	Shorter growing season due to summer drought.	↓	Chang et al., 2017
Northern Europe, part of alpine and continental regions	Under increased temperature, AGDW is expected to increase (mean change 82.6%) in alpine regions/northern Europe. In addition, these areas are predicted to receive increased rainfall under climate change, at least for part of the year.	↑	Dellar et al., 2018
Southern Europe, part of continental regions	Areas that will become warmer and drier are likely to see yield reductions.	↓	Dellar et al., 2018
	Longer growing season for pastures.	↑	Chang et al., 2017

Legend	
↑	Positive impact that leads to yield increases
↓	Negative impact that leads to yield decreases
?	No consensus on the climate change impacts

4.3.2 *Challenges in estimating how climate change will impact overall crop and biomass productivity*

Although projected yield studies are a highly developed field of research, using yield change as a metric for climate impacts does not directly reveal the consequences for total biomass production that is the purpose of this report. There are several ways to predict how climate change may impact yields, exemplified in this section.

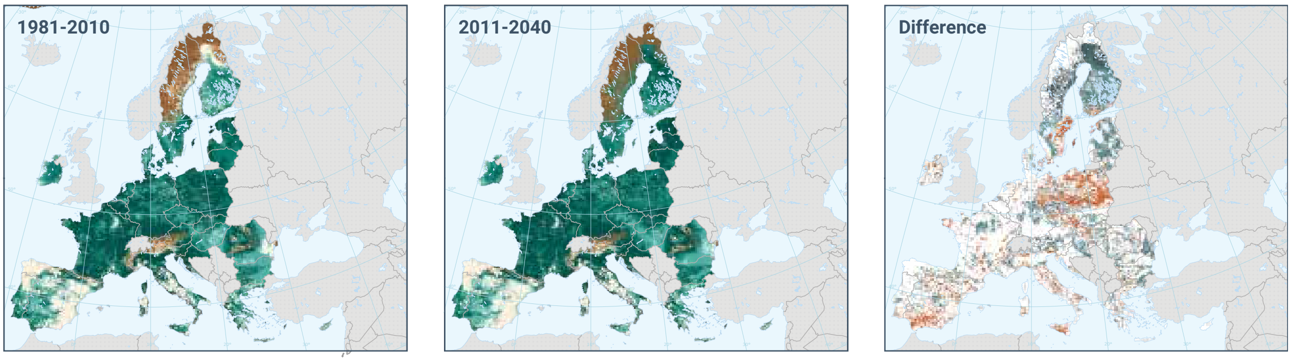
One metric with a wider scope that may be used to assess productivity is to include gross primary productivity, total ecosystem respiration and net fluxes in CO_2. By using this metric, scientists have shown that the 2003 heatwave led to a 30% reduction in gross primary productivity over Europe. This resulted in a strong anomalous net emissions of CO_2 to the atmosphere and reversed the effect of 4 years of net ecosystem carbon sequestration (Ciais et al., 2005). However, estimates totalling the future impacts of climate change on biomass are scarce — especially at the European level.

Integrated assessment models (IAMs) are another technique that can be used to predict holistic changes in production systems. IAMs use knowledge from and strengths of various disciplines related to climate change, and the contributions from different disciplines rely on mathematical representations of certain relationships connected to climate change. IAMs related to climate change involve socio-economic and natural sciences components. They are also used to predict changes in production systems and link crop and economic models. Yield estimates derived from crop models are adjusted based on the demand and supply balance. IAMs often use exogenous yield growth parameters linked to technological growth assumptions and result in more optimistic yield predictions. Dominguez and Fellmann (EC, 2018) modelled changes in total EU agricultural production per crop category using IAMs and their results differ quite significantly depending on whether enhanced CO_2 fertilization is assumed or not.

Another way to generalise the impacts is to consider the area under predominant crops for a given time-frame and factor it into a weighted average, as in Carozzi et al. (2021). This study shows that, overall, total crop production might increase by 5% until 2050, compared with the reference period but may decline later (e.g. by -13% by 2090 under RCP8.5). In low latitudes, production losses in the second part of the century equal -4% (RCP4.5) and -11% (RCP8.5). In middle latitudes, crop production increased in the first part of the century for both climatic scenarios (+5%), remained at about the same level for RCP4.5 in the second part of the century and decreased (-8%) for RCP8.5. In high latitudes, productivity increased to the end of the century under both scenarios (+8% (RCP4.5) and +14% (RCP8.5)). Irrigation in all cropland fuels increases in productivity under RCP4.5 and mitigates loss of productivity (to near reference levels) for RCP8.5. For grassland, productivity increases, on average, until mid-century for RCP4.5, and by the end of the century shows an average decline (-7%) for RPC8.5.

Suitability models are also used to assess biomass production potential in broad strokes across a large area. Based on modelling work in the context of the Global Agro-Ecological Zoning (GAEZ) project (FAO, 2022), Map 4.2 exemplifies how climate may affect biomass production potential in a spatially differentiated manner. Barley, being one of the main crops produced in the EU, was chosen for illustration purposes. Suitability models take into account crop-specific parameters and future climate projections to project how areas that are climatically favourable for a given crop may shift in the future, leading to lower overall productivity.

Map 4.2 **Areas currently suitable for barley production and predicted changes in suitability for the near future**



Reference data: © EuroGeographics, © FAO (UN), © TurkStat Source: European Commission – Eurostat/GISCO

Current suitability for barley crop and predicted changes in suitability for the near future

Level of suitability

Very High, High, Good, Medium, Moderate, Marginal, Very Marginal, Not suitable, No cultivation, No data, Outside coverage

Difference categories

-5 -4 -3 -2 -1 0 1 2 3 4 5

0 500 1,000 1,500 km

Source: Adapted from FAO (2022); licensed under CC BY 4.0.

A large swath of central Europe is currently very suitable for barley. In the near future, however, this will no longer be the case for many of these areas. As for the Baltic countries and Scandinavia, the trend for increasing suitability is recurring — but does not translate directly into improved overall biomass production potential. Indeed, wooded areas account for 50-70% of land cover in these countries. Therefore, converting forests into cropland to increase biomass production capacity would be counterproductive to climate change mitigation.

The trends for decreasing suitability across southern Europe and increasing suitability in northern Europe, with variable patterns in western and central Europe, are repeated across other crop categories.

4.3.3 Projected impacts on forests

Across scientific studies, understanding of the impacts of climate change on forests is less complete than for crops because of the complexity of forest ecosystems. While climate change may affect individual trees in a predictable way, the forest response is complex and multilayered. Several factors underpin possible variations in forest biomass under climate change, including how it impacts tree growth, the interactions between climate change and disturbances, and possible shifts in species composition.

How climate change impacts tree growth

Air temperature drives tree growth. In Europe, the overall increase in temperature is expected to extend the growing season, increasing forest productivity as a result. However, where actual precipitation trends remain unaltered, the expected increase in temperature could enhance losses via evapotranspiration and result in more frequent periods of low water availability (Ruosteenoja et al., 2018). Therefore, it is very important to consider the interplay between both warmer temperatures and water availability when considering how climate change impacts forest biomass overall. Studies have also shown that the timing of precipitation can be more important than the total amount of precipitation in driving the availability of water for vegetation (Ruiz-Pérez and Vico, 2020).

The CO_2 fertilisation effect, in which an increase in atmospheric CO_2 concentration increases productivity, also applies to forests. However, the magnitude and persistence of the effect of CO_2 fertilisation on biomass growth is debated. Norby et al. (2005) demonstrated that the impact would continue for multiple levels of productivity in temperate forests, pointing to an average increase in productivity of 23% for a 180 parts per million increase in CO_2 levels. Reyer et al. (2014) found that the negative impacts of climate change on productivity are almost entirely compensated for by CO_2 fertilisation, if it occurs persistently. It is worth mentioning that the CO_2 fertilisation effect may be obscured by low nutrient availability in some forest ecosystems (known as progressive nitrogen limitation) (Craine et al., 2018). In another study, experimental evidence showed that, in the absence of nutrient limitations, CO_2 fertilisation increases the productivity of some tree species, but this effect may diminish over time (Sperlich et al., 2020). However, another possibility is that trees will acclimatise to the CO_2 effect and the positive impact on productivity will wane. This creates significant uncertainty around the overall impacts of climate change on tree growth. By the end of the century, productivity continues to increase everywhere in Europe (except some southern regions under strong drought stress) under the assumption of sustained levels of CO_2, but decreases if forests acclimatise to the CO_2 levels and stop sequestering as much of it.

When including only precipitation, temperature and the CO_2 effect in a process-based stand model, Reyer et al., (2014) show that current trends are likely to continue: increasing productivity in temperate and boreal regions of Europe, and negative impacts in south-western Europe, including for temperate forests at the edges of their distribution range. However, when aiming to understand how climate change impacts forests overall, the impacts of rapid-onset events known as 'disturbances' must be considered alongside the long-term changes to basic climate parameters.

How climate change will impact disturbances and forest dieback

In parallel with an increase in overall forest productivity in Europe in the 20th century, damage from disturbances (unique events causing loss of forest biomass) has also increased. McDowell et al. (2020) assert that tendencies towards higher tree mortality have already tipped forest composition towards younger and shorter stands. Reyer et al., (2017) argue that disturbances and climate change are compound factors influencing productivity; moreover, productivity interacts with disturbances, as forests may be more susceptible to disturbances at specific stages of growth. As discussed in Section 4.1.1 , disturbances may be directly (wind speed, storm intensity, etc.) or indirectly (higher temperatures causing bark beetle outbreaks, increased susceptibility to wind damage because of frozen soils thawing, etc.) affected by climate change.

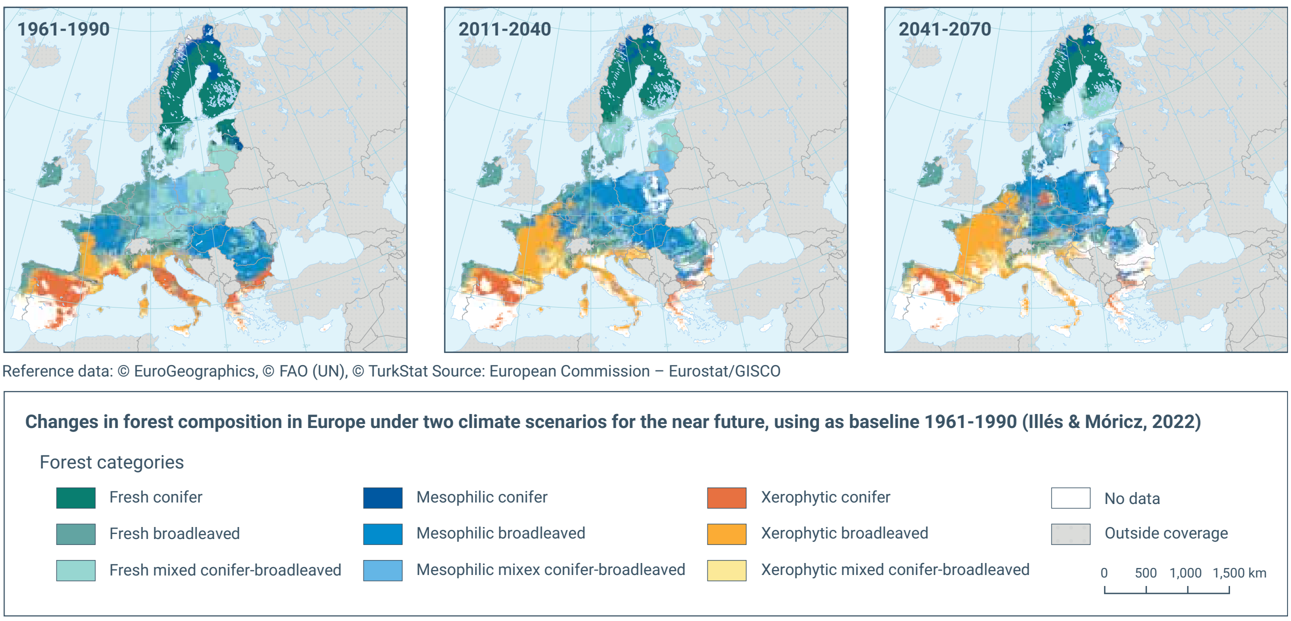
Researchers find that, overall, disturbances linked to climate change are likely to reduce gains and exacerbate losses in productivity across Europe (Reyer et al., 2017). In addition, future disturbances are likely to be most pronounced in coniferous forests (Seidl et al., 2017). Significant increases in fire activity are expected in western Europe, which will be driven by static precipitation trends combined with sharp temperature increases (Kim et al., 2017).

How climate change will impact species composition

In the second half of the century, climate change will strongly influence forest ecosystems and perhaps provoke species extinction (Settele et al., 2015). Already, the research of Morin et al. (2018) shows that new climatic conditions encourage new species to enter at the coldest sites while they cause local extinctions at warm sites. Such changes are more likely to occur under a 2°C warming scenario than under a 1.5°C warming scenario. The speed at which climate change occurs means that some forest species may not migrate fast enough to regions with more suitable climates to fully adapt to new conditions.

Climate-induced changes in productivity will manifest differently at the species level. Generally, spruce and pine are considered 'losing' tree species because of their low drought tolerance and because the areas occupied already extend far to the north, with limited possibility of further migration (Reyer et al., 2017). Although declines in the prevalence of beech have been observed in southern Europe, some studies consider beech to be resistant to the effects of climate change in central Europe (Dyderski et al., 2018). Meanwhile, oak has been found to be resilient to climate change in multiple studies (Illés and Móricz, 2022). Map 4.3 shows how forest categories may change under different future climate scenarios. It shows significant changes in the distribution of dominant tree species. Area gains are visible for mesophyll and xerophyte broadleaved composites, while area losses will occur for conifers and fresh broadleaved composites.

Map 4.3 Changes in forest composition in Europe under two climate change scenarios for the near future



Notes: Mesophilic species grow best in moderate temperatures (not too hot, not too cold), optimum growth temperatures range from 20°C to 45°C. Xerophytic species can grow and reproduce in conditions with a low availability of water.

Source: Adapted from Illés and Móricz (2022); licensed under CC BY 4.0.

In addition, analysis of Liang et al., (2016) demonstrated that forest productivity positively correlates with tree species richness, even under future climate conditions. This highlights the key role of biodiversity and specifically species diversity in making forests more resilient to climate change.

4.3.4 How climate change impacts overall biomass productivity

With existing methods and studies, it is difficult to provide a clear answer to how total biomass production (considering cropland, forests and grassland) will change in the EU due to climate change. Despite the uncertainties and caveats, the picture emerging is that crop productivity will begin to significantly change around 2050. Grassland and some forests stand are to gain from climate change — yet this is highly dependent on the recovery of water-stressed EU soils and, in general, water availability in some areas more than others.

Climate change impacts biomass growth in forest ecosystems in multiple and intertwined ways. Changing climatic conditions such as longer growing seasons and higher photosynthetic activity are projected to increase biomass growth — except where forest stands are water and nutrient limited (Gutsch et al., 2018). However, disturbances and the CO_2 fertilisation effect may counteract these positive trends. Therefore, both gains in and losses of productivity are likely to occur in Europe, with many regional disparities. Central and northern Europe might see boosts in forest productivity of up to 33%, while southern Europe might lose up to 37% in productivity (Reyer et al., 2017). Other studies on productivity changes for different tree species have shown some variabilities for different RCP scenarios and global warming levels (e.g. Martinez del Castillo et al., 2022; Poudel et al., 2011; ALRahahleh et al., 2018). However, when considering future wood supply, it is essential to also account for the relation between harvesting, future carbon stocks and carbon sequestration (discussed in Chapter 5 of this report).

It is worth adding that agricultural and forest management activities have always been a component of ongoing adaptation — whether to climate, environment or market factors. In agricultural systems, adaptation practices implemented at the farm scale (see EEA, 2019 for an overview) and technological developments at the sector level are reducing the risks of crop yield losses. In addition, various management options could make it possible to fix the imbalance in forest dynamics caused by climate change. Immediate adaptation measures include protecting forests against negative impacts of climate change (e.g. by establishing fire breaks, reducing or extending forest thinning). Long-term adaptation would include modifying forest composition to enhance stand diversity, which helps make forests more resilient to the stresses of climate change and sudden disturbances (Ammer, 2019).

Box 4.1

Climate change impacts on biomass productivity in France

Around half of the land area in France is agricultural land (28.5 million hectares in 2020) and one third is forest land (17.2 million hectares in 2020). France is one of Europe's major producers of wheat, barley, maize, rapeseed, sugar beet, potatoes and wine. While the actual number of farms is decreasing, the cultivated area has remained stable over the past decade. The majority (70%) of the French forest is deciduous and 30% of the forest area is pine. For more than a century, the French metropolitan forest area has been increasing, but the condition of French forests has been deteriorating due to climate change, mainly due to drought conditions. More severe weather events are likely to increase in the future and may reduce gains in carbon storage in forests.

Productivity trends observed over the past 20 years

- Trends in gross primary productivity show a stable, increasing trend for forests and stable results for cropland, with some regions where it decreases.
- For forestry, studies show an increase in forest area and above-ground biomass between 2000 and 2020.
- For agricultural crops, studies show stagnant wheat yields since the end of the 1990s. The stagnation is caused by different factors, e.g. the yield potential is reached, climatic conditions, political decisions and crop management. Further research into the causes is needed, currently impeded by a lack of data. Maize shows no evidence of stagnation.

Agriculture and forestry under a changing climate in the future

- Future conditions for agriculture will be more favourable in the north of France than in the south. Where, in general, climate risks (drought, heat) are more limiting in the south, warmer temperatures in the north may favour a longer growing season, and may offer the possibility of expanding the cultivated area.
- In general, there is a more favourable trend for winter crops than for summer crops and perennial crops.
- Crops that will be moderately affected are, for example, wheat, forage crops and sunflower. For these crops, yield formation takes place in spring or autumn. The damaging effects of climate change during summer are balanced by a lengthening of the growing period in spring and/or autumn.
- Wheat yields could increase in the near future, but responses are variable. There are large uncertainties. While several studies report positive impacts on yield, Gammans et al. (2017) concluded that projected yield declines range from 3.5% to 12.9% for winter wheat and from 2.3% to 12.1% for winter barley in the medium term (2037-2065). They conclude that ongoing technology trends would probably counterbalance the effects of climate change.
- For sunflower, overall yields are not expected to change much. Higher temperatures can reduce the problems associated with cold, and an expansion to the north of France is possible.
- Crops that are likely to be significantly affected are annual summer crops and perennial crops, for example maize, vineyards and forest production, for which summer climatic conditions are deciding factors for yield and quality. Climate change could mean moving the production zones further north.
- Grain maize is projected to be considerably affected by climate change. A lowering of yields of irrigated maize in the near future is expected due to a shortening of the growth cycle, which can lead to yield losses of about 1 tonne/hectare in the near future (Brisson and Levrault, 2010). To 2030, the yield decrease is expected to be more than 25% in the south (even with additional water supply), while a small yield increase (with an additional water supply) is expected for central and northern France (AgriAdapt, 2017).
- For forests and wood production, both deciduous and coniferous forests could be affected by climate change in the near future, and more significantly in the distant future. The impact expected up to 2030-2050 could, however, be more or less positive. Pine and beech species are an exception. Pine shows a decline in growth of 4.6% in the near future (Brisson and Levrault, 2010). For beech, decreases in growth of 20-30% are expected to affect most forests in central Europe, including even at some elevated sites in north-eastern France, from 2020 to 2050 (Martinez del Castillo et al., 2022). In the longer term (up to 2100), the effects on forests will be negative because of more frequent extreme events. There are, however, large uncertainties in the long-term effects.

