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EU Biomass supply, uses, governance and regenerative actions

10-year anniversary edition

2025

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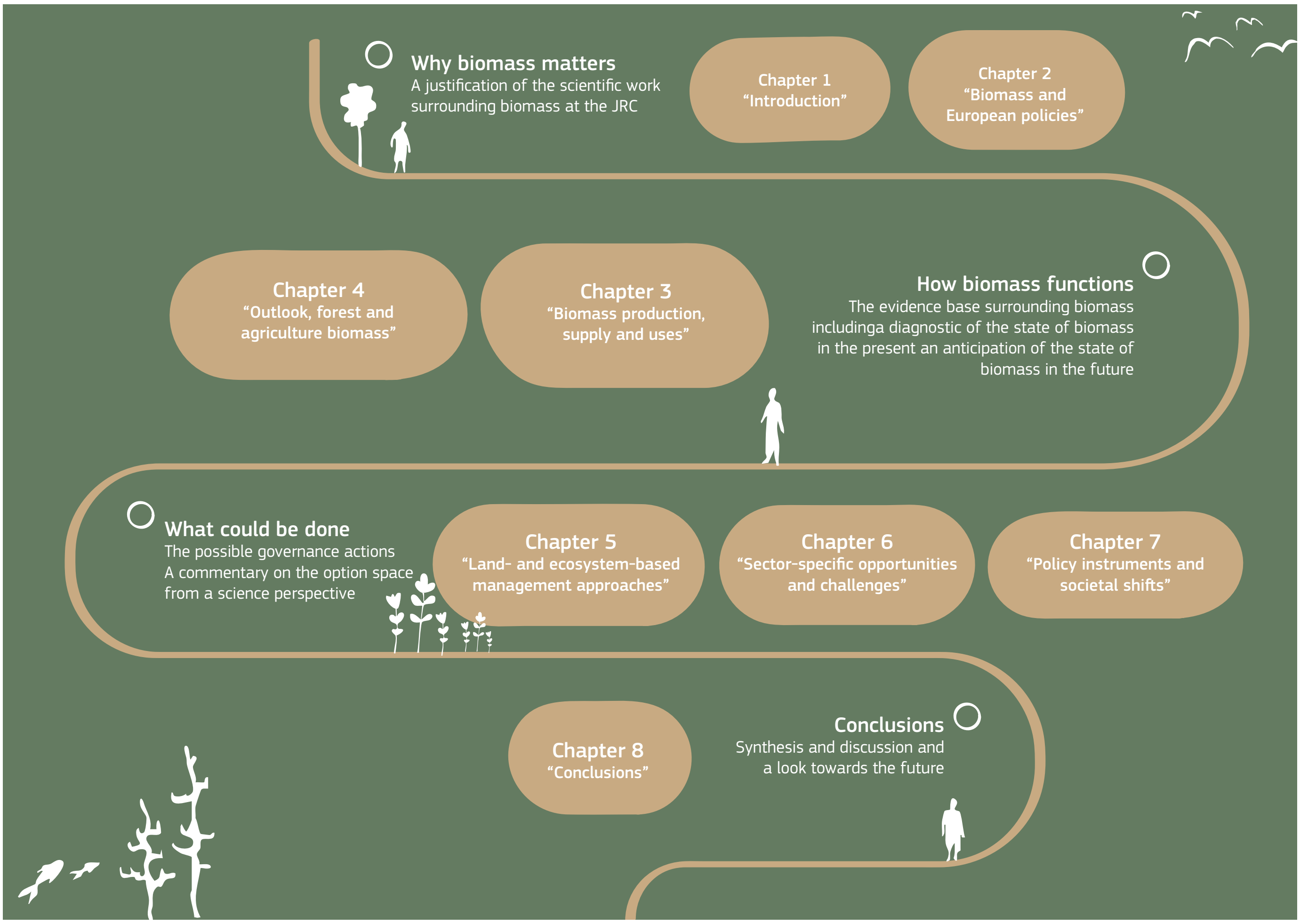
Contents

Abstract

This report is the fourth comprehensive public report by the European Commission's Joint Research Centre (JRC) entirely dedicated to the topic of biomass in its many shapes and forms. This is the ten-year anniversary edition of the JRC Biomass Mandate. In the sections that follow, we discuss the competing requirements for biomass, and why this makes it so important to address biomass governance. In the central chapters of the report, we quantify biomass supply from forests, agriculture, and marine ecosystems, as well as waste streams for a wide range of uses in the European Union. The second half of the report is dedicated to a presentation and discussion of various possible actions to address biomass governance. We conclude by highlighting the need for system's level assessments to facilitate policy coherence. This report reflects the direct work of JRC scientific staff and their collaborators, bringing together expertise from several units of the organisation, all united by a common attention to biomass.



Foreword

Biomass is our food and feed. It can be transformed into materials and energy, but extracting it for the products needs has social, economic and environmental consequences. Understanding the supply, demand, and the natural resource management surrounding biomass production is essential to develop sound, science-based policies.

Ten years ago, the European Commission's Joint Research Centre (JRC) was given a mandate, led by the Directorate-General (DG) for Research and Innovation, to provide **independent and evidence-based input to European policy** through long-term data, analysis, and modelling of biomass supply and demand. Ever since, the **solid data provided by the JRC Biomass Mandate** has been used throughout the policy cycle, with citations in several proposals, parliamentary discussions, progress and evaluation reports, and delegated acts, contributing to major policies such as the Fit for 55 package.

This report takes stock of where we are now. It highlights the complexities and challenges of biomass governance, including natural resource management and the quantification of biomass, and suggests possible policy actions.

Scientific evidence alone will not solve the many challenges faced in managing natural resources, but **robust and inclusive science** will help us explore natural resource stewardship in both traditional and innovative ways. By opening up solutions, we help develop cross-cutting policies for the benefit of all Europeans and the environment.

As we celebrate 10 years of the Biomass Mandate, this work offers **different perspectives** on the long-standing question of how we would like to co-exist with our natural surroundings. We invite you to use the findings of this report and we welcome the **sustainable, innovative and responsible solutions** it provides for future policy actions and decisions.

Bernard Magenhann
Director-General of the
Joint Research Centre

Marc Lemaître
Director-General of the DG
for Research and Innovation

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This report is the result of inputs from many different scientific teams, operating under different policy portfolios and with different scientific backgrounds and perspectives. While we try to cover many facets of this work, we acknowledge that there will be emphasis in some areas while others may be left under-reported.

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Executive summary

The Joint Research Centre (JRC) Biomass Mandate, celebrating its ten-year anniversary in 2025, was established to provide evidence-based analysis on biomass supply and demand to support EU policy development. The Mandate aims to address the competing demands for biomass across agriculture, forestry, marine, freshwater and waste sectors through our research and outputs, which includes a harmonised database about biomass supply and use. In this edition, in addition to the quantitative analysis this reporting scheme is known for, we focus our efforts towards examining the policies that are exerting expectations on biomass, as well as making room to discuss regenerative actions to address the various economic, social and environmental problems we face today.

In this report, we describe how the European Commission's policies surrounding biomass and bioeconomy converge around a single overall goal of addressing the multiple crises we are facing today: climate change, biodiversity loss, social inequality, excessive consumption and waste, etc. Hence the story told about these issues is coherent throughout our policies, but the proposed actions in each of these policies may not necessarily be in line or are sometimes under-developed. This stimulated us to consider the possible strategic actions more in depth, addressing the option space of policy and governance responses with an aim toward bettering the alignment of biomass uses with societal wants. This is the inspiration for the chapters where we explore different actions mentioned in the policies (and beyond) in more depth, highlighting their pros and cons to stimulate discussions on these actions.

The JRC Biomass Mandate has contributed to the mechanisms and causal relationships underlying biomass, especially biomass flows, demonstrating how supply chains, environmental constraints, and governance structures interact. The report contains this evidence, where we quantify the biomass availability and trends. In this edition of the report, we acknowledge that assessments of ecosystem condition are relevant to report alongside quantifying biomass. Biomass is primarily sourced from ecosystems and the reporting of ecosystem condition, and the contextualisation of provisioning services alongside regulating and cultural services, helps puts into the perspective that biomass is limited and the provision of it relies on the ability of the ecosystem to continue to produce it. Furthermore, the EU is dependent on imports, and importation implies production elsewhere. Any assessment of EU biomass supply and use must include the dependencies on third countries and the social, economic and environmental implications of trade on those countries must be considered. In this way, this reporting scheme has evolved to an improved cross-sectoral coordination and better integration of ecological and spillover considerations into policy decisions.

Policy context

In all her mission letters to the Commissioners, the President of the European Commission, Ursula von der Leyen, recommends that "Proposals must be evidence-based and the Joint Research Centre, our internal scientific service, can support you in that work." This report is therefore primarily intended to inform the policy officers who will be designing and implementing the priorities of the European Commission through legislative acts.

- **Fisheries:** This report contributes to the evidence base for the vision for the fisheries sector with a 2040 perspective, as well as to a new European Oceans Pact, ensuring coherence across all policy areas linked to the oceans and furthermore, to strengthen the EU's approach to maritime spatial planning. In this report, we cover the economic, social and environmental aspects of fisheries, aquaculture and macroalgae (3.3 *Fisheries and aquaculture biomass*; 3.4 *European and Global macroalgae production and uses*), with a specific chapter on a spatial assessment of macroalgae farming (5.7 *Seaweed farming*).

- **Environment:** This report contributes to the Circular Economy Act and the updated EU Bioeconomy Strategy, scheduled for adoption in 2025. The report will also contribute to the evidence base for the design of nature positive actions and to strengthen water security in Europe; honour international biodiversity commitments; and further develop the European Bauhaus. In this report, besides covering biomass supply and uses, which is central to bioeconomy, we discuss the competition for biomass resources (2.1 *The expectations of biomass in EU policies*). Furthermore, we explore different logics or narratives related to bioeconomy, as they are presented in the 2018 EU Bioeconomy Strategy and its Progress Report (2.3 *Bioeconomy narratives*). Also central to bioeconomy is policy coherence. This is supported by data coherence, to which the JRC Biomass Mandate contributes. Unfortunately, we are unable to produce our signature cross-sectoral biomass flows in this edition due to a break in the time series of data for woody biomass flows (see section 3.2.3.1 *Woody biomass for energy*). We provide data on agricultural biomass availability (3.1.2 *Agricultural production and supply*) and uses for both food and non-food purposes (3.1.3 *Food and feed uses of agricultural biomass* and 3.1.4 *Biofuel uses of agricultural biomass*); as well as forest biomass availability and uses (3.2.2 *Forestry production and supply and 3.2.3 Woody biomass uses*). These insights are relevant to the further development of EU thinking on bioeconomy, as is the scenario analysis of the forest sink and the development of the agricultural sector, covered in Chapter 4. Related to financing, we present a section describing the integration of environmental accounting in economic terms (7.3 *Mainstreaming ecological content into the economic context through an integrated environmental and economic accounting system*) and discuss implications of the "polluter pays" principle (7.2 *The 'polluter pays' principle and the use of taxation and subsidisation as policy instruments*). A special section is dedicated to wood and Bauhaus (6.3 *Biomass and the European Bauhaus*). Throughout Chapter 3, the report reminds the reader of the importance of good ecosystem condition to be able to support bioeconomy, with ecosystem specific discussions on indicators and thresholds for Forests (3.2.1 *Forest ecosystem condition*), agroecosystems (3.1.1 *Agroecosystem condition*), and marine ecosystems (3.3.1 *Safe fishing thresholds*).

- **Agriculture and food:** This report contributes to the evidence base for a Vision for Agriculture and Food, considering the long-term competitiveness and sustainability of the EU farming and food sector within the boundaries of our planet. The Common Agricultural Policy should provide targeted support to farmers who need it most, for example small-scale farmers. Furthermore, the CAP will aim for positive environmental and social outcomes through rewards and incentives for ecosystem services and thriving rural areas. Directly related to this, we cover the quantification of agricultural biomass, including from residues, using a method that can be extended to candidate countries (3.1.2 *Agriculture production and supply)*. We also cover the outlook of the agriculture sector with 4.1 *Agricultural medium-term outlook,* and a deep discussion on agroecology (5.2 *Agroecology: Strengthening farmers' position within food systems*) to address the situation of small scale farmers. Furthermore of interest to this topic is the chapter on pastureland management (5.3 *Pastureland management strategies*) and carbon farming (5.5 *Nature-based climate solutions and carbon farming*). The report also discusses the environmental and social implications of novel foods in section 6.4, and our experts discuss food waste quantities (3.5.1.1 *Food waste generation*) and behavioural aspects of food waste (7.4 *Societal shifts: Food waste reduction*).

- **Trade:** This report contributes to the evidence base for the enforcement of EU trade agreements on climate, environmental and labour standards. This report provides quantities of trade flow and environmental impact in section 3.6 *Biomass trade- volume, land footprint, deforestation and biomass loss of commodities potentially linked to deforestation*, and goes into a historical conversation and deeper discussion on trade in 7.1 *Responsible trade ofcommodities potentially linked to deforestation*.

- **Climate:** This report may contribute to the evidence base to implement the EGD targets and goals, the section on carbon farming (5.5) applies here, but the discussion on the forest sink in 4.2 *EU forest sink: scenario analysis*, is also very relevant.

- **Energy:** We include chapters on agricultural biomass availability (3.1.2), and uses for energy purposes (3.1.4); as well as forest biomass availability and both energy and material uses (3.2.2 and 3.2.3). The chapter on waste biomass for energy (3.5.2) provides data and discussion on this source as well.

In all mission letters to the Commissioners President von der Leyen mentions several common points throughout her introductory words around the guiding objective that the EU "must deliver and lead from the front", by ensuring security, prosperity and democracy. Here we refer to two points in particular that will catalyse a common narrative within the Commission: First, she wishes the College to work more closely together and take full ownership of what is agreed at that level, which implies a stronger cross-fertilisation of knowledge and a more system's level overview of each of the Commissioners. Second, she encourages local and regional presence, namely a reinforced dialogue with citizens and stakeholders, with special emphasis on youth, announcing the intent towards a "lasting culture of participatory democracy". This report aims to enhance policy coherence through a common knowledge base, and to tackle these cross-cutting issues such as natural resource management through a system's perspective. A common knowledge base requires coherence and continuity in data availability. Without this, we cannot address common questions related to biomass governance, and potential. We highlight a worsening on the situation with respect to data availability of woody biomass uses.

- While scientific evidence contributes to the understanding of natural resource management choices, it is not able, alone, to define the best course of action;

- There is no single solution to the multiple crises we face today, many actions can be taken but the implications of each must be deliberated openly and inclusively;

- Inclusive governance, including fostering collaborative strategies and respecting diverse knowledge systems, can help find solutions to achieve sustainable natural resource stewardship that lead to the regeneration and resilience of both ecosystems and societies;

- There are many ways to frame a study surrounding biomass. In this study, the JRC contextualises biomass within the broader system by describing the complexities surrounding biomass governance, including natural resource management, quantification of biomass and possible governance actions.

Key conclusions

"The more evidence one gathers, the more single models of complex systems fail" - Rocha (2001)

- Over the past decade, the JRC's findings have been updated in quantitative terms, and the overall findings are constant: there is a steady overall increase in use of biomass;

- To represent the context of biomass, assessments of ecosystem condition should always be reported alongside quantification of biomass supply and demand sourced from ecosystems;

- Any assessment of EU biomass supply and use should consider the dependencies on third countries and the implications of trade on those countries' populations and environment.

- Timely and high-quality data with good geographical coverage is a challenge in every sector and efforts should be made to improve data quality and availability;

Main findings

The JRC Biomass Mandate remains highly relevant, and its continued evolution is vital for addressing the EU's biomass-related challenges while ensuring policy coherence. However, when it comes to the stewardship of our natural resources, scientific evidence alone is not able to identify, define nor compel a specific course of action, and neither it should as this is the realm of policymaking. In the spirit of Post-Normal Science, which is to approach problem-solving with a range of alternative solutions based on many different inputs and not to prescribe one single solution, we recognise our role of science for policy support is not only to present rigorous quantitative and qualitative evidence ('What the science says is…') but to expand this with additional quality checks that can provide alternative problem framings and support the expansion of the option space available for policymakers.

The following points distil key messages from the report.

Why biomass matters

Chapter 2 explores the narratives, framings and discourses surrounding biomass in the European policies in a critical way, emphasizing the need for a holistic, system-thinking approach as it is the backbone of the European Green Deal. In this chapter, we analysed several EU policies, finding that biomass is mostly referred to in its function as a provisional service, as well as regulating and supporting services. In the selected EU policies, biomass is primarily treated as an economic and environmental resource, with limited attention made to the social implications of its profile of uses.

In a dedicated narrative analysis of the Bioeconomy Strategy (2018) and its Progress Report (2022), we find that the bioeconomy is framed through multiple different narratives as the result of to the multiple interpretations of the definition of bioeconomy in the EU. While some narratives identified in the Bioeconomy Strategy (2018) and the Progress Report (2022) emphasise innovation and large-scale technological change, others focus on shifting practices or maintaining current systems, leading to partially compatible but at times divergent interpretations of the bioeconomy. The bioeconomy discourse in these documents present a variety of win-win solutions, illustrating a strong will to find solutions, but there remain challenges in implementing these solutions.

How biomass functions

The assessment of agricultural biomass supply and uses under Section 3.1 highlights the essential role of agricultural biomass in the EU's bioeconomy, emphasising sustainable management and innovative uses. It underscores the need to balance biomass supply with ecological health and climate neutrality goals while addressing regional and crop-specific challenges. We report that 24% of EU agroecosystems are in good condition, 53% in moderate condition (restorable), and 23% in bad condition, where "condition" refers to the quality of an ecosystem measured in terms of its abiotic and biotic characteristics.

EU-27 agroecosystems

24 %
of agroecosystems are in **good condition**

53 %
are **below a good condition** threshold

23 %
are in **bad condition**

Total biomass production has increased over the last 22 years with intra-annual and geographical variations driven by climate, management, and area cultivated, with some countries exhibiting more variation than others. The total annual agricultural biomass production in the European Union for the reference period (2018 – 2022) is estimated at 921 Mt D.M. yr^{-1} (million tonnes dry matter per year) in the EU, where 54% are economic production and 46% are residues.

EU-27 agricultural biomass production

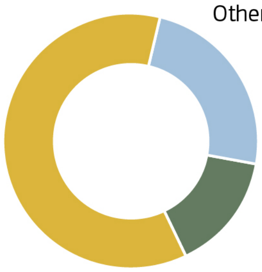
Total annual agricultural biomass production in the EU-27: 921 Mt D.M. yr^{-1}

54 %
are economic production

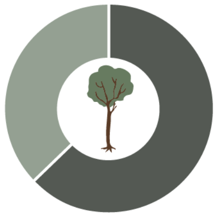
46 %
are residues

Cereals (wheat and maize) dominate biomass production, contributing significantly to both economic and residue biomass. Six member states compose 70% of agricultural biomass production: France, Germany, Italy, Poland, Spain, and Romania. France leads in both economic and residue production. Most of the available biomass was produced within the EU, with only 3% of it being net imports. Trade by EU MSs, including intra-EU trade, was considerably higher and showed significant variation across Member States. 76% of the total agricultural biomass supply (net trade) was used as food and feed. Another 24% of the available biomass is used for non-food purposes or discarded and cannot be allocated to a specific category. Of the biomass that is consumed as food and feed, approximately 80% of the total is used as animal feed or to produce animal-based food, while the rest is directly consumed as plant-based food or is food wasted before consumption.

EU-27 agricultural biomass uses



Change in European* forest condition between 2000 and 2018



*EU-27, UK, Switzerland, Norway, all Balkan countries, and partially Turkey

less than 3 % of Europe's forests are **primary and old-growth forests**

more than 70 % of European forests are **even-aged**

77 % of the forest area and 84 % of the growing stock of **European forests are available for wood supply**

Other uses of agricultural biomass include biofuels, such as biodiesel and ethanol. The EU is the world's largest market for both production and consumption of biodiesel and these represent a stable segment of biomass use. Biodiesel production relies heavily on rapeseed oil, used cooking oil, and animal fats. Ethanol production primarily uses grains and sugar beet. Advanced biofuels and biomethane plants increasingly utilise agricultural residues and waste.

The assessment of forest biomass supply and uses under Section 3.2 underscores the role of forest management in ensuring good ecosystem condition far into the future. It highlights the need for improved data harmonization and long-term strategies in forest management in the face of climate change, particularly within the current paradigm of increasing demands for wood products. Europe's natural forests have largely been replaced by managed forests in the last centuries, with primary and old-growth forests now accounting for less than 3% of the total forest area. 77% of Europe's forests and 84% of the growing stock are available for wood supply, with more than 70% being pure even-aged, highlighting structural deviations from natural conditions, which would be structurally diverse uneven aged forests. Between 2000 and 2018, forest condition improved in 63% of areas but declined in 37%, with significant degradation in Scandinavia, the Carpathians, and the Iberian Peninsula. In this section, we advise prioritisation of maintaining forest health, resilience, and multifunctionality (including increasing the forest sink) rather than only focussing on productivity.

Coniferous species provide about 80% of the total industrial roundwood production at EU level, and about 70% of fuelwood is provided by broadleaves. Broadleaves and coniferous species cover a similar forest area, equal to about 73 Mha (million hectares) for broadleaves and 83 Mha for conifers, and have a similar aboveground biomass stock, equal to about 16 and 20 billion m^3 in 2020, for broadleaves and coniferous species, respectively. Broadleaves species have a Net Annual Increment (NAI) equal to about 4.9 m^3 ha^{-1} yr^{-1} (cubic meters per hectare per year) and the fellings rate, i.e. the ratio between fellings and NAI, for broadleaves is equal to about 58-62% of the total aboveground NAI. Coniferous species NAI is equal to about 6.5 m^3 ha^{-1} yr^{-1} and the fellings rate is about 80-90% of the NAI within the same period (2019 – 2022).

Broadleaves and conifers in EU-27 forests

	Broadleaves	Conifers
Area in EU-27	47 %	53 %
Aboveground stock	16,000 Mm³	20,000 Mm³
Fellings to net annual increment (NAI) ratio	58-62 %	80-90 %
Trends in fellings to NAI ratio	Stable	Increasing
Wood provision	Provide about 70 % of the wood used as fuelwood	Provide about 80 % of the total industrial roundwood

Roundwood production has been, on average, **slightly above 500 Mm³ U.B.** the last 5 years of reporting

We report that production of total roundwood in the EU reached 481 Mm³ u.b. (million cubic meters under bark) in 2023, an increase from the 2017 figure of 474 Mm³ u.b. Northern and Central Europe contribute 70% of the harvest, while Eastern and Southern Europe provide smaller shares, mostly for local use. As for uses, the demand for wood for energy and materials is increasing. Fuelwood accounts for at least 27% of total removals, while industrial uses account for the remainder. The amount of fuelwood reported by official statistics are certainly underestimated, but this share, according to the official statistics, is slightly higher than the last reporting year (which reported 25%).

Challenges include inconsistencies in woody biomass data reporting, making it difficult to accurately assess supply and use in the energy sector at EU level. As far as materials are concerned, sawnwood and wood panel production have increased over the past decade: the produced sawnwood increased from 97.7 to 110.8 Mm³ product volume in the time span 2010 to 2022, while the apparent consumption has increased from 81.8 to 86.5 Mm³ product volume. Panels produced increased from 48.0 to 58.3 Mm³ product volume in the time span 2010 to 2022, while the apparent consumption increased from 53.2 to 59.9 Mm³ product volume. The EU remains a net exporter of these products. Wood pulp production has remained stable, but the EU is a net importer, reflecting demand beyond domestic supply.

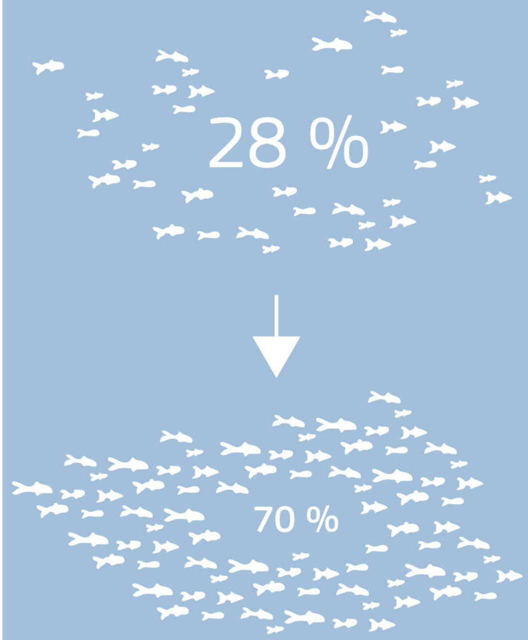
Forest biomass uses in the EU-27

	Sawnwood	Panels	Pulp	Energy
Trends in production from 2010-2022	+ 13.3 %	+ 21.6 %	+ 3.2 %	Further harmonisation efforts are needed to be able to interpret the data reported by the Member States under the Regulation (EU) 2018/1999 on the Governance of the Energy Union and Climate Action
Trends in apparent consumption from 2010-2022	+ 5.7 %	+ 12.6 %	- 4.1 %	
Trade	the EU is a net exporter	the EU is a net exporter	the EU is a net importer	

The assessment of fisheries and aquaculture biomass supply and uses under Section 3.3 reports the EU's efforts and challenges in its wish to balance ecological sustainability, economic profitability, and food security within its fisheries and aquaculture sectors. Overfishing occurs when fishing intensity exceeds the Maximum Sustainable Yield (MSY), leading to reduced catches and economic inefficiencies. The EU's Common Fisheries Policy (CFP) aims to manage fish stocks sustainably, with objectives including fishing at MSY, introducing landing obligations, and balancing fleet capacity with fishing opportunities. Between 2003 and 2022, the proportion of fish stocks fished at or below MSY in EU waters increased from 28% to 70%. Concurrently, the relative biomass of fish stocks improved, although rebuilding fish stocks to sustainable levels requires time.

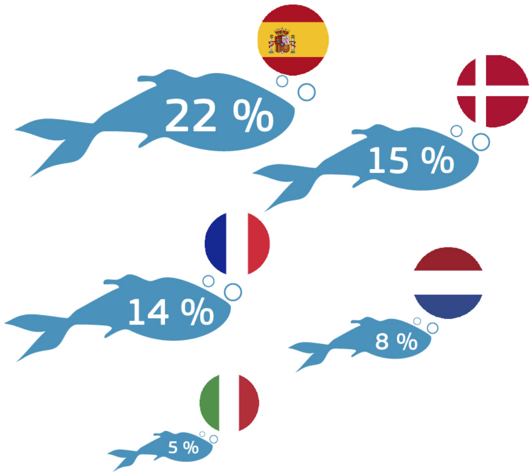
Replenishing fish stock

From 2003 to 2022, the share of EU-27 **fish stocks** considered to be within safe ecological limits **grew by 150 %.**



and the average biomass of assessed stock has **consequentially increased**

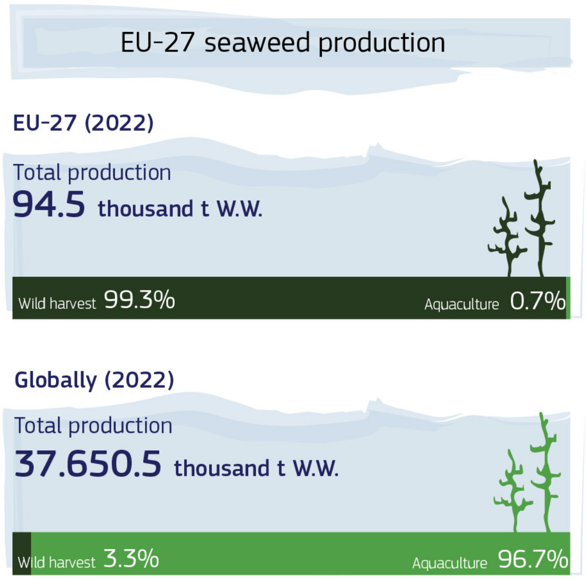
EU-27 Fish landings



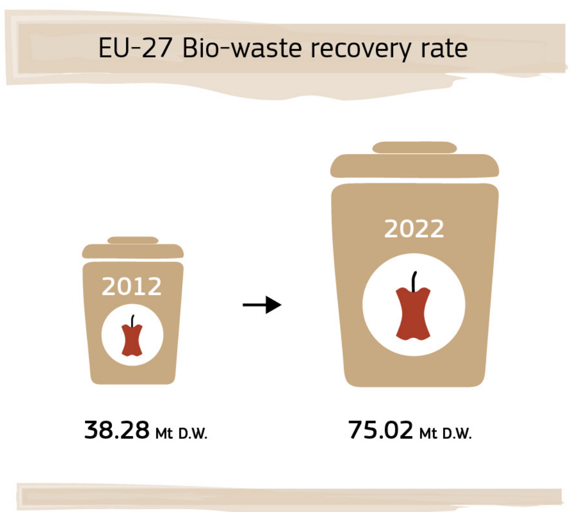
The **Spanish** fleet accounted for **22 %** of the total weight of landings in 2023, followed by **Denmark (15 %)**, **France (14 %), the Netherlands (8 %),** and **Ireland (5 %).**

Regarding the fishing fleet, in 2023, the EU fishing fleet landed 3.45 Mt W.W. (million tonnes wet weight) of seafood, decreasing by 2.8% compared to 2022. The value of landings reported was €6.6 billion in 2023 and remained stable compared to 2022. Major contributors to landings by weight include Spain, Denmark, and France. Skipjack tuna, European hake, and yellowfin tuna are among the most valuable species. EU aquaculture production achieved 1.12 Mt W.W. and a value of €4.77 billion in 2022. While production decreased slightly from 2021 values, the value added increased.

Section 3.4 reports on macroalgae. These play a crucial role in marine ecosystems, supporting global carbon cycling and food webs. Global macroalgae production is largely driven by aquaculture since the 1970's. It has grown exponentially, reaching 36.3 Mt W.W. in 2022, valued at €16 billion. In contrast, Europe's macroalgae sector primarily relies on wild harvesting, with aquaculture producing only 22,931 t.W.W. in the EU-27, contributing to less than 1% of global aquaculture production. Economic value from EU aquaculture amounted to €5.5 million in 2022, reflecting its early-stage development compared to global trends. Challenges include limited data availability, inconsistent reporting, and gaps in biological, technological, and market understanding.



In Section 3.5 we discuss biowaste, including food waste. The European Commission's Circular Economy Action Plan and Farm to Fork Strategy prioritize reducing food waste, with legally binding targets for Member States (MS) to cut waste by 10% in processing and manufacturing and 30% at retail and consumption by 2030. In 2021, food waste in the EU-27 was estimated at 73 Mt (solid) and 11 Mt (liquid), with households generating the largest share, particularly from perishable goods like fruits, vegetables, and dairy. We report stable biowaste generation since 2012, which is unexpected given the emphasis on waste reduction in EU policies. The recovery rate, corresponding to the share of biowaste recycled or used for energy recovery, had been steadily increasing from 2012 to 2018, but has since stabilised at around 90%. Challenges remain in harmonizing data and addressing gaps in biodegradable waste reporting.



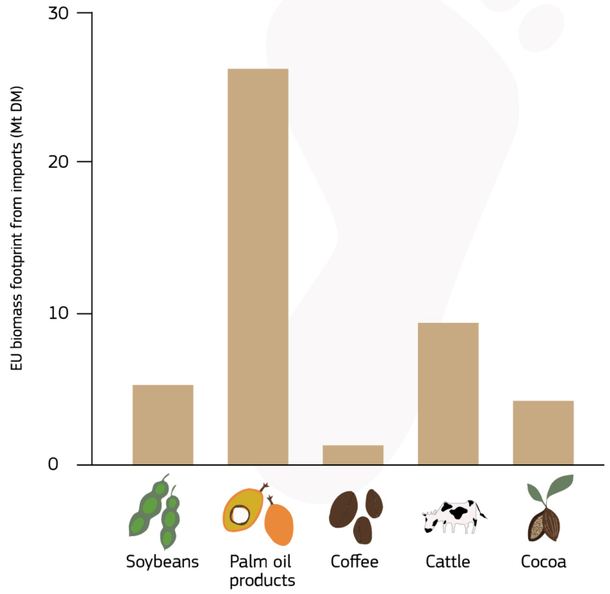
The recovery of biowaste for energy use reached 120 Mt D.M. annually, with significant increases in municipal and industrial biowaste recovery. The biogas production in EU-27, UK, NO and CH more than doubled from 2011 to 2015, increasing from 72 TWh to 158TWh, while biogas production was steady in the following years. The combined biogas and biomethane production grew due to biomethane increase (331%) from 14 TWh in 2015 to 44 TWh in 2022, with the UK having 11% in biogas production and 16% in biomethane production.

The EU is responsible for deforestation and forest degradation abroad through trade (Section 3.6). Global forests are threatened, with 420 Mha (million hectares) lost since 1990 due to land-use changes. The EU-27 contributes to tropical deforestation through imports of commodities like soy, cocoa, coffee, palm oil, and cattle, driving land conversion in regions such as South America, Africa, and Southeast Asia. The EU-27's annual land footprint for imported EUDR food-related commodities is approximately 27 Mha, disproportionately impacting producers in countries like Ghana, Ivory Coast, and Cameroon, where the EU market accounts for 40-63% of cocoa harvest areas. Between 2014 and 2019, EU-27 imports were linked to 74.2% of global cocoa deforestation, 23.7% for coffee, 15.9% for palm oil, and 15.6% for soybeans, resulting in forest biomass losses of 48.04 Mt D.M. from 2010-2015.

EU-27 Biomass footprint

The biomass losses per year for the import of

- palm oil products (**27.02 Mt D.M.** [million tonnes of dry matter])
- cocoa beans (**9.72 Mt D.M.**)
- soybeans (**5.50 Mt D.M.**)
- cattle (**4.42 Mt D.M.**)
- coffee (**1.39 Mt D.M.**)



Section 4.1 is dedicated to an outlook for agriculture. The EU-27's agricultural biomass outlook for 2035 highlights a cereal supply estimated at 348 Mt, primarily sourced domestically (79%), with wheat leading production, accounting for 43% of domestic production. Maize is foreseen to dominate the share of imports at 64%. Oilseeds availability is expected at 45 Mt., with 62% produced domestically. More than half of the domestic production is foreseen to be rapeseed. 65% of the available oilseeds are foreseen to become meal, which is predominantly used for animal feed and feed products. Milk production is expected to reach 151 Mt in 2035, with cheese production consuming the largest share. Meat production is projected at 41 Mt (carcass weight equivalent), led by pig meat, which accounts for 55% of exports. Among fruits and vegetables, 39 Mt are expected to be consumed fresh (56%) or processed (44%).

Section 4.2 presents a modelling exercise whose goal was to simulate the impacts of increased demand for industrial roundwood and fuelwood on the EU forest sink, driven by a simulated increased GDP of roughly 2% under a middle-of-the-road Shared Socioeconomic Pathway (SSP2). We find that the forest carbon sink, which absorbed -268 Mt CO_2eq in 2020, would decline to -168 Mt CO_2-eq by 2050 in an increased wood demand scenario, partly due to ageing forests and partly due to an increase in harvest. If this were to occur, the EU will face challenges in balancing increasing wood demand with sustainability goals. This modelling exercise underlines the need for enhanced sustainability practices to ensure that the forests support the achievement of EU-level targets for natural sinks. Further, improved forest monitoring and policy adjustments are needed to achieve long-term carbon sequestration targets.

What can be done

Over the past decade, through this Mandate, the JRC has reported that the EU's current production of biomass is not sustainable, because ecosystem condition continues to decline. Yet value added and employment in bio-based sectors are showing positive trends. The scale of human impact on the environment, including our role in climate and ecological breakdown, is undeniable. While we do not have a universal solution to this, we enlist the help of experts to take action to address the crises we face today. Chapter 5 is dedicated to a series of regenerative actions as follows: Sections 5.1 to 5.6 are land-based regenerative actions. The section on land aims to integrate uncommonly heard perspectives to expand the option space available to decision makers. The sections underscore the importance of integrating traditional knowledge and inclusive governance to achieve sustainable land stewardship, calling for fostering collaborative strategies and respecting diverse knowledge systems to promote regeneration and resilience for both ecosystems and societies. Section 5.7 is a marine-based action proposal.

Sections 6.1-6.4 discuss actions with a focus on the uses of biomass. In these sections, we emphasise that barriers to innovative uses of biomass include high initial costs, technological uncertainty, and trade-offs between economic viability and environmental benefits. Section 7.1 is dedicated to sustainable trade and offers a brief history of how we got to where we are today through unequal exchange. Here the key messages are that the EU's substantial market power and political influence can catalyse global adoption of sustainable trade regulations, similar to the EUDR, which offers potential for transformative change in supply chains with a more equitable and sustainable approach. Sections 7.2-7.3 discuss financial leverages as regenerative actions. In sections 7.4 and 7.5, we discuss efforts to reduce food waste and discuss dietary patterns.

Related and future JRC work

The JRC will continue to support the European Commission through the JRC Biomass Mandate. Three main pillars for the future are identified for this mandate:

- Strengthened institutional (JRC) mandate to be more agile and policy relevant through a broadened portfolio, and to including a mandate to work with Member States and data collection organisations to help improve the quality, timeliness and coverage of data;

- Active role in developing methods and tools to facilitate deliberation on questions surrounding natural resource management among policymakers and stakeholders, but above all beyond these, to include those whose voices are not normally heard;

- Development of formal system's level analyses to take the interconnectedness between ecosystems and human activities through structured assessments founded in system's theory.

1 Introduction

The Joint Research Centre's (JRC) Biomass Mandate celebrates a decade of providing evidence-based analysis on biomass supply, demand, and sustainability to support European Union (EU) policies. Over the years, the Mandate has addressed challenges arising from competing demands for biomass in the agriculture, forestry, marine, and waste sectors.

Key achievements include developing harmonized data sets, Sankey diagrams for biomass flows, and tools for scenario analysis. However, increasing biomass demand, ecological degradation, and competing priorities highlight the need for a systemic and holistic approach to biomass governance, and most of all, for an acknowledgement from all public and private domains that biomass as a material is finite, and that its extraction from ecosystems (excluding waste) has repercussions.

This report is the 4th comprehensive public-facing report by the European Commission's Joint Research Centre (JRC), that is completely dedicated to the topic of biomass[1]. This report also marks the ten-year anniversary of the inception of what has become known to be called the JRC Biomass Mandate.

1.1 Structure of report

Ansel Renner, Sarah Mubareka

This edition of the Biomass Mandate report aims for a more comprehensive than usual understanding of biomass. To achieve that and ensure the report insights are not only relevant but also robust and actionable, several varieties of analytical check are addressed across the report's eight chapters. Some upfront comment on the way the report is organised and how the chapters build on each other is constructive in advance of getting into it. The tripart framework of Giampietro (2025) lends structure to the discussion.

In a general sense, one can identify three types of narrative in this report—justification, explanation, and normative. Our investigation of justification narratives establishes the significance of biomass within European policy, underscoring the essential role it plays in practices and pursuits such as sustainability, trade, and economic development. Following suit and in step, our explanation narratives explore the mechanisms and causal relationships underlying biomass, especially biomass flows, demonstrating how supply chains, environmental constraints, and governance structures interact. Our normative narratives finally consider possible strategic actions, addressing the option space of policy and governance responses with an aim toward bettering the alignment of biomass uses with societal wants.

Chapter 1 establishes overall context, introducing the notion and nature of the report series as well as its historical evolution. Biomass is framed not as just another resource but as an essential component of all sectors of society, a component that, by its nature, demands the taking of a systemic approach to governance. The chapter situates biomass within the broader landscape of European policy and sets the stage for the subsequent analysis by outlining the tensions between economic growth, environmental concerns, and social equity. Chapter 2 goes deeper on how biomass is constructed within EU policies. In both the report's two opening chapters, justification narrative is the central preoccupation. Policy framings are dissected and implicit assumptions that shape governance decisions are presented. Chapter 2, for example, distinguishes between biomass use-oriented policies, which prioritise biomass as an economic driver, and conservation-oriented policies, which emphasise ecological restoration. This discussion presents to readers a take on the official framing as to why biomass is significant— why biomass matters—and raises fundamental questions about policy coherence, showing how biomass is often positioned simultaneously as a renewable resource, a climate mitigation tool, and an industrial commodity, despite the contradictions between these roles. Exploration of justification narratives in the report allows for the essential performance of a "semantic check", whereby the relevance and salience of the overall discussion is validated.

Chapters 3 and 4 are what returning readers will recognise as the familiar core of the report. Both chapters explore explanation narratives, classical domain of scientific endeavour. The chapters offer a detailed empirical analysis of biomass production, supply, and future availability. Chapter 3 focuses on the present, examining agricultural and forestry biomass through the likes of statistical assessment and spatial analysis. It highlights aspects such as inefficiencies in data reporting and the need for more accurate monitoring systems to track biomass flows across sectors. Chapter 4 extends the discussion into the future, modelling biomass demand projections and exploring the limits of sustainable harvesting. The analysis of the forest sector in particular, underscores the critical dialectic between increasing biomass demand and maintaining EU targets. Taken together, these two chapters serve as a bridge between the policy discourse established

[1] The other reports were:
https://publications.jrc.ec.europa.eu/repository/handle/JRC132358 and its Summary for Policymakers *https://publications.jrc.ec.europa.eu/repository/handle/JRC133505*
https://publications.jrc.ec.europa.eu/repository/handle/JRC109869.
https://publications.jrc.ec.europa.eu/repository/handle/JRC122719.
https://knowledge4policy.ec.europa.eu/projects-activities/jrc-biomass-mandate_en

at the report's start and the solutions-oriented discussions that follow. They explore the signification of biomass—how biomass functions in society, in nature, and on the science-nature interface. Explanation narratives allow for the performance of a "syntactic check", or evaluation of the robustness of the analytical evidence used to guide action.

Chapters 5 through 7 complete the three-part narrative framework with discourse on normative narratives, outlining what might be done to improve biomass governance and were inspired by the actions already described in the EU policies surrounding biomass governance. Chapter 5 presents land- and ecosystem-based management approaches as alternatives to conventional extractive models. It introduces agroecology, regenerative forestry, and other nature-based solutions, arguing that a responsible take on sustainability would suggest moving beyond harm minimisation toward active ecosystem restoration. The chapter connects these approaches with historical land stewardship practices, showing how traditional knowledge systems can also inform modern policy. Chapter 6 narrows the focus to sector-specific applications, examining biomass utilisation in bio-based industries, construction, transport, and novel food production. The discussion emphasises the importance of boosting biomass value through the cascade use principle, ensuring that biomass is allocated to its highest-value applications first, before any final end-use, such as being burned for energy. Chapter 7 broadens the scope once again, linking biomass governance with economic instruments, trade policies, and broader societal transformations. It critically assesses the role of aspects such as economic incentives and trade regulations in shaping biomass markets, arguing that governance strategies must extend beyond technical policy adjustments to encompass systemic shifts in consumption patterns and economic structures. Normative narratives in the report allow for the performance of a "pragmatic check", adding resolution to the option space available to decision-makers and checking whether proposed strategies are viable in a real-world context.

The report concludes with Chapter 8, which brings together the insights from the previous sections and provides a synthetic evaluation of whether this edition of the report's scope expansion is successful at integrating meaning, explanation, and practical application into a coherent, fully integrated structure—more precisely, whether the report achieves a "semiotic closure". This final discussion of the report is at the same time the opening of a new reflection on the interplay between different essential narratives on biomass in society, assessing how they variously do and do not align to form coherent policy framework. The chapter emphasises, among other points, the need for improved cross-sectoral coordination and better integration of ecological considerations into policy decisions. A key general-level message is that achieving sustainable biomass governance requires not just technical solutions but also deep structural and functional transformations in the way biomass is conceptualised, managed, and integrated in our institutions and governance frameworks.

1.2 Ten years of the JRC Biomass Mandate

Sarah Mubareka, Thomas Schleker, Andrea Camia

Ten years ago, a mandate was given to the Joint Research Centre (JRC), by twelve European Commission (EC) services to provide long-term data, analysis, and forward-looking modelling on biomass supply and uses within the European Union (EU) and in the global context. The JRC was, at the time, tasked with assessing biomass flows between supply and uses as a basis to understand the competition and synergies between different sectors for biomass resources, with the objective of assisting the policymaking process to implement policy measures, evaluate policy options and provide elements relevant for future impact assessments.

The scope of the JRC's work included, and continues to include, creating a comprehensive knowledge base on biomass, developing tools for assessing biomass availability and evaluating impacts of biomass extraction and use, in the present and in forward looking exercises. The research covers all sources of biomass: agricultural, forest, marine and freshwater, and waste; and includes an assessment of the competition and the synergies between sectors for biomass resources. The background documentation, the original text of the Mandate and the terms of reference for the first two years of the Mandate, are published on the European Commission's Knowledge Centre for Bioeconomy web platform[2].

The first detailed technical specifications laid out for the mandate, were set out for 2015-2016. Those technical specifications have served as guiding principles for the following years, where the objective continued to be to create a knowledge base for long-term biomass policymaking. The Mandate was divided into five key tasks as shown in Figure 1:

The activities for the individual tasks changed during the evolution of the JRC Biomass Mandate. While Task 1 was an important focus in the first two years, activities in the following years rather shifted towards research on the actual biomass flows, which naturally require a constant updated literature and dataset review. Over the years, as the JRC progressed, and once Sankey diagrams were developed for biomass flows, task 3 and 4 were no longer addressed in isolation and those task activities were therefore combined.

The JRC Biomass Mandate work is in constant evolution, nevertheless in its core design it still follows the original terms of specification. Now, ten years on, the JRC continues this work, and this landmark anniversary has given us the opportunity to take stock of the Mandate's accomplishments, and to reflect upon its future.

Figure 1. The tasks as originally defined within the JRC Biomass Mandate in 2005.

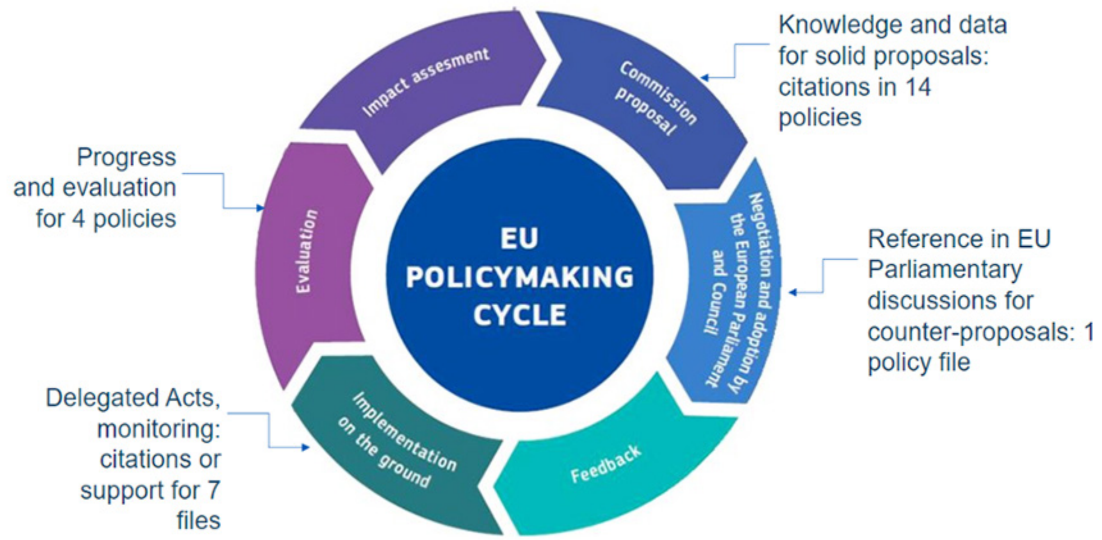
Source: JRC Biomass Mandate Technical Specifications, 2005.

[2] *https://knowledge4policy.ec.europa.eu/bioeconomy/background-information-jrc-biomass-mandate_en*

1.2.1 Accomplishments

The role of the JRC is to support European policymaking throughout the policy cycle. The JRC Biomass Mandate encompasses JRC's knowledge about biomass, however not all the biomass-related output is explicitly quoted under the umbrella of the JRC Biomass Mandate. The JRC Biomass Mandate itself has been specifically mentioned in several policies and policy-relevant documents (Figure 2 and Annex 1).

Figure 2. **Cited contributions in policy documents of the JRC Biomass Mandate since 2015.**



Source: JRC, own elaboration.

Since it's commencement, the JRC Biomass Mandate has brought together data and analyses from across the JRC to produce Science for Policy reports, consolidated internal reports, several peer-review papers, policy briefs, datasets, a glossary (see Box 1), and software and scripts[3]. Furthermore, the annual report including updates on all the tasks to the Steering Committee and the colleagues in the

[3] several are published in the dedicated website *https://knowledge4policy.ec.europa.eu/projects-activities/jrc-biomass-mandate_en*

involved European Commission services, helped the JRC to focus the efforts on imminent policy needs, leading to those more visible deliverables (e.g., report on woody biomass for energy production in the EU as a European Green Deal deliverable for the Biodiversity Strategy 2030).

Box 1. Glossary of terms and reference definitions of the Biomass Mandate

Valeria Magnolfi, Maria Teresa Borzacchiello, Andrea Camia

The glossary of terms and reference definitions is intended to serve as a reference collection of biomass-related terms, to establish a common ground for a shared understanding of concepts around biomass for scientists and experts working in different domains and policy areas within the European Commission. The idea is not to find or elaborate agreed definitions of terms, but rather to elaborate a collection of existing definitions of biomass-related terms from scientific literature and other classified sources.

The glossary was one of the first deliverables of the JRC Biomass Mandate in 2015 and is a living resource maintained within the KCB web platform and evolving over time.

Definitions of each term were sought from authoritative sources classified according to the following eight categories: EU legislation (LEG), EC policy document (ECP), EC technical document (ECT), International organisation document (ORG), Agency document (AGE), Scientific & technical literature (STL), Standards (STA), Dictionaries (DIC), JRC Own definition (JRC); the latter category is intended to flag the definitions found in JRC scientific reports. An additional subcategory Glossary (GLO) was also used, coupled with the label of the source body that created the referred glossary (e.g., EC, agency or international organisation).

An important contribution of the JRC Biomass Mandate has been to create a knowledge base, and to harmonise data where it made sense and where possible. In the last Science to Policy summary for policymakers, we summarise this knowledge base Table 1:

Table 1. JRC harmonised data dissemination.

Topic	Native distribution	JRC data portal	Knowledge Centre for Bioeconomy
All biomass in dry units	*Technical report* on methods Data-Modelling platform of resource economics *biomass flows*	*JRC Data catalogue*	*Infographics* Translated to indicator: *Bioeconomy Monitoring system - Total biomass for food purposes, including feed* Translated to indicator: *Bioeconomy Monitoring system - Biomass directly consumed by EU citizens as food* Translated to indicator: *Bioeconomy Monitoring system - Biomass production in EU from primary production systems (agriculture, forests, fisheries)* Translated to indicator: *Bioeconomy Monitoring system - Total biomass consumed for materials* Translated to indicator: *Bioeconomy Monitoring system - Total biomass consumed for energy* Translated to indicator: *Bioeconomy Monitoring system – Share of biomass used by primary sector*
Algae			*Algae production industry* pages *The bioeconomy in different countries* dashboards
Agriculture	*Technical report* on methods Data-Modelling platform of resource economics *biomass flows*	*JRC Data catalogue*	
Fisheries	*STECF website*		Translated to indicator: *Bioeconomy Monitoring system - Fishing mortality of commercially exploited fish and shellfish exceeding fishing mortality at maximum sustainable yield* Translated to indicator: Bioeconomy Monitoring system - Fish stock biomass in NE Atlantic & Mediterranean, *https://knowledge4policy.ec.europa.eu/visualisation/eu-bioeconomy-monitoring-system-dashboards_en?indicatorId=2.1.b.11&unit=biomass*

Forestry			
Reference data-base of forest biomass statistics at sub-national scale statistics for biomass stock, FAWS, BAWS, GAI and NAI	*Technical report* on methods to derive forest biomass *Science for Policy report* on The use of woody biomass for energy production	Forest biomass *-metadata* *-map* Net Annual Increment, Gross Annual Increment, Forest Available for Wood Supply, Biomass Available for Wood Supply *-metadata* *-maps*	Translated to indicator: *Bioeconomy Monitoring system - Ratio of annual fellings (m3/ha/year) to net annual increment (m3/ha/year)* Translated to indicator: *Bioeconomy Monitoring system – Roundwood removals*
Wood Resource Balance	*Technical report* on methods		Translated to indicator: *Bioeconomy Monitoring system -share of woody biomass used for energy* Country reports: *https://knowledge4policy.ec.europa.eu/publication/wood-resource-balances_en* Interactive web-based diagrams: *https://knowledge4policy.ec.europa.eu/visualisation/bioeconomy-different-countries_en#wrb*
Woody Biomass Flows	*Technical report* on methods		Translated to indicator: *Bioeconomy Monitoring system - cascading factor of wood resources* Country reports: *https://knowledge4policy.ec.europa.eu/publication/forestry-sankey_en* Interactive web-based diagrams: *https://knowledge4policy.ec.europa.eu/visualisation/interactive-sankey-diagrams-woody-biomass-flows-eu-member-states_en*
Waste	*Technical report* on methods to derive food waste		Translated to indicator: *Bioeconomy Monitoring system - biowaste generated by source* Translated to indicator: *Bioeconomy Monitoring system - biowaste recovered by source* Translated to indicator: *Bioeconomy Monitoring system - food waste along the supply chain* Translated to indicator: *Bioeconomy Monitoring system - food waste by food category*
Trade	*Software repository* and associated *Peer review paper* on trade data package		Translated to indicator: *Bioeconomy Monitoring system - Economic impact of trade in exporting countries (to EU)* Coming soon: Environmental impact of trade in exporting countries (to EU)

Source: JRC, own elaboration.

Signature products of the JRC have come out of the efforts, such as methodological advancements in assessing biomass supply and demand, harmonisation of biomass flows (Sankey diagrams in common measurement units) and the reporting. The sustained nature of this work has allowed the JRC to build upon knowledge towards closing data gaps across different biomass production and processing sectors.

1.2.2 Future of the JRC Biomass Mandate

There have been conclusions and lessons learned from this long-running project. The first remark is that the Mandate is still highly relevant today. Biomass is central to many EU policies (see Chapter 2) and the impact the JRC Biomass Mandate has had on the policy side is thanks to the overarching nature of the Mandate, currently with data collection and analysis at its core.

Here we reflect on what worked in the Mandate over the years, and we identify three main areas to improve upon: 1) Strengthened institutional (JRC) mandate to be more agile and policy relevant; 2) Active role in developing methods and tools to facilitate deliberation on questions surrounding natural resource management.; 3) Development of competence in system's level analyses.

1.2.2.1 Strengthened and more agile Mandate for policy relevance

A lot has changed since the initial signatures were posed on the original Mandate in some respects. On the one hand, the JRC's work has evolved from reporting biomass extracted from agricultural and forest land, and from the seas and oceans, to assessing the implications of extraction and modelling the future biomass availability. More research and data on trade and the EU's impact abroad, and reinforced efforts in outlook studies would help inform policy makers more broadly to understand policy implications of future demand in terms of quantities and diversity of markets; and on the supply side, understanding the implications of management strategies and climate change. This would ensure to maintain the overarching nature of the mandate and to address still existing data gaps at the long term.

The JRC Biomass Mandate was conceived to be overarching and agnostic to individual policy objectives yet aiming to be policy relevant. Strengthened direction within the JRC is needed to cover more topics related to biomass, for example moving into the realm of health and zoonotic disease (One Health); participatory methods to engage more people; involvement of ecologists to go beyond ecosystem condition mapping; modelling teams for outlook studies, including at global scale; structural engineers for assessments on bio-based building materials; and many more. With a significant institutional directive to serve the best possible knowledge related to biomass in the Commission, and a certain degree of flexibility to do so, the Mandate becomes more policy relevant. Furthermore, related to the third ambition detailed below: with a strengthened institutional mandate, the JRC could move towards true system's level assessments as described in section 2.4.

With a strengthened institutional mandate, the JRC could furthermore be more involved in data reporting processes. In this report we highlight in all sectors that data quality and coverage is an issue. The JRC could work more closely with Member States and data collection agencies to improve reporting.

1.2.2.2 Deliberation and facilitation for policy coherence

Throughout these years, the JRC's findings have been updated in quantitative terms, and the overall findings are constant: there is a steady increase in use of biomass. Indeed, what motivated the initial inception of the JRC Biomass Mandate is unfortunately that there is little doubt that our current overall use of biomass is unsustainable (Eversberg et al., 2023; Eversberg, Holz, and Pungas, 2022; Giuntoli et al., 2023; Ramcilovic-Suominen, 2022). A coherent narrative is more easily said than done (see section 2.3). However, in all of the Mission letters to the Commissioners-designate[4], President

[4] *https://commission.europa.eu/about-european-commission/towards-new-commission-2024-2029/commissioners-designate-2024-2029_en*

von der Leyen asks that evidence be the basis for EU legislation, and she also mentions she wishes the College to work more closely together and take full ownership of what is agreed at that level, which implies a stronger cross-fertilisation of knowledge and a more system's level overview of each of the Commissioners. Finally, she encourages local and regional presence, namely a reinforced dialogue with citizens and stakeholders, with special emphasis on youth, announcing the intent towards a "lasting culture of participatory democracy".

It is with this spirit in mind, that this report goes beyond the quantitative assessment ("evidence basis") that has been the trademark of the JRC Biomass Mandate these past ten years and begins to delve into more cross-cutting topics, as well as to move from the purely quantitative approach to biomass, to discuss the broader implications of biomass governance, which leads to a broader discussion of managing natural resources. This is an attempt to bridge the physical world with our quantitative assessment about biomass, speaking as plainly as possible (i.e. without necessarily succumbing to the need to use negativist or positivist language to exaggerate or downplay messages), and including the issues that people are concerned with, namely what actions can be taken to regenerate the ecosystems that we rely on, yet without losing our livelihoods and our quality of life. In other words: cross-cutting actions that require policy coherence, which is the backbone of the JRC Biomass Mandate. To do so, the authors make an attempt throughout this report, to link the biomass to their sources (e.g., the ecosystems or social systems in the case of waste), and where possible, to discuss some social or human implications, knowing that biomass stewardship is a matter of choices and decisions based on much more than scientific output (see Box 2, "Biomass Stewardship: a wicked problem"). This approach is an acknowledgement that continuous interaction between nature and society shapes the form and function of social-ecological systems, knowing that social (which includes economic) and ecological subsystems are coupled and interdependent (Berkes, 2017) because one (often-neglected) implication of studies like this, is that all the processes within social-ecological systems have a double nature: an ecological (material) one and a social (economic and historic) one.

Box 2. Biomass stewardship: a wicked problem

Biomass governance involves not only decisionmakers, but rather a wide constellation of communities of concern. It presents a 'wicked problem' (Churchman, 1967; Rittel and Webber, 1973), a member of a class of problems that tend to be societal problems, rather than technical problems. Wicked problems cannot be separated clearly from issues of values, equity, and social justice. (Berkes, 2017).

The categorical opposite of wicked problems are problems whereby a solution can be defined as right or wrong in relation to that understanding (e.g., building a safe and strong bridge, without considering social implications of this). In wicked problems, the nature of the problem itself is contested. The multiple perspectives of the actors involved (linked to different valid interests and values) mean that there can never be a general 'right' or 'wrong' solution, but only solutions judged 'better', 'worse' or 'good enough' in relation to a set or multiple sets of pre-analytically selected preferences used as proxy to describe desired outcomes.

In practical terms: Different actors understand biomass through legitimately different lenses, and serious trade-offs emerge as a result. While the co-existence of legitimately different problem formulations and solutions can be expected in relation to biomass governance, this is not to say that each proposal is compatible with biophysical reality. This report attempts to recall these limitations.

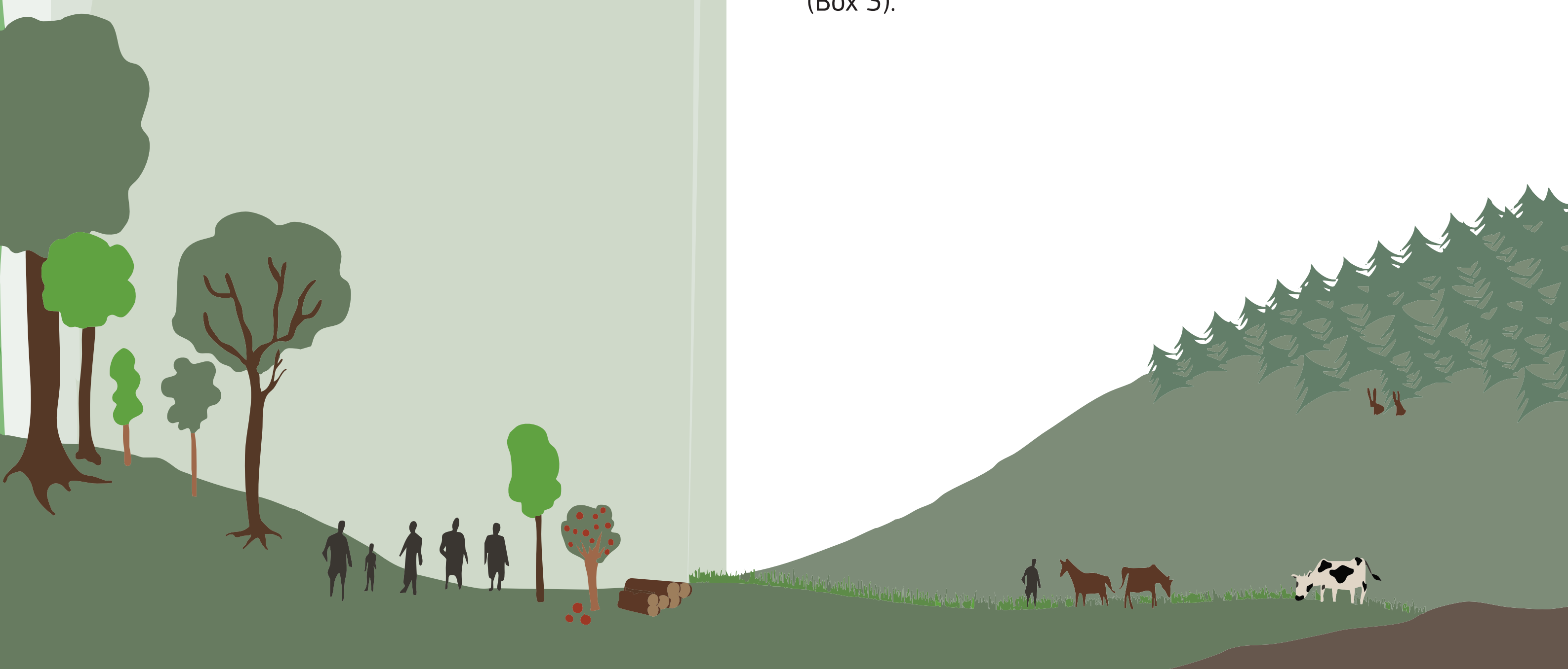
1.2.2.3 System's level assessments

Although from the very beginning of the JRC Biomass Mandate there was a strong desire and recognition for the need to harmonise the big picture with respect to the biomass production, supply and demand for all sectors, there was little progress on approaching the mandate with a fully systemic analysis, even though the three-dimensional approach to sustainability was defined as important guiding principle from the beginning. Today, there is no doubt that this should be done. The JRC Biomass Mandate is a coordinated effort between different scientific units of the JRC, each with its own set of competences, but additional efforts should be put into a whole system perspective. Thus, the work, although robust in its own sphere and for its own purposes, is not able to give a system's level assessment of the biomass demands and the biomass availability.

For future work, the JRC proposes to help renew focus on those urgent questions that are most relevant to broad, system-level assessment, and to work further toward cross-policy coherence through active facilitation of deliberation within the European Commission. This second point would mean adding a new set of skills to the mandate: from a predominantly silo approach to a means for understanding the full system behind biomass production and demand, as well as the implications of its extraction and processing. We fully dedicate Section 2.4 to this topic.

2 Biomass and European Policies

This chapter is dedicated to a critical discursive policy analysis concerning the role of biomass in the European policies. Instead of focusing solely on numeric data, statistics, or impacts, discourse analysis looks at the underlying values, collective aspirations and prevailing institutional structures. It does so by using three different methods: Content analysis, framing analysis and narrative analysis (Box 3).



Box 3. **What is the difference between content analysis, framing and narratives?**

Qualitative content analysis is "an approach of empirical, methodological controlled analysis of texts within their context of communication, following content analytic rules and step by step models" (Mayring, 2000, Pg 2). It systematically codes and analyzes the text to uncover recurring themes, concepts, and patterns. Through this process, content analysis unveils the underlying meanings and intentions within the documents, providing a clearer understanding of topic discussed (Hsieh and Shannon, 2005).