Source: Jacobs et al. (2022).

Box 4.2

Climate change impacts on biomass productivity in Finland

Current situation, agriculture and forestry production

Finland is the most forested country in Europe based on the proportion of forest area to total land area: forest covers about 75% of Finland's land area (approximately 26 million hectares). Most of the forest area is in commercial use. Roughly 2.7 million hectares of forests in Finland are protected or under restricted use. The main tree species in the managed forests of Finland are Scots pine, Norway spruce and birch. About 7% of the land area is agricultural land (approximately 2.27 million hectares in 2021). Cereals are cultivated on roughly half of the agricultural area, with spring varieties of barley, oats, wheat and rye cultivated on a wider scale. Production is primarily rain fed. While Finland's grain yield is small compared with the global scale, it is one of the largest producers and exporters of oats in the world.

Productivity trends observed over the past 20 years

- Satellite-based estimates of trends in gross primary production (GPP) suggest an increase across most of the regions in Finland for both forestry and agriculture. The most significant increases are found in the southernmost regions.
- For forestry, the productivity trend is supported by data from the national forestry inventory.
- For agriculture, observed grain yields from individual areas suggest that the productivity of rye has increased most, while it has declined for wheat. When analysing shifts in cultivated areas, it was found that farmers' crop choices have changed since the mid-1990s. The areas of the most widely cultivated cereals, barley and oats, have decreased, while spring wheat has become more popular.

Agriculture and forestry under a changing climate in the future

- Climate change could potentially have both negative and positive impacts on biomass production.
- Global warming is likely to extend the growing season and, together with elevated atmospheric CO_2 levels, enhance GPP and growth. Precipitation is more likely to increase than decrease in all seasons but may be spread more unevenly, leading to increased drought. By 2050, yearly drought days are projected to increase by 20 days in the south and by 5 days in the north. Wind damage is likely to increase with warming winters, as the period for which soil is frozen decreases, making trees more vulnerable to windthrow.

National studies (see in Jacobs et al., 2022) suggest the following impacts of climate change on future (tree or crop) yields/growth:

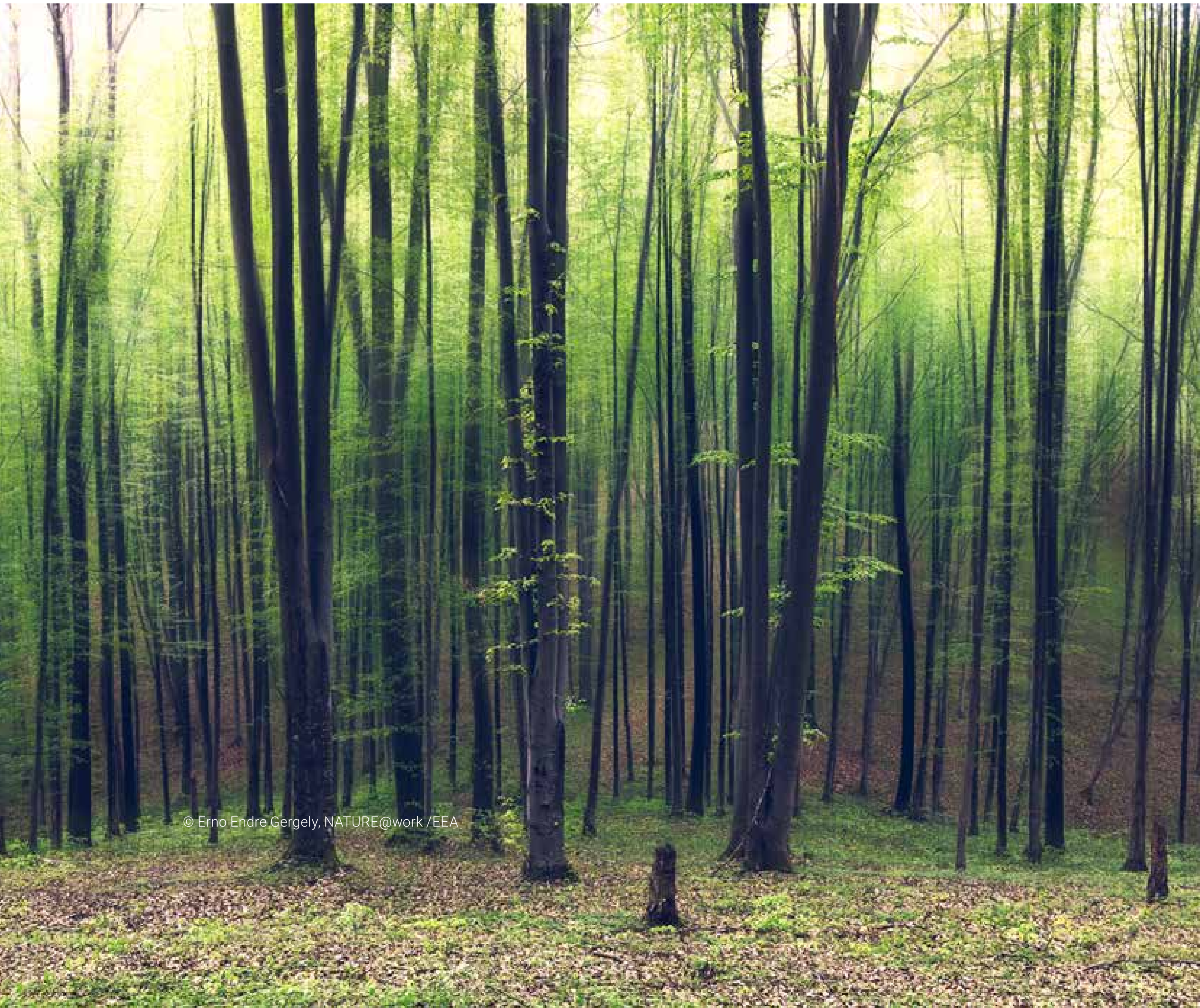
- The effect of elevated CO_2 concentrations alone is assumed to increase GPP in all main tree species.
- Forest GPP is assumed to increase by approximately 30% by mid-century under all climate scenarios, only after which do different climate scenarios make a difference to GPP. Growth of Scots pine is projected to benefit under all scenarios, especially in the north, independent of the site fertility. In the south, moderate increases in GPP are found for fertile and moderately fertile sites. Scots pine also has a lower probability of suffering wind damage than other species. Growth of Norway spruce and birch is projected to increase on a country level but decrease in drought-affected areas. Increasing temperature is projected to benefit GPP most in birch in comparison with other species.
- Depending on the study, enhanced growth is projected to support sustainable harvest levels, even up to 80 million m^3/year, with intensive forest management. However, these projections do not include the increased risks of different types of biotic and abiotic damage, which will play a bigger role in the warming climate and may substantially affect the GPP level.

Box 4.2

Climate change impacts on biomass productivity in Finland (cont.)

- Although projections of future changes in crop yields may vary across national studies, they suggest increased potential for achieving benefits. Considerable increases in the yields of spring cereals, rapeseed and grass, particularly in the north-west, could be achieved with favourable annual weather, dedicated breeding and management efforts, and responsive cultivars. For spring wheat, this could mean, on average, a yield increase of approximately 30% in the south and over 70% in the north-west. However, failing to address the concurrent challenges brought about by climate change, losses of productivity might impede potential gains and the possibility to capitalise on climate change in the long run.
- It has been found that the positive effects are likely to be reversed in barley with temperature increases exceeding 4°C and that oats might better adapt to a changing climate. Wheat has been found to be more sensitive to changes in temperature than precipitation in Finland.

Source: Jacobs et al.(2022).



5 Biomass, climate change mitigation and ecosystems

Key messages

- Biomass plays a crucial role in the EU's transition towards a climate-neutral economy. This is because carbon is sequestered during biomass growth; biomass is an alternative to fossil fuels and carbon-intensive materials; and greenhouse gas emissions can be reduced during biomass production and consumption cycles.
- Vegetation and soils are among the planet's major carbon sinks. The EU land use, land use change and forestry (LULUCF) sector has for the last 30 years been a net sink (meaning that it is responsible for more carbon removals than emissions), but this sink is decreasing because of various factors. These factors include the current state of EU forest and age structure, climate change impacts, land use changes, harvesting wood for economic use and adaptation of the forest sector to climate change.
- Forest land and harvested wood products account for significant carbon removals, while cropland, grassland, wetlands, settlements and other lands contribute to net emissions. Although at the EU level the LULUCF sector contributes substantially to carbon removals, it is not a net sink in all Member States.
- The expected reduction in the net annual increment of older trees and the expected increase in harvesting will further decrease the existing EU forest carbon sink. However, afforestation can lead to a slow increase in carbon removals over many years because of tree growth.
- Soils also sequester carbon. To maximise carbon sequestration, land management practices should focus on increasing carbon in mineral soils (for instance via increasing soil matter content) and stopping or reducing the loss of carbon from carbon-rich soils.
- To ensure resource efficiency, when using biomass as an alternative to fossil fuels and carbon-intensive materials, it is important to apply the cascading use of wood principle. This means using woody biomass for other products with a higher added value (in terms of carbon storage capacity) and a lower environmental impact before combusting it.
- An ecosystem's capacity to store carbon does not necessarily correlate with biomass productivity. For example, wetlands store large amounts of carbon in soils, and therefore are important to protect despite their low biomass productivity. If increasing biomass demand increases productivity within wetland areas or results in land use change, a significant amount of greenhouse gases may be released.

Biomass production and consumption, and the way human society interacts with ecosystems that provide biomass, greatly impact the EU's transition towards a climate-neutral economy. Biomass is a critical parameter in reaching the EU's 2030 and 2050 targets, which depends on the following factors:

- the extent to which carbon stocks are maintained and increased in ecosystems and wood products (the concept of harvested wood products (HWPs));
- the extent to which fossil fuels and other carbon-intensive materials are replaced by biobased materials and therefore the extent of the resulting greenhouse has (GHG) emission reductions.

These can be achieved only when the sustainability of the biomass raw material is ensured, the efficiency of biomass use is taken into consideration and indirect land use changes are avoided.

This chapter illustrates how this is a challenge for the EU and the policymakers of its Member States, as well as for the forestry and agriculture sectors.

The first part of this chapter reviews the role of terrestrial ecosystems in sequestering carbon and how land management, including harvesting biomass, impacts their extent, condition, level of species richness, and GHG emissions and removals. It discusses the potential for carbon sequestration in the forestry and agriculture sectors, viewed from the LULUCF Regulation's perspective. It also explains the role that land management choices play in biomass production, and how they influence ecosystem conditions and the level of species richness in different landscape types.

The second part of the chapter looks at how extracted biomass (from forestry and agriculture) is already being utilised to mitigate climate change.

Given the complexity of the topic, several information boxes are included in the chapter. These are intended to help you understand the policy responses, monitoring and reporting of carbon removals, and the opportunities and challenges around increasing carbon sequestration through land management.

5.1 Carbon removals, land management and biodiversity

As mentioned in previous chapters, vegetation and soils are one of the planet's major carbon sinks, absorbing around one third of anthropogenic CO_2 emissions worldwide (Nabuurs et al., 2022). In the process of carbon sequestration, CO_2 is removed from the atmosphere and stored in ecosystems' carbon pools, such as above- and below-ground biomass, roots, soils and harvested wood products (explained later in this chapter). The absolute quantity of carbon held in a carbon pool at any specified time is the carbon stock or amount of carbon stored. The rate at which plant and tree growth support additional carbon removal is called the carbon sequestration rate, mostly expressed as an annual value.

A range of factors needs to be considered to correctly estimate carbon sequestration potential, including climate, soil properties, water and nutrient availability, and topography. These factors affect vegetation types and their condition, and the richness of the species that grow. Other important factors include different land use categories and types of land management and the pressures that these create, the stage of life cycle (e.g. forest age class), and climate change impacts and adaptation actions.

5.1.1 The EU LULUCF sector and carbon removals

GHG emissions and carbon removals from land use are monitored and reported ([8]) by Member States as part of national GHG inventories for the LULUCF sector (following the IPCC Guidelines on National Greenhouse Gas Inventories (IPPC, 2006) and the LULUCF Regulation (Regulation (EU) 2023/839).

Box 5.1

Understanding the LULUCF sector: reporting greenhouse gas emissions and carbon removals

Anthropogenic emissions and removals from the land use, land use change and forestry (LULUCF) sector are reported by countries as a separate chapter in greenhouse gas (GHG) inventories, following Intergovernmental Panel on Climate Change (IPCC) guidelines and the relevant EU legislation. Emissions and removals from all types of managed land (meaning also land where biomass is being produced) are reported for the following six land use categories: forest land, cropland, grassland, wetlands, settlements and other land. For each land use category, countries report GHG fluxes and areas in hectares covered by a particular land use category (including land remaining in the same category and land converted to the respective land use category if the land use changed). The area of unmanaged land is also reported without including GHG fluxes. As a result, the sum of the areas for all six categories is equal to the reporting country's total land area.

In addition, countries report on changes of carbon stocks contained in the following carbon pools: above- and below-ground living biomass, deadwood, litter, soil carbon and harvested wood products (HWPs). Above- and below-ground living biomass refers simply to above- and below-ground plant tissues that sequester carbon. The pool of soil carbon is split into mineral and organic soils, the latter being soils with a high carbon content. HWPs constitute the only pool where carbon is stored outside the natural ecosystem. The HWP carbon pool encompasses wood products that are in use.

Emissions included are based on CO_2 emissions and removals, and methane (CH_4) and nitrous dioxide (N_2O) emissions. These come from:

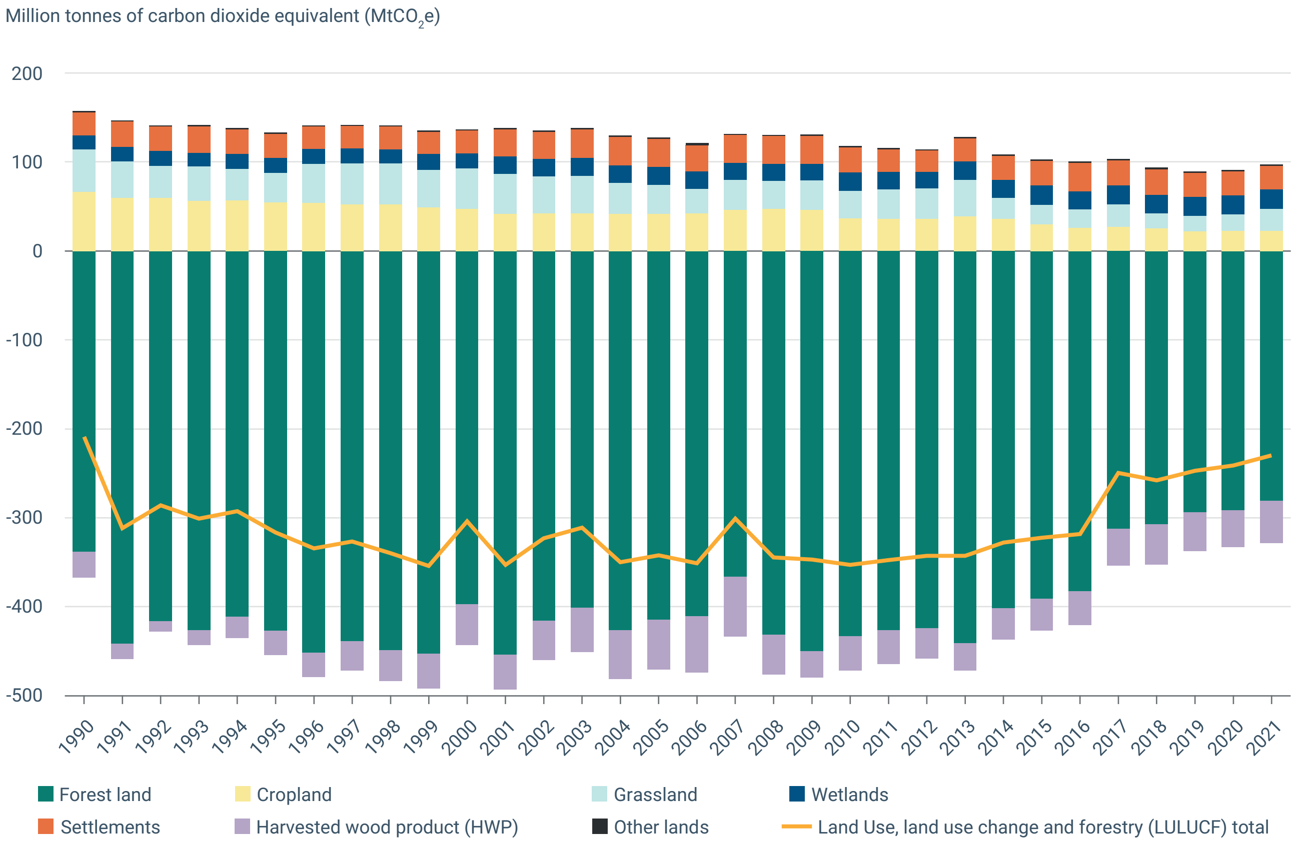
- rewetting and draining soils;
- nitrogen mineralisation/immobilisation associated with the loss/gain of soil organic carbon resulting from land use change or mineral soil management;
- nitrogen input to managed soils and fires.

Non-CO_2 GHG emissions from the agriculture sector are included in the GHG inventory reports under the agriculture sector, and in the EU those emissions are regulated by the EU Effort Sharing Regulation ((EU) 842/2018).

([8]) Anthropogenic emissions and removals from the LULUCF sector are reported by countries as a separate chapter in GHG inventories, following IPCC guidelines (IPPC, 2006) and the relevant EU legislation. The reporting covers time series from 1990 to the most recent years. The development of the EU legislation on monitoring and reporting GHG emissions/removals from the LULUCF sector started with the LULUCF Decision (Decision No 529/2013/EU) and was upgraded by the LULUCF Regulation (Regulation (EU) 841/2018), with amendments adopted in November 2022 (Regulation (EU) 839/2023).