Framing analysis focuses on how problems are described and constructed, how solutions are suggested, what elements are emphasized and downplayed, and whose voices are heard (van Hulst et al., 2024). It aims to identify problems, but it does not encompass the relation between the actors, the surrounding events or atmosphere. It focuses on the rational discourse. (Hellman, 2024)

A narrative is "a means by which political actors attempt to construct a shared meaning of the past, present, and future of international politics to shape the behaviour of domestic and international actors" (Miskimmon, 2017). Narratives are a form of storytelling. There is a plot that moves forward. Narrative analysis also analyses how the problem is framed, but this is only one aspect of the analysis.

All three approaches share similar ontological and epistemological starting points, but offer different results (van Hulst et al., 2024).

Section 2.1 is a content analysis of the role of biomass in the European Green Deal policies that analyses how biomass is referred to and which functions of biomass are prevalent in these policies. It highlights the different roles biomass is expected to play in the policies. Section 2.2 examines the different framings of the bioeconomy and biomass and their implications. The term "bioeconomy" has different framings in different countries based on the power of the engaged stakeholders. Biomass is often framed as a "sustainable" resource, which has significant implications on its use. Section 2.3. is a narrative analysis of the EU Bioeconomy as it is presented in the 2018 EU Bioeconomy Strategy and its Progress Report. It presents nine different narratives, highlighting the various storylines entangled in the bioeconomy concept and ultimately affecting current and future biomass consumption. Finally, section 2.4. shows the way forward by calling for a systems approach for governance surrounding biomass.

The purpose of this chapter is to provide insights and trigger reflection on how biomass is discussed and presented in the EU context, and to demonstrate that while biomass is addressed in different ways throughout the EU policies, the policies aim for the common goals of decarbonisation, healthier ecosystems, and an improved quality of life for EU citizens. As we show in the following sections, where the policies differ, is in the pathways that are identified to reach these goals.

2.1 The expectations of biomass in EU policies

Elena Zepharovich & Cristina García Casañas

This chapter analyses how various forms of biomass are referred to in different policies, related to the European Green Deal. The trend in biomass use is increasing, driven by demand for bioenergy and material (the uses of biomass for food and feed remains stable). While recycling of biomass and resource efficiency have increased in the past decade, so has sourcing of virgin fibres, resulting in an increasing impact on biomass-producing systems (Mubareka et al., 2023). This general pattern of a growing demand of biomass as environmental conditions deteriorate, may be exacerbated by climate change, increasing therefore degradation of ecosystems, and consequently of human well-being (Maes et al., 2021).

This chapter first describes the role of biomass in policies and proposals following the adoption of the EGD in general, considering that one policy document can mention several roles simultaneously. We proceed to describe the prevalent expectations towards biomass in the policies, helping to understand where the reported increasing demand for biomass stems from.

2.1.1 Methods

We analyse how biomass is referred to in the EGD policies, which forms of biomass are prominent, and what their role is in contributing to the EGD. In this context, "European Green Deal policies" include both legally binding and non-legally binding documents [5].

A qualitative content analysis approach is used to explore the expected contribution of biomass to the different policies. This approach involves systematically coding and interpreting the text to identify recurring themes, concepts, and patterns. By doing so, it reveals the deeper meanings and intentions behind the documents, offering a clearer picture of how biomass is viewed within these policies (Hsieh and Shannon, 2005). The policies that were analysed to assess the expectations of biomass in the EGD are the following:

1. Renewable Energy Directive (2018/2001) and its amending Directive (2023/2413)
2. LULUCF Regulation 2018/841 and its amending Regulation 2023/839
3. Climate Law
4. Circular Economy Action Plan
5. Conservation of fisheries resources and protection of marine ecosystems
6. Progress Report of Bioeconomy Strategy 2022
7. Framework for Carbon Removals
8. Transition pathways for a chemical industry
9. Farm to Fork
10. CAP Strategic plans
11. EU Soil Strategy for 2030
12. Biodiversity Strategy
13. Soil Monitoring Law
14. New EU Forest Strategy for 2030
15. EU Strategy on Adaptation to Climate Change
16. Towards a strong and sustainable Algae sector
17. REPowerEU
18. Nature Restoration Regulation (analysed in its state as a proposal, prior to adoption)

2.1.2 Results

The results of the quantitative content analysis of the policies assessed, show that biomass is expected to fulfil several roles, with the most prominent being:

- Functioning as a carbon sink (regulating service)
- Providing renewable energy (provisional service)
- Providing food and materials (provisional service)
- Habitat and biodiversity (supporting service)

In the policies, several of these roles are mentioned simultaneously. In what follows we highlight some policies in which the different roles are dominant.

Most policies, such as the Communication Towards a Strong and Sustainable Algae Sector, the New Forest Strategy for 2030 and the EU Strategy on Adaptation to Climate Change highlight the role of biomass as a carbon sink. This role is also particularly present in the LULUCF Regulation. For example, recital 7 states that "Sustainable management practices in

[5] The selection of policies was based on the recommendations of the Inter-service group on *Biomass of the European Commission*

the LULUCF sector can contribute to climate change mitigation in several ways, in particular by reducing emissions, and maintaining and enhancing sinks and carbon stocks. "(European Union, 2018).

The use of biomass as a source of renewable energy is also mentioned in many policies such as the LULUCF regulation, REPowerEU, and the Farm to Fork strategy. It is particularly prevalent in the RED II/III, for example "In order to exploit the full potential of biomass, which does not include peat or material embedded in geological formations and/or transformed to fossil, to contribute to the decarbonisation of the economy through its uses for materials and energy, the Union and the Member States should promote greater sustainable mobilisation of existing timber and agricultural resources and the development of new forestry and agriculture production systems, provided that sustainability and greenhouse gas emissions saving criteria are met". (European Commission, 2023a, Article 93).

Biomass in its role to supply food and materials is also present in most policies, especially in the Farm to Fork strategy, the CAP and the Circular Economy Plan. The New Forest Strategy for 2030 highlights the role of wood as a material, stating that wood should help turn the construction sector from CO_2 emitter to a carbon sink (European Commission, 2021a, Pg 7).

The role of biomass to provide habitat and biodiversity is particularly present in the Nature Restoration Regulation, but these aspects are also highlighted in the Biodiversity Strategy and the Soil Strategy. For example, the Biodiversity Strategy states "Nature regulates the climate, and nature-based solutions, such as protecting and restoring wetlands, peatlands and coastal ecosystems, or sustainably managing marine areas, forests, grasslands and agricultural soils, will be essential for emission reduction and climate adaptation." (European Commission, 2020)

Cultural services appear in two out of the 18 policies and are referred to as "recreational" services. The New Forest Strategy for 2030 highlights that "Forests and the forest-based sector provide multiple socio-economic functions and benefits, including additional jobs and growth opportunities in rural areas and recreational functions contributing to citizens' physical and mental health" (European Commission, 2021, Pg 2). The policy also mentions the multifunctionality of forests several times. Similarly, the Nature Restoration Regulation refers to recreational services, stating, "They [urban ecosystems] also provide many other vital ecosystem services, including natural disaster risk reduction and control such as for floods and heat island effects, cooling, recreation, water and air filtration, as well as climate change mitigation and adaptation" (European Commission, 2022, Pg 23).

Cultural services (such as spiritual, educational or recreational value) are of only limited focus in biomass-related policies. The most common roles are carbon sink, habitat and biodiversity, and material/ food and energy. These roles are discussed further in the next section.

2.1.2.1 The expectations towards biomass

Qualitative content analysis allows for the identification of recurring themes, concepts, and patterns within a body of text. We identified two prevalent expectations towards biomass in the EGD policies. On the one hand, we identify a set of biomass-related policies that refer to biomass as a means for a specific human end use and economic purpose (e.g., energy, materials, products, food) and to address environmental concerns (substitution of fossil-fuels). In other words, the role of biomass to provide energy, food and material is prevalent in these policies. On the other hand, we find a set of policies that refer to the protection, enhancement, and restoration of different ecosystems (e.g., forest, agricultural land and agroecosystems, fisheries and marine ecosystems, organic soils, etc.). These biomass typologies are recognized to play essential roles in regulating our ecological systems: providing clean water, carbon sequestration, biodiversity, and other important ecosystems services, and hence these resources need to be managed properly, with a long-term perspective.

There are overlaps in pathways identified to address the common goals between the policies. For example, a conservation discourse dominates the New Forest Strategy for 2030, yet it proposes to further "support sustainable forest-based bioeconomy" (European

Commission, 2021 Pg 3), endorsing the material use of wood. Another example is the EU Bioeconomy Strategy Progress report, where the dominant discourse is in the uses of biomass, yet it contains many statements about conservation.

We identified the following eight biomass use-side policies:

a. RED II/III. This directive aims to promote the use of renewable energy sources to reduce greenhouse gas emissions, enhance energy security, and drive sustainable economic growth. The directive defines both biomass sustainability and greenhouse gas emission savings criteria for bioenergy to be accountable in the Union's renewable energy goal. It also sets a cap for the use of food and feed crops for biofuels, with the intent to limit the impact on biodiversity, competition with food and feed, and land use. Biofuels produced from waste and residues, other than agricultural and forestry residues, are required to fulfil only the GHG emissions savings criteria. RED provides the definition for the biomass to be used, that includes biodegradable fraction of products, waste and residues from agriculture, forestry and related industries, including fisheries and aquaculture, as well as the biodegradable fraction of industrial and municipal waste. The Directive presents various expectations to a wide array of biomass, ranging from agricultural crops to forest residues, biowaste and animal manure. All these categories of biomass are expected to be sustainably sourced and used to produce renewable energy and thus to contribute to GHG emissions saving under certain rules, conditions and principles. For example, "Harvesting for energy purposes has increased and is expected to continue to grow, resulting in higher imports of raw materials from third countries as well as an increase of the production of those materials within the Union. It should be ensured that harvesting is sustainable."(European Commission, 2023a Paragraph 103). An increase in the use of biomass from agricultural crops is acknowledged.

b. REPowerEU Plan. The primary aim of this policy is to reduce the dependence on Russian fossil fuels. It is specified that "The focus should be on sustainable production, ensuring that biomethane is produced from organic waste and forest and agricultural residues, to avoid impacts on land use and food security. Bioenergy makes up 60% of the renewable energy in the EU. It is a domestically available and stable energy source, but sustainable sourcing is key. Current estimates show a moderate but steady increase of biomass use until 2030. Prioritizing use of non-recyclable biomass waste and agricultural and forest residues will ensure a sustainable energy production that can contribute to the REPowerEU objectives." (European Commission, 2022a Pg 8). Although this plan focuses on different types of wastes and residues to produce energy, and it might represent a minor contribution to the high energy requirements of our current socio-economic systems. In the RePower EU Plan, biomass is expected to be an "available and stable energy source".

c. Progress Report of the Bioeconomy Strategy 2022. One of the stated goals of this document is mitigation and climate adaptation to climate change (European Commission, 2022b Pg 6). It aims to decrease dependencies on non-renewables through the substitution with biomass. Different types of biomass (e.g., agri-food waste, algae, wood) are expected to be a source to produce food, feed, materials (e.g., bio-based products, biodegradable plastic, building materials) and energy. The Progress Report mentions the challenges concerning biomass use, for example trade-offs between policy targets and competing uses of land, sea and biomass.

d. Circular Economy Action Plan. The first sentence of the policy states "There is only one planet Earth, yet by 2050, the world will be consuming as if there were three (United Nations). Global consumption of materials such as biomass, fossil fuels, metals and minerals are expected to double in the next forty years (OECD, 2019), while annual waste generation is projected to increase by 70% by 2050" (European Commission, 2020). The plan involves expectations towards biomass to produce materials (even if the specific biomass typology is not explicitly mentioned in the Plan) and to generate economic value from unavoidable food waste, as well as to reuse and recycle following the waste hierarchy.

e. Transition pathways for a chemical industry. This policy document provides an actionable plan to achieve the twin transition and foster the competitiveness and resilience of the EU Chemical Industry. To this end, it outlines about 190 actions needed for the transformation of the EU Chemical Industry. The Pathway was co-created by the European Commission together with Member States, the Chemical Industry itself and other interest parties. Therefore, it reflects the input provided by stakeholders during the co-creation process. The Pathway underlines that biomass is expected to provide energy and alternative feedstock and therefore reduce both dependence of non-renewable energy sources, such as fossil fuels. This document distinguishes itself from the others by clearly highlighting the limitations using biomass. For example, "The prospect of the chemical sector becoming largely bio-based remains challenging. It will be difficult to achieve given: (i) the limited availability of sustainable primary biomass in the EU; (ii) the fierce competition for biomass resources from other sectors (in particular, the energy and transport sectors); and (iii) the sheer scale of demand." (European Commission, 2023 Pg 30). The difficulties and challenges expressed in relation to the biomass availability might be explained by the strong stakeholder participation in the creation of this document and that it does not reflect the official position of the European Commission, as specified in the legal notice (European Commission, 2023 Pg 0).

f. EU Algae Initiative. In the Commission Communication "Towards a strong and sustainable Algae sector", algae is expected to be a source of biomass to produce food, feed, fertilisers, plastics and energy. It should contribute to a thriving industry and create jobs. At the same time, these sources of biomass are seen as means to relieve the pressure on the environment, as algae could replace materials and energy produced and generated from fossil energy sources. Further, the farming of algae should capture carbon and excess nutrients, contribute to biodiversity goals, zero pollution and help maintain ecosystem services. The expansion of the use of algae is not without risks, as acknowledged it the communication in one sentence "But expansion of seaweed cultivation at sea should not affect the equilibrium of marine ecosystems and should avoid reproducing in oceans the same environmental mistakes historically done on land" (European Commission, 2022c Pg 2).

g. Farm to Fork strategy. This strategy expresses specific expectations towards biomass, especially on agriculture. Food should be affordable, sustainable and healthy. Agriculture should promote organic practices, reduce pesticides and reduce food waste. It also expresses expectations for algae, which could serve as an alternative feed material or protein (European Commission, 2020). It states "The circular bio-based economy is still a largely untapped potential for farmers and their cooperatives. For example, advanced bio-refineries that produce bio-fertilisers, protein feed, bioenergy, and bio-chemicals offer opportunities for the transition to a climate-neutral European economy and the creation of new jobs in primary production." (European Commission, 2020, Pg 7). It endorses the increased use of biomass.

h. The CAP Strategic plans have many expectations towards biomass. For example, "The CAP should keep ensuring food security, which should be understood as meaning access to sufficient, safe and nutritious food always. Moreover, it should help to improve the response of Union agriculture to new societal demands on food and health, including sustainable agricultural production, healthier nutrition, animal welfare and reduction of food waste. The CAP should continue to promote production with specific and valuable characteristics while helping farmers to proactively adjust their production according to market signals and consumers' demands." (European Commission, 2021). It is a policy framework that tries to address the various trade-offs of biomass use through different tools.

In summary, we observe that this set of policies mainly promotes the use of biomass for human purposes as a part of the solution to address the common goals of decarbonisation of the EU economy, halting biodiversity decline and enhancement of quality of life for Europeans. Current environmental problems, such as climate change and biodiversity loss are indeed explicitly acknowledged in the policies. An increase in demand for biomass in the future is mentioned in most documents.

We identify the following ten policies that place emphasis on the necessity of protecting, managing and restoring the ecosystems:

a. Climate Law is the legal basis for the EGD target to reach climate neutrality by 2050 and establishes a framework to reduce GHG emissions. Biomass is often referred to in its role as "sink" but the expectations are multiple. For example, for forests: "Furthermore, the 'triple role' of forests, namely, as carbon sinks, storage and substitution, contributes to the reduction of greenhouse gases in the atmosphere, while ensuring that forests continue to grow and provide many other services." (European Commission, 2021). Further, the law highlights how climate change substantially impacts ecosystems, affecting carbon sequestration and storage capacities of forest and agricultural land.

b. The LULUCF Regulation sets the accounting rules for GHG emissions and removals from land use, land use change and forestry in EU climate policy. The role of biomass is mainly to function as a carbon sink and reservoir, but it also refers to its use as material and source of energy (European Commission, 2023).

c. The Nature Restoration Regulation sets targets on restoring ecosystems stating that healthy ecosystems provide food and food security, clean water, carbon sinks and protection against natural disasters caused by climate change. They are essential for our long-term survival, well-being, prosperity and security, as they are the basis for Europe's resilience (European Commission, 2022d Pg 1). Hence, this law focusses on the whole ecosystems carrying the biomass and not just biomass itself. It is very explicit in showing how human-wellbeing depends on the wellbeing of the ecosystems.

d. EU Strategy on Adaptation to Climate Change. This policy states: "The climate adaptation gap is wide and increasing, so we must bridge it more swiftly. The European Environment Agency has regularly highlighted this issue in its assessment reports on adaptation (European Environment Agency, 2020). Progress in adaptation planning remains slow, and implementation and monitoring even slower. Current measures mostly focus on awareness raising, institutional organisation or policy development, but rolling out physical solutions, such as creating more green spaces to reduce the impacts of heatwaves or adjusting sewerage systems to better cope with storm overflows, is lagging. The aim of this strategy is therefore to shift the focus to developing and rolling out solutions, to help reduce climate risk, increase climate protection, and safeguard freshwater access." (European Commission, 2021d, Pg 12). Biomass is mentioned mostly indirectly, often in the context of a nature-based solutions and nature restoration actions. For example, preserving and restoring forests and rewetting dried lands is essential to sequester carbon, filter and purify surface waters and aquifers and reduce heatwave impacts.

e. The New EU Forest Strategy for 2030 highlights the use and importance of forest in all its aspects. It states "To succeed in this transition we will need larger, healthier and more diverse forests than we have today, notably for carbon storage and sequestration, reduction of the effects of air pollution on human health and halting loss of habitats and species." (European Commission, 2021 Pg 2). However, it also claims that forests are needed for economic purposes, like energy and material uses.

f. Soil Monitoring Law. There are few direct mentions of biomass. Soils host more than 25% of biodiversity and are the second largest carbon pool of the planet (European Commission, 2023). Currently 60-70% of European soil are unhealthy because of the current management practices (European Commission, 2020). This

policy suggests different actions to improve our soil management and concludes "Our soils need to be healed. It is a matter of our own survival." (European Commission, 2023b Pg 24).

g. Biodiversity Strategy lies out how our survival depends on the well-functioning of ecosystems, guaranteed by biodiversity and further highlights how our environment is in a bad state. Different forms of biomass are mentioned such as agricultural lands, wood and wetlands. It calls for the protection and restoration of various ecosystems (European Commission, 2020).

h. EU Soil Strategy The strategy repeatedly stresses the importance of soil as a carbon sink. The policy also refers to trees and their essential role in in adaptation to climate change. To keep the precious functions of soils working, it is crucial to ensure their health (European Commission, 2021).

i. Framework for Carbon Removals is a voluntary regulatory framework for the certification of permanent carbon removals, carbon farming and carbon storage in products. The framework sees biomass as an important biogenic carbon pool (European Commission, 2022e, Pg 10). Different forms of biomass are mentioned such as aboveground biomass, forests, deadwood and waste streams from biomass, which are mainly referred to in their role as sink and carbon storage, but also in their material function.

j. Conservation of fisheries resources and protection of marine ecosystems. It sets out rules on how, where, when, which and how many fish can be caught in EU waters in order to conserve the species and protect marine ecosystems. Hence, it calls to protect ecosystems and their habitat (European Commission, 2019).

These ten policies highlight the role of biomass in mitigating climate change, protecting biodiversity, and ensuring human prosperity and security. They primarily claim more biomass be protected, enhanced and restored.

2.1.3 Discussion

In analysing the role of biomass in the different EGD policies and (at the time of writing) proposals from a perspective of the environment, society and the economy, we found that biomass is either expected to provide material, energy and food (i.e. to be used in an extractive way or to be produced to meet demands of our current systems) rather focusing on the economic sphere, or to be protected and enhanced (i.e. to support its role as a carbon sink, habitat and host for biodiversity), emphasising environmental aspects. The social dimension of biomass is hardly mentioned in the policies, figuring aspects of environmental justice, power imbalances or access to resources. This is in line with the findings of other studies (Backhouse et al 2021; Giuntoli et al., 2023; Ramcilovic-Suominen, Kröger, and Dressler, 2022; Ramcilovic-Suominen et al., 2025).

All policies mention in one way or another the environmental problems we face, such as degraded soils, climate change and biodiversity loss. Regarding climate change, biomass is announced as a central means to achieve these EGD goals: biomass is seen both by its role i) as a carbon sink and ii) as a source to produce bio-based materials and energy and thus getting away from fossil fuels. In the latter sense, an increase for demand in biomass is expected, but this evokes some tension (e.g., with the forest ecosystems that are desired to be protected and enhanced). Such tensions and trade-offs are sometimes acknowledged, and many policies call for 'sustainable procurement' and the like. However, this recognition does not necessarily translate into actions to reduce resource use (Fleischmann et al., 2024).

Policies remain conflicted as they attempt to balance addressing the environmental crisis with promoting economic growth and biomass extraction. As a result, these policies tend to prioritise market-based solutions while neglecting preventive legal measures to preserve ecological limits (Brand, 2016; Pichler, Brand, and Görg, 2020).

This strategic approach overlooks the fact that economic growth is a key driver of escalating resource consumption and environmental degradation (Haberl et al., 2020; Hickel, 2019; Hickel and Kallis, 2020). As a result, the potential for a substantial reduction in resource use is inherently limited (Brand, 2016). This is also reflected in the fact that most policies assume an increase in biomass demand and use, rather than calling for a dramatic shift.

An integrated framework that places biomass use in a broader ecological and systemic context and prioritises its use for basic human needs is still lacking. Filling this gap is crucial given the potential competition for biomass between different uses (and non-uses).

2.1.4 Conclusion and key messages

In conclusion, our analysis underscores the central role of biomass in achieving the goals of the European Green Deal (EGD). The EGD places high and increasing expectations on biomass, as reflected in the discussed policies, despite concerns about potential negative impacts on ecosystem services and human well-being (Maes et al., 2021). Biomass is seen as a key factor in reaching climate neutrality and phasing out fossil fuels, with governments turning to it as a renewable substitute. However, as herein reported by the JRC, current exploitation practices risk significant environmental degradation and the limited availability of biomass necessitates careful management. The European Commission is increasingly aware of the trade-offs and challenges associated with biomass use, particularly its environmental impact and the competition among various applications. A more holistic systems approach, as discussed in Section 2.4, would contribute to policy coherence, but as discussed in Box 2, there is no clear right or wrong approach in managing biomass and the decisions are ultimately political. What is uncontested is that a more robust understanding of social-ecological systems is needed within the evidence base provided for policy.

- Biomass is heavily referred to in the European Green Deal policies;
- In the selected EU policies, biomass is mostly referred to in its function as provisional service, as well as a regulating service;
- In the selected EU policies, biomass is primarily treated as an economic and environmental resource, with limited attention made to the social implications of its profile of uses;
- A systemic and integrative understanding of social-ecological systems to identify environmental and social synergies and trade-offs of biomass management choices is needed.

2.2 Framing bioeconomy and biomass: Insights into Policy, Sustainability, and Values

Elena Zepharovich

In the context of the JRC Biomass Report, understanding how “bioeconomy” and “biomass” are framed is crucial for shaping effective policies and strategies that support sustainable resources management. This chapter shows how these terms and their various frames are currently discussed in the scientific literature. By investigating the framing of bioeconomy and biomass, we aim to offer insights into how these frames (see Box 4) can be shaped to better align with long-term sustainability. The purpose is not to assess the accuracy of the different frames, but to shed light on how certain topics are discussed and which values and ideas are prevalent.

Box 4. What is framing?

Frames are unconscious structures, which help to make sense of the world. They show how we think about an issue (Rein and Schön, 1996).

“To frame is to select some aspects of a perceived reality and make them more salient in a communication text, in such a way as to promote a particular problem definition, causal interpretation, moral evaluation, and/or treatment recommendation for the item described.” (Entman, 1993, Pg 53)

Hence, a frame is a way to describe a problem in a certain way and propose solutions accordingly. Because frames often depict the world in a way that calls for a specific style of decision or response, their creators strongly benefit from them (Perri, 2005). Hence, the framing of a topic is strongly related to power structures and material realties (Tittor, 2021).

2.2.1 Bioeconomy

The term bioeconomy itself sets a particular tone, suggesting an integration of environmental and economic goals toward sustainable development. When the prefix “bio” is added to the word “economy”, it suggests that bioeconomy integrates environment and economics to accomplish sustainable development (Vivien et al., 2019). Many framings position the bioeconomy as an approach that in many cases do not fully reflect on biomass limitations or existing material and social structures.

Multiple interpretations of bioeconomy exist, each highlighting different priorities such as biotechnology, innovation, green growth, or the recognition of biophysical limits (Bugge, Hansen, and Klitkou, 2016; Hausknost et al., 2017; Vivien et al., 2019, Giampiero et al., 2025). Each of these frames presents unique perspectives on sustainability, governance, future economic growth, technological paths, and concepts of nature (Vivien et al. 2019). Predominant frameworks often focus on biotechnology and biomass, alongside concepts like substitution and green growth, with a strong focus on economic considerations (Böcher et al., 2020; D'Amato, Bartkowski, and Droste, 2020; Eversberg, Holz, and Pungas, 2023; Hausknost et al., 2017; Vogelpohl, 2023). By contrast, alternative approaches centered on agroecology or self-sufficiency are less prominent (Dieken and Venghaus, 2020; Hausknost et al., 2017). Also, the social dimension of the bioeconomy, figuring concerns regarding justice, inequality or neocolonialism, is hardly present in the mainstream bioeconomy discourse (Ramcilovic-Suominen et al 2025; Ramcilovic-Suominen 2022; Giuntoli et al. 2023).

These strategies and framings of bioeconomy are not uniform and often reflect regional and national priorities. For instance, in Argentina, the bioeconomy is heavily framed around the production and expansion of biomass, particularly using GMO crops. This framing highlights the influence of agricultural lobbies, which utilise the concept of the bioeconomy to further their own interests, moving environmental concerns to a secondary position (Tittor, 2021).

A similar pattern can be observed in Brazil. According to Bastos Lima, (2021), although the bioeconomy has emerged as a compelling concept for promoting environmentally friendly technologies and institutional improvements, it has mainly favoured large corporate agribusinesses in Brazil. He shows how already powerful actors used their instrumental, structural and discursive power to shape the bioeconomy policies to their benefits.

In contrast to Latin America, environmental concerns play a more central role in the European Bioeconomy framing. However, Lühmann (2020) finds that while actors advocating for stronger environmental protection sometimes succeed in embedding their ideas into strategic documents, the actual policy measures implemented remain marginal. This is also reflected in an analysis of the political bioeconomy framing in Germany, Finland, France and the Netherlands, which found that the integration of environmental concerns is manly a rhetorical one, using a win-win argument, claiming "Environment benefits from economic growth" (Kleinschmit et al., 2017). Overall, nature is framed as a resource and service provider for humans in the European Bioeconomy concept (Ramcilovic-Suominen, 2023). Hence, also in Europe the economic dimension of bioeconomy is prevalent (Böcher et al., 2020; D'Amato, Bartkowski, and Droste, 2020; Eversberg, Holz, and Pungas, 2023; Hausknost et al., 2017; Vogelpohl, 2023).

Despite regional and thematic variations, a common thread across all bioeconomy framings is the central role of biomass as a material foundation (Boyer et al., 2023). This shared emphasis calls for further examination of how biomass itself is framed within the bioeconomy context.

2.2.2 Biomass

Biomass holds an important position in bioeconomy discussions, typically portrayed as a 'renewable' and therefore 'sustainable' resource (see Box 5). This framing underpins the argument for transitioning to a bio-based economy as an effective strategy for addressing the climate crisis (Pfau et al., 2014; Priefer, Jörissen, and Frör, 2017). Nonetheless, numerous experts have raised concerns about the practicality of sustainably increasing biomass utilization within the bioeconomy (Backhouse, 2021; Erb and Gingrich, 2022; Giampietro, 2019; Giampietro and Pimentel, 1990).

Box 5. **Framing of biomass in the German Bioeconomy**

Given the multiple biomass uses, Boyer et al., (2023) investigated how policy discourses sustain the idea biomass use being sustainable in the German bioeconomy, notwithstanding the fact that there are no full calculations available and that those that exist are cautions about using biomass for the German bioeconomy. They identified four ideological strategies:

- Seeking managerial solutions: Sustainability can be achieved through better management and technical process. It suggests that goals are objectively based on quantification and numbers, for example biomass monitoring. However, most indicators are oriented on economic efficiency and effectiveness, leaving aside issues such as access to resources;
- Relying on technical innovation: Technology is presented as a solution to complex-socio ecological problems. When presenting an ecological and social problem, like biodiversity loss and land use degradation instead of a resource conflict as a technical problem, it is easier to find consensus;
- Relegating solutions to the future: The focus on the future draws the attention away from present conflicts. The vision of sustainability is kept vague and ambiguous to facilitate consent;
- Obscuring the materiality of nature: There is no clear definition of biomass and its biophysical qualities. Also, many concepts such as 'cascade use' and methods to assess the sustainability of products vary widely. If biomass use would be upscaled, land-use conflicts would emerge.

These four strategies are underpinned by well-structured knowledge, incorporating calculations, quantifiable data, and models to foster a sense of predictability and rationality. Hence, framing biomass in this way, using these four strategies allows for the bioeconomy to present itself as inherently sustainable.

An example of biomass framing is the work by Elomina and Pülzl, (2021), who investigated how forests are framed in 36 EU forest-related policies. They identified nine distinct frames, with the most prominent being one that portrays forests as a ”provider of wood and non-wood products”. This framing underscores the prioritization of economic utility and aligns with a broader trend that emphasizes resource extraction. Similarly, Lindahl et al., (2017) who studied the forest frames of Swedish policy documents, found that the dominate frame "more-of-everything" prioritizes economic growth over environmental and social aspects.

In theory, how forests are framed directs attention and where to take action (Perri, 2005). Promoting forests primarily as sources of biomass and wood has become a widely accepted solution to address climate change and support sustainability within the bioeconomy framework. This framing channels efforts towards maximizing wood production as the main strategy for achieving sustainability.

Although there are alternative approaches such as multifunctionalforestry (see section 3.2.1) that balance ecological and social benefits, the deeply entrenched exploitative framing continues to shape policies. As a result, these policies often default to strategies that favour economic expansion through increased wood production, sidelining more integrated, sustainable options (Sotirov and Storch, 2018).

However, there has been progress toward more comprehensive bioeconomy policies, as described in section 2.1. Other recent analyses indicate that some policies have become more integrative than in the past, incorporating broader perspectives and considering multiple stakeholder interests (Elomina and Pülzl, 2021).

Despite these advances, significant challenges remain. Issues related to uncertainties, trade-offs, and potential conflicts surrounding biomass use are still insufficiently addressed within policy frameworks, for example for woody biomass (Elomina and Pülzl, 2021; Lindahl et al., 2017). Aggestam (2015) points out that solutions framed to make clear economic sense—such as those presenting a win-win outcome—are more likely to gain acceptance and be implemented. This behaviour may explain why discussions of conflicts and trade-offs, which do not easily align with narratives promoting economic growth, are often marginalized or excluded from policy documents.

2.2.3 Conclusion

Enhancing frame awareness can improve policy coherence and coordination, addressing a common criticism related to biomass and bioeconomy policies. By adopting this broader awareness, policies could better balance economic, environmental, and social dimensions, leading to more sustainable and equitable outcomes. In conclusion, recognizing how a topic is framed is essential for policymakers to develop more holistic and inclusive policy proposals.

2.3 Bioeconomy narratives

Elena Zepharovich, Thomas Völker, Zora Kovacic, Paloma Yáñez Serrano

In order to comprehend the underlying discursive policy challenges related to biomass, it is essential to understand what the bioeconomy is and under which premises biomass is being used.

The bioeconomy is presented in many different ways in the 2012, 2018 Strategies and the 2022[6] Progress Report, creating an overall complex picture. The bioeconomy is at once: a grand vision that aims to address the double challenge of enhancing the competitiveness of the EU and responding to impending environmental challenges; a driver of innovation; a creator of employment; and "a major component for the implementation of the European Green Deal" (European Commission, 2022).

One way of making sense of the multiple facets of any policy is narrative analysis. A narrative is "a means by which political actors attempt to construct a shared meaning of the past, present, and future of international politics to shape the behaviour of domestic and international actors" (Miskimmon, 2017). Narratives are a form of storytelling. There is a plot that moves forward. Narrative analysis also analyses how the problem is framed (see Box 6), but this is only one aspect of the analysis. Through narrative analysis it is possible to disentangle and separate the different individual ideas, claims and rationales and present them as distinct logics. The aim of the analytical process is to identify different rationales and to look for intersections, inconsistencies and implicit assumptions of these narratives. This allows for making sense of the multiple visions (and revisions of policies) and by doing so possibly open-up a space for debate.