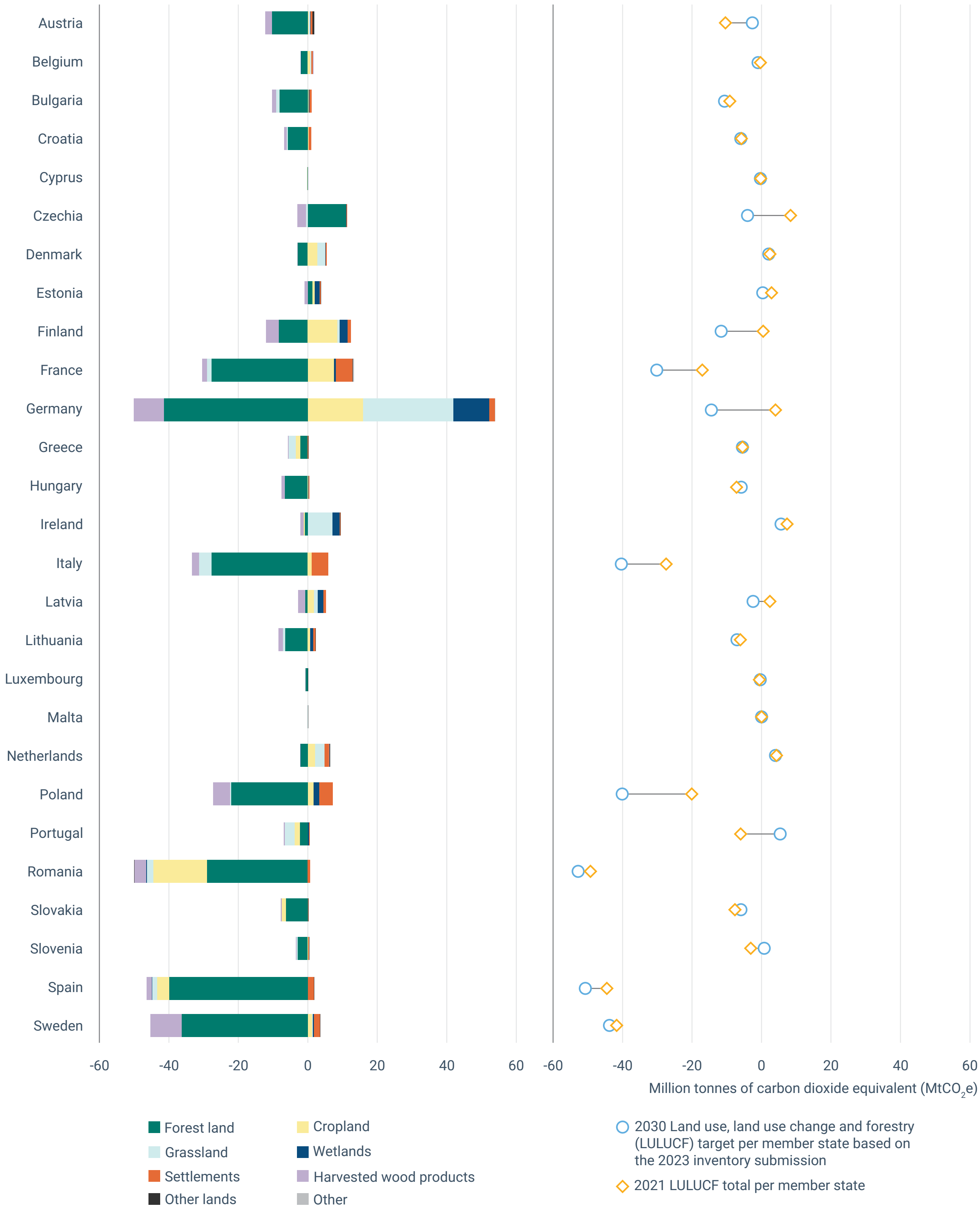
From 1990 to 2021, the EU LULUCF sector was a net sink (meaning that it was responsible for more carbon removals than emissions), with forest land and harvested wood products accounting for significant removals, and cropland, grassland, wetlands, settlements and other lands accounting for net emissions (as shown in Figure 5.1).

Figure 5.1 **LULUCF sector emissions and removals in the EU-27, by main land use category**



Source: EEA based on EC (2023a).

Figure 5.2 **Carbon sequestration in forests and other land use categories by Member State in 2021**



Source: EEA based on EC (2023a).

Although at the EU level the LULUCF sector is a net sink, this is not the case in each Member State. As illustrated in Figure 5.2, in some Member States the LULUCF sector as a whole has become a net source (Czechia, Denmark, Estonia, Finland, Germany, Ireland, Latvia, Malta and the Netherlands). The reasons are country specific and are described briefly below, based on information from these countries in their 2021 national inventory reports:

- In Denmark, Ireland and the Netherlands, cropland and grassland generate significant emissions. These emissions arise from, for instance, the cultivation of organic soil, and the forest areas in these countries are insufficient in terms of carbon removals to compensate for these emissions.

- Malta has a small forest area providing a comparably small forest sink.

- Finland and Germany generate significant emissions from organic soil cultivation, and, in 2021, their declining forest sinks were not able to compensate for these emissions.

- In Finland, increased emissions from drained organic soils in forests where warming temperatures have caused dead organic matter to decompose faster contribute to these emissions.

- Increased harvesting in forests in Estonia, Finland, Germany and Latvia has led to declining forest sinks.

- Latvia reported that its ageing forests have led to an increase in natural tree mortality and a reduction in the rate of increment. At the same time, harvesting has increased. As a result, the LULUCF sector in Latvia is a net source of emissions.

- Similarly, Estonia reported that the age structure of its managed forests is dominated by mature stands, with approximately 39% being more than 60 years old. In addition, the proportion of forest area belonging to the first development classes (treeless area, area under regeneration and young stands) has increased. Therefore, carbon sequestration in forests has decreased in recent decades.

- Czechia and other countries in central Europe have been severely impacted by drought followed by insect infestation, leading to a massive increase in salvage logging and thus leading to forests becoming a source of emissions.

5.1.2 Carbon sequestration in forests

Forests have the highest carbon sequestration rates among terrestrial ecosystems, reaching up to three times that of wetlands and agroecosystems (EEA, 2022a). In 2021, EU forests, including forests soils, removed -280.83 million tonnes of CO_2 equivalent ($MtCO_2e$).

The amount of carbon that can be sequestered in the forest sector depends on various factors, such as the current state of the EU forest and age structure, climate change impacts, land use changes, harvesting wood for economic use and adaptation of the forest sector to climate change.

State of European forests

EU forests comprise a variety of ecosystems. However, most of them have been managed or modified, which means that their extent, structure, species composition and function have transformed over the years as a result of human intervention (Forest Europe, 2020). Forests across EU Member States are semi-natural ecosystems (more than 90%) and mostly planted. Some characteristics of natural forest vegetation have remained in the beech forests in central Europe, different types of oak forests in the Mediterranean region and coniferous forests in northern Europe, among others (Forest Europe, 2020).

Information on age structure provides insights into harvesting potential (Verkerk et al., 2011) and carbon stocks (e.g. in Pregitzer and Euskirchen, 2004; Böttcher et al., 2008), as illustrated in Box 5.2. There is neither a linear nor infinite relation between forest age and carbon sequestration. The rotation cycle/period of commercial forests varies depending on the planted tree species (60 to 80 years for most coniferous trees; 100 to 120 years for most broadleaved species) (Statista, 2023). As a result of various strong afforestation waves in the last century, a significant share of managed EU forests is now reaching harvesting age (Vilén et al., 2012). Furthermore, the declining net annual increment of older trees translates to declining net carbon removals (Avitabile et al., 2023). This means that either increased harvesting or a reduction in annual increment will ultimately reduce the carbon sink provided by the existing forest stock in Europe. In addition, dead organic matter in forests is decomposing faster than before because of the warmer climate (Pilli et al., 2017). This is problematic because the faster the decomposition, the greater the carbon stock loss.

Forest stand ageing is most pronounced for broadleaved species; the decline in net carbon removals that has been observed since 2015 is expected to continue for the period between 2020 until 2025 (Avitabile et al., 2023). Although harvesting leads to abrupt carbon stock reductions, it is followed by rejuvenation and the subsequent carbon sequestration that comes from newly planted trees. In other words, new trees take some time to reach carbon sequestration rates equivalent to those of mature trees.

Box 5.2

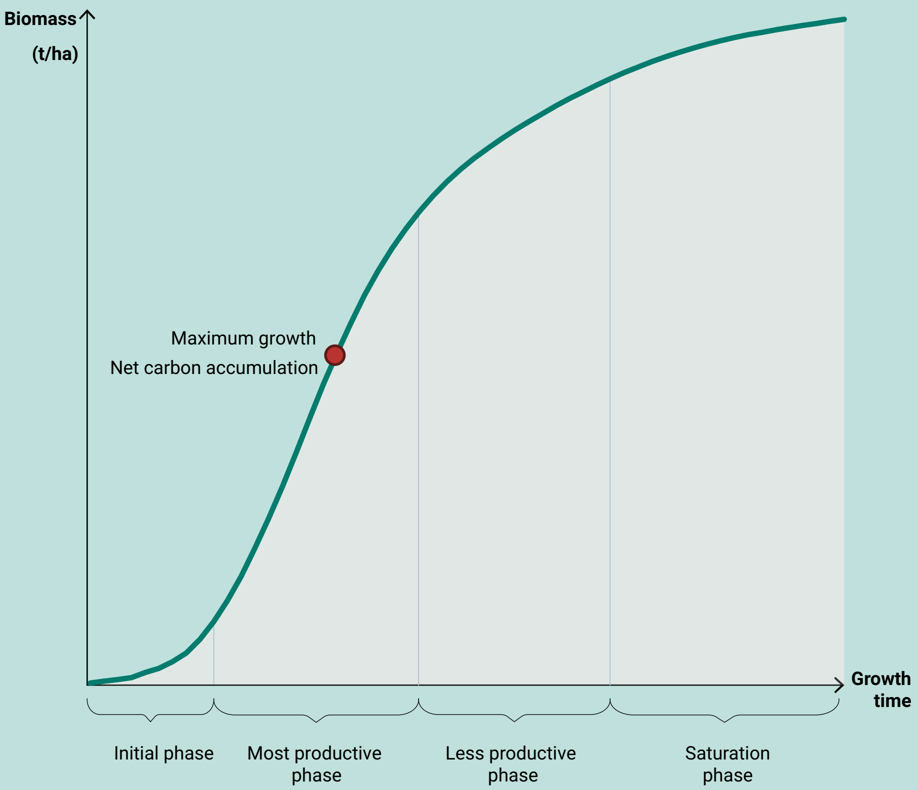
Understanding the LULUCF sector: the relationship between biomass growth and carbon cycling in a forest

The biomass growth curve of a tree or forest stand has in principle an 'S' shape, with net carbon accumulation being highest at an intermediate size/age (IPCC, 2019). At maximum size (in terms of biomass), annual regrowth equals the annual decay rate. The ultimately decreasing growing capacity is due to multiple factors, including nutrient and water availability, hydrologic factors, changing photosynthesis-respiration balance, and damage from wind, lightning, fire, flooding and infections. Trees can get very old and net carbon uptake by an individual tree can continue over hundreds of years (see in Köhl et al., 2017).

The exact shape of the S-curve (as in Figure 5.3) is site and ecosystem specific and can be modified to some extent through dedicated management practices (drainage, fertilisation, thinning, etc.) and crop/tree choice. At any point on the curve, however, the standing crop will decline if the harvesting rate exceeds the net annual increment (annual growth minus natural decay). Conversely, if the harvesting rate falls below the net annual increment, biomass will accumulate. Maximum growth rate is achieved at the flex point in the curve, maximum pool at the right extreme and maximum annual average growth rate somewhere in between these two points. So, carbon stocks and annual increment/growth rate cannot be maximized simultaneously (Kindermann et al., 2013).

To keep forests exactly at the point where annual sequestration is the highest is in many cases not the aim of forest management. To optimise economic output, forest management often aims to harvest trees at a size where the price is high, even if the maximum annual sequestration has decreased, but well before the carbon storage capacity reaches saturation.

Figure 5.3 Generalised biomass growth curve



Source: EEA.

Annual variability of carbon removals by forests

Interannual variability in the amount of carbon removed by the forest sector, as illustrated in Figure 5.1, can be explained by climate change impacts, e.g. natural disturbances, extreme temperatures and long periods without precipitation, leading to droughts that have the potential to reduce photosynthesis and tree growth (Senf et al., 2020). All of this reduces the forest carbon sink.

As detailed in Chapter 4, natural disturbances such as forest fires, strong windstorms and drought have been increasing in frequency and intensity in Europe in recent decades as a result of climate change. These disturbances reduce carbon stocks and lead to degradation/damage in forests and increased vulnerability to pests and diseases. This results in biomass loss and a reduction in carbon removal by Europe's forests.

Interannual variations between countries depend on the magnitude of natural disturbances. In recent years, central Europe (e.g. Czechia) suffered the effects of droughts followed by bark beetle infestations, which required salvage logging. The harvesting rate in Czechia in 2020 was the highest ever recorded, with 95% of the volume harvested that year being the result of mandatory sanitary tree felling in response to the bark beetle outbreak (Czechia, 2022). As a result, the forests in Czechia went from being a carbon sink to a source of CO_2 emissions.

Similarly, Italy reported a significant reduction in its forest sink as a result of large wildfires in 2017. The area of burned forest in 2017 was almost four times the annual average for 2015-2021, and net removals from the total LULUCF sector in Italy dropped by 37% in that year compared with the annual average for this period (Italy NIR, 2023). More information on trends in recent years is provided in Section 5.1.1.

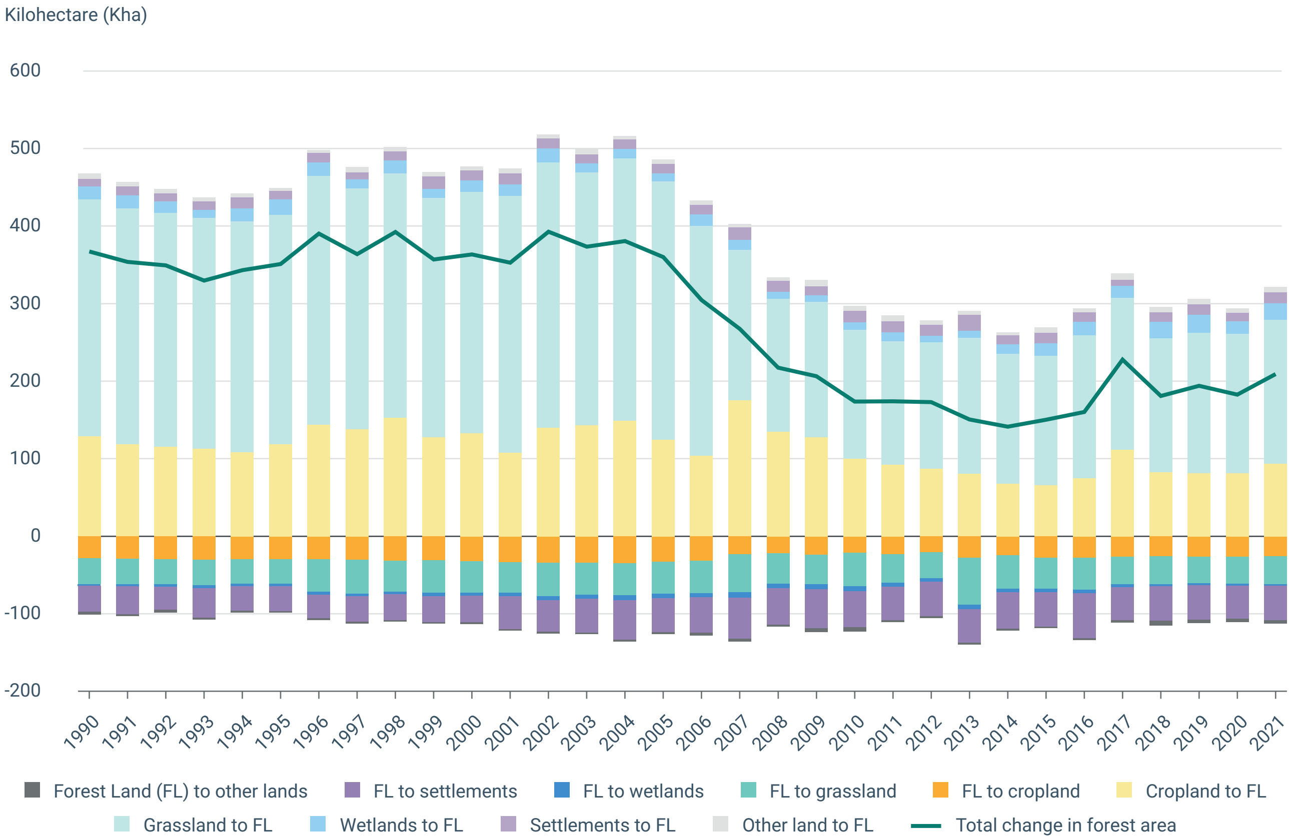
Land use changes

Chapter 2 of this report provided detailed information about forest land in the EU and the afforestation that has occurred in the last 20 years. Generally, deforestation and afforestation impact the total net GHG balance coming from forest land. However, there is a big difference between these two land use changes. Deforestation causes the most emissions in the year it takes place because of the direct loss of above- and below-ground biomass. Meanwhile, afforestation leads to a slow increase in removals over many years as a result of tree growth. Halting deforestation is therefore a mitigation option that will show immediate results, while increasing afforestation is a mitigation option that can contribute to annual removals over many years.

According to EU GHG inventory data for the LULUCF sector (EC, 2023a), deforestation during the period 1990-2021 in the EU fluctuated between 100,000 and 140,000 hectares per year, with an annual average of 116,000 hectares (as in Figure 5.4). While this was less than 0.1% of the total forest area in 2021, it was responsible for emissions of almost 28MtCO_2e in that year. Considering the full period 1990-2021, 36% of the deforestation area arose from converting forests to settlements, such as urban and infrastructure developments, 34% arose from converting forests to grassland and 25% arose from converting forests to cropland.

The areas reported to have been converted from other land use categories to forests (afforestation) each year in the EU during the same period were larger, averaging 395,000 hectares per year, with large interannual fluctuations. However, there was a visible decline in the afforestation area from an annual level of around 450,000-500,000 hectares for the period 1990-2005 to around 300,000 hectares per year for the period 2005-2008. After 2005, the afforestation area stabilised. Considering the full period 1990-2021, 63% of the afforestation happened on grassland and 29% on cropland.

Figure 5.4 **Afforestation and deforestation in the EU-27 based on GHG inventory data — LULUCF sector**



Source: EEA based on EC (2023a).

All biomass harvested and removed from forests is reported as a loss of biomass and thus a source of CO_2 emissions. Some of the harvested biomass is used for long-lived wood products that may store carbon outside forests temporarily. This is discussed in more detail in Section 5.2.

Adaptation and forest carbon sink

Adaptation measures are also important for maintaining forest stands and minimising the risk of natural disturbances that lead to biomass and carbon losses in forests. Adaptation measures support long-term sink viability, but, because of some adaptation measures (e.g. altering tree species composition via harvesting and planting new ones), it may be challenging to maintain the same level of carbon sequestration over time. Closer-to-nature forest management is an example of an adaptation practice that increases forest resilience (see Box 5.3).

Other examples of adaptation measures in forests are described below:

- Assisted migration of tree species will be needed to a considerable extent to support sustainable forest management (Fady et al., 2016). In particular, it will be important to replace species not well adapted to the changing climate for example in places where the climate is expected to get warmer, e.g. by bringing oak species from the Mediterranean to central Europe.

- Embracing active management approaches is necessary for limiting the impact of fires on forest productivity. These approaches include modifying forest composition, switching from coniferous to deciduous species and introducing new species that are better adapted to a changing climate (Fady et al., 2016).

- Altering tree species composition can enhance stand diversity. This helps to make forests more resilient to climate change and sudden disturbances (Ammer, 2019) (in terms of implementation, an increased level of species richness is preferable, and the species chosen should have complementary functional traits).

- Avoiding monoculture plantations and fostering biodiverse forests is important for reducing threats from fires and pest infestation.

- Stand thinning helps to protect stands against water stress (since stand density is directly correlated with water consumption) (Gebhardt et al., 2014).

Box 5.3

Closer-to-nature forest management

Closer-to-nature forest management is a new concept proposed in the EU forest strategy for 2030. It aims to improve the conservation values and climate resilience of multifunctional, managed forests in Europe.

A recent report by the European Forest Institute (Larsen et al., 2022) provides guidance on the implementation of closer-to-nature forest management, which is defined as an overarching 'umbrella' covering all approaches and terminologies. Together with sustainable forest management, it supports biodiversity, resilience and climate adaptation in managed forests and forested landscapes.

Closer-to-nature forest management builds on seven principles:

1. retention of habitat trees, special habitats and deadwood;
2. promoting native tree species as well as site-adapted non-native species;
3. promoting natural tree regeneration;
4. performing partial harvesting and promoting stand structural heterogeneity;
5. promoting tree species variation and genetic diversity;
6. avoiding intensive management operations;
7. supporting landscape heterogeneity and functioning.

Adopting closer-to-nature forest management will mean employing a variety of silvicultural methods to develop multifunctional forests that reflect local climates, and forest and site types; sustain biodiversity and facilitate adaptation; and provide the desired range of ecosystem services. Managers should embrace diversity, learn from the natural processes that influence their forests, anticipate the impacts of climate change and plan to develop forest ecosystems that can be sustained through an era of profound uncertainty. This should be done in consultation with stakeholders, and it will take an appreciable amount of time for the effects of adopting this approach to become apparent. Adaptive learning will be needed for achieving a success.

While the concept is new, it is closely related to some existing forest management systems such as continuous forest cover systems. However, there is a lack of statistical information on the extent of the implementation of closer-to-nature forest management. The European Commission has also recently developed guidelines for closer-to-nature forest management, in reference to the EU Forestry Strategy 2030 (EC, 2023b).

The impact of closer-to-nature forest management to climate change mitigation is difficult to assess. On average it can be expected that carbon stocks will be higher with continuous forest cover systems compared to forests management with harvesting done as clear-cuts. However, a very important benefit is likely to be an increase in resilience to the impacts of climate change compared with a homogenous forest. In this case, more diverse and resilient forests are better for climate change mitigation.

5.1.3 Carbon sequestration in agricultural soils

Soils and carbon

This section focuses on carbon sequestration in agricultural soils, particularly of cropland and grassland. Healthy and fertile soils are essential for producing biomass sustainably. At the same time, soil carbon sequestration has been recognised as a climate change mitigation strategy and promoted within carbon farming initiatives in the EU (EC, 2021a; Mattila et al., 2022). Mineral soils constitute most of the soils in Europe and have much less carbon than organic (meaning carbon-rich soils). 92.1% of the EU land area is covered with mineral soil, while the rest is organic soil (EC, 2023a). Organic soils are found mostly in northern Europe (EEA, 2022b).

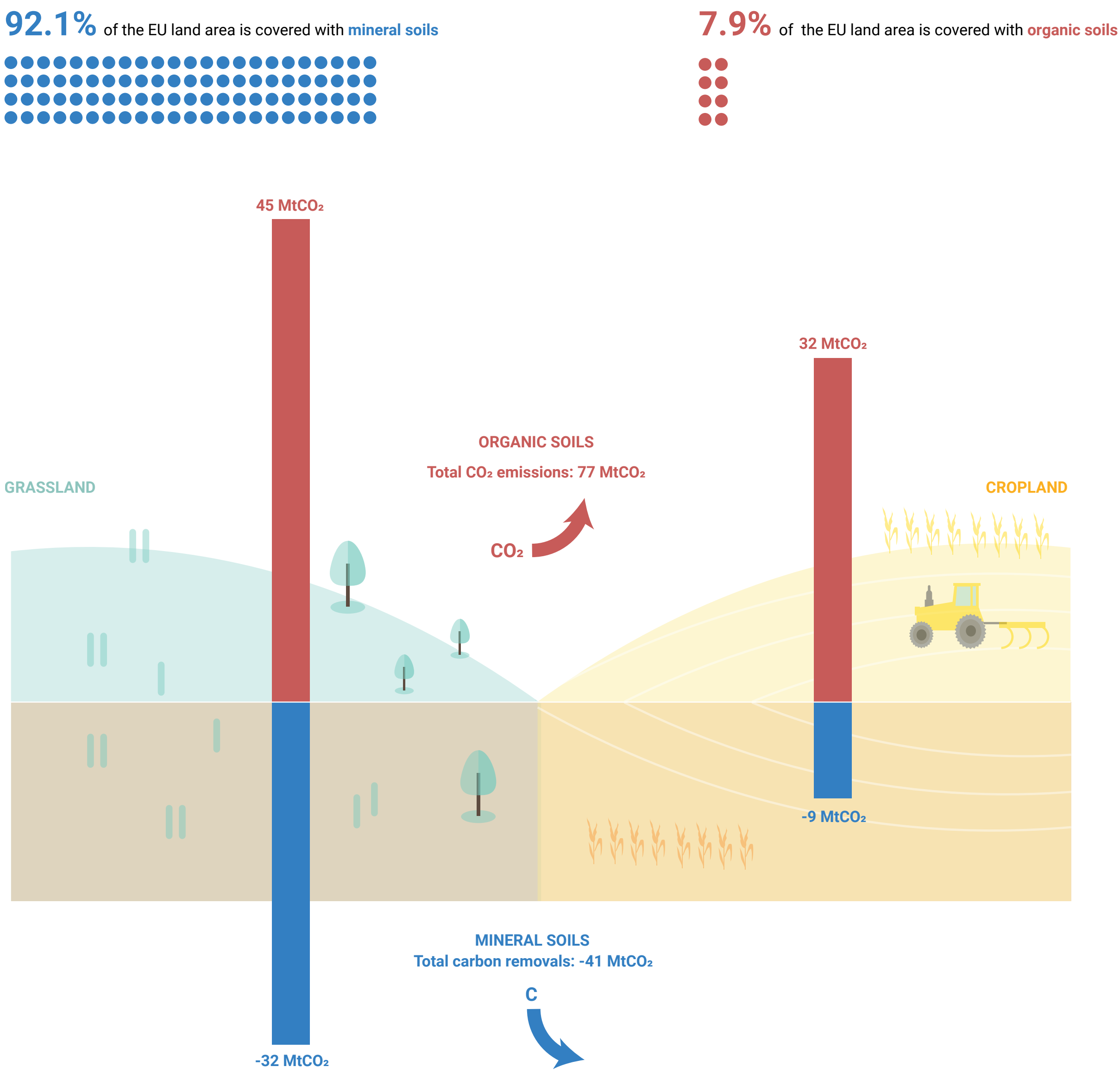
Soil carbon that is stored in soils includes soil organic matter, which is an indicator of soil health (EC, 2022). There is evidence that EU cropland soils are losing carbon every year as a result of land management practices and climate change (EC, 2022). Practices aimed at soil restoration are needed, since 60-70% of mineral soils are estimated to be in poor condition and around 45% of the EU's mineral soils have low or very low soil organic matter (EC, 2022). Key regional hotspots where soil organic matter is decreasing are in the Mediterranean and central-eastern Europe (EC, Directorate-General for Research and Innovation et al., 2020).

EU agricultural soils: $C0_2$ emissions or carbon removals?

CO_2 emissions from cropland and grassland are mainly the result of carbon losses from soils. Depending on soil type, crop type, climate conditions and management practices, it may be possible for any given type of land use in one Member State to loss carbon and gain carbon in another. For example, some areas of permanent grassland have exhibited carbon sequestration levels comparable to those of forested areas, depending on the extraction rate (Schils et al., 2022).

While the goal for mineral soils is to increase soil organic matter, for organic soils the main goal is to stop or reduce the loss of carbon. In the EU, net CO_2 emissions from agriculture mineral and organic soils in 2021 were -41.1MtCO_2 and 77.6MtCO_2 respectively (meaning that mineral soils at the EU level actually generated carbon removals while organic soils generated emissions) (see Figure 5.5), (EC, 2023a). So, for cropland and grassland together, total CO_2 emissions from EU soils reported under the EU LULUCF sector in national GHG inventories were greater than carbon removals.

Figure 5.5 **EU cropland and grassland net emissions and removals from managed mineral and organic soils in 2021**



Source: EEA based on data from EC (2023a).

Since 1990, CO_2 emissions for both cropland and grassland have fallen. The reduction in emissions from cropland can be attributed to a reduction in cropland areas, including cropland with organic soils where emissions are normally high. GHG emissions from cropland reached 21MtCO_2, representing a decrease of 67% compared with 1990.

In 2021, reported emissions from grassland reached 22MtCO_2, representing a decrease of 49% compared with 1990.

The emissions trend for grassland and cropland indicates an increase in carbon removals from mineral soils. To some degree, this is complemented by increased carbon stocks in vegetation. However, to understand the potential for reducing overall emissions in these two agricultural land categories, land management practices, in addition to land use/land cover changes, need to be looked at in detail. (Frelih-Larsen et al., 2022). The case study on conservation agriculture described in Box 5.4 illustrates how many elements of land management with regard to soils may influence GHG emissions.

Box 5.4

Improving soil organic carbon management on farmland — conservation agriculture

Conservation agriculture is based on the principles of minimum soil disturbance and permanent soil cover, combined with appropriate crop rotation (meaning growing different crops after each other in a multiannual cycle) (Verhulst et al., 2010; Powlson et al., 2016; Francaviglia et al., 2023). Compared with conventional agriculture, this system improves soil properties, enhancing the delivery of ecosystem services, including climate regulation and reduced GHG emissions. Yields are comparable to those from a conventional system, while farm productivity is increased by reducing production time and labour (Grigoras et al., 2012). Conservation agriculture is based on the following three principles:

1. no or minimal mechanical soil disturbance (so no or minimum tillage);
2. permanent vegetation cover of soils;
3. appropriate crop rotation.

Conservation agriculture brings a range of benefits, including energy savings, increases in soil organic matter and a range of associated benefits (e.g. erosion reduction and improved sediment retention) (Palm et al., 2014). Some studies have even calculated carbon sequestration in crops through the adoption of conservation agriculture compared with tillage-based systems (González-Sánchez et al., 2021). Available evidence on actual changes in crop yields suggests that conservation agriculture has the greatest potential to increase crop yields when implemented as a set of integrated practices in rainfed systems in water-limited or water-stressed regions (Miralles-Wilhelm, 2021). The LIFE Agricarbon project (ECAF, 2020) has also shown yields that, depending on the crop, are similar to or slightly higher than those of conventional agriculture.

In the EU-27, conservation agriculture has the potential to adapt crops to a changing climate by reducing year-to-year yield variability and developing more sustainable agriculture (Basch and González-Sánchez, 2022). Semi-arid, Mediterranean and Atlantic regions seem to show the most promise for conservation agriculture.

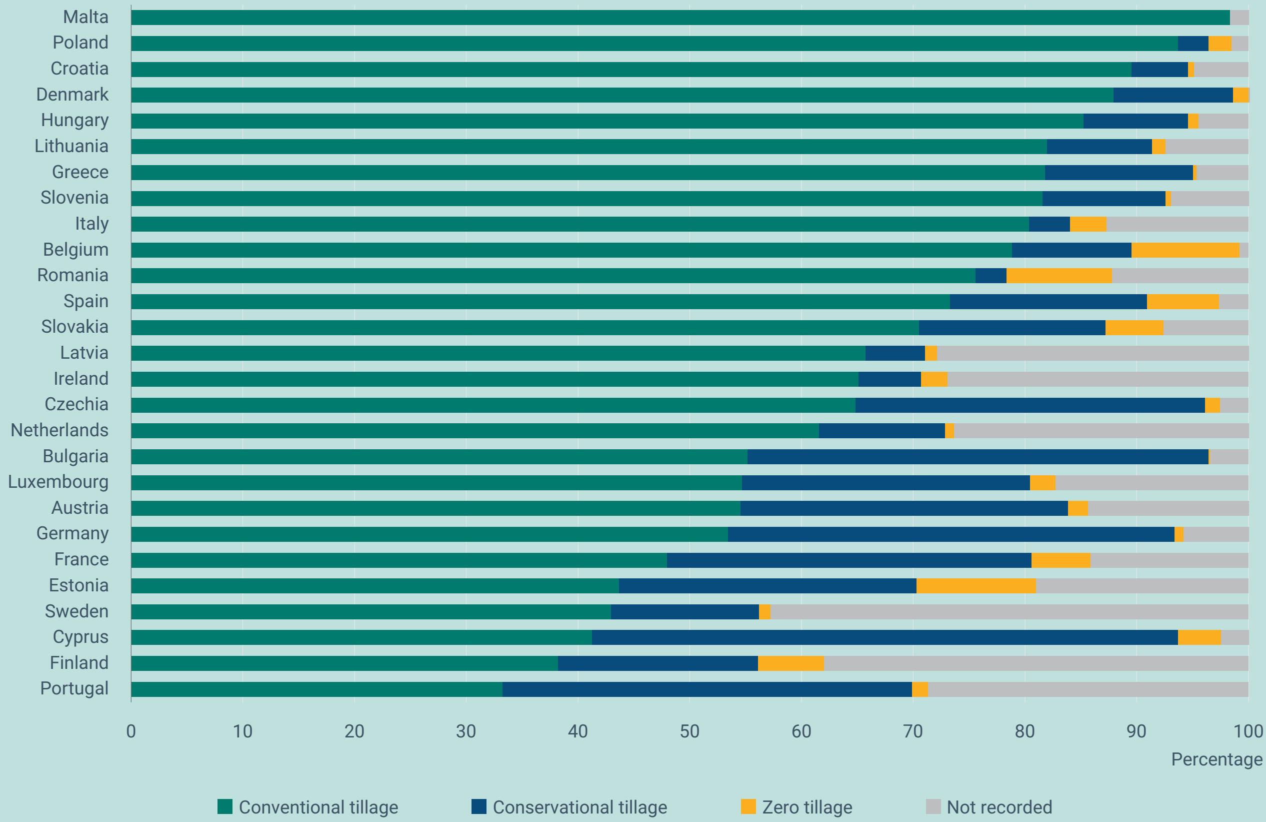
Figure 5.6 presents an overview of the share of different tillage practices in arable areas in the EU-27. Conservational tillage refers to arable land treated by conservation (low, minimum) tillage, which is a tillage practice that leaves plant residues (at least 30%) on the soil surface for erosion control and moisture conservation (Eurostat, 2023a).

Geographically, the highest shares of arable areas under conservation tillage were reported in west-central Europe, Portugal (Alentejo and the island of Madeira), eastern Germany (Thüringen, Chemnitz and Sachsen-Anhalt), south-western and western France, Cyprus and Bulgaria (Eurostat, 2023a).

Box 5.4

Improving soil organic carbon management on farmland — conservation agriculture (cont.)

Figure 5.6 Share of tillage practices in arable areas in the EU in 2016



Source: Eurostat (2023a).

Increasing soil organic carbon — a blessing or a burden for climate change mitigation?

Although carbon sequestration in agricultural soils has been proposed as one strategy to mitigate GHG emissions in agricultural systems, scientists debate the mitigation potential of soil carbon sequestration in cropland and grassland because of the risk of intentional or unintentional reversal of carbon sequestration by certain land management practices. Guenet et al. (2021) explain the interrelation between carbon and nitrogen cycles; for instance, they show that reduced or zero tillage reduces carbon losses and may even lead to increased carbon inputs to soils. However, if soil organic matter is high, additional sequestration may promote denitrification and increase nitrous oxide (N_2O) emissions from soils. N_2O is another challenging GHG to mitigate; its potential to heat the atmosphere is much higher than that of CO_2. Therefore, if management practices aimed at increasing soil organic carbon also caused an increase in N_2O emissions from soils, any climate benefits would essentially be offset (Frelih-Larsen et al., 2022; Haas et al., 2022). Another example is the use of cover crops, which can increase soil organic carbon content in topsoil (Poeplau and Don, 2015; Abdalla et al., 2019). Here, emission fluxes are not yet fully understood; quite often, any impact is site specific. To adjust agricultural practices to optimise soil fluxes, GHG volume concentrations would need to be properly measured in soils; there are tools available on the market for this (as mentioned in Fielder et al. (2022)). This process would need to be combined with specialist knowledge on different practices and field-specific information. This can be a challenging task for land managers, such as farmers, who are directly responsible for implementing practices on the ground.

5.1.4 Land management, and how biomass production and harvesting impact ecosystems

Relationship between land use intensity and biodiversity

This section reviews the impacts of producing or harvesting biomass on four landscape types: forest areas, intensively managed farmland areas (such as cropland and grassland), semi-natural farmed areas and wetlands. These landscape types are briefly described in Table 5.1 according to their naturalness. One key principle to consider when analysing the potential impacts of producing or harvesting biomass on different types of landscape is that the environmental effects largely depend on the baseline state of the landscape under consideration.

In areas of very intensive, large-scale agriculture, the impact of cultivating new crops (e.g. rapeseed, maize) will often not be very significant and will be very different from the impact of cultivating the same crops in semi-natural landscapes or wetland areas. In addition, the intensity of production and harvesting also determines these activities' direct impacts. It should be noted that the analysis presented here does not take into account the direct and indirect land use change resulting from crop production for energy or other new biomass uses.

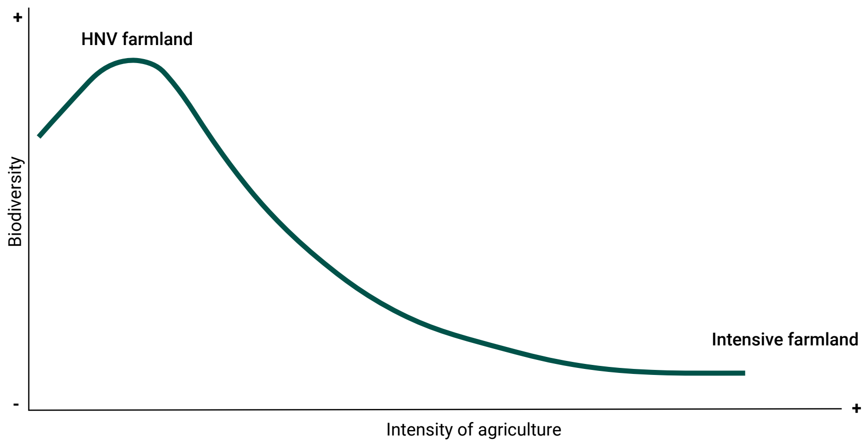
Table 5.1 Review of key landscape types

Landscape types	Characteristics
Forested areas (semi-natural and natural ecosystems)	Forest ecosystems have been extensively transformed by human intervention; nevertheless, Forest Europe (2020) classifies 94% of them as 'semi-natural'. The most impactful intervention is the change in tree composition from diverse, multi-age, native stands to non-native species (often conifer), often grown in single-species, mono-age forest stands. Other impactful changes are extensive drainage of wet forest areas and forest road building, both of which increase productivity and/or ease of harvesting. Intensively managed forests have little structural diversity in and between forest blocks, and very few to no old or dead trees (which are essential for many rare forest species). However, some forest management systems retain some characteristics of natural forests by relying mainly on native species and selective, single-tree harvesting.
Intensively managed cropland/grassland	This kind of landscape has emerged over the last 100 years and is characterised by a (near) complete transformation of farmed areas into intensively exploited arable land, permanent crops, and ploughed and re-seeded grassland. The presence of structural landscape elements, such as hedgerows, ponds and stone walls, has been severely reduced; drainage and irrigation are widely employed; and fertiliser and pesticide use is generally high, which contributes to GHG emissions and impacts soil structure. Livestock are stabled all or most of the year, with imported and/or cultivated feedstuff constituting a large part of their diet. This landscape is generally managed with the help of heavy machinery, which affects the soils.
Semi-natural grassland/ cropland	This landscape archetype is the outcome of extensive farming systems, where livestock graze on semi-natural habitats (heath and moorland, semi-natural grassland, Mediterranean maquis, etc.). Often, these areas also retain many traditional landscape features, such as hedgerows and terraces, which support livestock raising and crops. Crop production relies less on outside fertilisers and can involve traditional fallow.
Wetlands	Wetlands are areas that are currently, or have been historically, permanently or seasonally wet. In the past, this enabled grazing, hay making or reed harvesting, but not arable cultivation. Today, their vegetation cover is often substantially altered as a result of large-scale drainage and/or peat extraction. Moreover, they may be under intensive arable cultivation. However, they retain a substantial layer of organic soils (undergoing mineralisation in most cases) and could easily be rewetted if drainage infrastructure were to be removed.