The different narratives of the bioeconomy have been studied intensively, focusing on different countries (Bastos Lima, 2022; Tittor, 2021), bioeconomy fields like biorefineries, forestry and renewable energy (Bauer, 2018; Eckert, 2021; Elomina and Pülzl, 2021) or policy documents (Vivien et al., 2019; Hausknost et al., 2017; Bugge, Hansen, and Klitkou, 2016; Pfau et al., 2014).

Thus, when we look at narratives, we are aiming to better understand the discursive dimensions underlying bioeconomy.

[6] The EC first adopted a Bioeconomy strategy in 2012, "Innovating for Sustainable Growth: A Bioeconomy for Europe" (European Commission, 2012). The strategy was then updated in 2018 and published as "A sustainable bioeconomy for Europe: strengthening the connection between economy, society and the environment"(European Commission, 2018). In 2022, the EC published a progress report with the title "Stocktaking and future developments" (European Commission, 2022).

The purpose of this chapter is to provide insights and stir reflection on how the bioeconomy is discussed and presented in the EU context. It does not assess the validity, rationality or truthfulness of the analysed content, but provides insights into the institutional use of the bioeconomy framework.

Box 6. Narratives as an institutional analysis

Narratives are deeply connected to the institutional, cultural, moral, and material structures of society, with organizations and institutions both shaping and being shaped by them. Through narratives, societies express and stabilize broader ideas about how the world is and ought to be, making narrative analysis a form of institutional analysis. In the social sciences, institutions are understood as the formal and informal rules guiding interactions among individuals and groups, encompassing everything from laws and organizations to values, ideas, and social processes.

Viewed through this lens, narrative analysis becomes a tool for understanding how groups create and share meaning. By examining narratives, we gain insight into the specific "stories" actors tell about the world and how these narratives shape, and are shaped by, their vision of reality. Understanding these narratives thus provides a window into why certain decisions and actions are meaningful within a particular organizational context.

2.3.1 Methods

This narrative analysis was conducted by systematically analysing the European Bioeconomy Strategy (2018) and the Progress Report of EU Bioeconomy Strategy (2022) using a set of categories, see Annex 2 Narrative analysis categories. The categories embrace eight building blocks: problem framing, assumptions, claims, promises, theory of change, subject positions, governance models, reasoning/causality and two reflexive elements: coherence of policy narratives and pedigree. To distil the narratives the two policy documents were read several times in detail to identify the different problem framings, claims, promises, etc. Based on the findings, the different narratives were formed and refined through 27 semi-structured interviews with an extended peer community. For more details concerning narrative analysis, please see Kuckarzt (2014).

2.3.2 Findings

A total of nine narratives were identified from the two policy documents based on the framework described in the Methods section and Annex 2. These narratives present distinct problem framings together with their own sets of assumptions, claims, and promises, as presented in Table 2, where the first column presents a condensed summary of the narratives; the second column displays the function of bioeconomy is in this narrative; the third column contains the problem framing i.e. what is presented as the issue that needs to be tackled; the fourth column shows the theory of change, i.e. how the problem should be solved; and lastly, in the fifth column, some statements from the policy documents are presented to exemplify the narratives.

Table 2. Summary of narrative analysis in the EU Bioeconomy Strategy (2018) and its Progress Report (2022).

Narratives	Executive Summary	Function of Bioeconomy	Problem framing	Theory of change	Quotes from documents
1. Biophysical boundaries	Emphasises dependence on biological resources and planetary boundaries awareness. Lacks clear pathways for implementation beyond awareness. Advocates for ecosystem restoration, reduction of CO_2 and nature preservation. Unclear how to address surpassing biophysical limits. Hope that scientific evidence will catalyse change.	Restoring ecosystems, limiting resource use, reducing CO_2 emissions and raising awareness	Grand planetary challenges, which provides scientific legitimacy to Bioeconomy Strategy and creates sense of urgency.	Scientific evidence will act as agent of change. Economic growth is presented as compatible with biological limits.	"more work needs to be done in order to move from a better understanding towards a better implementation of the bioeconomy within the planetary boundaries" (EC 2022).
2. Transition from fossil-based to bio-based economy	Advocates for a shift from fossil-based to bio-based production through technological innovation. Top-down transition approach. Bioeconomy as the ideal economic model.	A sustainable economic model to be achieved that is independent from fossil-based resources and delivers economic growth, renewal and prosperity.	Fossil-based central to problem and is described as environmentally unsustainable and geopolitically problematic.	Fossil-based substitution or resource renewability and circularity based on large-scale innovation (e.g., biorefineries)	"a scaled-up and strengthened bio-based sector can do more than non-renewable substitution: it can support the renewal of the EU industrial base; it can contribute to the greening of industrial products; and it can help to systematically turn bio-waste and discards into value, thus achieving circularity" (EC 2018). "development of new sustainable biorefineries in Europe at scale, to provide emerging applications substituting fossil-based products" (EC 2022).
3. Agroecology	Underscores importance of using biological resources sustainably, with focus on agroecology. Represents minority viewpoint and faces tensions with other narratives.	How to live and produce more sustainably helping to restore nature..	Unsustainable food production, water scarcity and pressures on land.	Change the way we produce and consume food to prevent soil erosion, reduce fertiliser use and resore ecosystems equilibrium through bottom-up systems.	"The benefits from biodiversity-rich ecosystems will be better integrated in primary production through a specific support to agro-ecology, the development of microbiome-based solutions, new tools to integrate pollinators in value chains and specific support for agro-ecology" (strategy); "Food and farming systems are a fundamental part of the bioeconomy, but they urgently need to be transformed to become more sustainable, nutrition-sensitive, resilient and inclusive in view of a growing world population, climate change and other environmental challenges, including water scarcity and loss of biodiversity and of productive land." (EC 2018).
4. Circular bioeconomy	Aims to address sustainability in biomass use through circularity. Relies on notions of waste-to-value conversion and waste reduction. Faces challenges due to unique characteristics of bio-materials.	Is presented as a means of achieving circularity, but also as a goal for the bioeconomy. Idea is to make the bio-material flows "circular" by turning waste into useful resources	Increase in demand of biomass, need to be more sustainable	Waste can be turned into a resource	"To be successful, the European bioeconomy needs to have sustainability and circularity at its heart" (EC 2018). "It can turn bio-waste, residues and discards into valuable resources and can create the innovations and incentives to help retailers and consumers cut food waste by 50% by 2030." (EC 2018).

5. Bio-innovation	Centers "bio" at the core of innovation for economic growth and environmental benefit. Champions bottom-up innovation, particularly through start-ups. Aims to modernize and increase profitability of bio-based sectors. Emphasizes win-win scenarios and competitiveness.	A strategy for harnessing economic opportunities that emerge from bio-innovation.	Room for increased innovation, need for secure financing, competitiveness and modernisation	Bio-innovation is a business opportunity and solution to environmental problems, for example through start-ups.	"the need to achieve sustainability constitutes a strong incentive to modernise our industries and to reinforce Europe's position in a highly competitive global economy" (EC 2018). "to overcome the particularly large "valley of death" in bioeconomy innovations, caused by lack of financing to transfer knowledge into innovations and lack of a long-term policy pull" (EC 2022).
6. Expanding the bioeconomy	Advocates for bio-based solutions for economic growth and modernisation Links to self-sufficiency and security Synergy with bio-innovation narrative. Belief that there is potential for growth	A strategy for green growth; call for economic and fiscal incentives to help increase the value added of bioeconomy sectors	Low productivity of primary sector, need for modernisation	Change through new business models, economic and fiscal incentives, modernisation.	"untapped potential of bioeconomy" (EC 2018). "strengthen and scale-up the bio-based sectors and unlock investments and markets" (EC 2018).
7. Jobs perspective in the bioeconomy	Mirrors "Fair and just transition" discourse, emphasizing need to address winners and losers in transition process. Focuses on job creation and inclusivity.	New way of organising economic activity	Transition entails promoting certain practices, actors and regime configurations while phasing out others.	Job creation aims are to be achieved by providing education and reskilling as an enabler for the bioeconomy.	"Transforming and re-skilling of Europe's work force" (EC 2022). " In the bio-based industries one million new jobs could be created by 2030" (EC 2018).
8. Bioenergy	Emphasises need for sustainable biofuels, acknowledges ongoing development. Ambiguous about the role of biofuels as substitute for fossil fuels.	A stable bio-based source of energy	Need to increase energy provision independence and to reduce use of fossil-fuels	Substitute fossil-fuels with bioenergy.	"The current crisis following the unprovoked Russian invasion of Ukraine clearly shows that Europe requires to increase its independence on energy and to strengthen food security, without leaving the path towards a sustainable, resilient, and fair economy as outlined by the European Green Deal" (EC 2022). "To meet the high stakes and ambitions of the European Green Deal it is essential to ensure environmental integrity and to close the projected 'biomass gap' between supply and demand of biomass for food, materials and energy" (EC 2022).
9.Bioeconomy as a policy	Narrative specific to progress report. Bioeconomy is defined as a policy and progress is thus measured with regard to the policies that Member States have drafted, reviewed and adopted to support the bioeconomy. Main idea that a regulatory framework helps "de-risk" investments in the bioeconomy. Only narrative that acknowledges risk.	Bioeconomy has no clearly defined form of implementation in this narrative, so that it is flexible enough to be embraced by different Member States.	Private investments in sustainable solutions are risky	Government provides legal stable framework and financial incentives for private investments.	"market access remains challenging due to the lack of a comprehensive regulatory policy approach" (EC 2022). "The EU will deploy a targeted financial instrument - the EUR 100 million Circular Bioeconomy Thematic Investment Platform38 (Action 1.2) - to de-risk private investments in sustainable solutions" (EC 2018).

Source: JRC, own elaboration.

2.3.3 Discussion

These narratives present different narratives of the bioeconomy together with their own sets of assumptions, claims, and promises. The narratives rest on (mostly) unquestioned theories of change with subject positions and governance models. Not all narratives mention a governance model.

First, although the nine narratives co-exist and are sometimes interlinked in the policy documents, overall, they do not constitute a coherent whole. In some cases, the bioeconomy is a new economic model to be achieved (narrative 2 and 4) and in other cases, there already exists a bioeconomy that needs to be expanded (narrative 6). Yet in another case, the bioeconomy is a matter of policymaking, setting roadmaps, plans and indicators (narrative 9). These differences create space for quite diverging interpretations of what action may mean: it may be about change, continuity, or about drafting of policy documents.

Second, there are very different visions on how to achieve/expand the bioeconomy, that range from changing practices (for example, from high input intensive farming to agroecology, narrative 3), to maintaining current practices but substituting the biophysical inputs (from fossil-based to bio-based, narrative 2), and more vague accounts of how change happens that rely on innovation and yet-to-be invented technologies (be it large-scale in narrative 2, or bottom-up in narrative 5). These visions are partly, but not fully compatible.

Third, there are narratives that are under-specified. For example, energy (narrative 8) and jobs (narrative 7) are mentioned very frequently through statements about the importance of using sustainable energy and creating new jobs – however, how exactly these concerns relate to the bioeconomy or are to be enacted by a bioeconomy is not spelled out. Agroecology (narrative 3) is mentioned as a good practice, but it is not defined.

Finally, it should also be noted that in some cases, the synergies are clear. The transition narrative (2), the bio-innovation narrative (5) and the circular bioeconomy narrative (4) rely heavily on innovation and have complementary approaches that can be easily seen as reinforcing each other. The transition narrative mentions bio-refineries and a large-scale transformation of the industrial sector, while the bio-innovation narrative highlights the potential of startups. In all cases, the focus is on technological innovation.

2.3.4 Conclusions and key messages

The narrative analysis shows that there is not one single institutional approach to bioeconomy. The multiple narratives that compose the EU Bioeconomy Strategy and that appear in the related policy documents, present an overall promise that the bioeconomy can bring about win-win solutions to the grand challenges of environmental protection and social and economic prosperity.

The narratives assemble different and sometimes contrasting logicsaction. Examples are the agroecology and biophysical boundary narratives, which suggest that the bioeconomy is an economic system that adapts to the limits and rhythms of nature, and the radically different expansion and innovation narratives, which suggest that bio-resources and bio-based activities are a yet underexplored and underexploited sector that can and should be put at the service of economic growth and competitiveness.

An important feature of win-win discourses is their ability to offer solutions to policy conflicts, regardless of whether these win-win solutions can materialise in practice. One of the core challenges in managing complex sustainability issues is that policies in one area often lead to trade-offs in another area, as highlighted in the Progress Report (European Commission, 2022). In such contexts, win-win solutions provide an ostensibly value-neutral simplification of the option space. By promoting concepts such as efficiency, innovation, or other (mostly) uncontested forms of progress, win-win solutions are framed as the rational choice, effectively simplifying the policy balancing act by narrowing the range of available options.

This narrative analysis suggests that policy coherence involves more than harmonising different measures. Expanding the bioeconomy conflicts with the concept of respecting biophysical limits. The trade-off between economic growth and environmental considerations is not merely a technical issue. Framing the environmental crisis as something that can be resolved solely through technology, innovation, and green growth shifts responsibility away from current actions and delays meaningful change, worsening further environmental degradation.

- The bioeconomy holds great potential as a transformative solution for addressing some of the most pressing global challenges. By embracing a multifaceted approach, it aims to bring together the need for economic development with a commitment to environmental protection;

- In the Bioeconomy Strategy (2018) and its Progress Report (2022), the bioeconomy is framed through multiple different narratives as the result of to the multiple interpretations of the definition of bioeconomy in the EU;

- While some narratives identified in the Bioeconomy Strategy (2018) and the Progress Report (2022) emphasise innovation and large-scale technological change, others focus on shifting practices or maintaining current systems, leading to partially compatible but at times divergent visions of the bioeconomy;

- The bioeconomy discourse in the Bioeconomy Strategy (2018) and the Progress Report (2022) presents a variety of win-win solutions, illustrating a strong will to find solutions, but without clarity on how to implement these solutions;

2.4 Biomass, a systems approach is needed

Ansel Renner

“The almost fabulous comfort, let alone the extravagant luxury, attained by many past and present societies has caused us to forget the most elementary fact of economic life, namely, that of all necessaries for life only the purely biological ones are absolutely indispensable for survival.”
—Georgescu-Roegen[7]

2.4.1 Systems approach

As society pursues increasingly ambitious goals in such existential domains as sustainability and bioeconomy, adopting a systems approach in foundational research is becoming more and more essential. The interconnectedness between natural ecosystems and human activities means that any policy affecting biomass can have far-reaching consequences—from impacts on biodiversity and soil health to those on climate regulation, social equity, or economic stability. A systems approach to the study of biomass provides a structured way of assessing how changes in biomass lifecycles influence these diverse phenomena, helping policymakers understand the broader implications of their efforts and to navigate complicated decision profiles.

At the core of a systems approach is a highly interdisciplinary philosophy that departs with the insight that, in many contexts, the whole is more than the sum of its parts. It proceeds from there to emphasise the why and how of understanding systems as integrated wholes. It is an approach that gives focus on the interconnections between components, rather than on components in and of themselves, adding nuance and breadth of understanding to observed phenomena. In the context of biomass and its management, the taking of a systems approach means first and perhaps foremost acknowledging that the many processes of biomass extraction, transformation, use, and disposal are tangled up with broader social-ecological dynamics.

[7] From his 1971 work *The Entropy Law and the Economic Process*. Nicholas Georgescu-Roegen is widely understood as the “father of bioeconomics”.

Box 7. Brief history of systems theory

"Systems approaches" are grounded in systems theory, an interdisciplinary field of study that examines complex systems through the relationships and interactions between their constituent components. Systems theory emphasises concepts such as feedback loops, emergence, self-organisation, and adaptation, all of which are fundamental to both natural and social systems.

Systems theory as a formal, academic discipline emerged between the 1940s and 1960s. Foundational works include the cybernetics of Wiener then Ashby, where emphasis was made on the study and formal understanding of circularities in biological and social systems, alongside the sociologies of Parsons and Rapoport as well as the economics of Boulding, among many others. Von Bertalanffy's "general system(s) theory" and his similarly titled 1968 textbook will likely be familiar among readers with a research background.

Feedback loops, to take one example of interconnection, are a class of relation key to the understanding of biomass. Changes in one component of a system, such as an increase in biomass extraction, can have cascading effects, amplifying or dampening aspects of the overall system's behaviour. Consider high forest biomass extraction rates. They may initially boost jobs, value added, and, perhaps, materials and energy production. In the longer term, however, they are likely to lead to degradation of forest ecosystems—reductions in biodiversity, lowerings of water availability, perturbations of biogeochemical cycles including but not limited to decreasing of the capacity to store carbon. Non-linear dynamics play a confounding role here, where small changes in biomass management—such as the relatively minor altering of crop rotation practices—can lead to significant outcomes, including for the crop rotation example disproportionately major shifts in soil fertility or agricultural yields.

Still more troublesome for scientific modelling is the existence of emergent properties. Such properties—characteristics of a system that arise from the complex interactions of its parts—cannot be anticipated through study of individual system components. In the context of ecosystems, stability and resilience are two key emergent properties that result from the interactions between species, their habitats, and environmental conditions. This statement holds true both for natural ecosystems and human ecosystems, the latter being those ecosystems where the species of focus is the human species, existing in a societal habitat. A systems approach to biomass must therefore pay attention across scales of analysis, understanding how human activities impact not just individual species or ecosystems but effect emergent properties only observable at relatively higher levels—properties including but not limited to such broad aspects as the resilience and stability of embedding ecosystems.

2.4.2 Practical implications for policy and governance

Just as the taking of a systems approach can be valuable in scientific efforts, it can also make fundamental contributions to policy efforts. Effective biomass governance strategies must navigate often-competing priorities ranging from long-term environmental sustainability to resource use efficiency or general economic prosperity. Policies that endorse a systems approach avoid addressing goals in isolation—they account for both the synergies (positive interactions that enhance outcomes) and the dysergies (negative interactions that create conflicts) between these priorities.

One of the more substantial challenges on the science-policy interface is therefore to translate system-wide scientific understanding into actionable policy insight. The set of scientific models must include those that are comprehensive and integrative, capable of capturing the essential interconnectedness of biomass systems. However, this is only part of what is needed. Scientific models must be highly relevant for and easily digestible by policymakers. The task of science on the interface and in relation to biomass is not just to generate system-wide models but also to actively work with policymakers and to contribute to shaping the very process that allows for integrative governance.

Central to this process is incorporation of a broad range of stakeholders, from farmers to foresters, industry, local communities, and environmental organisations. Such stakeholders will often present divergent realities—contradictory indications expressed in different descriptive domains that may nevertheless be equally legitimate. Engaging such diversity on the science-policy interface, while far from trivial, is essential for ensuring that multiple of the many relevant knowledges are considered. This consideration in turn lends itself to the development of strategies better suited to the complexities of the real-world—strategies that are more robust and more suitable to the facing of deep uncertainties related to aspects like technological advancement, market fluctuations, a fragile natural environment, or a chaotic geopolitical landscape.

To this same point, it is worth drawing attention to the fact that incorporation of a broad range of stakeholders is a fickle task. The field of post-normal science suggests to those wanting to better engage with a diversity of relevant stakeholders the absolute essentiality of starting with humility. Post-normal science also suggests that, when faced when high doses of uncertainty, it is best to not focus directly on a high-quality result but rather to focus on guaranteeing a high-quality process, from which a high-quality result—whatever its final form may be—can be expected to emerge.

This overall shift in thinking encourages a more exploratory approach to biomass futures. Ensemble predictions and probability ranges are invaluable tools, but they are all the more useful when complemented by discussion on what kind of future we want to create—what grand narratives may motivate and unify us (see Section 2.3). Biomass-related policies must not be purely reactive, responding to current trends. They much also be proactive at shaping more responsible pathways of resource use.

Adopting a systems approach to biomass management is hence both a scientific necessity and a policy imperative. Although the way forward is relatively poorly understood and undoubtedly significant challenges will present themselves, the potential benefits of a successfully applied systems approach are transformative, promising more resilient ecosystems, balanced resource uses, and, hopefully, a more sustainable way of living together.

Box 8. Toward responsible biomass use in Europe

At the Joint Research Centre, the ongoing Integrated Bioeconomy Land Use Assessment[8] project is one on several timely examples of a focused effort to build up a systems approach on biomass futures in Europe. The project deploys a multi-scale and multi-domain accounting methodology to navigate, in broad strokes, the breadth of interactions between society and local ecosystems.

In contrast to some conventional futures-oriented modelling efforts, which often aim to outline trends or explore probable outcomes based on existing empirical data, the project engages more of a post-normal science approach. Post-normal science, a mode of science designed for contexts where "facts are uncertain, values are contested, stakes are high, and decisions are urgent," is especially well-suited for analysing complex systems like those related to the bioeconomy. While "conventional models" are essential for understanding system linkages and informing decision-making in social-ecological systems, they represent just one of several valuable approaches.

Instead of focusing on questions like "What future is most probable?" or the sometimes "Which future is best?", the project probes further along the lines of "What futures are possible and preferable?". It focuses not on generating a definitive vision of the future but rather on improving the quality of the continuous process by which that imaginary is cocreated.

See European Commission: Joint Research Centre, Renner, A., Giuntoli, J., Barredo, J.I., Ceddia, M., Guimaraes Pereira, Â., Paracchini, M.L., Quaglia, A.P., Trombetti, M., Vallecillo, S., Velasco Gómez, M., Zepharovich, E. and Mubareka, S.B., Integrated assessment of bioeconomy sustainability, Publications Office of the European Union, Luxembourg, 2025, https://data.europa.eu/doi/10.2760/2356728, JRC136919.

2.4.3 Key messages

- A systems approach, considering the interconnectedness of natural ecosystems and societal activities, is essential for addressing sustainability and bioeconomy goals;
- Systems approaches emphasise understanding the interconnections between components rather than the components in and of themselves, acknowledging the entanglement of biomass processes with broader social-ecological dynamics;
- Effective biomass governance requires navigating competing priorities, accounting for synergies and dysergies between long-term climate neutrality, environmental sustainability, resource use efficiency and economic prosperity, the profile of societal wants, and so forth;
- Translating system-wide scientific understanding into actionable policy insight is a substantial challenge that requires scientific models that are integrative and progressively disclosable;
- Incorporating a broad range of stakeholders into the deliberations over decisions to be made is essential for considering multiple knowledges and developing strategies suited to real-world complexities and uncertainties.

[8] *https://knowledge4policy.ec.europa.eu/projects-activities/integrated-bioeconomy-land-use-assessment_en*

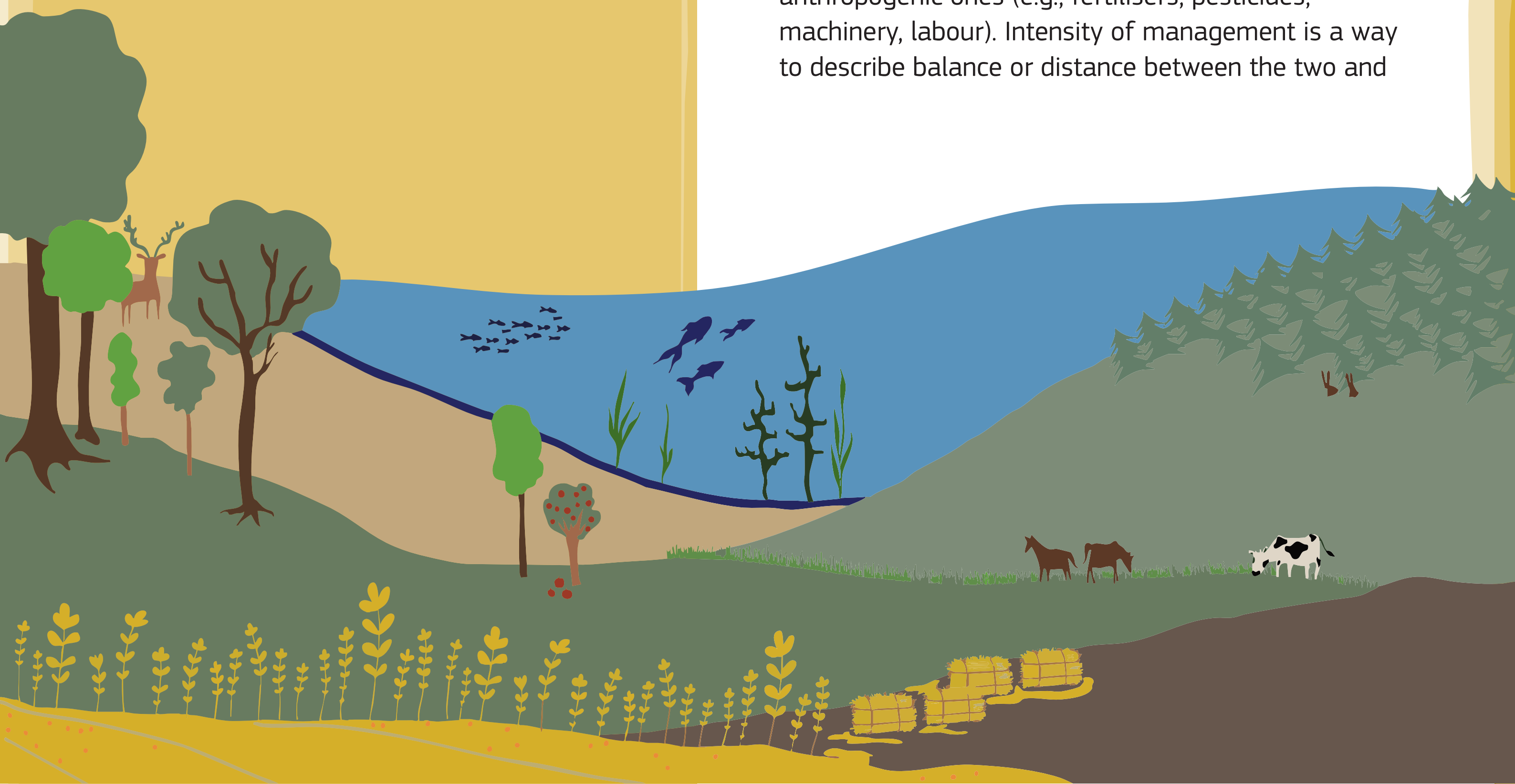
3 Biomass production, supply and uses

3.1 Agriculture

3.1.1 Agroecosystem condition

Maria Luisa Paracchini and Marco Trombetti

Agroecosystems originate from the interaction between socio-economic and ecological processes with the objective to produce biomass for human direct or indirect use and consumption, and as such are true social-ecological systems. Crop production is based on the exploitation and use of natural resources (e.g., soil, rain, sunlight, biodiversity) and anthropogenic ones (e.g., fertilisers, pesticides, machinery, labour). Intensity of management is a way to describe balance or distance between the two and



is characterising the agroecosystem as being close to or distant from a semi-natural state (see Box 9). Examples of the two extremes of the scale are semi-natural grasslands on one side and intensive mono-cropping systems on the other. In the intensification scale, there is a point above which environmental costs become unsustainable. This concerns not only the negative impacts on air and water quantity and quality, soil health, and other parts of the ecosystem (plant, fungi and animal species including soil biota and above-ground species), but as well depletion of natural resources. Thus, besides impacting on other ecosystems (e.g., causing chemical and nutrient pollution), intensification processes, when stretched over certain thresholds, lead to degradation of agroecosystems, decrease their resilience to climate change and in the long term jeopardise their capacity to generate biomass and healthy food for human use and consumption (Vallecillo et al., 2022).

Box 9. Thresholds for sustainable production

The JRC is working on a methodological framework for assessing reference levels defining when agroecosystems within Europe are in good condition or when they are in need of restoration. Various indicators are identified describing six key ecosystem characteristics, that include abiotic (e.g., soil erosion), biotic (e.g., percentage of farmland species with good population status), and landscape-level indicators (e.g., crop richness or number of distinct crops in a reference area) (Vallecillo et al., 2022). The approach applied is to normalize the indicators, so they become comparable, then to compute a final index by aggregating all of them. The computed value will fall somewhere between a worst condition, equivalent to 'maximally degraded' condition and 'optimal' condition. If a so-called "reference value" is established, it may be used as the basis upon which to quantify deviations. For example, if the scale is 0-1, with 0 referring to very bad condition and 1 as very good, a "reference value", otherwise known as a target for restoration, may lie at a value of 0.6 (this is the threshold that is defined for the Ecological Quality Ratio (EQR) under the Water Framework Directive (WFD) and for the condition variables in Jakobsson et al. (2020)).

There are two main challenges to this approach: first, optimal and pessimal values have to be identified per each indicator. Second, setting a reference values for good condition (the threshold value) is not an easy task and requires considerable expertise and deliberation.

The JRC is taking a spatially explicit approach, which provides results at the highest possible resolution (e.g., 1 km pixel), to support the targeting of restoration measures. Preliminary findings suggest that much of Europe's cropland falls in moderate condition, while grasslands show slightly better condition outcomes, influenced by soil erosion and nutrient balance.

This work is being conducted within the framework of the Integrated Land Use Assessment project (see Box 8, Section 2.4).

In a frame of sustainable use of biomass, the concept of ecosystem condition is key. It is defined at UN level as the quality of an ecosystem measured in terms of its abiotic and biotic characteristics (United Nations, 2021), and even more interesting for the purpose of bioeconomy is the concept of "good condition". In the case of agroecosystems, the latter is intended as a state characterized by a regenerative, non-depleting and non-destructive use of natural resources. An agroecosystem in good condition is expected to bring long-term social-ecological resilience, which is the capacity to adapt or transform in the face of change in social-ecological systems, including climate change, and particularly of unexpected changes, in ways that continue to support human well-being (Chapin et al., 2010). Ecosystems, in fact, provide services to society contributing to human well-being, while socio-economic systems drive changes in ecosystems with positive and/or negative impact on their condition.

Good condition is resulting from sustainable management of biotic and abiotic resources. It supports biodiversity and ecosystem functions, processes and structure. Moreover, a good condition is the foundation for the supply of critical ecosystem services, including food provision, carbon sequestration and soil, water and climate regulation (Vallecillo et al., 2022). Importantly, an agroecosystem in good condition will continue to support agricultural production and the supply of ecosystem services for the benefit of present and future generations.

A structured set of indicators is needed to assess to which extent EU agroecosystems are in good condition. Such set should describe the six key ecosystem attributes that contribute to the overall ecosystem integrity (Gann et al., 2019): physical, chemical, compositional, structural, functional, landscape. A process of normalisation and aggregation of nine indicators (Table 3), available in a geospatial format, allows providing a first estimate of condition of agroecosystems.

Table 3. Agroecosystem condition typology framework: list of available indicators (in grey the ones currently under development).

Ecosystem condition typology (ECT)		Condition indicators	
Group	Class	Cropland	Grassland
Abiotic	Physical	Soil depth	
	Chemical	Pesticide residuals Nitrogen balance (surplus) P balance Soil Organic Carbon in mineral soils HMs content (contamination and deficit)	
Biotic	Compositional	Percentage of farmland/grassland species with good population status Abundance of farmland/grassland bird species Damage by Invasive Alien Species	
	Structural	Share of landscape features	
	Functional	Share of fallow land	Phyto-toxic Ozone Dose
Landscape and seascape	Landscape	Crop richness	Connectivity of grassland patches

Source: JRC, own elaboration. To be noted that indicators may not be reported in the table when thresholds for good condition are not available in scientific literature or other sources (e.g., share of small woody features in relation to grasslands).

The JRC is currently in the process of assessing agroecosystem condition in Europe, through the Integrated Bioeconomy Land Use Assessment project[9]. According to first results, approximately 24% of the agroecosystems is in good condition, while roughly 53% is in moderate condition, meaning that it is below the threshold for good condition, but can be restored with limited efforts. The remaining 23% is in bad condition.

3.1.2 Agriculture production and supply

Iacopo Cerrani

The bioeconomy policies play a key role in the green and fair transition in Europe by, inter alia, taking a cross-sectoral perspective to improve policy coherence and by identifying and resolving trade-offs, for example on land and biomass demands. However, an increased focus on how to better manage land and biomass demands to meet environmental and economic requirements in a climate neutral Europe is needed (European Commission, 2022).

Since the main source of biomass is agriculture for food and feed purposes, quantifying the available agricultural biomass is key to ensure adequate and nutritious food, as well as other biomass-demanding sectors for bio-based products. This assessment may also help maximise co-benefits, such as production of biomass and, for instance, mitigation of climate change, fair living and working conditions for primary producers, and enhancing biodiversity while safeguarding and benefiting from ecosystem services.