Semi-natural grassland and wetland areas rarely occur in a 'pure' form, as intensive farmland patches are often found within them. Intensive farmland can similarly harbour some 'islands' of remnant semi-natural and wetland areas. The analysis presented here can only partly address the real-life diversity of farming and ecosystem types and the many different grades of landscape transformation following intensive land use practices.

Table 1.1 in Chapter 1 explained how different ecosystem groups are impacted by human land use. For agricultural landscapes and farmed wetland areas, it is important to consider the general relationship between farming intensity and the nature value agricultural systems. Extensive farming and grazing practices increase habitat and species diversity (compared with a completely forested landscape), which are then lost as farming intensifies. However, adding semi-natural elements to intensively managed ecosystems will generally improve species diversity.

Figure 5.7 **General relationship between agricultural intensification and biodiversity**



Source EEA.

Figure 5.7 shows that a certain level of biomass extraction (e.g. for grazing, crops, or heating or building materials) from semi-natural landscapes is compatible with and even supports a high level of species richness. It also shows that biodiversity decreases sharply as intermediate management moves towards intensive management (Gabriel et al., 2013; Pedroli et al., 2013; van der Sluis et al., 2016).

This is due to several factors. First, intensive farming practices lead to less crop diversity and more intensive grassland management, impacting vegetation structure richness and habitat types. Second, nitrogen and phosphorus application favours species that are better adapted to take advantage of additional nutrients; as a result, these species grow more quickly than and outcompete other species (Dise et al., 2011). Finally, intensive farming often prioritises more productive areas and abandons those that are less productive or more remote — leading to a loss of semi-natural habitats.

As a result of the intensification of farming in Europe, most agricultural areas correspond to the bottom-right corner of the diagram in Figure 5.7. This has led to a decline in genetic diversity among crops and a loss of species diversity among flowering plants, butterflies and other insect species across Europe (EEA, 2007). In most farmed areas, there has been a substantial reduction in structural elements such as grass verges, hedges and ponds. This, too, has impacted species diversity by eliminating habitats and reducing species migration possibilities (Eriksson, 2021). Specialised farming practices (e.g. arable farming and specialised dairy production) have also significantly reduced crop diversity.

At the same time, economic and social factors continue to drive the abandonment of less productive or remote farmland. This also has negative effects on biodiversity, as semi-natural habitats that rely on grazing or mowing to exist disappear (Halada et al., 2011).

How biomass production and harvesting impact landscape types

The impact of biomass production significantly depends on the type of annual or permanent crop chosen, the intensity of the land use it is replacing (e.g. going from extensive farming to intensive farming) and/or the biomass harvesting methods used (EEA, 2007).

In **forest areas**, the impact of biomass harvesting is determined by its effect on the forest structure, tree composition, and volume of standing and lying deadwood. Managed forest ecosystems will generally increase in species diversity when human intervention decreases. This means that, from a biodiversity perspective, less harvesting and more natural stands are generally better. There are exceptions, however, for example the thinning out of Mediterranean forests to reduce fire risk or the transformation of uniform, non-native conifer plantations into more natural stands by taking out conifer plantations.

In **intensive agricultural areas**, using intensively cultivated crops for energy purposes (e.g. maize for biogas or oilseed rape for biodiesel) exerts pressure on biodiversity and food provision. However, energy cropping can positively impact biodiversity if it increases structural diversity. Introducing perennial crops as blocks, or linear or point elements of different sizes, creates cover, feeding and even breeding opportunities in areas where many such elements (e.g. hedges and tree lines) have been removed in previous decades (Pedroli et al., 2013). Examples of these kinds of crops are short-rotation willow coppice, perennial energy grasses (e.g. Miscanthus) and the Jatropha bush in the Mediterranean region. Cultivating semi-permanent vegetation in strips increases landscape diversity and creates migration pathways for certain species within intensive agricultural areas. Sourcing woody biomass from hedges and similar landscape elements installed in intensively managed cropland or grassland could also be considered. This would re-establish an economic purpose for such landscape elements and could incentivise their conservation and even restoration (Pedroli et al., 2013).

Farmed semi-natural areas generally contain a diverse set of often-threatened habitats. Orchid-rich meadows, sedge and rush vegetation in wetlands or heathlands are examples of such habitat types. However, these are often overgrown with invading shrubs or have lost species diversity as a result of abandonment or undergrazing. As a result, the level of structural diversity is generally high in semi-natural landscapes.

From a biodiversity perspective, grazed or mown semi-natural areas should be maintained under their current vegetation cover — whether the area is in active agricultural use or not. From this perspective, introducing arable or permanent crops in areas under semi-natural vegetation would lead to significant negative impacts on biodiversity. This conservation rule is valid for large-scale, semi-natural landscapes and patches of semi-natural vegetation, which can still be found in many intensive agricultural landscapes.

Measures that support the economic viability of extensive land use benefit these habitats. These measures help to remove unnecessary biomass re-growth, which supports conservation and potential restoration. In other words, if using biomass from semi-natural habitats for energy production is feasible, natural and semi-natural habitats can be preserved while ensuring economic returns from these areas (EEA, 2007; Melts et al., 2013).

There are multiple options for using such areas as a source of biomass. Moreover, if regular biomass harvesting occurs at the right time of year and in a suitable manner, semi-natural habitats can be kept in a good state — which supports nature conservation objectives. Some concrete examples can be found in previous EEA work (EEA, 2007).

However, measures that aim to maintain and improve habitat quality by removing nutrients or biomass from the ecosystem (e.g. to restore eutrophicated habitats) will not increase carbon sequestration and stocks. More positively, using biomass from these habitats can make a small contribution to fulfilling society's energy and food needs (EEA, 2022a).

Wetlands are areas that are permanently or seasonally wet. They used to cover large areas of Europe but have been substantially altered or even destroyed in many places. Natural wetland ecosystem types in Europe include swamp forest, intertidal flats, saltmarshes, coastal lagoons and estuaries, freshwater mires, bogs, marshes, fens and riparian grasslands. Carbon sequestration rates in unmanaged wetlands are often relatively low but storage in soils is very high after centuries of accumulating organic carbon. Wetlands typically boast high biodiversity value (Pedroli et al., 2013), and mires, fens and bogs (peatlands) are the second-largest terrestrial carbon pools, with carbon stocks of up to 883 megagram C per hectare (Malak et al., 2021).

As a result of past large-scale drainage and/or peat extraction, many wetlands have been converted to farmland. Even under intensive cultivation, they typically retain a substantial layer of organic soils (undergoing mineralisation, in most cases) and could easily be rewetted if drainage infrastructure were to be removed. Wetland restoration (particularly peatland) is a key target of climate and biodiversity policies, as drained, organic soils are also a net source of GHG emissions. This restoration typically requires rewetting by increasing the water table (Malak et al., 2021) and limiting biomass exploitation, although biomass harvesting during drier periods or in winter often remains possible (Pedroli et al., 2013).

Wetlands that remain under extensive management (e.g. for livestock grazing) or have recently been abandoned still retain a lot of species-rich, semi-natural vegetation or other features worth preserving. They should be treated in the same way as the other semi-natural areas discussed above (Pedroli et al., 2013). The various semi-natural habitats that wetlands contain have different biomass yields and thus different energy potentials. Nevertheless, many highly diverse grasslands on wet soils can provide a reasonable amount of energy. For example, a study from Melts et al. (2013) showed that the average weight of herbaceous biomass from alluvial and mesic meadows was at least twice high as that of mesic and wooded meadows. It also showed that the highest fresh biomass yield can be harvested in alluvial meadows.

For wetland areas with low biodiversity value, introducing permanent, low-intensity energy crops, for example willow coppice or energy grasses, could be a valid option. These would maintain soil cover and provide large biomass outputs per hectare. Further review of potential permanent energy crops and their environmental impacts appears in earlier EEA publications (EEA, 2007, EEA, 2013).

5.2 Biomass as a substitute for fossil fuel and carbon-intensive materials to mitigate climate change

5.2.1 Substitution effect and cascading use

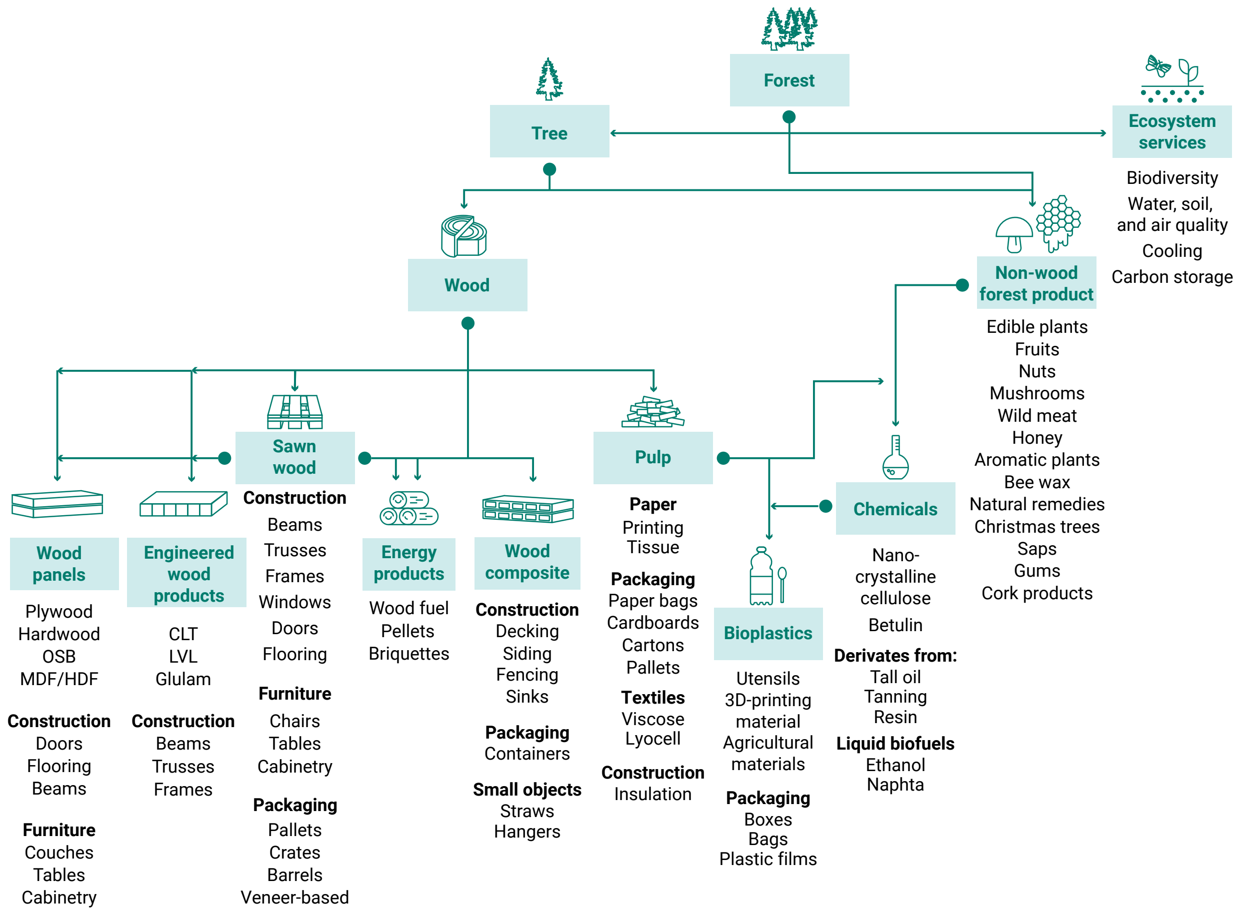
Wood-based products/materials are associated with a lower carbon footprint because they may substitute other products such as concrete, steel, and other non-renewable goods that when used lead to higher emissions (Hetemäki and Kangas, 2022). Quantifying the effect of the substitution and the carbon storage in these products is technically complex and challenging. Overall, the substitution effect depends on the product that is being used as a substitute, the GHG emissions associated with this product and its expected lifetime. Figure 5.9 presents typical forest product utilisation pathways and shows how broadly wood materials/products are applied in many economic sectors. (Please note that not all of these are recognised as harvested wood products).

Box 5.5

Harvested wood products

Harvested wood is converted into many wood products and materials. Wood-based products with a long-life cycle may store carbon outside forests, which can lead to a sink effect. Member States report in their greenhouse gas (GHG) inventories under the land use, land use change and forestry (LULUCF) sector on three different types of harvested wood products (HWPs): sawnwood, wood-based panels, and pulp and paper. These products have half-lives of 35, 25 and 2 years, respectively. Net carbon removals of harvested wood products' pool are possible only when more carbon is added every year to compensate for the annual loss due to decay of these products. So far, the harvested wood products' pool increases every year. In 2021, carbon removals from HWPs accounted to -47.4MtCO_2.

Figure 5.8 Typical forest product utilisation pathways



Notes: CLT, Cross-laminated timber; HDF, High-density fibreboard; LVL, Laminated veneer lumber; MDF, Medium-density fibreboard; OSB, Oriented strand board.

Source: Adapted from Verkerk et al. (2021).

Table 5.2 shows the substitution effect of some product categories. Some studies argue that substitution effects will reduce over time because products are expected to be produced with lower fossil fuel-related emissions overall as a result of decarbonisation strategies (Brunet-Navarro et al., 2021).

Table 5.2 Substitution effects by product category

Product category	Average substitution effect (kg C/kg carbon wood product)
Structural construction (e.g. building, internal or external wall, wood frame, beam)	1.3
Non-structural construction (e.g. window, door, ceiling and floor cover, cladding, civil engineering)	1.6
Textiles	2.8
Other (e.g. chemicals, furniture, packaging)	1.0 to 1.5

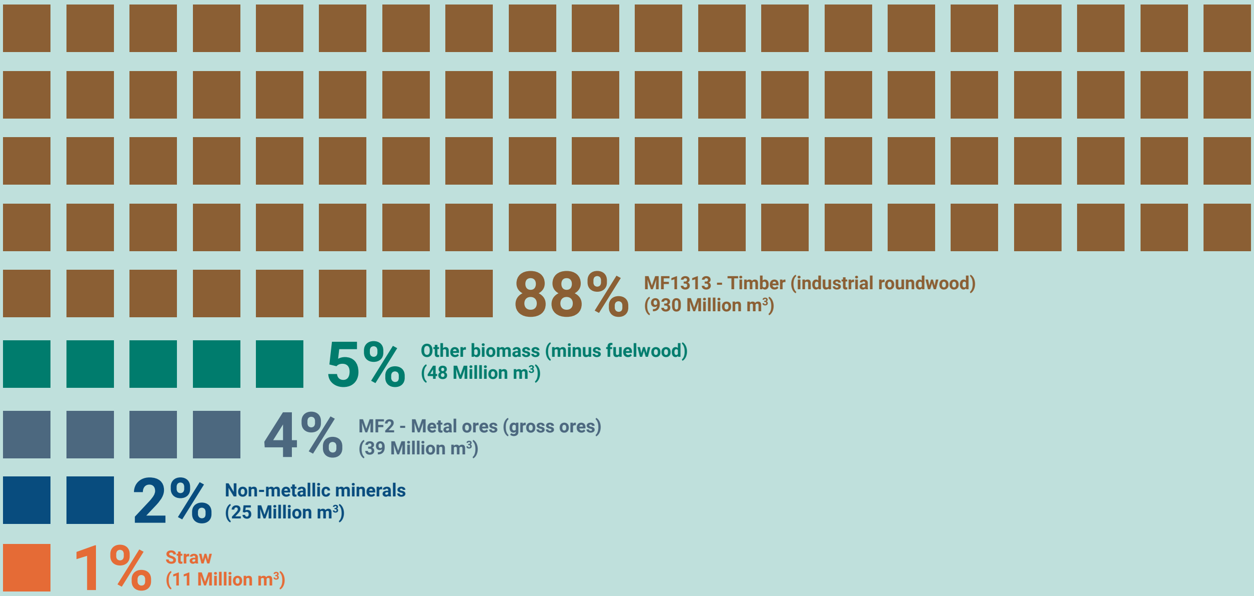
Note: Substitution effect means that for each kg of C in wood products that substitute non-wood products, an average emission reduction occurs expressed in kg C.

Source: Examples based on Leskinen et al. (2018).

Biomass in building materials for the construction sector

Bio-based materials (based on biomass feedstocks) represent 3% of the total mass of building materials used in the EU. Wood materials account for two thirds of this share but other feedstocks such as straw, hemp and flax are also used. The EU's renovation wave strategy and the new European Bauhaus initiative, circular economy action plan and adaptation strategy have acknowledged the contribution of bio-based products (e.g. in insulation of walls and floors) in reducing the overall carbon footprint in construction sector. However, none of these makes direct reference to using them for energy renovation (e.g. to support improvements to the building envelope, retrofits or modernisation, to reduce energy demand).

Figure 5.9 Bio-based materials in volume in building materials used in the EU-27, 2018



Source: EEA based on Cardellini and Mijnendonckx (2022).

Although wood-based materials come from a renewable resource, they are also a finite resource. Therefore, increasing resource efficiency through the cascading use of wood is important. This means putting woody biomass to good use, and prioritising uses with higher added value and lower environmental impact, before it is reused, recycled and finally burnt for energy purposes. The cascading use of wood concept has many similarities to the circular economy concept; the difference is that the former focuses on bio-based materials, whereas the latter embraces many kinds of resources (Mair and Stern, 2017). Using biomass in products that create the most economic value over multiple lifetimes maximises resource efficiency. The availability of wood for other uses may increase by up to one third as pressures on forest ecosystems and the use of industrial wood decline (Bais-Moleman et al., 2017).

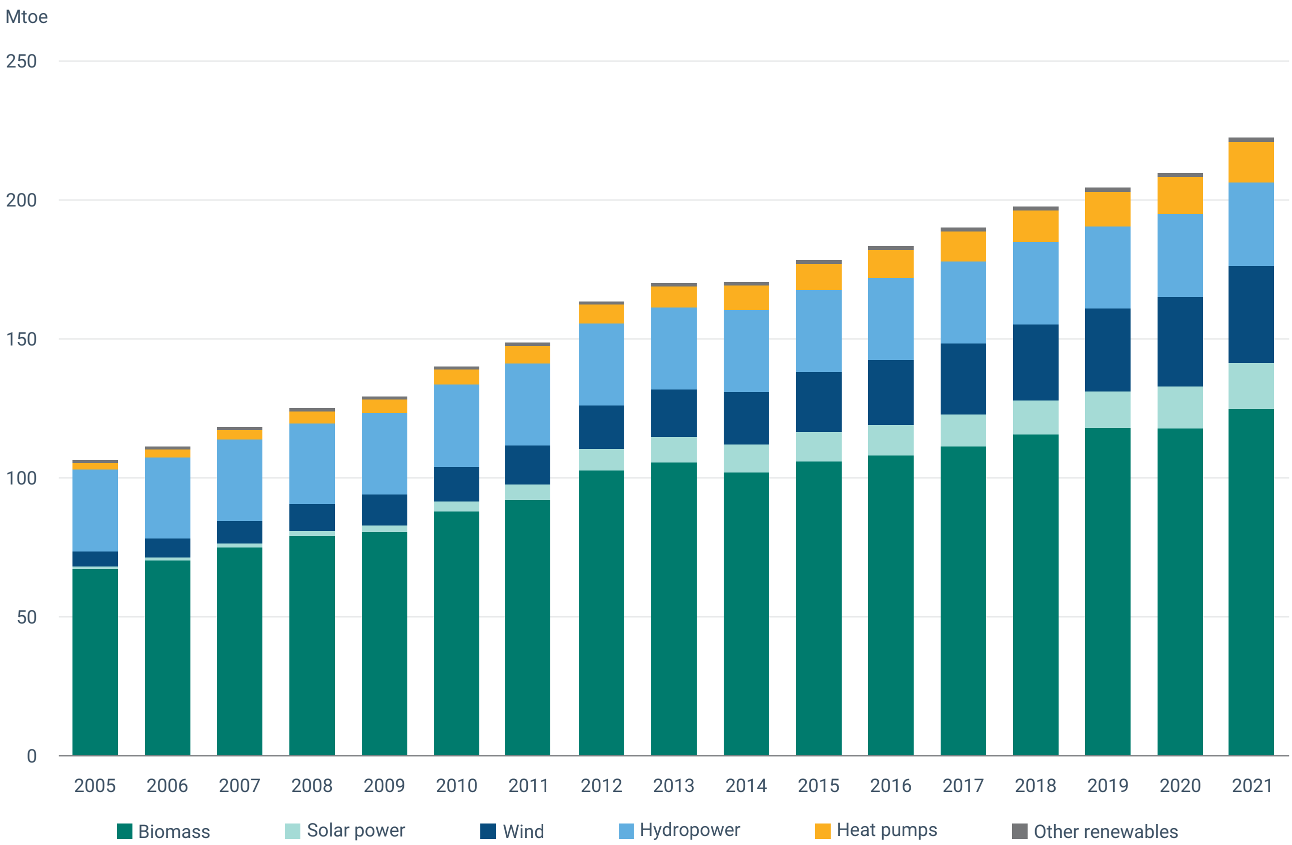
To ensure the optimal, cascading use of wood, interactions between forest management practices, industrial processes and legislation measures must be considered (Zargar et al., 2022). Industrial processes have been optimised to utilise wood in a way that reflects wood properties, enabling more efficient wood processing and the production of quality products. However, the need to preserve biodiversity and the impact of climate change on forests calls for new wood processing techniques and green chemistry protocols for wood modification for example to enhance recycling (Schubert et al., 2023). The forest sector's contribution to avoided carbon emissions depends on assumptions regarding average substitution effects and the market response to increased cascading. Although there is potential to reduce environmental impacts with cascading use of wood, more evidence for this needs to be better established. Policy incentives could also be more favourable, to encourage the implementation of the cascading principle.

5.2.2 Woody biomass and bioenergy

Renewable energy consumption in the EU remains dominated by biomass over the period from 2005-2021 (as illustrated on Figure 5.10). Biomass accounted for 56% (i.e. 125 million tonnes of oil equivalent (Mtoe)) of the overall EU's renewable gross final energy consumption in 2021 (this share was 63% in 2005). The lower share of biomass in 2021 than in previous years was due to growing contribution of other renewables, such as wind and solar. Biomass was used the most for heating and cooling purposes.

There has been a significant increase in the use of solid biomass, particularly woody biomass, to produce bioenergy in almost all Member States between 2000 and 2020. Table 5.3 explains how various types of woody biomass contribute to bioenergy through combustion.

Figure 5.10 Renewable gross final energy consumption in EU-27 by technology



Source: EEA (2022c); Eurostat (2023c).

Table 5.3 Woody biomass types used for combustion

Woody biomass type used for combustion	Description
Primary wood and bark (meaning woody biomass extracted directly from either forests or outside forests without further treatments or conversion)	The share of primary wood for energy purposes has increased by 32% between 2010 and 2017 (Gurria et al., 2022). This increase can be partly linked to the soaring frequency of natural disturbances impacting forests, which leads to salvage logging. The wood obtained from this process is damaged and low quality; therefore, it usually goes to the energy sector for combustion or is used for wood pulp and wood-based panel production. A survey conducted by the European Commission showed that salvage logging increased from 10.7% in 2014 to 22.8% in 2018 across 17 EU Member States (Camia et al., 2018). Assuming that much of the wood harvested through salvage logging was damaged helps to explain the increase in the share of wood that is mainly used for energy purposes in recent years.
Industrial roundwood by-products and residues from processing and manufacturing (secondary sources)	Industrial roundwood is processed into a variety of wood products. During this process, a significant share is turned into by-products that can be used in the energy sector (e.g. wood pellets). However, other uses of biomass residues and by-products have a higher value than their use for energy production, for instance use in the bio-chemical sector or the panel industry.
Waste/post-consumer wood	Recovered used wood from transport (pellets) and private households, and used wood from construction, the demolition of buildings and civil engineering works can be suitable for use as a fuel or for the production of wood pellets and particle board. (Source: UNECE/FAO Forestry and Timber Section 2018.)

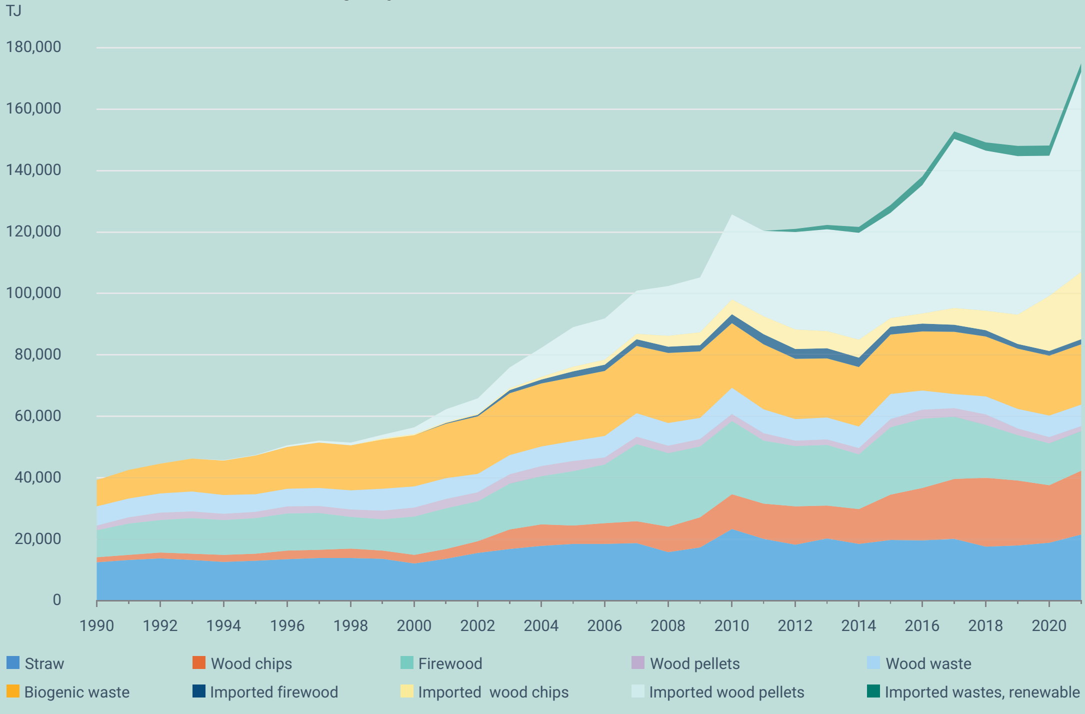
Comprehensive analysis of how much and what kind of woody biomass is combusted is difficult because of gaps in the available data on biomass flows. Moreover, data show that the use of solid biomass (woody biomass in particular) for bioenergy is very country specific, and there are large differences between countries in how they use roundwood. An example of a country that experienced a large increase in biomass consumption for energy purposes is Denmark (Box 5.7).

Box 5.7

Biomass use for energy purposes in Denmark

In Denmark, the biomass consumption for energy purposes (out of which 75% was woody biomass in 2021) increased by 346% between 1990 and 2021. In 2021, 48% of the biomass used for energy was domestically produced and 52% was imported from both inside and outside the EU. The main import comes from the Baltic countries. Figure 5.11 shows both domestic and imported biomass used for energy purposes in terajoules (TJ), where significant increases in imported wood pellets, as well as domestic and imported wood chips, are observed.

Figure 5.11 Consumption of different types of solid biomass for energy purposes in Denmark



Source: EEA, based on data from Danish Energy Agency (2021).

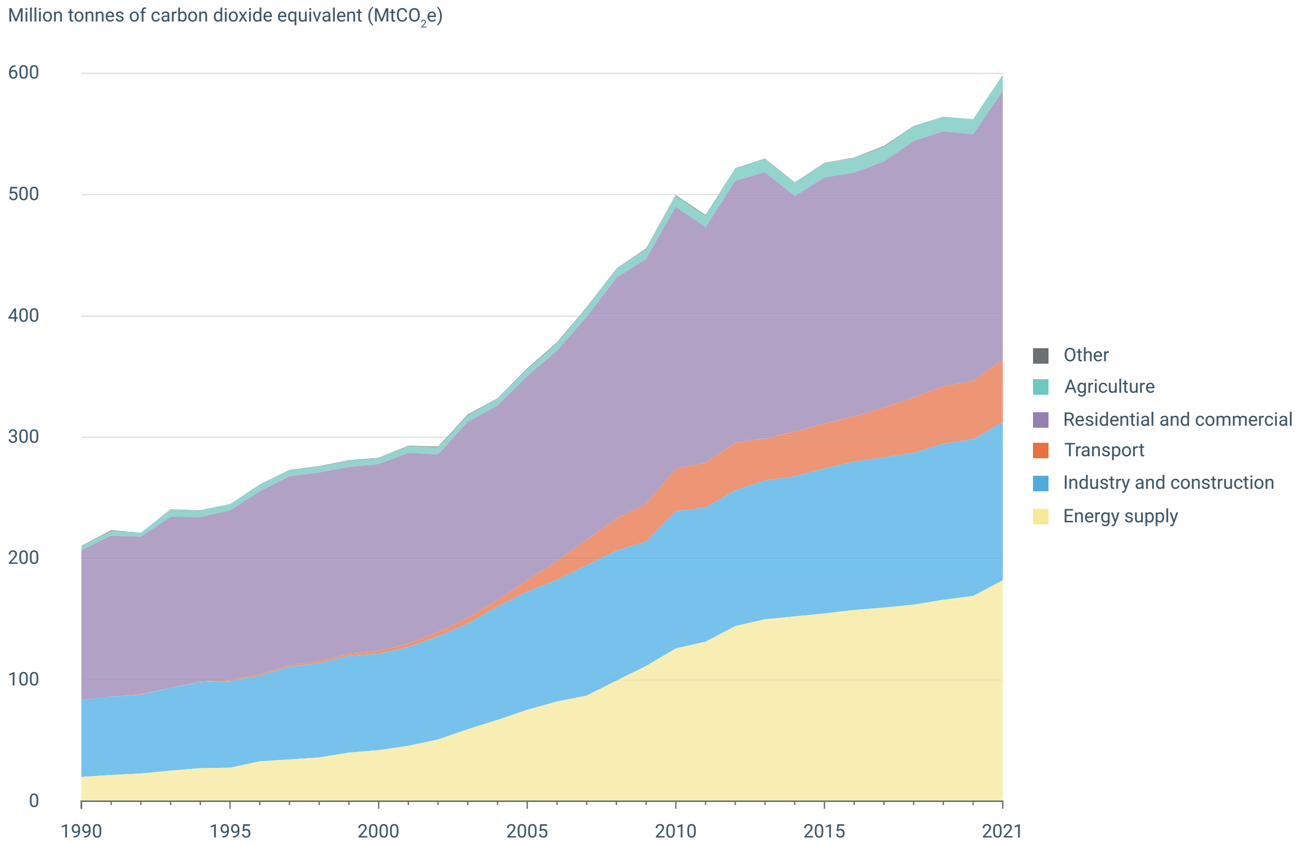
This increase in biomass use, accompanied by more investments into wind and solar energy, and an increase in fossil gas use and during the latest years even biogas, have reduced coal and oil consumption. As a result, accounted GHG-emissions from Denmark's energy sector has dropped.

Combined heat and power plants were the largest consumer of wood pellets for energy (71%), followed by domestic households (25%) and other industrial uses (4%). Approximately 73% of the imported wood pellets in 2021 came from other EU Member States such as Estonia and Latvia. However, some came from Sweden, Finland, Portugal, Spain and Poland; 12% came from the US and Canada, and 10% from Russia. Other imports include biomass from Norway, Ukraine and Belarus.

Sources: Danish Energy Agency (2021).

According to the national GHG inventories, data on biomass combustion show that over the last 30 years the greatest share of CO_2 emissions from combusting biomass came from energy supply (e.g. electricity and heat production, often as part of co-firing with fossil fuels), and the residential (households) and commercial (services) sectors. Of the 340MtCO_2e increase in CO_2 emissions from biomass combustion between 1990 and 2020 in the EU, 44% came from energy supply, 20% from residential and commercial, 19% from industry, 14% from transport and 3% from agriculture (Figure 5.12).

Figure 5.12 Annual combustion of all types of biomass for energy purposes in different sectors in the EU-27



Note: CO_2 emissions from biomass combustion are reported as a Memo Item in national GHG inventories and are not included in national GHG emissions totals.

Source: EEA based on the EC (2023a).

Although increased biomass combustion has helped to reduce fossil fuel consumption, it have led to air pollution and higher emissions of particulate matter and volatile organic compounds from the renewable energy sector in almost all EU countries compared with 2005 levels (EEA, 2019).

In addition, although transforming energy into heat and electricity in thermal stations has become much more efficient, substantial efficiency losses still lead to both lost energy and additional GHG emissions. Therefore, producing heat from biomass is substantially more efficient than producing electricity. Based on energy statistics (Eurostat, 2023b), the efficiency of heat-only plants was about 84% in the EU in 2020 compared with just under 50% for electricity-only plants. In terms of combined heat and power, efficiencies were about 63% in 2020. This suggests that, when biomass is used, it is more efficient in systems that deliver heat to residential, commercial and industrial consumers.

5.2.3 Agricultural feedstocks and biofuels

The vast majority of agricultural biomass is used directly as food and feed. However, it is also used as feedstocks for biofuels or for biogas production. These uses contribute to achieving the EU's renewable energy targets. The discussion about the future of biofuels in the EU is ongoing, and data about EU and national biofuel production and consumption are still incomplete (ECA, forthcoming). This section therefore explains some of the opportunities and pitfalls of using biofuels, and the current and forthcoming legislation to address them.

Biofuels in the transport sector

Biofuel demand in Europe has been growing in recent years (IEA, 2021). Biofuels are one of the technological options currently available to the transport sector to reduce its dependency on fossil fuels. They are of particular interest given their relatively short time to market and the possibility offered by some to partially or completely replace conventional hydrocarbon products without substantially modifying existing engines, associated components and distribution infrastructure. This is especially important in sectors such as aviation and maritime, where technical requirements complicate the adoption of other technologies.

The two most common biofuels used in the EU to date are biodiesel and ethanol. Biodiesel is produced mainly from rapeseed (45.2%), used cooking oil, waste vegetable oil, animal fat (15.0%) and palm oil (11.3%) (data as of 2020 based on (Vourliotakis and Platsakis, 2022). Bioethanol is produced mainly from crops such as maize (56.1%), wheat (16.0%) and sugar beet (6.1%) (Vourliotakis and Platsakis, 2022). Biofuels produced from edible feedstocks are often called first-generation biofuels.

The use of first-generation biofuels comes with disadvantages, and has turned out to be more controversial than first thought (Løkke et al., 2021). This is because indirect land use change (ILUC) associated with producing these biofuels can be significant. (Løkke et al., 2021). ILUC is when arable land is expanded to cultivate crops to produce feedstocks for biofuels; as a result, it may be that CO_2 emissions resulting from land conversion or land management related to cultivating these crops are higher than the GHG savings from using biofuels instead of fossil fuels. There is still debate about how to account robustly for ILUC-induced emissions; many methodologies and models have been used and have led to significant differences (Løkke et al., 2021, Taheripour et al., 2021). Regardless, EU legislation recognises ILUC as a criterion for the sustainability of biofuels. In addition, since feedstocks are needed for biofuels, this may create competition with other crops (e.g. those grown for food purposes) on arable land.

EU legislation (the recast Renewable Energy Directive (RED II — Directive (EU) 2018/2001)) differentiates between three biofuel categories based on feedstock or technology used:

- biofuels that use feedstock produced from food and feed crops (i.e. first generation biofuels);

- biofuels that use feedstock produced from wastes, residues and co-products that can be processed with advanced technologies (advanced biofuels);

- biofuels that use feedstock produced from wastes, residues and co-products that can be processed into biofuels with mature technologies.

In 2020, 6.8% of the total fuel supply for road transport in the EU-27 came from biofuels (Vourliotakis and Platsakis, 2022). Less than 1% of these biofuels were advanced biofuels ([9]), meaning that the majority of biofuels consumed in the EU in 2020 were based on food and feed feedstocks. The use of biofuels in the maritime and aviation sectors was not significant overall. For the maritime sector, in 2020, the International Maritime Organization Data Collection System indicated that 99.91% of worldwide marine fuel use came from carbon-based conventional fuels (European Maritime Safety Agency, 2022). Similarly, for the aviation sector during 2020, sustainable fuels (either biobased or synthetic) constituted less than 0.05% of total EU fuel use (EASA, 2022).

RED II - Directive (EU) 2018/2001 sets sustainability criteria for biofuels that aim to reduce the risks of negative effects on the environment and climate in relation to ILUC. These criteria define, among other things, where agricultural feedstock should not be obtained from (e.g. high-carbon stock or biodiversity value areas), that forest biomass must come from legal harvesting operations and the GHG savings that must result from the use of biofuels compared with the use of fossil fuels (Article 28 of RED II).

The 2023 amendments to RED (called RED III) gives possibility for member states to choose between a binding target of 14.5% reduction of GHG intensity in energy in all transport sectors (baseline 2010) by 2030, or a binding share of at least 29% of renewables in transport within the final consumption of energy in the transport sector by 2030 (Council and Parliament of the EU, 2023). RED III also puts more emphasis on advanced biofuels and sets a target of a 5.5% of advanced biofuels (derived from non-food feedstocks) and renewable fuels of non-biological origin (RFNBOs) in the share of renewable energies supplied to the transport sector in 2030. In addition, RED II already includes limitations on first-generation biofuels. It states that the share of biofuels and bioliquids produced from food and feed crops in a Member State shall be no more than 1% higher than the share of such fuels in the final consumption of energy in the road and rail transport sectors in 2020 in that Member State, with a maximum of 7% of final consumption of energy in the road and rail transport sectors in that Member State to count against renewable energy targets. RED III retains this capping and adds that biofuels with a high ILUC risk, namely those produced from palm oil, will not be allowed to be counted towards the renewable energy targets. Capping the share of food and feed crop biofuels that count towards the renewable energy target does not mean that the sale of biofuels that are produced from food and feed crops beyond this cap are banned.

In addition, a new regulation in the maritime sector, FuelEU Maritime (EU, 2023), and a new initiative in the aviation sector, ReFuelEU (EC, 2021b), introduce targets to increase the share of renewable and low-carbon fuels in these sectors; however, in the case of these two sectors, crop-based biofuels are not eligible (ECA, forthcoming).

([9]) Following the definition of advanced biofuels in RED II (Annex IX, part A).