The work presented in this study aims to assess the available biomass from agriculture following the blueprint established with the work published in García-Condado et al. (2019).

In this study, the quantification of agricultural biomass and residue production for the complete time series (2000-2022) with updated statistics is conducted. Furthermore, the impact of the different drivers determining the variability in production and yield, based on the new time series, are estimated and a detailed analysis of the most cultivated crops, with a view on their future availability in EU, is provided.

The agricultural biomass database covers the years from 2000 to 2022, but the main results are given as an average over the reference period of the last five years 2018-2022. Results and analysis are provided by crop, both at Member State and at EU level. In this report, results are presented only for EU-27.

3.1.2.1 Agricultural biomass production – statistical based assessment

The assessment of agricultural biomass includes the major crops cultivated in Europe, grouped in 9 main categories: cereals, sugar and starchy crops, oil-bearing crops, plants harvested green, permanent crops, vegetables, pulses, industrial crops and energy crops.

Total agricultural biomass production is estimated by differentiating two main components:

- Economic production: primary products, i.e. grains, fruits, roots, tubers, etc.;
- Residue production: secondary products, i.e. leaves, stems and husks.

Economic production is assessed by processing crop production statistics compiled by Eurostat and the National Statistics Offices to generate a consistent archive of all commodities for the Member States across all administrative levels (NUTS 0-3). The main steps of the processing algorithm consist in homogenising, filtering, filling gaps and merging crop statistics from the different data sources. In this update, figures for economic production normalised at standard values of moisture content (m) are considered.

On the other hand, there are no systematic agricultural statistics for residue production. Therefore, the estimates are deduced from crop production figures using empirical models, established from an extensive dataset of observations for each individual crop (as described in García-Condado et al., 2019) based on the

[9] *https://knowledge4policy.ec.europa.eu/projects-activities/integrated-bio-economy-land-use-assessment_en*

relationship between crop economic yield (*Y*), provided by crop statistics, and residue yield (*R*), through a parameter named *Harvest Index* (*HI*):

Equation 1. Estimate of crop residues

$$R=YHI-Y$$

Residue production is then calculated by multiplying the derived residue yields by crop area, and aggregating values to provide results at different administrative levels.

No estimation of crop residues is made for plants harvested green, vegetables and energy crops, because all aboveground biomass is considered as economic production for these categories.

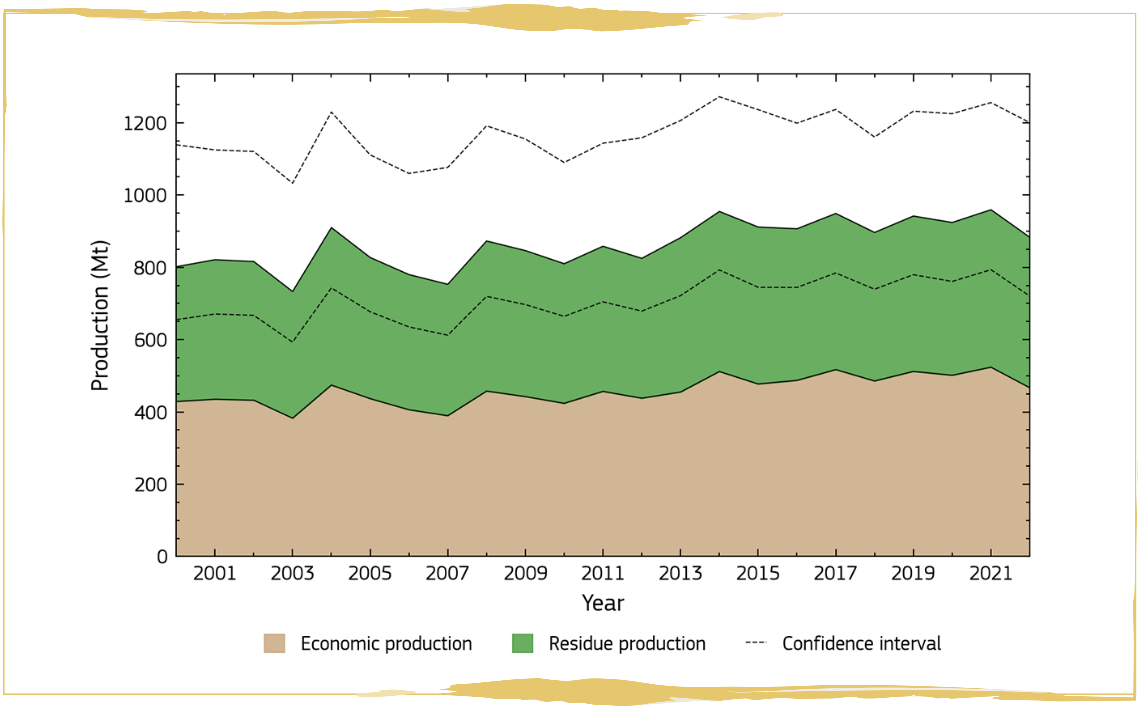
While temporary grasslands are present in the presented biomass estimation, reliable and timely estimates on permanent grassland and their management practices are not present on a European scale. However, many initiatives such as EUROSTAT's SAIO implementation, the planned satellite-based CLMS grassland layers or ground surveys like LUCAS and EMBAL were designed to have specific information about grasslands in Europe. Such data sources are crucial for accurate models and methods for prediction and estimation of permanent grasslands. Based on these the JRC is currently implementing and testing different methods and models to establish a European wide grassland productivity forecasting system.

3.1.2.1.1 Contribution of crop groups

The total annual agricultural biomass production in the European Union for the reference period (2018 – 2022) is estimated at 921 Mt D.M. yr^{-1} (million tonnes dry matter per year) in the EU, where 54% are economic production and 46% are residues. As reported in Figure 3, the production has slightly increased over the years, as the 2000-2004 average of agricultural biomass was around 817 Mt D.M. yr^{-1}.

Considering the last five years, a significant decrease is observed for the years 2018 and 2022 because of adverse weather conditions. As a matter of fact, in 2018 and in 2022 a more wide-ranging drought affected yields in Europe (JRC MARS Bulletin, June 2018, June 2022 and September 2022)[10].

Figure 3. Evolution of agricultural biomass production (economic production and residues in Mt dry matter per year) in the EU from 2000 to 2022.

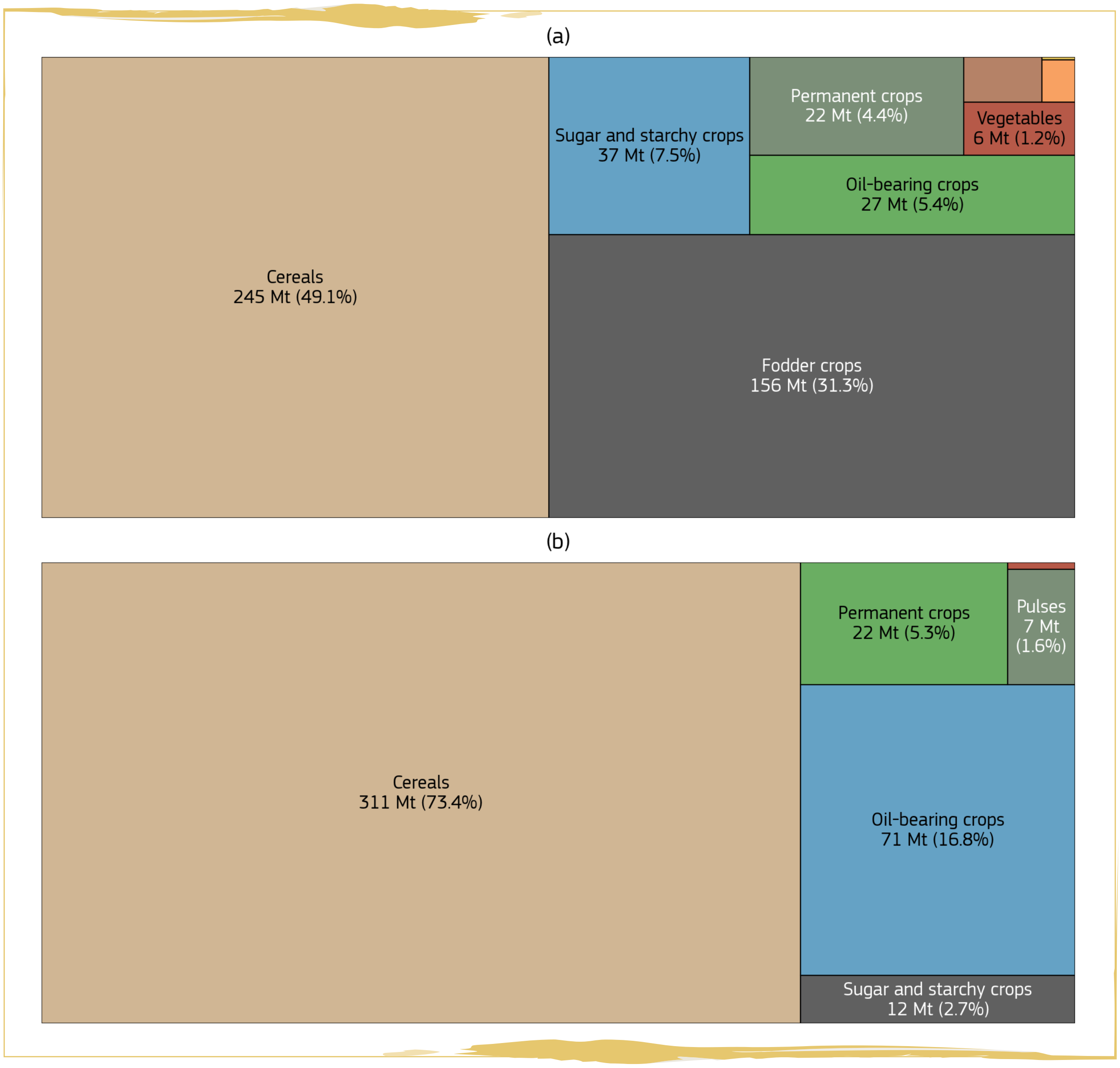


Source: JRC, based on Eurostat data.

[10] *https://agri4cast.jrc.ec.europa.eu/BulletinsArchive*

The last 5-year average shows that cereals (245 Mt D.M. yr^{-1}) and plants harvested green (156 Mt D.M. yr^{-1}) dominate economic production, jointly accounting for about 80% of total biomass production, followed by sugar and starchy crops (37 Mt D.M. yr^{-1}), and oil-bearing crops (27 Mt D.M. yr^{-1}). Cereals (311 Mt D.M. yr^{-1}) rank first also for residue production, second place for oil-bearing crops (71 Mt D.M. yr^{-1}). In both of these crop groups, the biomass of residues is higher than economic production (Figure 4).

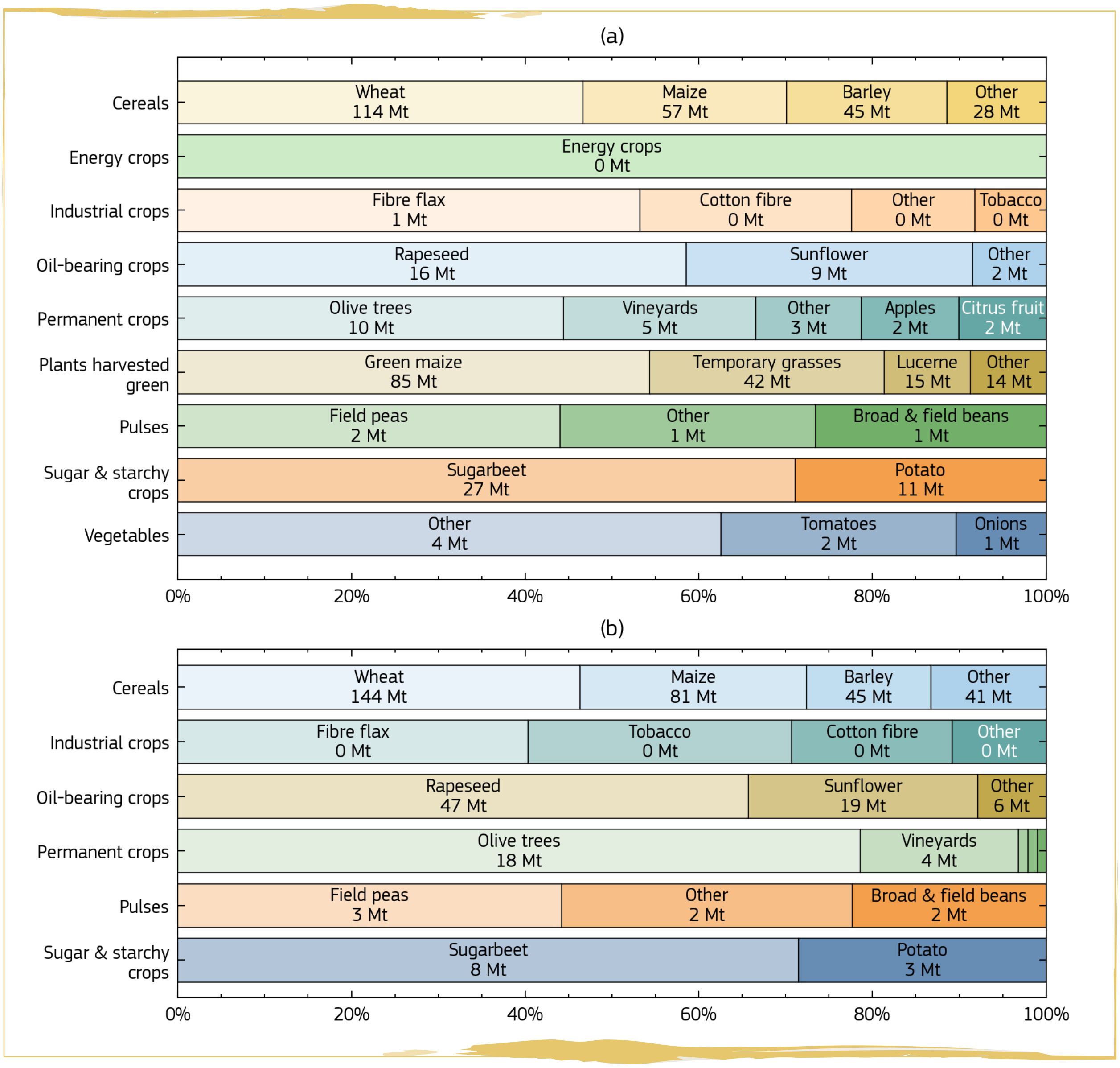
Figure 4. Economic production (above) and residue production (below) in the EU-27 (expressed in Mt dry matter per year) and the shares for each crop group. Average values over the reference period 2018-2022.



Source: JRC, own elaboration.

When investigating the distribution of each crop in detail, it is noted that the greatest contribution in terms of biomass is provided by wheat (whose average production exceeds 100 Mt D.M. yr^{-1} for both economic and residue), followed by green maize (84 Mt D.M. yr^{-1}), maize (57 Mt D.M. yr^{-1}) and barley (45 Mt D.M. yr^{-1}) for economic production. Maize (81 Mt D.M. yr^{-1}), rapeseed (47 Mt D.M. yr^{-1}) and barley (45 Mt D.M. yr^{-1}), on the other hand, rank second, third and fourth respectively for residue production (Figure 5).

Figure 5. Economic production (above) and residue production (below) in the EU-27 (expressed in million tonnes dry matter per year) and the shares for each crop within the respective crop groups. Average values over the reference period 2018-2022.



Source: JRC, own elaboration.

3.1.2.1.2 Distribution by Member States

About 70% of both the economic produce and their residues (358 Mt D.M. yr^{-1} and 296 Mt D.M. yr^{-1}respectively) is produced in six Member States: France, Germany, Italy, Poland, Spain and Romania.

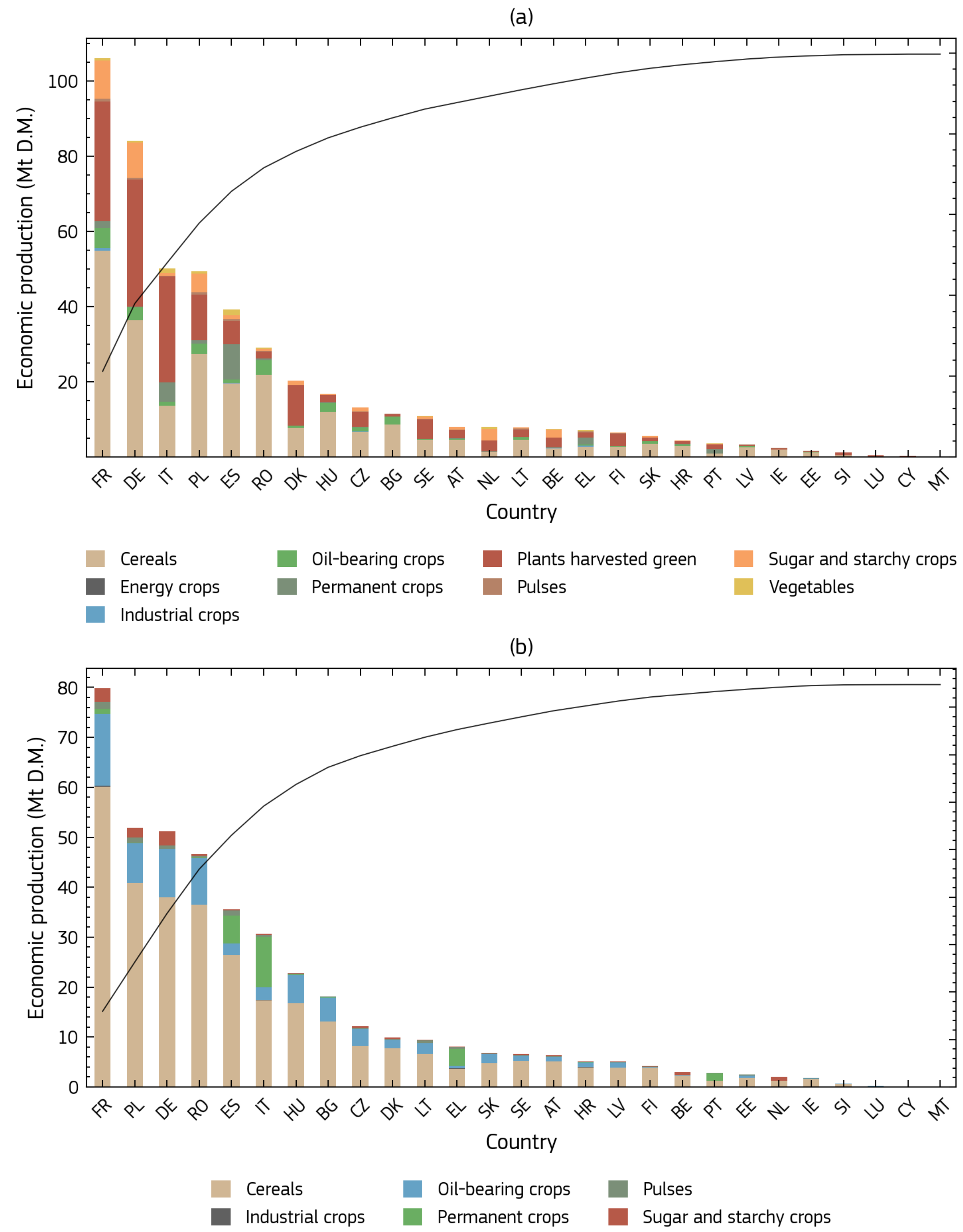
France is the first producer, for both economic and residue production. Germany is second for economic and third for residue production. In the last two years Poland has overtaken Germany in residue production and ranks fourth for economic production, comparable to Italy.

Romania is the fourth contributor to EU residues production whereas it only occupies the sixth place in terms of economic production. As a matter of fact, Romania is a large producer of maize that can produce large amounts of biomass in leaves and stems, even when grain yields are average or low. On the contrary, Italy is the third contributor to EU economic production but the sixth contributor to residue production, since the major production derives from plants harvested green that account only for the economic part (Figure 6).

Regarding residue production, after cereals the contribution of oil-bearing crops is most relevant in most Member States, except for Spain, Italy, Greece and Portugal where pruning residue derived from permanent crops prevail due to the extended cultivation of olive trees and vineyards that can be found in these countries.

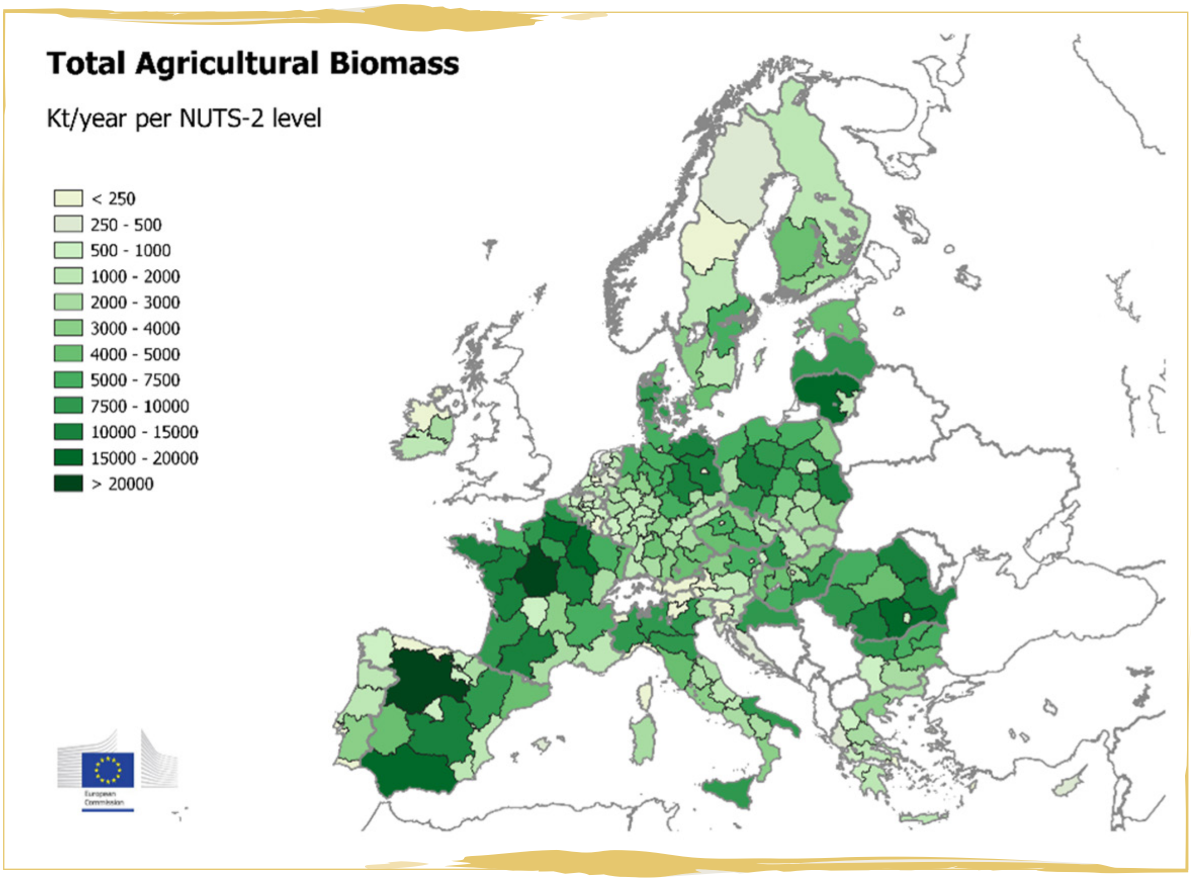
Moreover, the most productive regions in each Member State can be seen in Figure 7, which represents the distribution across EU NUTS-2 regions of the total aboveground biomass available from the agricultural sector.

Figure 6. **Economic production and residue production from the main crop groups per Member State, expressed in million tonnes of dry matter per year. Average values over the reference period 2018-2022.**



Source: JRC, own elaboration.

Figure 7. **Distribution of agricultural biomass production (in thousand tonnes dry matter per year) across the EU (NUTS-2 regions) for the reference period 2018-2022.**



Source: JRC, own elaboration.

3.1.2.1.3 Inter-annual variability in crop residue production

The inter-annual variability of crop residue production has been quantified using the coefficient of variation CV:

Equation 2. Coefficient of variation

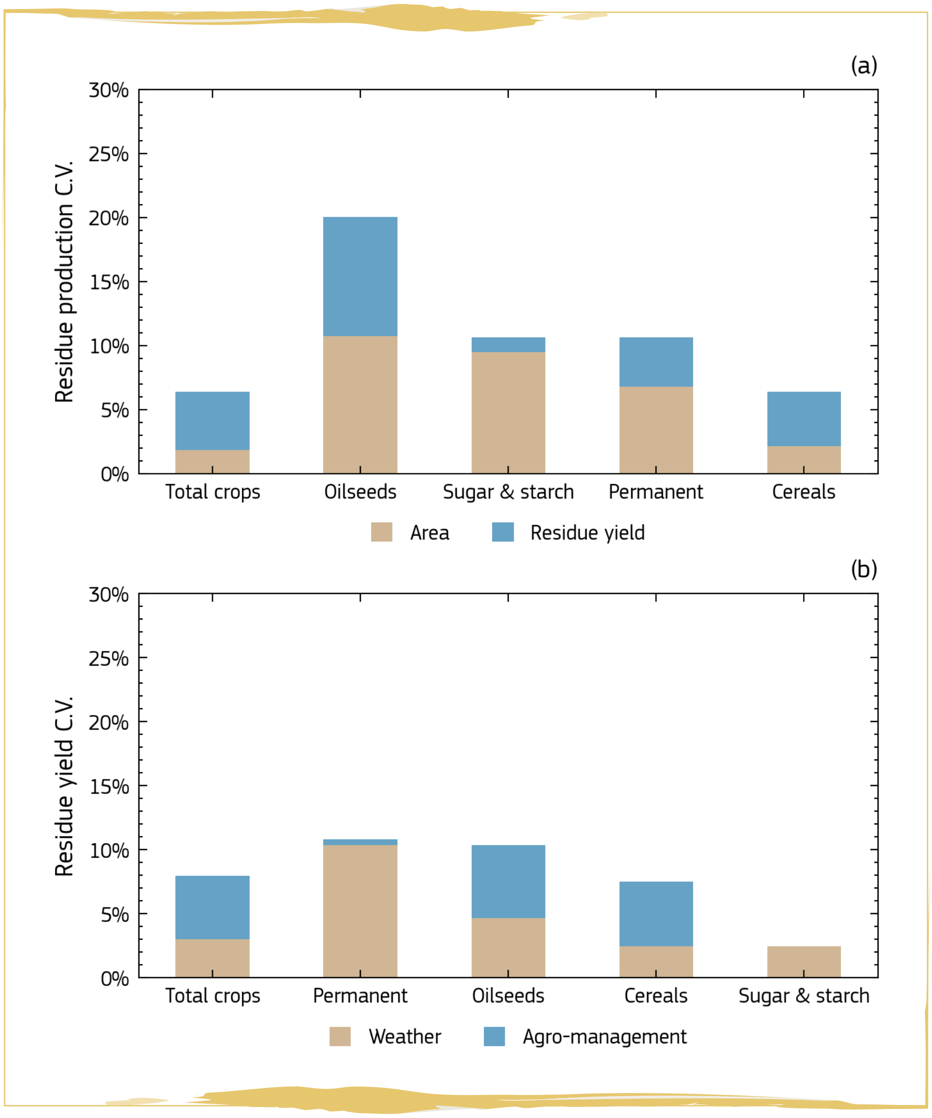
$$CV_i\ (\%) = \sigma_i/\mu_i \times 100$$

The explanatory factors to this variability are identified in changes in area (A), weather (W) and agro-management drivers (T).

The computation of these factors has been performed by reproducing the approach described in García-Condado et al. (2019). First, the fraction of the variance in residue production that is attributable to changes in area and residue yields (R) is quantified by conducting a multiple linear regression analysis. Then, the variance of R is decomposed in the factors T and W, with a linear trend model over the considered period (2000-2022). The resulting coefficient of determination r2 and its complement to unit 1-r2 are interpreted as the proportion of the variance of R that is explained by T and W, respectively.

The inter-annual variability for residue production (Figure 8a) considering all crops is greater than 6%, and would be primarily driven by changes in residue yield, with a minor influence of changes in area. Being the most important contributors to total production, cereals present similar values. Conversely, the inter-annual variability of residues from oil seed crops, permanent crops, sugar and starchy crops is much higher and mostly affected by area changes, compared to cereals. The variability of residue yield is largely due to agro-management factors for cereals and oilseed crops (Figure 8b), whereas the effect of weather conditions explains the variance in residue yield for permanent crops and sugar crops.

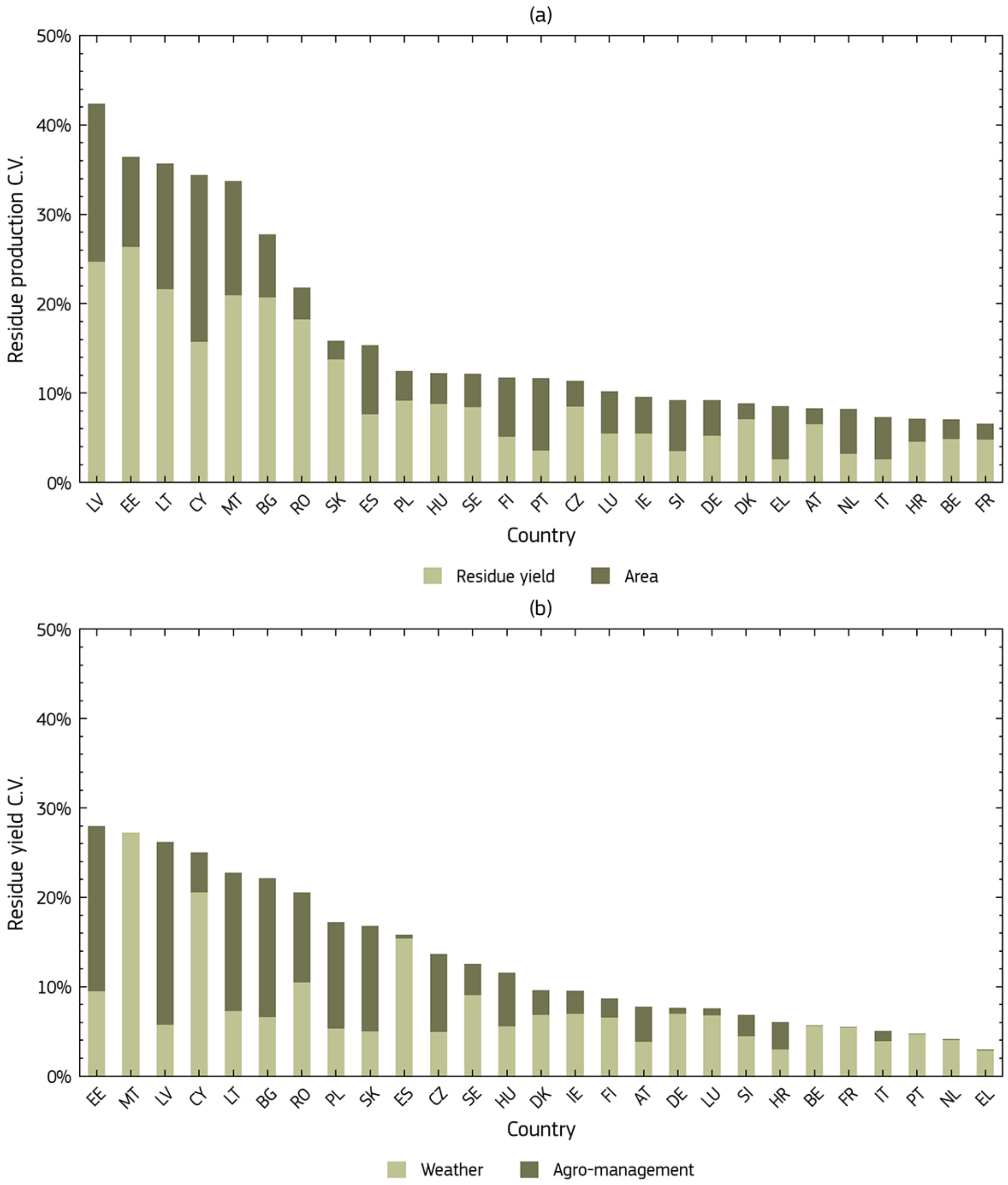
Figure 8. **Inter-annual variability – expressed as coefficient of variation in percentage, CV% – of (a) residue production; and (b) residue yield at EU level from 2000 to 2022, calculated for the complete set of crops evaluated (Total crops) as well as for each crop group separately: cereals, oilseeds, permanent, sugar and starch crops.**



Source: JRC, own elaboration.

The estimated inter-annual variability of biomass production from crop residues in most of the EU countries is quite low (below 10%), while in the Baltics (i.e. Lithuania, Latvia and Estonia), Romania and Bulgaria the variability exceeds 20% (Figure 9a). The variability of residue production is primarily driven by variations in residue yield, rather than changes in area. Among the top producers, only in Italy is the relevance of crop area changes higher than the residue yield, as well as in Spain, where there is an equal contribution of area and yield changes. The cause of the variability of residue yield, whether they are due to agro-management factors or weather conditions, varies from country to country, with no clear pattern (Figure 9b).

Figure 9. Inter-annual variability – expressed as coefficient of variation in percentage, CV% – of (a) residue production); and (b) residue yield for each Member State from 2000 to 2022, calculated for the complete set of crops evaluated (Total crops).



Source: JRC, own elaboration.

3.1.2.2 Key messages

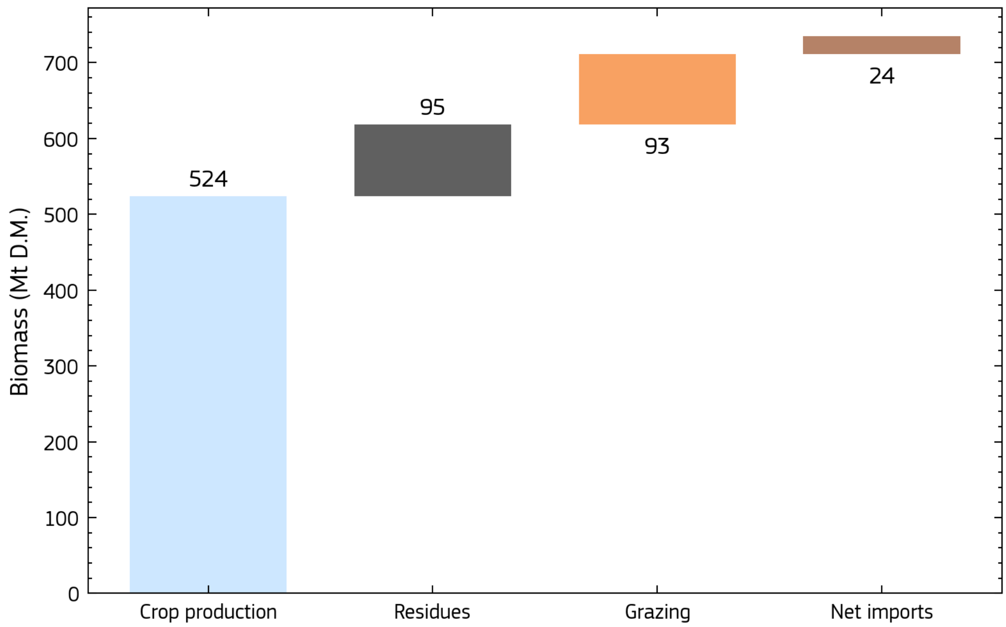
- Agriculture is the primary source of biomass in EU and the total biomass is shared almost equally between economic and residue production;
- Approximately 70% of the agricultural biomass is produced in six Member States, namely France, Germany, Italy, Poland, Spain and Romania;
- Wheat and maize are the major contributors to agricultural biomass. For both crops, residual biomass is higher than the economic part;
- During the last 22 years, the biomass available from agriculture has increased thanks to, depending on the crop and country, changes in the cultivated areas or improvements in agro-management practices which impacted crop yields;
- Based on the information provided, it is expected that biomass production, including both economic and residue production, willslowly increase and eventually reach a plateau in the coming years

3.1.3 Food and feed uses of agricultural biomass

Patricia Gurría & Robert M'barek

In 2021, the EU-27's available agricultural biomass supply amounted to approximately 736 Mt D.M. (million tonnes of dry matter). This biomass quantity was mainly sourced in the form of crops, but also included net imports, residues harvested to be used as feed or for other purposes, and grazed biomass (Figure 10). 78% of the agricultural residues were left on the fields to ensure soil fertility and are therefore not considered available biomass.

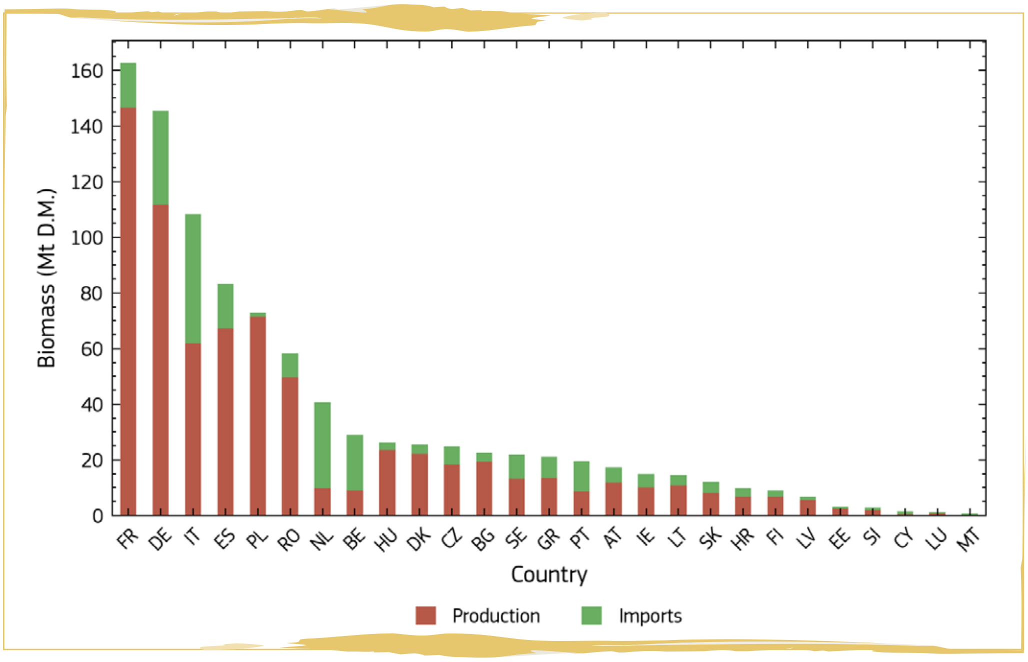
Figure 10. Agricultural biomass origin in the EU-27, net trade, 2021 (Mt D.M.).



Source: JRC Biomass Flows (2025).

Most of the available biomass was produced within the EU, with only 3% of it being net imports. Trade by EU MSs, including intra-EU trade, was considerably higher and showed significant variation across Member States, as shown in Figure 11:

Figure 11. **Domestic and imported agricultural biomass, net trade, 2021 (Mt D.M.).**

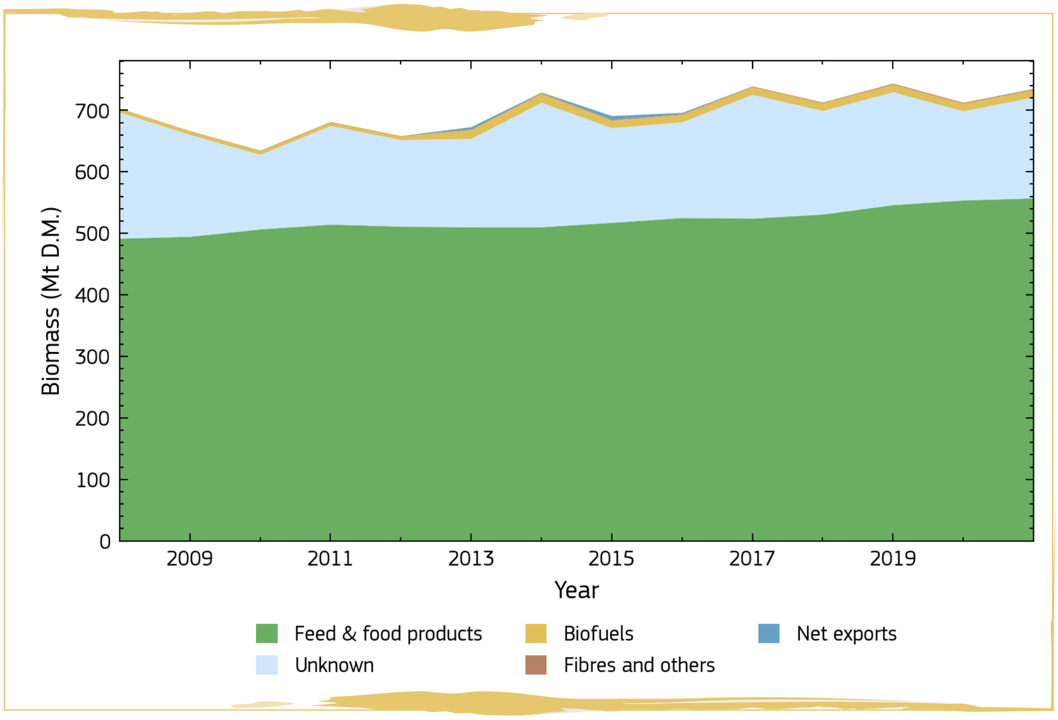


Source: JRC Biomass Flows (2025).

In 2021, 76% of the total agricultural biomass supply (net trade) was used as food and feed. Another 24% of the available biomass is used for non-food purposes or discarded and cannot be allocated to a specific category (Figure 12). The inability to allocate the final use of almost a quarter of the agricultural biomass results in non-food use quantities being underestimated.

Figure 12. **Agricultural biomass uses, net trade, 2021 (Mt D.M.).**

Note: Exports refer to exports of agricultural material or live animals and do not include food exports.



Source: JRC Biomass Flows (2025).

Within the EU-27, Germany (108 Mt D.M.) and France (82 Mt D.M.) were the biggest producers of food and feed in 2021. Table 4 shows the proportion of biomass dedicated to producing animal- or plant-based food in each Member State.

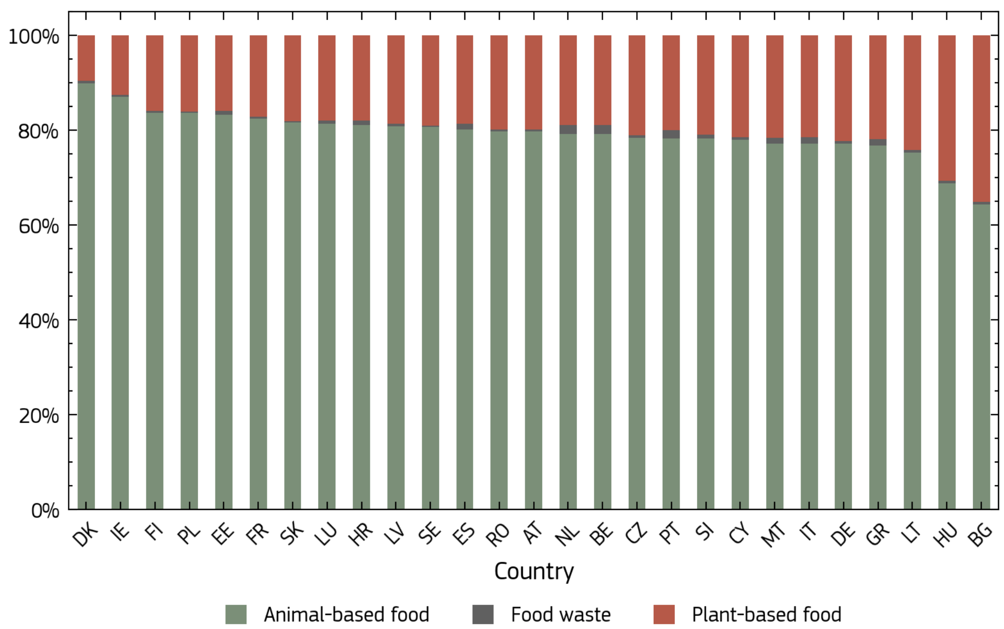
Table 4. Biomass used for food purposes, net trade, 2021 (1000 t D.M.).

Country	Animal-based food		Food waste (before consumption)		Plant-based food		Total
Germany	83,086	77.1%	570	0.5%	24,110	22.4%	107,766
France	67,247	82.4%	359	0.4%	13,989	17.1%	81,595
Italy	50,858	77.1%	891	1.4%	14,176	21.5%	65,925
Spain	44,578	80.1%	653	1.2%	10,399	18.7%	55,630
Poland	43,371	83.6%	147	0.3%	8,364	16.1%	51,882
Romania	18,140	79.7%	105	0.5%	4,518	19.8%	22,763
Netherlands	18,648	79.2%	418	1.8%	4,475	19.0%	23,541
Belgium	13,415	79.2%	315	1.9%	3,206	18.9%	16,936
Hungary	8,837	68.7%	79	0.6%	3,946	30.7%	12,862
Czechia	9,646	78.4%	53	0.4%	2,604	21.2%	12,303
Portugal	8,949	78.3%	197	1.7%	2,287	20.0%	11,433
Austria	8,874	79.7%	51	0.5%	2,211	19.9%	11,136
Greece	8,044	76.7%	144	1.4%	2,304	22.0%	10,492
Sweden	9,032	80.6%	40	0.4%	2,132	19.0%	11,204
Denmark	11,566	89.9%	59	0.5%	1,242	9.7%	12,867
Ireland	8,337	86.9%	49	0.5%	1,205	12.6%	9,591
Bulgaria	4,985	64.3%	45	0.6%	2,722	35.1%	7,752
Finland	5,696	83.6%	29	0.4%	1,085	15.9%	6,810
Slovakia	4,573	81.5%	18	0.3%	1,018	18.1%	5,609
Croatia	3,698	81.0%	42	0.9%	824	18.1%	4,564
Lithuania	2,789	75.2%	19	0.5%	900	24.3%	3,708
Slovenia	1,674	78.2%	18	0.8%	449	21.0%	2,141
Latvia	1,681	80.7%	11	0.5%	390	18.7%	2,082
Estonia	1,355	83.2%	13	0.8%	261	16.0%	1,629
Cyprus	875	78.0%	5	0.4%	242	21.6%	1,122
Luxembourg	624	81.4%	5	0.7%	138	18.0%	767
Malta	399	77.2%	6	1.2%	112	21.7%	517

Source: JRC Biomass Flows (2025).

Of the biomass that is consumed as food and feed, approximately 80% of the total is used as animal feed, for the production of animal-based food (either for domestic consumption or for export), while the rest is directly consumed as plant-based food or is food wasted before consumption (vegetal biomass at the processing and manufacturing stage) (Figure 13). One third of the collected[11] crop residues is used for feed and bedding and horticulture purposes. The remaining two thirds are discarded or used in downstream sectors (material uses or bioenergy). The reader is invited to Section 3.1.4 for further details on how much of this secondary biomass is used as bioenergy, but quantities discarded and used for biomaterials are not well reported and are therefore unknown to us at EU level.

Figure 13. Food production shares, net trade, 2021 (1000 t D.M.).

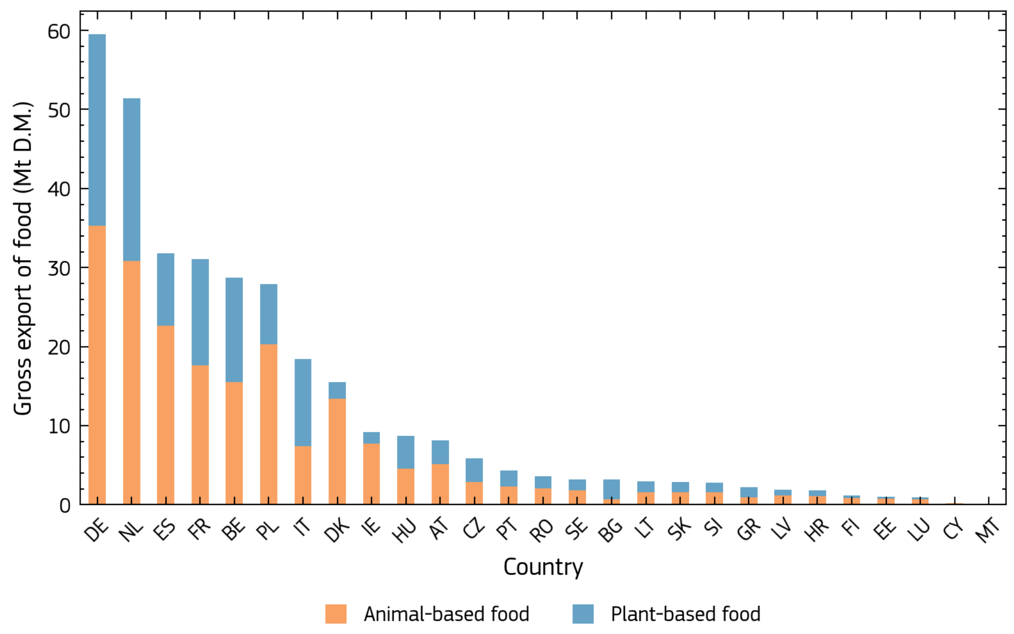


Source: JRC Biomass Flows (2025).

In terms of food exports, Germany, The Netherlands and France are the EU's biggest exporters of food (in tonnes of dry matter, including intra-EU exports). However, Denmark and Ireland are the Members State with the highest share of animal-based food exports of their total exports. On the other hand, Bulgaria, Italy and Greece export the highest share of their food as plant-based food (Figure 14).

[11] Roughly 22% of residues are collected

Figure 14. **Gross exports of food, gross trade, 2021 (Mt D.M.).**



Source: JRC Biomass Flows (2025).

3.1.4 Biofuel uses of agricultural biomass

Vincenzo Motola, Michele Canova, Nicolae Scarlat

Directive (EU) 2018/2001 on the promotion of the use of energy from renewable sources (RED II), in its Article 2, further defines different fuels produced from biomass (biobased fuels) as follows:

- biomass fuels are gaseous and solid fuels;
- biogas are gaseous fuels;
- bioliquids are liquid fuels for energy purposes other than for transport, including electricity and heating and cooling;
- biofuels are liquid fuels for transport;
- advanced biofuels are biofuels produced from the feedstock listed in Part A of the RED Annex IX;
- low indirect land-use change-risk biofuels, bioliquids and biomass fuels are biofuels, bioliquids and biomass fuels, the feedstock of which was produced within schemes which avoid displacement effects of food and feed-crop based biofuels, bioliquids and biomass fuels through improved agricultural practices as well as through the cultivation of crops on areas which were previously not used for cultivation of crops, and which were produced in accordance with the REDIII sustainability criteria.

In this context, Directive 2008/98/EC on waste in its Article 3 provides the following additional relevant definition:

- bio-waste means biodegradable garden and park waste, food and kitchen waste from households, offices, restaurants, wholesale, canteens, caterers and retail premises and comparable waste from food processing plants.

Three different main categories of biofuels exist based on feedstock or technology:

- Conventional biofuels: biofuels from starch or sugar crops and oil crops (food and feed crops) cultivated on agricultural land as a main crop. The production of these fuels is capped;
- Advanced biofuels: biofuels from feedstock listed in Part A of Annex IX of the RED, such as wastes, residues, co-products or any cellulosic feedstock that are not in competition with the food and feed sector and do not lead to land use change. These fuels are expected to become the only way to expand biobased fuels production, following the RED sustainability and GHG reduction criteria in place;
- Mature waste biofuels: biofuels from wastes, residues and co-products that can be processed into biofuels with mature technologies, listed in Part B of Annex IX of the RED. The production of these fuels is also capped.

Biofuels are liquid fuels used for transport. Biofuels are produced nowadays mostly from food and feed crops (oil, sugar and starch crops), waste and residues of biological origin from agriculture and forestry, other industrial wastes, as well as the biodegradable fraction of municipal waste. These biofuels derived from agriculture, within the limitations and respecting the criteria of the RED, serve as a renewable alternative to fossil fuels in the transport sector, contributing to the renewable energy targets, helping to, reduce greenhouse gas emissions and to the EU's security of fuels supply.

The key points to take away are:

- Currently, biofuels are produced mostly from food and feed crops; their production at EU level is decreasing since 2018, when the Renewable Energy Directive entered into force;
- Several advanced biofuel technologies are being developed and are slowly progressing toward reaching commercialisation;
- Sustainability and GHG reduction criteria are in place in the EU legislation to ensure sustainable biofuel production and alleviate some potential negative impacts;
- Advanced biofuels are expected to play a key role in the decarbonisation of hard to decarbonize sectors such as aviation and maritime sectors and possibly in heavy-duty road transport (see section 6.2).

3.1.4.1 Conventional and advanced biofuels production in the EU

As for the EU biofuel production in 2023, four technologies have reached market maturity (Fatty Acid Methyl Esters – FAME; HVO/HEFA, conventional ethanol and biomethane) and are widely deployed in Europe (Table 5).

Table 5. **Capacity of biofuel production in 2023 in Europe.**

Fuel/pathway	2023 production capacity
FAME (all feedstock categories)	12 Mt y^{-1}
HVO/HEFA (all feedstock categories)	5.1 Mt y^{-1}
Conventional ethanol	5.8 Mt y^{-1}
Biomethane from anaerobic digestion	3.8 Gm^3 (billion cubic metres)
Advanced ethanol[10]	200 kt y^{-1}
ATJ	-
Gasification + methanol/DME	600 t y^{-1}
Gasification + SNG	2000 t y^{-1}
Gasification + FT – diesel	-
Pyrolysis – bio-oil	100 kt y^{-1}
HTL – biocrude	1,400 t y^{-1}

Source: European Commission, 2024.

Splitting current biofuels production among food/feed feedstocks, Annex IX Part A, and Annex IX Part B feedstocks is difficult to assess since different categories are often reported combined. Estimated current production per feedstock group is displayed in Table 6.

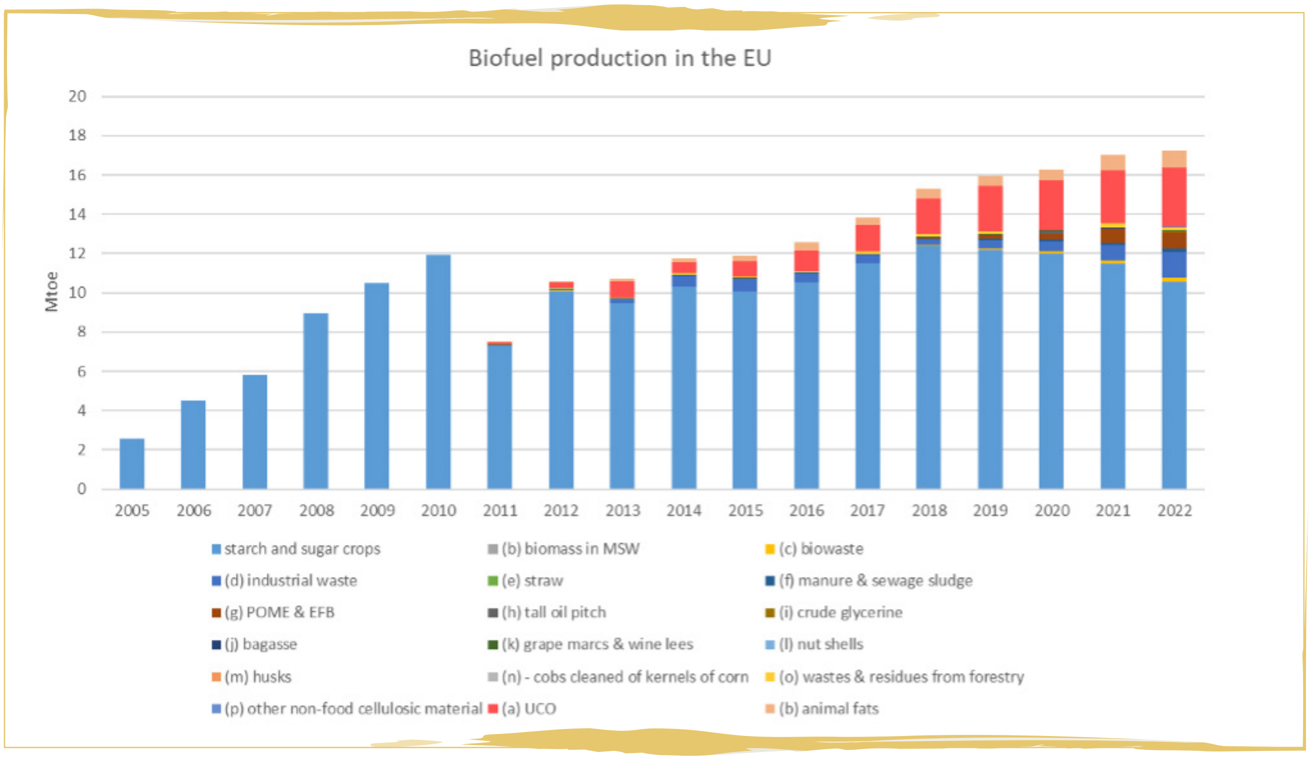
Table 6. **Estimated current production per feedstock group in 2023 in Europe.**

Fuel/pathway	Estimated current production [Mtoe y^{-1}]	Share of total [%]
Conventional biofuels		**63**
FAME	4.60	
HVO	5.25	
Ethanol	3.16	
Annex IX Part A		**22**
FAME	1.06	
HVO	0.14	
Ethanol	0.13	
Pyrolysis – bio-oil	0.04	
Biomethane from anaerobic digestion	3.20	
Annex IX Part B		**15**
FAME and HVO	3.09	

Source: European Commission, 2024.

The evolution in use of feedstocks as defined and listed in the RED annex IX is reported in Figure 15.

Figure 15 . The evolution in feedstocks for conventional and advanced biofuels.



Source: JRC elaboration of Eurostat 2024 data.

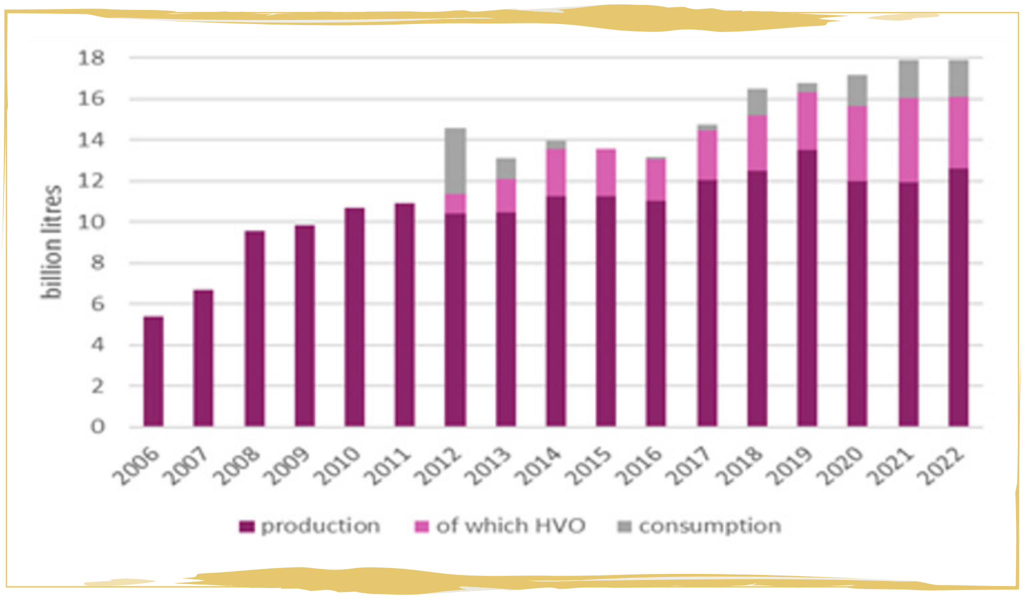
Most of the biofuels produced in the EU are biodiesel, i.e. FAME made from lipids and bioethanol, made from sugar and based crops.

3.1.4.1.1 Biobased Diesel

Biobased Diesel includes Fatty Acid Methyl Esters (FAME) and renewable diesel as Hydrotreated Vegetable Oil (HVO). The EU is the world's largest market for both production and consumption of biodiesel. In recent years, there has been a shift in the EU's biofuels policy towards promoting the use of more sustainable, renewable and low-carbon fuels, such as advanced biofuels made from various waste and residues, hence non-food based crops. Biodiesel production from oil crops results with an important byproduct: oilseed cake that is used as animal feed, in particular. Oilseed cake produced in this process represents about 60% of the oilseeds used for biodiesel and it is used as feed. Commercial production of biofuels made of non-food-based crops mostly consists in HVO (Hydrotreated Vegetable Oil) produced from lipids, or from waste and residues listed in Annex IX part B of the RED (Used Cooking Oil – UCO and animal fats).

The production of FAME (biodiesel) made from vegetable oils increased to about 12 billion litres in the EU in 2022 compared to almost 6 billion litres in 2006. In addition, about 3.5 billion litres of renewable Diesel (VHO) were produced in 2022. The import of FAME reached about 1.8 billion litres in the EU in 2022. With a consumption of about 18 billion litres in the EU in 2022, the import of biodiesel plays a small role in biodiesel supply, with about 1.8 billion litres or a share of 10% (Figure 16). Important to note is that the net import of oilseeds for all uses represent about 40% of the domestic use of oilseeds.

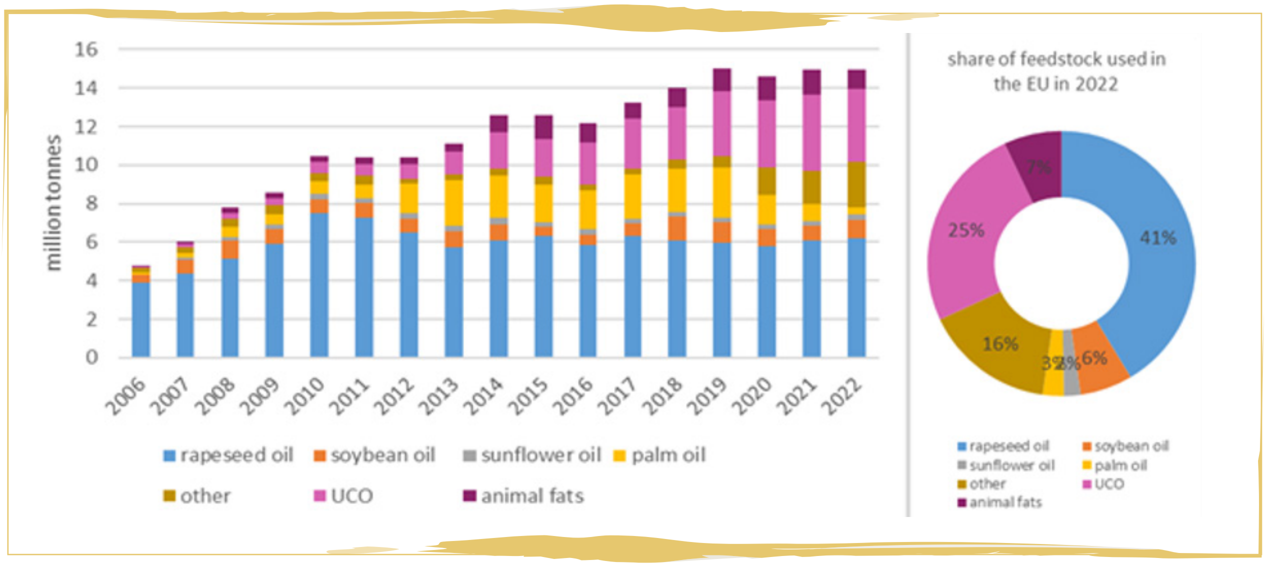
Figure 16. **Production and use of biodiesel and biobased renewable Diesel in the EU.**



Source: USDA Foreign Agricultural Service et al., 2024, EUROSTAT.

In the EU, the production of FAME relies on the use of vegetable oils, UCO and animal fats from domestic or imported oil crops. The total amount of feedstock used for FAME production increased to 10.5 Mt (million tonnes) of vegetable oil and 4.5 Mt of UCO and animal fats. About 68% of the feedstock use for biodiesel came from vegetable oils in 2022, of which 41% rapeseed oil at 6.2 Mt in 2022, 6% soybean oil near to 1 Mt the same year, and 13% other vegetable oils. There is a trend mainly toward the reduction of rapeseed oil and the increase of used cooking oil. Used cooking oils had a share of 25% of the feedstock used for biodiesel and animal fats had a share of 7% (feedstock listed in Part B Annex IX of the RED) for the production of renewable diesel, as shown in Figure 17. UCO was the second most important feedstock in 2022. The popularity of rapeseed oil is grounded in its domestic availability as well as in the higher winter stability of the resulting rapeseed methyl ester (RME) compared to other feedstocks.