6 Conclusions and the way forward

The EU has started its transition towards a climate-neutral economy. Different types of biomass production and use and the associated impacts on ecosystems have a key role to play in this process. Choices about how the EU produces and consumes biomass, for which purposes, and the related policy incentives and implementation mechanisms will shape the future of European markets and overall biomass demand up to 2050.

Policymaking is crucial in enabling this transition towards climate-neutral and sustainable economy. Reaching the various EGD's targets is about finding a balance between different policy incentives and regulations so that biomass production and biomass end-use sectors (e.g. construction, transport, energy, manufacturing), consumers, and industries act sustainably within land, ecosystem, climate and global limits. This balance is important as biomass holds great potential to help society follow a more sustainable path, not only up to 2050 but also beyond that year. However, biomass must be used and managed in such a way that its production, extraction, and use do not damage the ecosystems.

The challenge for policymakers is that biomass production and consumption often compete in relation to potential end uses and the foreseen roles of biomass in the EU policies. The foreseen solutions related to the use and management of biomass can differ between various societal, economic and political stakeholders, and also between those who are producing (farmers and foresters) and consuming biomass. This report addresses some of the key questions about the production and consumption of biomass in Europe.

How does climate change impact total biomass production in the EU and what is expected in the future?

Climate change has impacted biomass production from agriculture and forest lands in the EU through both a northward shift in climate zones (that includes changes in temperature and precipitation) and changes in the growing seasons, along with the increasing frequency and severity of extreme events. These impacts affect European agriculture and forest lands both positively and negatively.

Yet certainly, climate change leads to more extreme annual meteorological conditions that is one of the reasons behind the annual variability of crop yields, with the impacts becoming more noticeable over time. Trends over the last decades (studied since 1960) show contrasting effects for the main annual crops. Maize yields have been impacted negatively, with the strongest effects reported in southern Europe. For wheat, the impacts on yield trends have been negative in many Member States. For barley, sorghum and soybean, the impacts were slightly but unanimously negative. For rapeseed, temperatures and precipitation changes negatively impacted yields in western and southern Europe, and positively impacted eastern and northern Europe. For sugar beet, the impacts were mixed, though pronouncedly negative in southern Europe.

Climate change is already affecting forest growth and stability in Europe. Understanding the different climate variables impacting forests is important for explaining forest productivity changes (see Chapter 4 of this report). Evidence from the past (since 1960) shows that forest growth in some parts of Europe had benefitted from climate change though warmer temperatures and longer growing seasons, except at sites where water availability was low. However, climate change is becoming a more prominent threat to forest ecosystems due to excessive heat, droughts, late frosts, storms and wildfires that are becoming more frequent and intense. These threats are affecting forest health negatively leading to a decline in forest growth, weakening of trees, and even a loss of living biomass. A decline in a forest's health makes it more vulnerable to an increasing occurrence of pests and diseases (e.g. the European spruce bark beetle), which causes significant harm to forests and destroys forest stands. Those extreme events lead to negative long-term impacts on forest productivity, tree mortality and forests soils, and result in biomass and carbon losses. Evidence is growing that monoculture forests are more vulnerable to these impacts than forests that are diverse in structure and composition. This is particularly the case for mid-altitude mixed forests where forest management favoured coniferous trees over broadleaf species. Tree species richness and uneven-aged forest stands are expected to improve forest resilience, even under future climate conditions.

Further shifts in climate zones in Europe are expected to be noticeable around the middle of this century. Knowledge about these upcoming shifts provides a general overview of how ecosystems and vegetation types may change in the EU. This knowledge helps to determine what is to be grown and where in the future, how much biomass in total could be produced, how much carbon could be sequestered. However, what is expected is that these climate shifts will alter many of the high potential agriculture and forestry areas in the EU-27 existing today. In addition, some regions in the EU will experience poor or very poor conditions for crop cultivation and forest ecosystems.

Future-oriented studies project significant climate change impacts on crop yields in southern Europe, variable impacts on central Europe, and possible yield increases in northern Europe. Maize and wheat might be very difficult to cultivate in southern Europe, even if it will be possible to maintain irrigation. Barley production in the EU will need to shift from central Europe to the Baltic and Scandinavian countries.

Studies projecting future climate change impacts on forests are inconclusive and show large variations per country/region and species. This is because a forest's response to climate change can be complex and multilayered. Typically, biodiverse forests are more resilient to the effects of climate change than monotypic forest stands. Both productivity gains and losses are projected to occur in Europe, with many regional disparities and a tendency toward more losses. Studies consistently mention losses in southern Europe, and some productivity gains in central and northern Europe.

How much biomass is estimated to be needed for the EU's economy in 2030 and 2050, and for which purposes?

The use of biomass for bioenergy and bio-based materials through to 2050 is projected to increase according to several scenario studies and national energy and climate plans of many EU Member States. The scenario studies analysed in this report show a variation of that increase ranging from similar amounts as used at present (6 to 10 EJ) to a doubling or tripling (18 to 20 EJ) by 2050 depending on which scenario study is considered. To meet this demand, some studies point to an increased dependency of the EU on imports: biomass imports could increase by 4% to 60% depending on the assumptions. Other studies assume that the increase in biomass demand will be met through production changes in the EU that prioritise growing advanced, high-energy lignocellulosic crops (assumed to replace food and feed crops currently used for biofuel production). It is projected that there will be a growing gap from now to 2050 between policy-driven biomass demand and biomass availability for bioenergy and biobased materials. However, the size of the projected gap cannot be reliably assessed. There is a high degree of uncertainty around these projections due to modelling assumptions, uncertainties, and lack of comparability.

The increasing biomass demand for bioenergy and biobased materials leads to a range of concerns among various stakeholders. There are questions about the intensity and scale of biomass production and extraction that potentially can conflict sustainability and impact negatively biodiversity, ecosystems and human health.

Many global scenarios project an increase in food demand, including in the EU. The EU is self-sufficient when it comes to food production and an increase in the quantity of exported agriculture products over the last 20 years has been noted. While the EU imports mostly simple unprocessed agricultural goods, exports from the European Union are principally processed food products.

Many studies project that the EU's agricultural production could decline in the future due to the implementation of European Green Deal and Common Agriculture Policy objectives (cereal crops decline between 13% to 42%, and oilseeds decline between 10% to 60% depending on the study). This is connected to the policy targets that aim at reducing both nutrient losses and use of pesticides, as well as at increasing areas in the EU covered with organic farming and high-diversity landscape features.

What are the ecological limits to increasing biomass production and extraction and how can we limit the environmental impacts?

Scientific research shows that a range of human activities, including intensive farming and forestry practices, have strongly impacted the extent and condition of European ecosystems, especially since about 1950. This means that many ecosystem types, including those where biomass is produced, are in poor or even bad ecological condition. There are ecological limits to the use of ecosystems across the entire EU land surface and globally. However, these limits vary depending on the type of ecosystem and land use being considered. The relative intensity of current land use is one of the important parameters to consider when deciding whether to increase or decrease biomass production and extraction.

In many areas of the EU the intensity of current land use and its overall negative impact on ecosystems indicate that continued or even increased biomass production under 'business as usual' conditions is not compatible with several objectives of the EGD. These include the objectives to preserve and restore ecosystems and biodiversity, and farm-to-fork objectives which call for using fewer external inputs, less intensive practices and less harmful chemical substances while focusing on nature-based solutions. In other EU regions the abandonment of traditional agricultural and forestry practices, such as grazing or firewood extraction, increases the risk of large forest fires, endangering people and properties and making some of the EGD's objectives impossible to achieve.

Different ecosystem types require different solutions to reduce the pressures on them or to support nature restoration. In many cases these solutions will lead to a reduction in biomass production, in other cases it means changing management practices so that biodiversity and production can both benefit.

In extensively used, semi-natural agricultural landscapes (approximately 20% of farmland), one can find some synergies between certain levels of biomass extraction and biodiversity (e.g. preventing invading shrubs and thinning forests to protect against forest fires). Yet in intensively used agricultural and forest lands, the pressures on the environment are consistently too high.

In natural ecosystem types (e.g. forests and wetlands), opportunities for nature restoration can be found by reducing harvesting, keeping or expanding no-harvest areas, and leaving larger amounts of deadwood. Re-wetting wetlands allows organic carbon to be preserved in (peatland) soils.

Semi-natural ecosystem types, such as species-rich grassland, heathland and agroforestry systems, can be maintained or restored through practices that mimic traditional uses, allowing for a certain level of biomass extraction (i.e. once or twice a year, via grazing or with appropriate machinery). For example, using biomass from semi-natural areas for energy purposes in Mediterranean landscapes can support the EU's biodiversity objectives, and at the same time reduce fire risk. In Mediterranean regions, the extraction of forest biomass following sustainable forest management practices is also beneficial to maintaining the landscape, promoting rural development in areas with high depopulation levels and preventing large forest fires, thus protecting livelihoods and the condition of ecosystems.

In intensively used landscapes (80% of current farmland and forestry areas) the first priority is to follow restrictions that limit land use intensity for the sake of soil health, water protection, and preserving landscape features for biodiversity. In addition, sourcing woody biomass from hedges and similar landscape elements (e.g. strips of short rotation coppice) that are part of intensively-managed croplands or grasslands would re-establish an economic purpose for such elements, and thus contribute to restoring them.

What are the expected environmental and climate co-benefits and trade-offs in relation to biomass production and consumption?

This report highlights several synergies and trade-offs in relation to land use, land management and biomass uses. In addition, given the variety of stakeholders involved in or benefiting from land management, a benefit for one stakeholder might be perceived as a disservice by another.

Level 1: land use dimension under different policy files

Analysis of various EU legislation under the EGD (in Chapter 3) indicates a tension between the largely policy-driven, projected increase in European demand for biomass, and the projected decline in European biomass production. On the one hand, if unmitigated, this tension may increase the pressure on global resources (when the EU will import more biomass from non-EU countries). On the other hand, while implementing objectives of the EGD may lead to decline in biomass productivity, it is required for reaching long-term (production) capacity and maintaining biodiversity.

According to the EU's 2030 biodiversity strategy, 30% of land should be protected, of which 10% should be strictly protected by 2030. However, it is unclear so far which lands will be included in these protection targets and to what extend the rules of protection (and strict protection) would allow for human interventions related to biomass production and extraction.

Hence, there could be a trade-off between the amount of available biomass for food, material and energy uses that would have been produced on these lands. Nevertheless, these areas will sequester carbon (depending on the type of ecosystem and time dimension) and provide other ecosystem services.

The pathways for reaching renewable energy targets by 2030 may require the further development of other renewables that have some land-use demands for their technical facilities and that could stand on agricultural or semi-natural land. These renewables include organic waste and residues-based biogas facilities, wind turbines and photovoltaic panels. However, some solutions emerge, such as combining photovoltaic panels with farming use underneath. Although infrastructure demands related to these renewables are rather small, the scale of these infrastructures and the technical choices for their development will matter regarding their impacts on semi-natural and agricultural lands.

Level 2: Land management dimension (relevant for farmers, foresters, and the agri-food industry)

At the land-parcel level, co-benefits and trade-offs between biomass availability, biodiversity, and carbon sequestration are linked to choices of agricultural or forestry practices related to production, fertilisation, harvest, and the type of ecosystem and land use being considered. Grasslands, wetlands and forests could satisfy demands for both increasing carbon sequestration and increasing biomass production and later harvest. However, these two demands compete with each other and cannot be maximised at the same time on one parcel of land. In addition, production that expands one type of biomass can lead to land use or management changes that adds pressure on ecosystems and soils. Further, the competition for land coming for example from urban developments may lead to a decline of agricultural land more often than a loss of forestry land around cities.

Intensively managed croplands or grasslands can deliver high yields, but these areas often generate pressures on biodiversity. The amount of carbon sequestered in such areas is relatively low compared to semi-natural grasslands, wetlands and forests. To positively impact biodiversity in intensive croplands, an option could be to introduce structural diversity to the landscape. An example would be the use of short rotation willow coppice as energy crops or grasses, shrubs. These plants could be set in blocs, as linear or point elements of different sizes, or as semi-permanent vegetation in strips that would bring back landscape elements such as hedges or other woody features. The introduction of cover crops could also be relevant due to their role in terms of biomass production, increasing carbon sequestration and groundwater levels.

In contrast, some semi-natural areas, such as orchid-rich meadows or heathlands, are being overgrown with invading shrubs or have lost species diversity due to abandonment or under-grazing. Therefore, measures such as grazing or mowing that would remove shrubs or other biomass would support the conservation and potential restoration of these ecosystems, while also providing some biomass that could be harvested and used.

Due to the high biodiversity and carbon storage value of wetlands, their restoration (particularly of peatlands) is one of the targets of climate and biodiversity policies. Restoration typically requires rewetting, which has potential trade-offs. These include productivity loss or changes in the type of production when rewetting agricultural lands, initial die-back or the rapid exploitation of forest stands when rewetting forest lands, increased methane emissions alongside the reduction in CO_2 emissions.

Forest ecosystems already face many challenges related to climate change, natural disturbances, forest development stages, and an increased demand for wood. Some of the challenges can be mitigated by forest management, for example by making a forest more heterogenous in structure and species composition to increase its resilience to the impacts of climate change.

As forests age, the capacity of trees to absorb CO_2 decreases, resulting in a reduced carbon sink potential compared to middle-aged forests. Furthermore, the higher prevalence of logging in older forests exacerbates this issue. Although young trees are typically planted to replace the harvested ones, it takes a considerable amount of time for these to reach their optimal growth phase, during which they can effectively absorb a substantial portion of CO_2 and contribute to biomass formation. Part of the harvest that is used for materials and long-lived wood products may store carbon outside forests temporarily and add to more carbon removals (e.g. harvested wood products) to the LULUCF sector.

One of the measures that could increase the carbon sink and biomass availability over time is afforestation, which converts land from other uses to forest areas. Afforestation leads to an increase in removals over many years due to tree growth. Based on the LULUCF data reported by Member States, afforestation in the EU from 1990 to 2021 averaged 395,000 hectares per year. There were large interannual fluctuations. For the full period, 63% of the afforestation happened on grassland and 29% on cropland. This report has not assessed the extent to which afforestation has led to a specific trade-off (for instance, a decrease in the agricultural production of biomass, drying wetlands or mono-culture planting).

Level 3: product use dimension

Biomass is a renewable resource but its supply depends on natural growth rates, which vary between agricultural crops, trees, and grasslands. In the case of forests, biomass regrowth often requires several years depending on the species and geographical location and is not guaranteed, especially under a changing climate. The possibility of using biomass for various purposes makes it a very valuable product. This is the basis of the competition between different economic sectors for the resource. In sectors where emissions are hard to abate by other technologies or products, biomass could be prioritised.

Chapter 5 emphasised that many wood-based products/materials are associated with a lower carbon footprint than products currently on the market. Substituting these products would lead to lower emissions. However, quantifying the substitution effect and the change in carbon storage for these wood products is technically complex and challenging. Overall, the substitution factor will depend on the product that is being substituted, the GHG emissions associated with these products and their expected lifetimes, as well as the source of the biomass.

Today, a significant share of woody biomass is used for energy, which limits its use for other purposes (e.g. chemicals, textiles and construction). Developing a more cascading and circular use of wood could improve the climate benefit of harvested wood and increase the wood supply, even though this strategy could reduce the amount of wood available for energy in the short term. A piece of furniture may be used or otherwise recycled into panels instead of being chipped for energy. The energy sector will likely continue to need to burn biomass for biochar production (carbon rich material made from biomass through thermochemical conversion process like pyrolysis) and bioenergy with carbon capture and storage. However, biomass retired from other uses can also be used here.

How do we make sure that the transition to a climate-neutral and circular economy remains sustainable over time?

The challenge in answering this question is that not all pieces of the biomass puzzle are well-known, and policies are not always coherent in their key objectives on the role of biomass. However, there is a need to decide how to prioritise biomass and for which purposes. Policy incentives need to strike a balance between using biomass to reach the 2030 European Green Deal's targets while keeping ecosystems in good condition and maintaining their capacity to deliver biomass and carbon sequestration in the long term. What biomass feedstocks/products are to be prioritised and for which purposes needs to be evaluated against the economic and societal costs, and in relation to the following biomass functions highlighted in this report:

- **remove** CO_2 from the atmosphere by increasing carbon sequestration in Europe's ecosystems and ensuring long-term carbon storage both in living biomass and biomass products;

- **reduce** the climate change and environmental impacts of biomass production and consumption within and outside the EU and make biomass production systems more resilient to those impacts;

- **replace** fossil and mineral-based materials with bio-based materials and products to reduce GHG intensity/emissions;
- **restore** nature and biodiversity to maintain the diversity of European landscapes;
- **reuse** and **recycle** to make the best use of bio-based materials and products in relation to their economic and environmental value.

There are limits on the amount of biomass that can be produced in a sustainable manner. This means that a balance between different functions of biomass and ways of biomass production and consumption needs to be found in order to safeguard long-term biomass supply.

There is an element of urgency in finding this balance in the EU because the conditions of ecosystems are in general not good and declining. The forest carbon sink on which the EU relies so much to meet 2030 and 2050 climate targets has been on a declining trend in recent years. In addition, the primary production sectors are already experiencing climate-change impacts that threaten carbon sinks and biomass production even further. Policy interventions on land use and land management, especially for forests and agriculture, will deliver results over the next decades. When planning for 2030, 2050 and beyond, decisions are already needed today.

The knowledge presented in this report provides important considerations for developing a long-term EU and Member State policy strategy for biomass. This report highlights that there is a puzzle to be solved and that there are still some considerable gaps in knowledge. We have shown that various stakeholders are involved that need to decide jointly on policy development, land management, and consumer choices. Stakeholders will have to deal with various trade-offs between reaching policy objectives and how to use the available biomass now while safeguarding its future supply. If the facts included in this report are not taken into consideration and the identified knowledge gaps are not addressed, then there is a risk that the biomass puzzle will be addressed in an ad hoc manner and not based on fact and analysis.

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1 Introduction

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Annex 1 Glossary

All chapters

C4 and C3 plants: plant types differentiated in terms of their photosynthesis metabolism. Plants following a C3 carbon fixation metabolic pathway are most common and widespread (including wheat, barley, oats and rye), whereas plants following a C4 carbon fixation metabolic pathway generally have a higher photosynthetic efficiency and are better adopted to hot and arid conditions (including maize and sorghum).

Carbon pool: a component of the climate system that has the capacity to sequester, accumulate or release carbon. Soils and forests are examples of carbon pools.

Carbon sequestration: the process of increasing the carbon content of a carbon pool other than the atmosphere.

Carbon sequestration rate: the rate at which the carbon content of a carbon pool is increased, also known as carbon flux.

Carbon stock: the mass of carbon stored in a carbon pool at any specified time

Cascading use: the efficient utilisation of resources by using industrial residues and recycled materials for other industrial processes, to extend total biomass availability within a given system. From a technical perspective, the cascading use of wood takes place when wood is processed into a product and this product is used at least once more, for either material or energy purposes.

Fallow land: all arable land included in the crop rotation system, whether worked or not, for which there is no intention to produce a harvest for the duration of a crop year. The essential characteristic of fallow land is that it is left to recover, normally for the whole of a crop year. Fallow land may be bare land bearing no crops at all; land with spontaneous natural growth, which may be used as feed or ploughed in; or land sown exclusively for the production of green manure (green fallow).

Global warming levels: levels to which global average temperatures rise, for example to well below 1.5°C or 2°C above pre-industrial levels.