Figure 17. **Feedstock use for biodiesel and renewable diesel in the EU.**



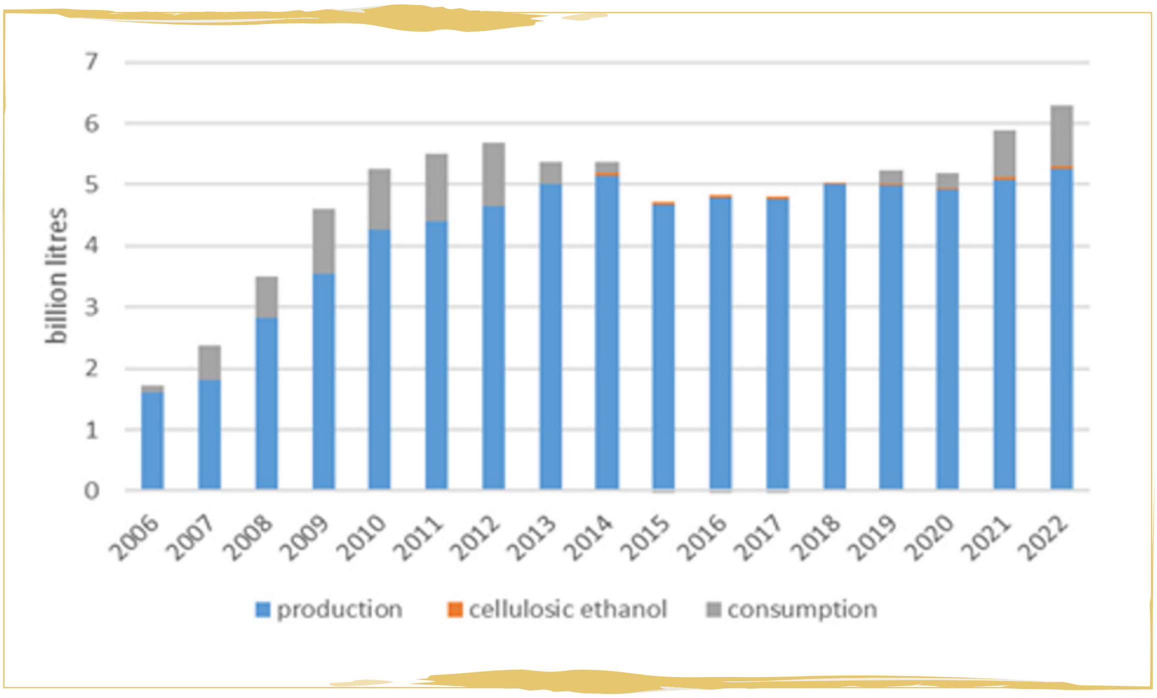
Source: USDA Foreign Agricultural Service et al., 2024, EUROSTAT.

3.1.4.1.2 Bioethanol

Bioethanol is produced by fermenting the carbohydrate components of starch or sugar materials. In the EU, the most used feedstocks are grains, such as maize, wheat, other coarse grains and sugar beet. The total feedstock (grains and sugar beet) used in the EU for bioethanol production represented about 5% of the total use of grains and sugar beet in the EU in 2022. The production of ethanol generates an important byproduct: Distiller's Dried Grains with Solubles (DDGS) that are a nutrient rich co-product from ethanol production that is used as feed and a protein supplement. From 1 tonne of ethanol produced, about 1.8 tonnes of DDGS are produced, which represent about 40% of the grains used for ethanol production. Ethanol is a basic chemical that is used beyond bioenergy sector, in the chemical and food industries. Cellulosic ethanol, an advanced biofuel resulting from the fermentation of the lignocellulosic material, is produced to a limited extent, as the technology is not yet demonstrated in commercial operations. The technology involves several conversion steps of lignocellulosic material, including pre-treatment of lignocellulose, followed by enzymatic hydrolysis into sugars and fermentation of the sugars into alcohols.

The production of ethanol to be used as a fuel in transport reached about 5.3 billion litres in 2022, with a marginal production of cellulosic ethanol (advanced ethanol) of about 50 million litres. In addition, net import of ethanol of 1.4 billion litres represented about 20% of domestic ethanol production for fuel; when adding also the ethanol consumed for other industrial chemicals the total was 7.4 billion litres. As Figure 18 below shows, the production and consumption of ethanol for fuel showed quite large variation over time, in relation to policy uncertainties. It is important to note the difficulty of differentiating, in statistics, including trade statistics, between ethanol for its use as a fuel and ethanol for industrial use. Anyway, in relation to the increased demand for ethanol for fuel, the share of the ethanol used for fuel in the EU increased from about 56% in 2006 to more than 80% of the total ethanol use in 2022. The feedstock uses for ethanol production had a share on just 5% of the total cereals and sugar beet in 2022.

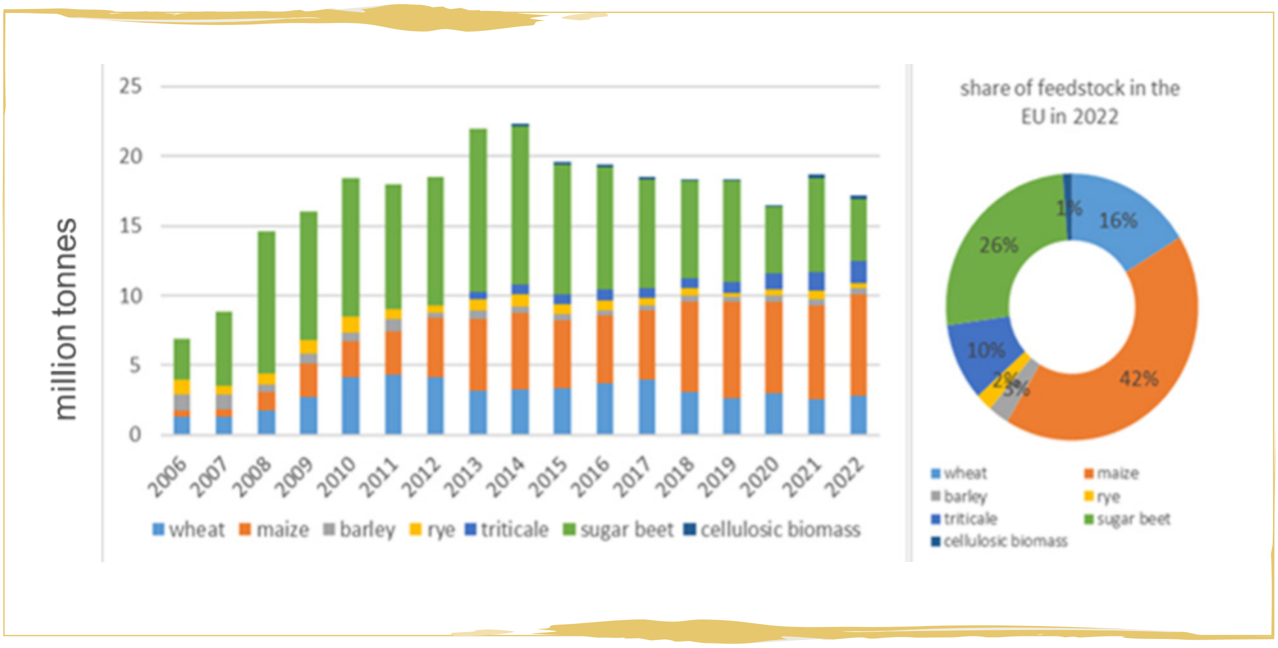
Figure 18. Production and use of ethanol as a fuel in the EU.



Source: USDA Foreign Agricultural Service et al., 2024, EUROSTAT.

Regarding ethanol in 2022, about 42% of ethanol, equal to 6.25 Mt, was produced from maize kernel in the EU, 26% corresponding to 4.46 Mt from sugar beet root, 16% or 2.78 Mt from wheat kernel, etc. From a total EU domestic use of cereals of almost 260 Mt in 2022, about 12 Mt were used for bioethanol production. In addition, about 8.5 Mt sugarbeet was used for bioethanol production, in comparison of a total use of 95 Mt sugarbeet in the EU for sugar production. The use of lignocellulosic biomass (e.g., crop residues, forest residues, dedicated energy crops) account for a very small share of total feedstock use for bioethanol production, Figure 19.

Figure 19. **Feedstock used for ethanol production for the use as a fuel in transport in the EU.**

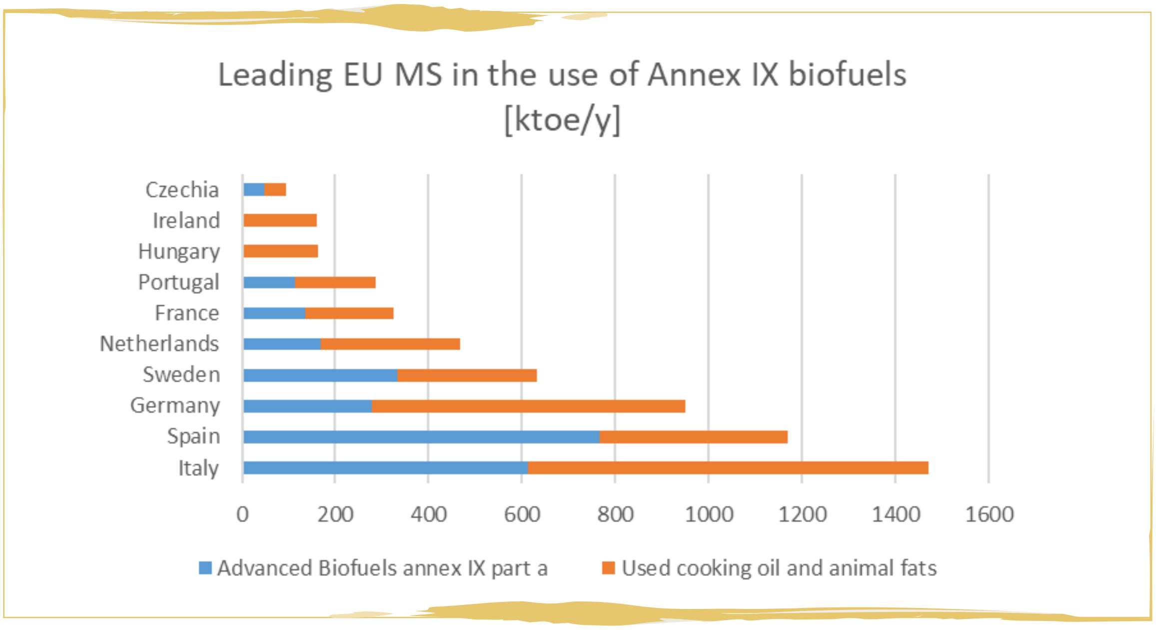


Source: USDA Foreign Agricultural Service et al., 2024, EUROSTAT.

3.1.4.2 Member States biofuel consumption

For biofuel produced using feedstock listed in Annex IX of the RED Italy, Spain and Germany are the consumption leaders in the EU for the year 2022, mainly due to the use of HVO from used cooking oil and animal fats (Figure 20).

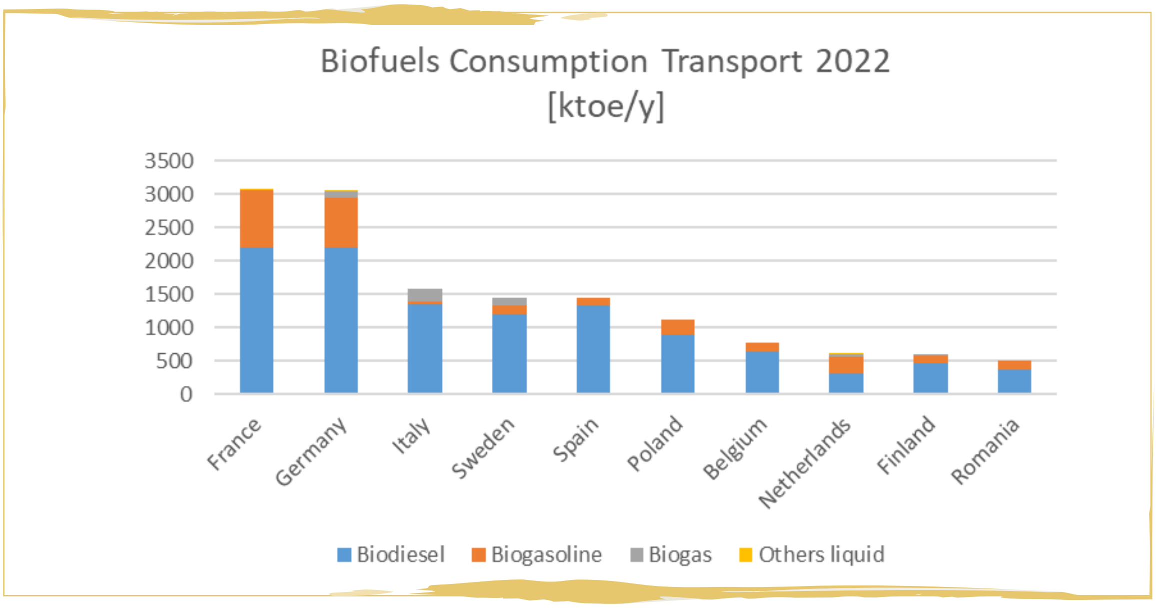
Figure 20. Feedstock used for ethanol production for the use as a fuel in transport in the EU.



Source: JRC elaboration of USDA Foreign Agricultural Service et al., 2024 data.

Germany and France were by far the main biofuel consumer in Europe in 2022, with 3 Mtoe each, followed by Italy with more than 1.5 Mtoe consumed (Figure 21).

Figure 21. The use of biofuel, including advanced biofuels, and biogas by EU Member State in 2022.

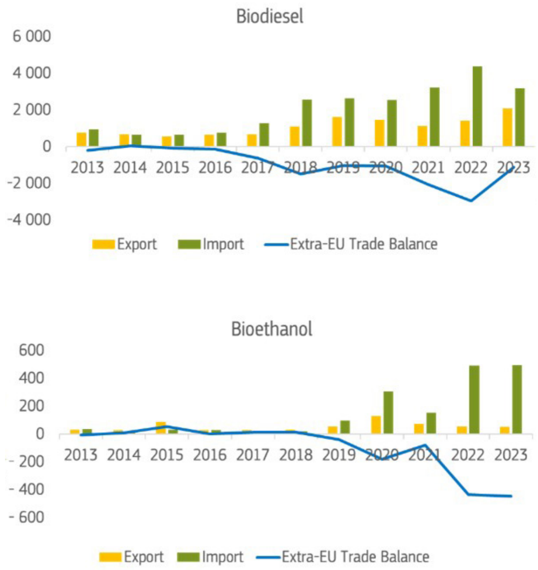


Source: JRC elaboration of Eurostat, 2024 data.

3.1.4.3 EU biofuel trade balance

The majority of EU biofuels imports and exports consists of biodiesel followed by bioethanol. The trade analysis focuses on biodiesel and bioethanol to examine the trends in those markets the extra-EU exports of biodiesel increased by 47% compared to 2022, reaching almost EUR 2.1 billion, while extra-EU imports shrank by -27%, reaching around EUR3.2 billion. The trade deficit shrank from almost EUR-3 billion in 2022 to EUR-1.1 billion in 2023. The extra-EU exports of bioethanol decreased by -10% at EUR 51 million, while extra-EU imports remained stable at EUR 0.5 billion, maintaining the trade deficit at EUR-0.4 billion (Figure 22).

Figure 22. Extra-EU trade for biodiesel (left) and bioethanol (right) [EUR Million].



Source: JRC elaboration of Eurostat, 2024 data.

3.2 Forests

3.2.1 Forest ecosystems condition

José I. Barredo & Nicolas Mansuy

Over the last centuries, forests used and managed to varying degrees of intensity have replaced almost all Europe's natural forests (Kaplan et al. 2009; McGrath et al. 2015). At present, primary and old-growth forests account for less than 3% of Europe's forests area (Sabatini et al. 2020; Barredo et al. 2021; Barredo et al. 2024), and 77% of the forest area and 84% of the growing stock of European forests are available for wood supply (FOREST EUROPE, 2020) (see Box 10 for a discussion on safe wood production thresholds). In addition, more than 70% of European forests are even-aged (FOREST EUROPE, 2020), which indicates forest ecosystems with structural features far from a natural condition (Barredo et al. 2024).

Box 10. Thresholds for safe production

The twin crises of climate change and biodiversity loss call for stronger efforts to increase the resilience of forest ecosystems. This aim is high on the agenda for foresters and policymakers (Barredo et al. 2024). At the same time, synergistic opportunities for restoring forests and biodiversity are emerging to safeguard these ecosystems. Novel disturbances and changes in disturbance regimes (Senf et al. 2021) delineate a complex scenario for foresters and policymakers in the EU. This situation approximates a wicked problem with multiple valid, albeit often divergent, options, and no single optimal solution (Mubareka et al. 2022). To make things even more complicated, policies aimed at divergent goals and centred on forest ecosystems should be implemented in a coordinated fashion, oriented to satisfy various forest services. These appear to drive trade-offs, such as between wood production and carbon sequestration in forests (Korosuo et al. 2023).

The multiple drivers affecting forest ecosystems necessitate a comprehensive approach capable of incorporating the social-ecological complexity of these systems within a common framework. Ecosystem-based forest management (Seymour and Hunter, 1999; Mansuy et al. 2024), which prioritises maintaining or improving forest condition at the landscape level, offers some hope for a successful path toward delivering forest ecosystem restoration where required, as well as enhanced resilience in *sensu stricto* (see for example Thompson et al. (2009)). This approach encompasses the concept of multifunctional forest management (see Box 11), protected areas, retention forestry, closer-to-nature forestry, and intensive management strategies, all executed in a manner and at a rate that ensures forests are in good condition at the landscape level (Barredo et al. 2024; Mansuy et al. 2024).

For instance, silvicultural operations that modify forest traits at the landscape level, such as creating younger, monospecific forest landscapes, represent a major threat due to the implicitly decreased resilience. New frameworks and tools for monitoring forest ecosystem conditions, such as the SEEA-EA approach operationalised in Maes et al. (2020), provide promising means to monitor and achieve the objectives of improving forest condition, increasing resilience, and delivering provisioning forest ecosystem services. Living within a safe operating space is a guiding star that policymakers and land managers should take very seriously (Rockström et al. 2009; Steffen et al. 2015) before it is too late.

Ecosystem condition, which is defined as the quality of an ecosystem measured in terms of its abiotic and biotic characteristics, is one of the accounting metrics adopted by the UN's System of Environmental-Economic Accounting - Ecosystem Accounting (SEEA-EA) (United Nations et al. 2021). SEAA-EA is an integrated and comprehensive framework for collecting and organising data on ecosystem condition, including ecosystem services, tracking changes in ecosystem assets, and linking this information to economic and other human activity. Maes et al. (2023) created maps of forest ecosystem condition using the SEEA-EA approach and an array of spatially explicit variables, representing each category of the SEEA-EA Ecosystem Condition Typology (ECT) (Czúcz et al. 2021), namely, vegetation water content index, soil organic carbon, species richness of threatened forest birds, tree cover density, forest productivity (NDVI), forest connectivity, and landscape naturalness. The study delivered forest condition maps for 44 forest ecosystem types across Europe. The use of spatially explicit data to assess ecosystem condition enables a seamless large-scale monitoring system with an objective estimation of the area to be considered as in a degraded condition, to establish conservation actions, or to set restoration priorities (Maes et al. 2023).

The maps of forest condition for 2000 and 2018 show variations in condition, ranging from 0.31 to 0.78 in the condition index (0–1) in Europe (Figure 23). Across the continent, improvements in forest ecosystem conditions occur locally, alongside areas experiencing decline. Condition improved between 2000 and 2018 in 63% of the forest area, although the change was limited to an average increase of 4.3%. In contrast, the condition deteriorated in 37% of the forest area. Forest degradation was more pronounced in northern Scandinavia, the Carpathians, the Balkans, the northern Apennines, and throughout the forests of the Iberian Peninsula. The mean forest condition across the 44 forest types was 0.566 in 2000 and increased to 0.585 in 2018, an improvement of 1.9%. Although condition improved in 33 out of the 44 forest types, a threshold for good ecosystem condition was not established in Maes et al. (2023). This is a point that warrants further investigation. Information on uncertainty, sensitivity analysis, as well as the complete description of the methodology for the creation of the maps of forest condition is available in Maes et al. (2023).

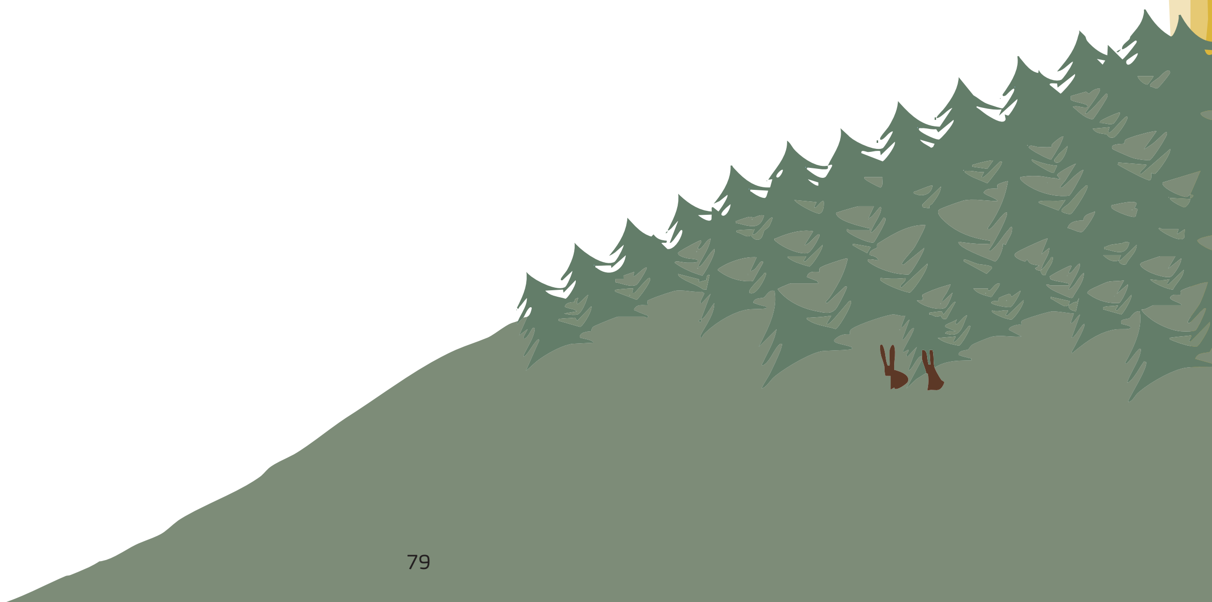
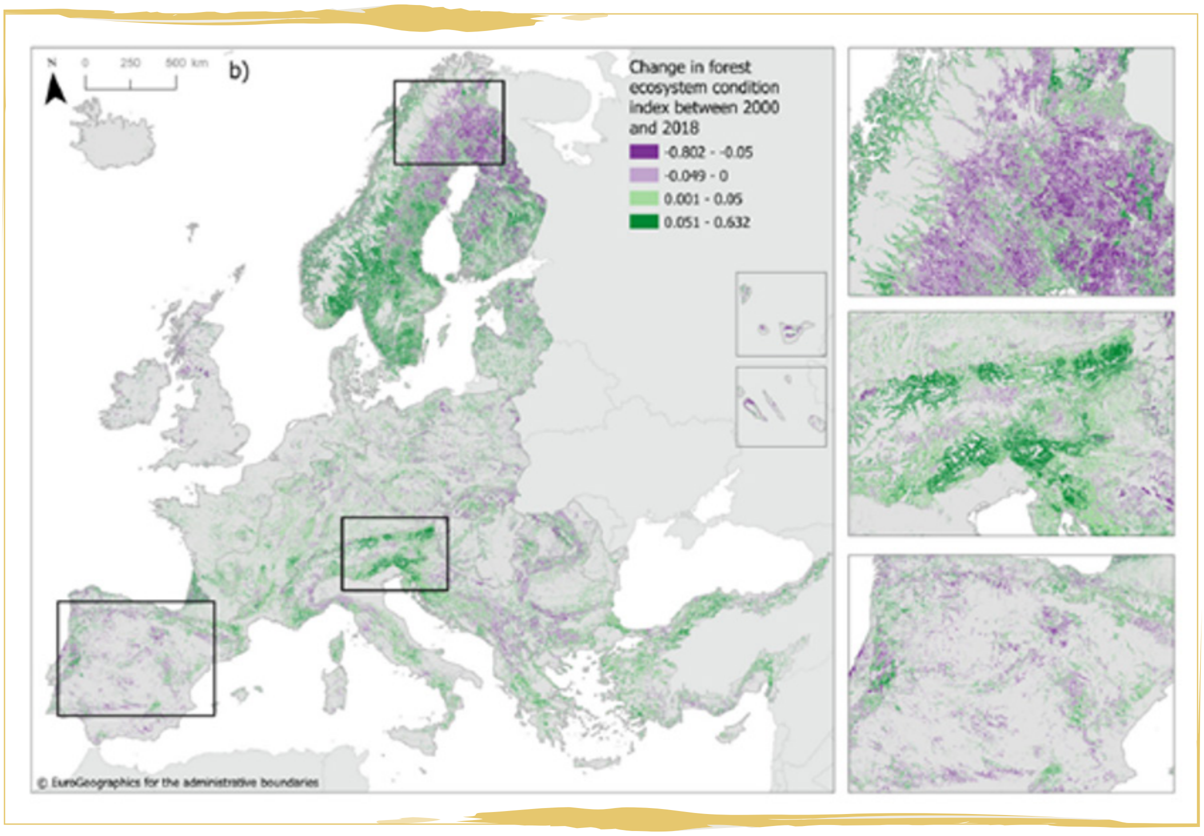


Figure 23. **Change in forest ecosystems condition between 2000 and 2018. Insets illustrate changes in Boreal, Mediterranean, and Alpine forests. Average forest condition inside the Boreal bounding box declined by 2%, mainly driven by lower ecosystem productivity and lower soil organic carbon. Average forest condition inside the Alpine bounding box increased by 3.4% as a result from increases in all condition variables. Average forest condition inside the bounding box covering the Iberian Peninsula decreased slightly following reductions in tree cover density.**



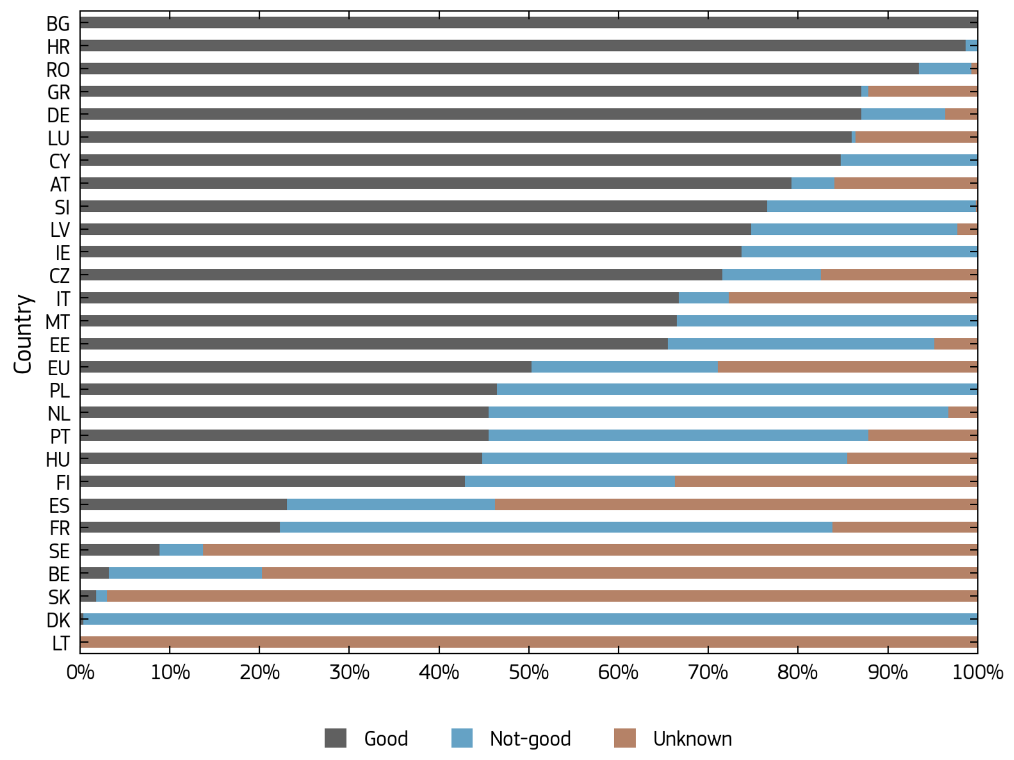
Source: Maes et al. (2023).

3.2.1.1 The role of forestry on the condition of forest habitats of Annex I of the Habitats Directive

This section describes the results of the official reporting presented in the State of Nature Report (EEA 2020), which utilises data from assessments carried out by each Member State concerning forest habitats as stipulated under Article 17 of the EU Habitats Directive, specifically, forest habitats included in Annex I of the Directive. Member States submit area-based information on habitat condition to calculate the structure and function parameter. This parameter is one of four used to derive a conclusion on the conservation status of habitats. Despite certain issues with the data reported for assessing the conservation status of habitats (Maes et al. 2020), the information depicted in Figure 24 is important for drawing conclusions about the condition of forest ecosystems in the EU, in particular in the area of the forest habitats, that corresponds to the 28% of EU forest land. However, tracking changes in condition over time using this data remains challenging (Maes et al. 2020).

Aggregated at EU level, 482 657 km^2 of Annex I forest habitats were assessed between 2013 and 2018, of which 242,821 km^2, or 50%, was found in good condition, 100,244 km^2, or 21%, in not–good condition, and 139 592 km^2, or 29%, in unknown condition) (Figure 24). The proportion of unknown condition opens questions about the 'real' share of forest habitats in good and not-good condition. We speculate that the area in not-good condition would climb if the unknown area were assessed. The State of Nature Report (EEA, 2020) concludes that forestry practices are the dominant pressure on forest habitats and the second largest pressure on species, particularly affecting arthropods, mammals, and non-vascular plants. Annex I habitats are subject to special protection measures under the EU Habitats Directive, which suggest that they are in better condition compared to unprotected forests outside of these habitats.

Figure 24. Share of forest habitats in good, not-good, and unknown condition in the EU countries based on data from the Art. 17 conservation status assessment reports of the Habitats Directive.



Source: JRC elaboration of EEA (2024) data.

3.2.1.2 Key messages

- Forests used and managed to varying degrees of intensity have replaced almost all of Europe's natural forests. At present, primary and old-growth forests account for less than 3% of Europe's forests area, and 77% of the forest area and 84% of the growing stock of European forests are available for wood supply;

- The condition of forest ecosystems declined in 37% of their area between 2000 and 2018;

- Of the 482 657 km^2 of Habitats Directive's Annex I forest habitats, 50% is in good condition, 21%, in not–good condition, and in 29% the condition is unknown. Forestry practices are the dominant pressure on these forest habitats and the second largest pressure on species;

- The twin crises of climate change and biodiversity loss call for stronger efforts to increase the resilience of forest ecosystems in Europe.

Box 11. Towards multifunctional forest management

The global demand for woody biomass is increasing rapidly to meet energy and climate targets aiming at net-zero emissions by 2050 and have raises concerns about the capacity of forest ecosystems to sustain their diverse services and functions. Besides biomass, forests provide a wide range of functions and services vital to the environment, society, and well-being. In the face of climate change, rapid human population growth, and the growing demand for forest resources, finding the right balance between wood products, the maintenance and enhancing of biodiversity and carbon storage is an increasing challenge (Mansuy et al. 2024). Research on forest multifunctionality has attracted considerable interest as a management principle to mitigate increasing pressures on EU forests while continuing to meet the growing demand for forest products and ecosystem services (Martynova et al. 2021; Castro et al. 2022). Although there is no universal definition of forest multifunctionally, it can be defined as a holistic approach that enables the simultaneous provision of multiple forest or ecosystem functions in a broad, multi-stakeholder territorial perspective (Manning et al. 2018). Therefore, finding trade-offs and synergies among the different uses and services of the forest is central to foster multifunctionality while contributing to improved forest resilience and condition (Toraño Caicoya et al. 2023). Given its role as a source of biomass and a key indicator of biodiversity, deadwood has been the subject of particular attention in terms of multifunctional management (Müller and Bütler, 2010; Giuntoli et al. 2022; Mansuy et al. 2024) and conservation and restoration policy (https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32024R1991). One of the lessons learned from these studies is the importance of the reference level to assess the current state of the forest in relation to the natural conditions of the ecosystem. The assessment of natural conditions is essential to evaluate the potential for multifunctionality at the ecosystem or landscape level and to define a threshold of harvest without increasing the pressure on the ecosystem, that may, in turn, affect ecosystem condition. It is particularly relevant in the case of deadwood since currently estimated levels are well below their natural level across EU countries and ecological regions (Mansuy et al. 2024). However, multifunctionality remains a complex concept due to the lack of an agreed method for measuring and reporting it at different spatial and temporal scales. Consequently, another lesson is the need for standardized or harmonised data to improve forest monitoring and inventory, to build up a comprehensive portrayal of forest conditions and dynamics across the EU (Maes et al. 2023). Standardised or harmonised data are also essential to help policy makers develop coherent policies, so that efforts in one policy area do not compromise efforts in another and contribute to mutually beneficial forest management. Obtaining accurate and timely data on EU forests is one of the main objectives of the proposed Forest Monitoring Regulation[12].