Gross primary productivity (GPP): the gross uptake of CO_2 from the atmosphere to fuel photosynthesis. GPP is used as an indicator of biomass productivity.

Growing stock: the total volume of the standing stems of all living trees above a minimum size (10cm in diameter at 1.3m above ground level).

Increment: the net increase in volume or biomass of a forest or a tree over a specific period of time.

Industrial roundwood: roundwood (wood in the rough) except wood fuel that is intended for use in the manufacture of wood-based products. It includes sawlogs and veneer logs; pulpwood, round and split; and other industrial roundwood.

Integrated nutrient management: an approach to manage nutrients in agriculture to optimise nutrient use efficiency, minimise nutrient losses and enhance soil health, as outlined in the European Green Deal.

Mineral soils: soils that are not organic and typically have relatively low amounts of organic matter. They occur under moderately well- to well-drained conditions and predominate in most ecosystems except wetlands.

Natural disturbances: ecosystem disturbances caused by nature, such as wildfires, storms, floods, droughts, diseases and insect outbreaks.

Organic soils: soils with a high carbon content (minimum of 12-20% organic matter by mass) that develop under the poorly drained conditions of wetlands.

Particulate matter (PM): the mixture of solid and liquid particles suspended in the air, which vary in size, composition and origin, and have the potential to be harmful to human health.

Photosynthesis: the process by which plants convert light energy into chemical energy that can later be used to fuel the plant's activities. Some of this energy is stored in carbohydrate molecules such as sugars and starches, which are synthesised from CO_2 and water. Photosynthesis produces and maintains the oxygen in the Earth's atmosphere.

Primary woody biomass: see roundwood.

Rejuvenation: the process of forest recovery after harvest, which can occur naturally through succession or by replanting with young trees.

Renovation wave: a term referring to an EU initiative that aims to accelerate the energy-efficient renovation of buildings across the Member States as part of the European Green Deal.

Representative concentration pathways (RCPs): trajectories adopted by the Intergovernmental Panel on Climate Change describing different future CO_2 equivalent concentrations in the atmosphere (and thus different future changes in radiative forcing). They depend on the volume of greenhouse gases emitted in the years to come. For example, RCP 4.5 is considered an intermediate scenario, with emissions peaking around 2040 and then declining. RCP 8.5 is a scenario in which emissions continue to increase throughout the 21st century.

Roundwood: all wood removed with or without bark from the forest (e.g. as a result of harvesting or felling), including wood removed in its round form; split or roughly squared form; or in other forms (e.g. branches, roots, stumps and burls (where these are harvested)). All roundwood is also referred to as primary wood or primary woody biomass.

Salvage logging: the practice of removing trees from forest areas that have been damaged by natural disturbance (wildfires, storms, pests) to recover economic value from the timber.

Secondary woody biomass: biomass resulting from processing in at least one industry. This includes solid by-products, such as chips and particles, and other by-products, such as black liquor, bark and post-consumer wood.

Stand thinning: a cultural treatment to reduce the stand density of trees, primarily to improve growth, enhance forest health or recover potential mortality.

Soil carbon: the solid carbon stored in global soils. This includes both soil organic matter and inorganic carbon as carbonate minerals.

Volatile organic compounds (VOCs): a group of organic chemicals that easily evaporate and take gaseous form, and that have the potential to be harmful to human health.

Wetlands: land that is covered or saturated by water for all or part of the year (e.g. peatland) and that does not fall into the forest land, cropland, grassland or settlements categories. The wetland category can be sub-divided into managed and unmanaged wetlands according to national definitions. It includes reservoirs as a managed sub-division and natural rivers and lakes as unmanaged sub-divisions.

Wood fuel: roundwood that is going to be used as fuel for purposes such as cooking, heating or power production. It includes wood harvested from main stems, branches and other parts of trees (that are normally of lower quality than roundwood used for industrial purposes), and wood that will be used directly as fuel, e.g. charcoal (in pit kilns and portable ovens), wood pellets and wood chips that are made directly (i.e. in the forest) from roundwood.

Annex 2 Abbreviations and units

CAP	Common agricultural policy
CO_2e	Carbon dioxide equivalent
EC	European Commission
EEA	European Environment Agency
EJ	Exajoule
EU	European Union
EU ETS	EU Emissions Trading System
EU-27	27 EU Member States
GHG	Greenhouse gas
GM	Genetically modified
H&C	Heating and cooling
HWP	Harvested wood product
IA	Impact assessment
IAM	Integrated assessment model
ILUC	Indirect land use change
JRC	Joint Research Centre of the European Commission
LULUCF	Land use, land use change and forestry
Mt	Megatonne (million tonnes)
$MtCO_2e$	Million tonnes of CO_2 equivalent
Mtoe	Million tonnes of oil equivalent
RCP	Representative concentration pathway
RED	Renewable Energy Directive
UAA	Utilised agricultural area

Table A3.4 **An overview of the scopes of recent literature sources that project bioenergy and bio-based material demand and supply up to 2050**

	Study	Model(s) used	Model type	Sectors covered	Geographical coverage	Scenario details	Scope	Limitations
Demand	**EC (2020a)**	PRIMES and PRIMES-TREMOVE GLOBIOM-G4M model for projections of LULUCF emissions and removals; CAPRI model for agricultural activity projections	All models are bottom-up partial equilibrium models (price-induced market equilibrium systems)	All sectors	PRIMES includes all EU Member States as of 2020, including EU candidate countries and, where relevant, Norway, Switzerland and Bosnia and Herzegovina; GLOBIOM covers 50 world regions/ countries, including the EU-27; CAPRI is global	6, including baseline and varying policy options. 1 2015, 6 2030, 5 2050, including baseline	Bioenergy demand-driven, with two general objectives: • to increase the EU's GHG emission reduction target to 55% by 2030 compared with 1990 • to lay the groundwork for adapting policies that play a key role in decarbonising the European economy. • Specific relevant pieces of climate and energy legislation considered: • the Emissions Trading System (ETS) Directive • the Effort Sharing Regulation (ESR) • the Renewable Energy Directive (RED) • the energy-efficiency policy framework, notably the Energy Efficiency Directive • CO_2 emissions performance standards for cars and vans • the Land Use, Land Use Change and Forestry Regulation (LULUCF) Regulation	Assumptions predate the COVID-19 crisis, which heavily impacted the EU economy and therefore the economic projections made. A sensitivity-run COVID baseline was also made but was written when the situation was still evolving, and the outcome was still uncertain Fuel price assumptions do not consider the Ukraine conflict (applies to all)
	Giuntoli et al. (2022)	Qualitative assessment, analysing the possible pathways to increase the supply and their possible impacts on biodiversity and GHG emissions	Product perspective borrowed from life cycle assessment, presented in a nexus matrix	Forestry	EU-27+UK	24 pathways to ascertain biodiversity and ecosystem's condition assessment, and carbon emissions mitigation	Bioenergy demand-driven Three specific interventions covered: • removal of different types of logging residues • afforestation of different types of non-forest land with different types of forests • conversion of primary and semi-natural forests into plantation forests	Qualitative, covers only forestry sector

Table A3.4 **An overview of the scopes of recent literature sources that project bioenergy and bio-based material demand and supply up to 2050 (cont.)**

	Study	Model(s) used	Model type	Sectors covered	Geographical coverage	Scenario details	Scope	Limitations
Demand	**Mandley et al. (2022)**	IMAGE 3.2, within which the recursive dynamic global energy system model, TIMER, calibrates International Energy Agency (IEA) energy data	Integrated assessment model	All sectors	IMAGE regions western Europe and central and eastern Europe	4 scenarios: baseline, Global <2°C, no BECCS (no carbon capture and storage), no bio (no bioenergy investments after 2°C)	Demand-driven model Relevant for comparison of relative emission mitigation targets at EU level Focus on modern applications of biomass only exclude traditional uses (e.g. fuelwood for heating and cooking) • Bioenergy developments included: • total bioenergy demand • sectoral level demand • feedstock demand • regional mitigation potential • interregional trade	IMAGE regions do not match the EU-27 exactly Agricultural and woody residues grouped. Imports assumed
	Tsiropoulos et al. (2022)	PRIMES Global Biosphere Management Model (GLOBIUM) for land-use; GHG-Air Pollution Interactions and Synergies (GAINS) for waste and non-CO_2; Common Agricultural Policy Regionalised Impact Modelling System (CAPRI) for agricultural projections	All models are bottom-up partial equilibrium models (price-induced market equilibrium systems)	All sectors	EU-27	4 scenarios	Demand-driven, addresses supply Covers different emission reduction targets (at least 80% emission reduction by 2050 compared with 1990, and net-zero emissions by 2050) and different mitigation options, including electrification, behavioural changes and synfuels	Sectoral/ feedstock split less apparent

Table A3.4 **An overview of the scopes of recent literature sources that project bioenergy and bio-based material demand and supply up to 2050 (cont.)**

	Study	Model(s) used	Model type	Sectors covered	Geographical coverage	Scenario details	Scope	Limitations
Demand	**Material Economics (2021)**	Material Economics estimate taking into account technical, economic and sustainability constraints as outlined in current studies	Multiple, literature review	All sectors	EU-27+UK	5 shown: current; IEA; International Renewable Energy Agency (IRENA); European Commission's long-term strategy (EU LTS — based on the analysis of 8 scenarios produced by the Commission); and individual sector claims (shipping, chemicals, aviation, industrial heating, building heating, road transport and power)	Bioenergy supply and demand Assesses material and energy demand, and agriculture, forestry and recycled waste supply Also interprets biomass demand projections from the IEA, IRENA, EU LTS, and individual sector claims	Modelling parameters and specific models used somewhat unclear Unlike many studies, includes material use rather than just energy use, complicating comparisons with other studies COVID-19, Ukraine crises not considered
Supply	**Ruiz et al. (2019)**	ENSPRESO is the database developed CAPRI model used LUISA model used to input into CAPRI and estimate evolution of built-up areas for yield inputsields and yield levels in CAPRI derived from OECD's AgLINK modelling system EFISCEN model used for forestry	CAPRI, LUISA, AgLINK — partial equilibrium models; EFISCEN — Markov chain stochastic model	Wind, solar and biomass energy potentials. 17 different biomass categories. All agriculture, forestry and other land use sectors covered	EU-28, 276 regions EU-27 data derived	3 (high, medium, low)	Bioenergy supply. 4 target areas: • suitable areas • raw resource potentials • specific energy production • general energy production accounting for a wide range of technologies	Considerable uncertainty, even in the 'today' scenario, particularly in fuelwood residues COVID-19, Ukraine crises not considered

Table A3.4 **An overview of the scopes of recent literature sources that project bioenergy and bio-based material demand and supply up to 2050 (cont.)**

	Study	Model(s) used	Model type	Sectors covered	Geographical coverage	Scenario details	Scope	Limitations
Supply	**CE Delft (2019)**	Based on a comprehensive literature review	Literature review	Biomass availability for material and energy applications Non-utilised biomass not covered	EU-28 Global sustainable biomass availability also presented	2 (min, max)	Bioenergy supply Both technical sustainable potential and sustainable potential included	Data metric energy units and EU-28, complicating comparison with ENSPRESO Uncertain whether the 'sustainable potential' indeed relates to what the EU considers to be sustainable COVID-19, Ukraine crises not considered
	Material Economics (2021)	Value curve, own methodology based on multiple sources	Value curve, own methodology based on multiple sources	All sectors using biomass for materials and energy production	EU-27+UK	Current supply is provided, as is potentially available supply (Material Economics) estimate range, and a range of values based on several existing studies	Woody biomass: • wood removals • residue removals • industrial by-products • Agricultural biomass: • agricultural crops (energy crops) • agricultural residues • Recycling and waste: • paper waste • wood waste • other waste	Modelling parameters and specific models used somewhat unclear Unlike many studies, includes material use rather than just energy use, complicating comparisons with other studies COVID-19, Ukraine crises not considered

Table A3.5 **An overview of the main bioenergy feedstock demand and supply in 2050, as projected by recent literature sources**

	Source	Bioenergy feedstock			
		Crops	Agricultural residues	Forestry	Waste
Demand	EC (2020a) ([a])	~267% increase	~100% increase	~67% increase	~50% increase
Demand	Giuntoli et al. (2022) ([b])	Not available	Not available	Not available	Not available
Demand	Mandley et al. (2022) ([c])	~50-90% increase, excluding residues	~50-90% increase, excluding residues	0EJ, excluding residues — 1-2EJ/year, excluding residues	Not available
Demand	Tsiropoulos et al. (2022) ([d])	Increase	Increase	Increase	Increase
Demand	Material Economics (2021) ([e])	Not available	Not available	Not available	Not available
Supply	Ruiz et al. (2019)	~20% increase, including residues		~10% increase, including residues	~25% increase, including residues
Supply	CE Delft (2019)	~139% increase, including residues		~10% increase, including residues	Not available
Supply	Material Economics (2021) ([f])	~25% increase to ~125% increase	~43% increase to ~114% increase	~1.4% decrease to ~2.7% increase (including wood removals, residue removals, industrial by-products)	~43% increase to ~64% increase (including paper, wood and other waste)

Notes: ([a])Together with associated studies (EC, 2021), suggests increases of bioenergy demand from ~140Mtoe to ~250Mtoe.

([b]) Qualitative assessment, no numbers projected.

([c]) In 2050, bioenergy projected to account for up to 27% of total energy demand, increasing from the current 5EJ to 18EJ/year. Model projects imports to increase from 4% of biomass supply to 60% to match this demand.

([d]) 58-82% demand increase projected by 2050, 95-125% supply increase mainly met by cellulosic crops.

([e]) Quotes increases from several sources. Own demand projections are split by end use, quoting a rise from 10.3EJ current demand (6.2EJ energy, 4.1EJ materials) to 18-19EJ (of which 12-13EJ is energy (a 94-110% increase) and 6EJ is materials (a 46% increase)).

([f]) Includes material use. Of 10.3EJ used currently, 4.1EJ is materials (2.8EJ wood products and 1.3EJ pulp production), 6.2EJ is energy. In 2050, approximately 6EJ is expected to be allocated to materials (up from 4EJ today), while 5-7EJ is expected to be allocated to industry and energy. Energy Transitions Commission (2021) suggests a 2050 allocation of 30% to forestry, 20% to crops, 20% to residues and 30% to waste.

Table A3.6 **An overview of the main food and feed supply changes in 2030, as projected by recent literature**

Source	Cereal crops	Oilseeds	Protein crops	Starch crops	Sugar crops
Guyomard et al. (2020)	Decrease	Not available	Decrease	Not available	Not available
Barreiro Hurle et al. (2021)	-13% to -15% depending on CAP changes	-12% to -15% depending on CAP changes	Not available	Not available	Not available
EC (2022)	Decrease	Decrease	Not available	Not available	Not available
Beckman et al. (2020)	-20% to -40% depending on type of cereal	-60.70%	-13.2% (rice)	Not available	-20.50%
Coceral (2021)	-8% to -35% depending on type of cereal	-10% to -36%	Not available	Not available	Not available
Bremmer et al. (2021)	~-14% to ~-19% depending on type of cereal	~-18%	Not available	Not available	Sugar beet = ~-1%
Noleppa and Cartsburg (2021)	-22% to -26% depending on type of cereal	-22% (sunflower)	-20%	-23%	-21%
Henning and Witzke (2021)	-21.4%	-20%	Not available	Not available	Not available

Table A3.7 **Overview of the scope of agricultural biomass studies referenced above**

Study	Model used	Model type	Sectors covered	Sectors not covered	Geographical coverage	Scenario details	Scope	Limitations
Guyomard et al. (2020)	Economic assessment and qualitative policy analysis	Simulation based on FADN 2018 data under a number of assumptions	All sectors	NA	EU and non-EU	2	3 targets	Focus on European Green Deal and CAP reform. Reliance on crude assumptions for changes in the EU-28 farm sector, corresponding with the alignment of the CAP to the author's recommendations for consistency with the farm-to-fork (F2F) strategy objectives. Aim is to understand the main economic points that should be addressed through a future impact assessment, and thus it is not intended as forecast.
Barreiro Hurle et al. (2021)	CAPRI	Partial equilibrium model (agriculture separated)	All agriculture sectors	Tomatoes	EU and non-EU	3 (including baseline)	4 targets combined	Omits key F2F strategy actions and supportive policies. Report acknowledges the limitations of CAPRI to fully capture the potential impacts of the F2F and biodiversity strategies, as the model is not perfectly capable of representing the new environmental and climate targets — results presented as indicative and exploratory. No change considered in food diet and waste.
EC (2020b)	Qualitative analysis only	Not available	All agriculture sectors	Not available	EU and non-EU	2 (including baseline)	2 targets combined	The complexity of the interconnections and non-linear relationships between the various drivers of change (by increasing global demand for food and fuel, technological and dietary shifts, productivity constraints, climate change and the new policy landscape) limits the availability of reliable predictions of change to 2030 in the baseline. These limitations are not bridged in the literature, and significant outstanding research and innovation gaps exist in relation to (1) fully integrated and viable (technically and economically) solutions that reduce the need for pesticide inputs and (2) robust and integrated characterisation of impacts on the environment and across the wider range of stakeholders of the mix of policies that will shape the baseline. The synergistic nature of policies makes it difficult to estimate the additionality of Sustainable Use Directive EC/128/2009 relation to its contribution to reaching the pesticide-related targets announced in the F2F strategy, and its associated environmental, economic and human health impacts.

Table A3.7 Overview of the scope of agricultural biomass studies referenced above (cont.)

Study	Model used	Model type	Sectors covered	Sectors not covered	Geographical coverage	Scenario details	Scope	Limitations
Beckman et al. (2020)	GTAP-AEZ and IFSA	General equilibrium model	All sectors	Not available	EU and non-EU	3	4 targets combined	Omits key F2F actions and supportive policies. Assumption of a 10% decrease in productive agricultural area (i/o 10% non-productive agricultural area); 25% of UAA in organic farming not considered; no change considered in food diet and waste; no change considered in agricultural methods.
Coceral (2021)	Qualitative analysis only	Not available	Arable crops (cereals and oilseeds), and impacts on meat/ dairy and biofuels	Root crops, fruit and vegetables, speciality crops	EU	5 (including baseline)	4 targets combined	Omits key F2F strategy actions and supportive policies. Does not consider legislative proposals not finalised and implemented, such as the CAP reform; addresses the F2F strategy's impact on only cereal and oilseed production, not agriculture as a whole; demand-side measures not considered.
Bremmer et al. (2021)	AGMEMOD and 25 case studies at farm level	Partial equilibrium model (agriculture separated)	Permanent and arable crops	Animal products	EU, based on 7 EU Member State case studies	4 (including baseline)	3 targets combined	Omits key F2F strategy actions and supportive policies, new technology uptake, dietary changes, positive effects of biodiversity gains on production, cost of inaction, policy changes in trading partners and financial resources to support the transition.
Noleppa and Cartsburg (2021)	Own multi-market model	Partial equilibrium model (agriculture separated)	Arable crops	Fruit and vegetables, wine	EU		4 targets combined	Omits key F2F strategy actions and supportive policies.
Henning and Witzke (2021)	CAPRI	Partial equilibrium model (agriculture separated)	Animal products and arable crops	Fruit and vegetables, wine	EU and non-EU	4	4 targets combined	Omits key F2F strategy actions and supportive policies. No change considered in food diet and waste.

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European Environment Agency

Title of the report — subtitle of the report
2023 — 170 pp. — 21 x 29.7 cm

ISBN 978-92-9480-604-8
DOI 10.2800/834565

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of the European Union

TH-09-23-458-EN-N
DOI 10.2800/834565