3.2.2 Forestry production and supply

Roberto Pilli

According to the latest data made available by FAOSTAT (2025), the total roundwood production of EU-27 was equal to 481 Mm^3 u.b. (million cubic meters under bark) in 2023, decreasing by 6.0% compared to 2022 (Figure 25a). Even if still provisional, this value represents a first inversion after the abrupt increase reported since 2018, when the total roundwood production increased from 474 Mm^3 u.b. reported in 2017 to 502 Mm^3 u.b. removed in 2018 (+5.8%), maintaining similar levels also within the following years. Within the same period, the share of roundwood material exchanged, i.e. the

[12] *https://environment.ec.europa.eu/publications/proposal-regulation-forest-monitoring-framework_en*

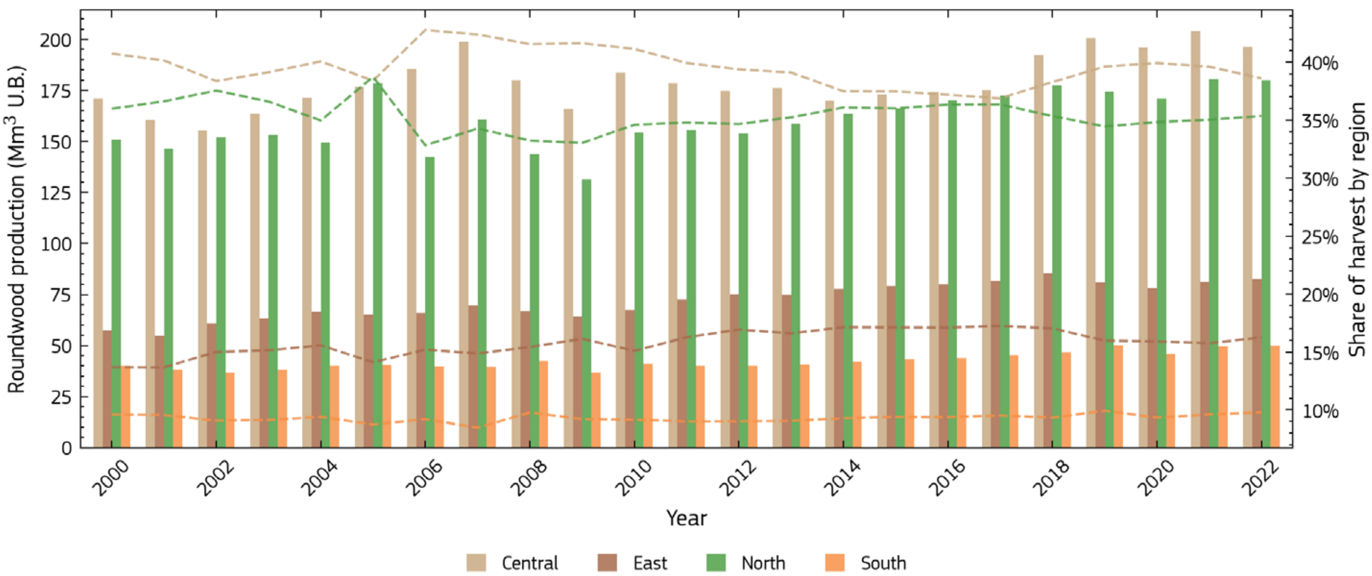
percentage net trade on total roundwood production, moved from about -5% of the total roundwood production until 2008, to about -3%, within the period 2009 - 2016. Negative values, in this case, highlight that absolute imports exceed the exports. Within the most recent years, the share further decreased, ranging between +0.1- 1.4% within the period 2019-2022, highlighting that net export exceeded the import.

Figure 25. **(a) Total roundwood production for EU-27, further distinguished between industrial roundwood (IRW) and fuelwood (FW), with the share of fuelwood reported on the right axis. (b) total roundwood import and export quantity for EU-27, and share of roundwood material exchanged, i.e. percentage net trade (total roundwood export minus total roundwood import) on total roundwood production (reported on the right axis).**

Source: JRC elaboration of FAOSTAT data 2025.

The abrupt increase of harvest, and consequent increase of export, from 2018 onward was initially a consequence of salvage logging activities induced by the exceptional windstorms that occurred between 2017 and 2018 in some central European countries (Petacca et al., 2022). Within the following years, the same regions experienced various bark beetle outbreaks, due both to the previous disturbance events and to adverse climatic conditions. Because of this continuous supply of roundwood material made directly available as a deadwood pool, until 2022, Central European countries supplied a relatively higher amount of harvest at EU level. This surplus was partially compensated by a relatively lower share of harvest provided by Northern European countries (Figure 26).

Figure 26. Total roundwood production and share of harvest by region.



Geographical region are as follows: East= Bulgaria, Croatia, Hungary, Poland, Romania, Slovenia; Central= Austria, Belgium, Czechia, Germany, France, Ireland, Luxemburg, Netherlands, Slovakia; North= Denmark, Estonia, Finland, Lithuania, Latvia, Sweden; South= Cyprus, Spain, Greece, Italy, Malta, Portugal.

Source: JRC elaboration on FAOSTAT data 2025.

Similar interactions, between Northern and Central European countries - which supply about 70% of the total roundwood at EU level - are also evident within the previous periods and highlight that an exceeding harvest supply provided by one region is generally compensated, in the short term, by a reduction of silvicultural activities carried out on the other region. This is not the case for Eastern, and especially Southern European countries, which supply less than 30% of the total harvest. Their harvest is mostly used at local level and does not reflect any interactions with harvest levels in other European regions.

The share of harvest provided by different geographical regions is not always proportional to the relative amount of biomass available for wood supply (BAWS) at regional level (Table 7). Indeed, while removals provided by Central European countries are proportional to the relative amount of biomass available within the same region, Northern countries provide a larger share of harvest, while the amount of harvest supplied by Southern, and above all Eastern, European countries is relatively lower, if compared with the BAWS.

Table 7. The total forest area, the forest area available for wood supply (FAWS) and the share of FAWS distributed between geographical regions; the total aboveground biomass stock, the biomass available for wood supply (BAWS) and the share of BAWS distributed between geographical regions; the percentage distribution of total removals reported by FAOSTAT between different geographical regions. All data refer to 2020.

2020	Forest area (kha)			Forest Biomass (tonnes dry biomass 10^3)			Removals
Region	Total	FAWS	Share in EU-27	Total	BAWS	Share in EU-27	Share in EU-27
North	59,068	49,560	35%	4,696,144	4,103,692	24%	35%
Central	38,658	35,976	26%	6,792,489	6,392,141	38%	39%
East	26,168	23,493	17%	4,591,031	4,132,645	24%	16%
South	35,445	31,340	22%	2,532,153	2,319,124	14%	10%
EU-27	159,339	140,368	100%	18,611,817	16,947,602	100%	100%

Geographical region are as follows: East= Bulgaria, Croatia, Hungary, Poland, Romania, Slovenia; Central= Austria, Belgium, Czechia, Germany, France, Ireland, Luxemburg, Netherlands, Slovakia; North= Denmark, Estonia, Finland, Lithuania, Latvia, Sweden; South= Cyprus, Spain, Greece, Italy, Malta, Portugal.

Sources: Avitabile et al., 2024 and FAOSTAT, 2025.

As reported in Figure 25, between 2007 and 2010, the share of harvest used as fuelwood increased by 6%, because of the combined effect of the financial crisis, reducing the industrial roundwood demand, and the entry into force of the EU Renewable Energy Directive, pushing up the fuelwood demand (Jonsson 2024). Within the last decade, however, the share of fuelwood was quite stable and equal to about 25% of total removals, even if increasing to 27% in 2023.

This means that, despite some uncertainty on the amount of fuelwood reported by official statistics, certainly underestimated (Avitabile et al., 2023), the increasing amount of roundwood supplied within the last years was due both to industrial and fuelwood demand.

While industrial roundwood is mostly supplied by coniferous species, providing about 80% of the total industrial roundwood production at EU level, about 70% of fuelwood is provided by broadleaves (FAOSTAT 2025). Both these shares are quite stable within the last decade, and they highlight an unbalanced use of wood resources available at EU level. Indeed, broadleaves and coniferous species cover a similar forest area, equal to about 73 Mha (million hectares) for broadleaves and 83 Mha for coniferous, and have a similar aboveground biomass stock, equal to about 16 and 20 billion m^3 in 2020, for broadleaves and coniferous species, respectively (Pilli et al., 2024). At the same time, even considering the fact that broadleaves species have a lower Net Annual Increment (NAI) equal to about 4.9 m^3 ha^{-1} yr^{-1}, the fellings rate, i.e. the ratio between fellings and NAI, for broadleaves is equal to about 58-62% of the total aboveground NAI for the entire period 2010 – 2022 (Figure 27). On the other hand, for coniferous species, where the NAI is equal to about 6.5 m^3 ha^{-1} yr^{-1}, the fellings rate has been increasing over time, from about 70% of the NAI in 2010 to about 80-90% of the NAI within the period 2019 – 2022. Further extrapolations of the fellings rate to 2023, assuming a stable average NAI at EU level, are not possible, since various countries recently reported a declining NAI, mostly attributed to drought and other adverse climatic conditions (Luke, 2024; SLU, 2024). This means that, despite the reduction of the amount of fellings, the corresponding fellings rate have not been proportionally decreasing, because the absolute NAI was also decreasing.

Even if the State of Europe 2020 suggests that, under some condition, utilisation rates larger than 100% of NAI could still be sustainable (FOREST EUROPE, 2020), in general, at regional or country level, a felling rate lower than 90% can be recommended. This safeguard boundary prevents both abrupt biomass losses due to unpredictable natural disturbances, such as the ones occurred on central European countries within the period 2018-2022 (Cienciala & Melichar, 2024), and inter-annual fluctuations of the NAI, due to adverse climatic conditions, such as the ones reported from various Northern and Central European countries within the latest years.

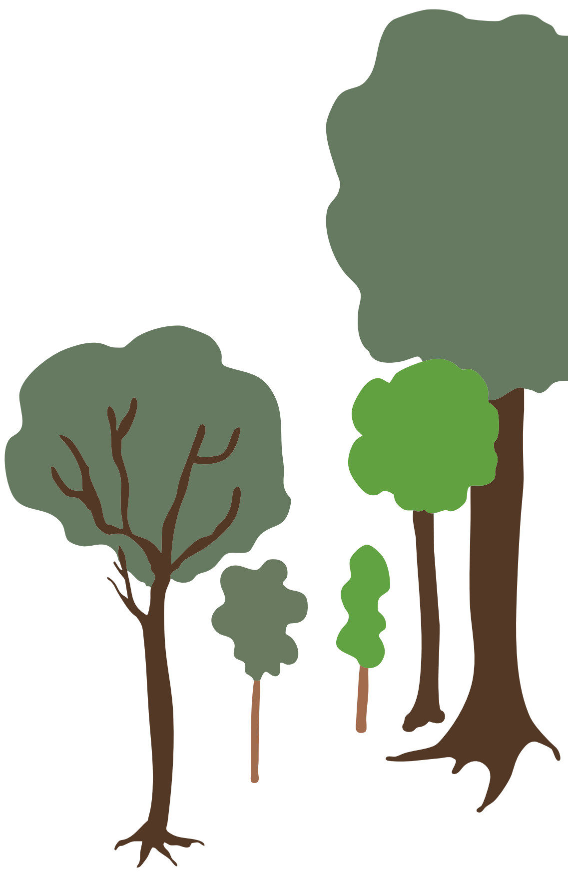
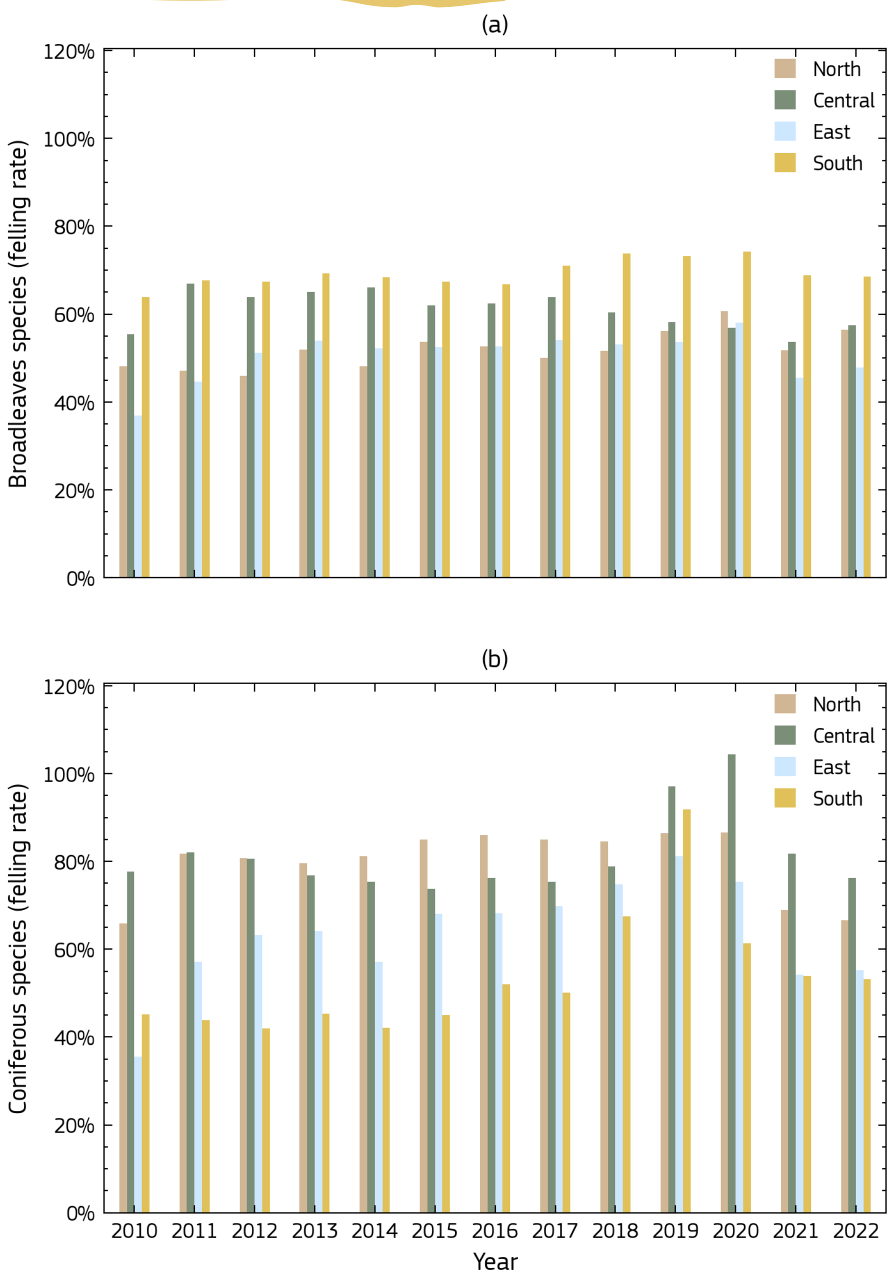


Figure 27. (a) The evolution of the above ground Net Annual Increment estimated by the JRC EU Forest Carbon Model (CBM) and the amount of fellings estimated by the same model and derived by removals reported by FAOSTAT. All data are referred to the total aboveground biomass per unit of area. (b) A comparison of the fellings rate derived from previous data sources.

Source: JRC elaboration of FAOSTAT data 2025 and data reported by Pilli et al., 2024 (see Annex 3 for methodological details).

Similar patterns, but with larger differences between various geographical regions, can be highlighted when considering the fellings rates estimated for broadleaves and coniferous species, distinguished at regional level (Figure 28). In this case, for Southern European countries, the fellings rate is quite stable for broadleaves species, and increasing, since 2018 onward, for coniferous species, due to windstorms and bark beetle outbreaks affecting some of these countries. For the same reasons, the fellings rate abruptly increased in Central European countries for coniferous species, with an opposite effect, within the same region, on broadleaves species. The larger amount of biomass made available from these two regions, may have also reduced the harvest rates in Eastern and North European regions, at least for coniferous species.

Figure 28. Evolution of the fellings rate estimated for (a) broadleaves and (b) coniferous species, distinguished by geographical regions. Data estimated from the JRC EU Forest Carbon Model (for the period 2011 – 2020), and combining previous data with latest data reported by FAOSTAT (for 2010, 2021 and 2022).



Geographical region are as follows: East= Bulgaria, Croatia, Hungary, Poland, Romania, Slovenia; Central= Austria, Belgium, Czechia, Germany, France, Ireland, Luxemburg, Netherlands, Slovakia; North= Denmark, Estonia, Finland, Lithuania, Latvia, Sweden; South= Cyprus, Spain, Greece, Italy, Malta, Portugal.

Sources: JRC elaboration on Pilli et al., 2024 and FAOSTAT, 2025.

3.2.2.1 Summary of findings

Between 2018 and 2022, the overall harvest rate at EU level was permanently above 500 Mm^3 u.b. per year, but according to the latest data made available by FAOSTAT, it decreased to 481 Mm^3 u.b. in 2023. Within the same period, the share of roundwood material exchanged, ranged between +0.1- +1.4%, highlighting that, at EU level, net export exceeded the import.

- At least 70% of the total roundwood used at EU level is provided by Northern and Central European countries. The intensity of ordinary and sanitary management activities (i.e., salvage logging after major disturbance events) carried out between these geographical regions is clearly intercorrelated;
- Eastern and Southern European countries provide a relatively lower amount of harvest. Despite that, South European countries have the highest fellings rate on broadleaves species, mostly used for fuelwood, and both these regions experienced an increasing fellings rate on coniferous species in 2019, after major disturbance events affecting some of these countries;
- Use of wood resources available from broadleaves and coniferous species is quite unbalanced both at EU and at regional level. Indeed, for coniferous species, which provide about 80% of the total industrial roundwood, the fellings rate is increasing in time, from about 70% of NAI in 2010 to 80- 90% of NAI between 2019 and 2022. For broadleaves species, which provide, according to FAOSTAT, about 70% of the wood used as fuelwood, the fellings rate is quite stable and equal to about 60% of the NAI for the entire period 2010 – 2022;
- A felling rate lower than 90% can be recommended, both at country and sub-national level. This safeguard boundary prevents both abrupt biomass losses due to unpredictable natural disturbances, such as the ones occurred on central European countries within the period 2018-2022 (Cienciala & Melichar, 2024), and inter-annual fluctuations of the NAI, due to adverse climatic conditions, such as the ones reported from various Northern and Central European countries within the latest years (Luke, 2024; SLU, 2024);
- The increasing impact of climate change and natural disturbances, not only on forest biomass but also on NAI, and the uncertainty on data reported by official statistics, above all for wood used for energy, stongly suggest to develop a near-real-time monitoring system of the overall flow of wood material through the forest supply chain, from the harvest to final use of wood products. Remote sensing techniques already play a key role (Ceccherini et al., 2022; Stahl et al., 2023; Fassnacht et al., 2024), but they can be only complementary to data directly collected at national level, such as through periodic National Forest Inventories, but also through a continuous monitoring system, possibly integrated at EU level (such as proposed through the Forest Monitoring Law).

3.2.3 Woody biomass uses

Noemi E. Cazzaniga, Marilene Fuhrmann, Ragnar Jonsson, Sarah Mubareka, Andrea Camia

For many years now, the JRC has been producing a harmonised data time series of the woody biomass flows across the main economic sectors for the 27 Member States of the European Union (see Box 12). The dataset highlights the evolution of biomass use in the wood-based economy over time as well as disclosing internal inconsistencies in available official statistics on wood production and use.

Box 12. **Scripts and data behind the woody biomass flows developed up to 2021.**

The Sankey diagram of woody biomass flows is a signature product of the JRC and it is used for illustrating the complex, wood-based sector value chain, showing the relations between biomass sources and uses, including circularity, and highlighting gaps and inconsistencies in the data.

The latest published set of Sankey diagrams includes the flows of woody biomass across the different subsectors of the forest-based economy for all EU Member States (MS) up to the semi-finished products, for the timespan 2009-2017. The results provide a detailed quantification of woody biomass sources, uses and flows, revealing inconsistencies in the reported data, and serving both researchers and policymakers. The data are all expressed in thousand cubic meters Solid Wood Equivalent (see definition in UNECE/FAO Timber Section 2010).

The related datasets, with the linked definitions, are downloadable at *https://zenodo.org/records/8427652*. Sankey diagrams are accessible at *https://zenodo.org/uploads/10599934* or visualized interactively at *https://knowledge4policy.ec.europa.eu/visualisation/interactive-sankey-diagrams-woody-biomass-flows-eu-member-states_en*. The code used to generate the dataset can be downloaded from the permalink *https://zenodo.org/records/10598618* and is maintained in this repository: *https://code.europa.eu/woody-biomass-flows/woody_biomass_tools*.

Throughout all these years, the JRC has repeatedly commented on the poor timeliness of the data availability, as well as the incomplete geographical coverage. Available data on wood sources and uses is often fragmented, inaccurate, and not harmonised across EU countries. A number of studies have indicated a tendency to underreport wood removals and fellings and/or to provide unreliable data for some commodities in official statistics (Buongiorno, 2018; Kallio and Solberg, 2018, Pilli et al 2015; Jochem et al 2015). Acknowledging these challenges, in the new EU Forest Strategy (EC 2021a) the European Commission (EC) pledges to prepare a proposal for a regulation ensuring a coordinated EU forest monitoring, data collection and reporting system (see Box 13).

Box 13. **The EU Forest Monitoring Law**

The European Union’s Forest Monitoring Law, proposed by the European Commission on November 22, 2023, aims to enhance the resilience of European forests by establishing a comprehensive monitoring framework. This initiative seeks to address information gaps and provide detailed, accurate, and timely data on the status and trends of EU forests. By leveraging Earth Observation technology and ground measurements, the law intends to support Member States, forest owners, and managers in responding effectively to environmental pressures such as pests, droughts, and wildfires, which are exacerbated by climate change.

At the time of writing, the Forest Monitoring Law remains a proposal and has not yet been enacted. The European Commission’s proposal outlines the framework and objectives of the law, but it requires approval from the European Parliament and the Council of the European Union before it can be implemented.

The analyses presented in this section are based on different data sources (see Table 8).

Table 8. Data sources used for the analysis on wood uses.

Data source	Organization	Data
Joint Forest Sector Questionnaire (JFSQ, rel. 2023)	EUROSTAT, UNECE, FAO, ITTO	Production, imports and exports of roundwood and wood-based products
Eurostat dataset nrg_cb_bm (accessed 2024)	EUROSTAT	Domestic production, imports, exports and change in stock of woody biomass for energy
Input/output coefficients	(Mantau, 2010)	Input/output coefficients for wood products
Forest product conversion factors (2020)	UNECE, FAO	Bark correction factor, input coefficients

Source: JRC, own elaboration.

3.2.3.1 Woody biomass for energy

In previous reports of the Biomass Mandate[13], wood for energy was mainly derived from the Joint Wood Energy Enquiry[14] whose published results are presently only available until 2019 with incomplete geographical coverage. Another key source was the data from the National Renewable Energy Action Plans (NREAP) Progress Reports, however this reporting scheme has been discontinued. Currently, the most up-to-date data source on biomass for energy is the new Eurostat dataset *nrg_cb_bm*, that publishes on-line the data reported by the Member States pursuant to the Regulation (EU) 2018/1999 (Governance Regulation). Up to now, only one year (2021) has been reported and unfortunately some limitations identified in the published datasets have hampered a comprehensive analysis. Uncertainties have emerged with respect to the actual units used by the countries to report the different feedstock categories, some unclear products categories definitions to be clarified, some anomalous values in the reported data, the completeness of the reported data. The issues reported here is the result of an assessment carried out to the best of our knowledge. To better understand the reasons behind the apparent inconsistencies found, country data providers should be consulted.

Concerning completeness of reporting not all the mandatory data were reported by MSs, and only three MS reported all the mandatory and voluntary data required by the Governance Regulation. An overview of the data report completeness by MS is given in Table 9.

[13] see Footnote 1, Chapter 1 for a list of previous public-facing reports

[14] https://unece.org/forests/joint-wood-energy-enquiry

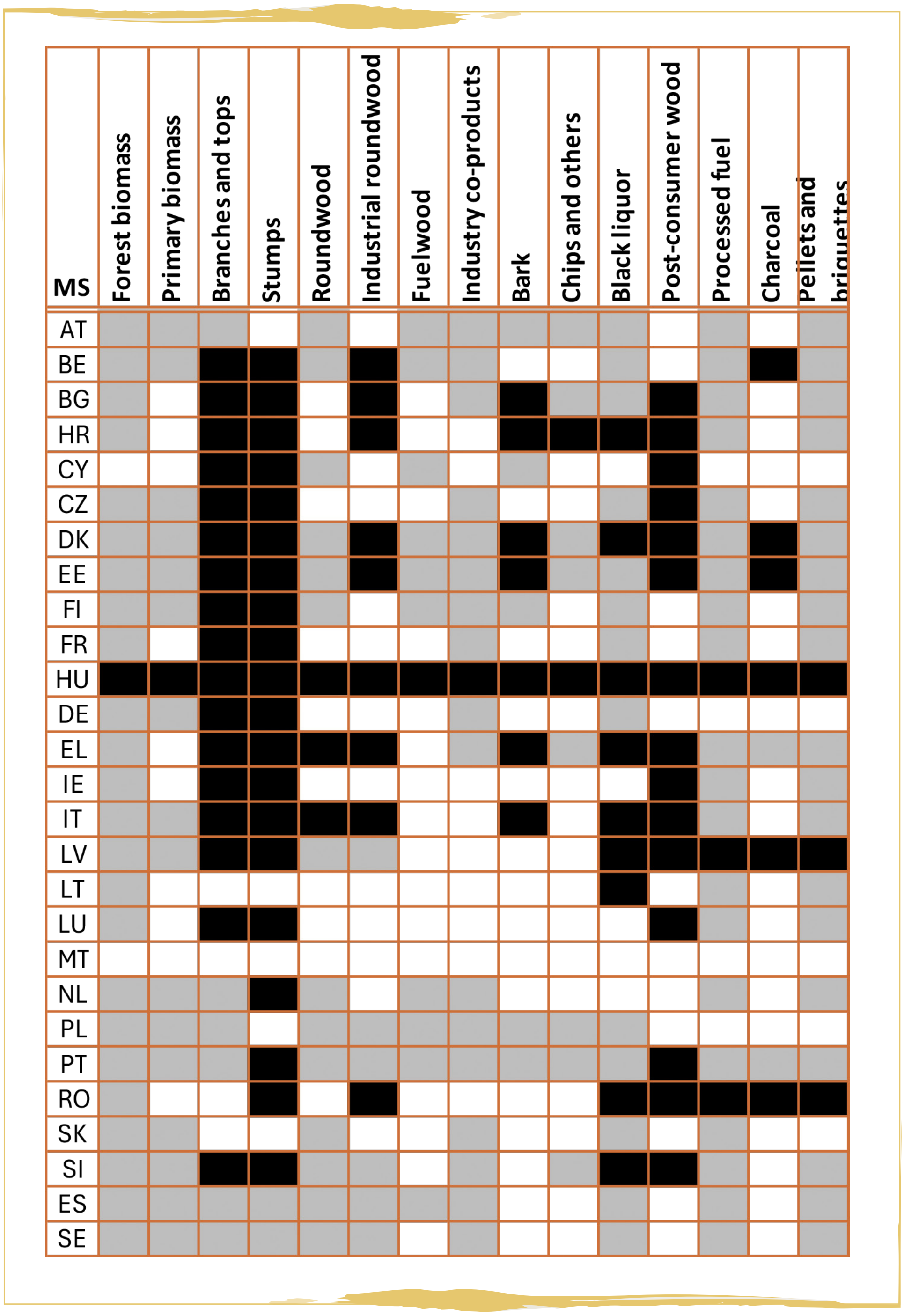
Table 9. Completeness of 2021 data reported under the Governance Regulation by MS (reported items on total requested items in %). The colour of the production and import cells is green when all mandatory and voluntary items were reported, orange when voluntary items were not completely reported (with the percentage referring to the fraction of mandatory items reported). Export and stock change are reported on a voluntary basis, the blue bars represent the relative amounts of related reported items. Hungary is not listed as no report was submitted.

MS	Production	Import	Export	Stock change
AT	full	full	100%	100%
BE	83%	83%	0%	0%
BG	83%	75%	60%	27%
CY	100%	100%	0%	0%
CZ	100%	100%	0%	0%
DE	100%	100%	53%	0%
DK	67%	50%	0%	0%
EE	75%	50%	53%	53%
EL	67%	50%	33%	0%
ES	full	full	100%	100%
FI	100%	100%	67%	67%
FR	100%	100%	80%	0%
HR	67%	33%	27%	13%
IE	100%	100%	80%	80%
IT	67%	67%	0%	0%
LT	92%	92%	87%	0%
LU	100%	100%	0%	0%
LV	100%	100%	0%	0%
MT	full	full	0%	0%
NL	100%	100%	93%	0%
PL	full	full	100%	100%
PT	100%	100%	100%	100%
RO	58%	8%	7%	7%
SE	full	full	27%	0%
SI	92%	83%	0%	0%
SK	full	100%	0%	0%

Source: JRC, own elaboration.

Concerning preliminary quality checks of the production data in *nrg_cb_bm*, results by country are summarised in Figure 29. Following this assessment, we concluded that before using this data a discussion and cross-check with the reporting MS would be recommended.

Figure 29. Summary of the JRC checks on reported data on production of woody biomass for energy uses in the dataset *nrg_cb_bm*. Cells are black when the item is unreported, grey when issues were identified in the reported data and further checks with MS are suggested before data usage, white when no issues were identified. The items (i) Postconsumer wood, (ii) branches and treetops and (iii) stumps are all reported on a voluntary basis.



Source: JRC, own elaboration.

Data checks were carried out considering various sources such as for example the numbers reported in the Joint Forest Sector Questionnaire (JFSQ)[15]; the historical series and comparability with the NREAP data; forest-based sector production in each country; and cross-checks with woody biomass reported and energy production. Although final conclusions or statements on data quality cannot be drawn, some inconsistensies were identified.

An example is the fuelwood category, a subcategory of primary wood. In many countries, including major producers, domestic fuelwood reported in *nrg_cb_bm* is significantly larger than in JFSQ (reaching proportions of 6:1 in the worst case).

Another example is the amount of industrial roundwood declared to be used for energy. In some countries this is a very large amount compared to previous analysis of historical data. After a closer look a few critical issues have been identified in the data. Here we report the case of Spain to exemplify, but similar issues are in other reporting countries such as Latvia or Slovenia. In *nrg_cb_bm*, the domestic industrial roundwood declares for energy use in 2021 is 23.9 Mm^3, but for the same year we see in JFSQ that the total domestic industrial roundwood production is 14.1 Mm^3, and that most of this production is declared as used for wood products manufacturing.

In some cases, the primary and secondary woody biomass appear to be misclassified or accounted for twice. So, it is not possible to correctly derive the related shares at the EU level.

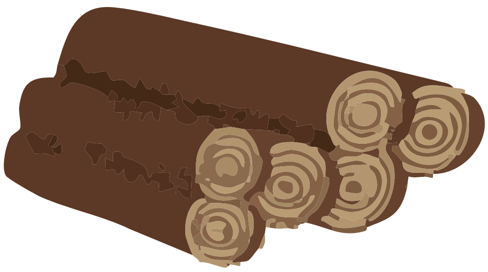
The conclusion of our preliminary assessment is that *nrg_cb_bm* is not yet sufficiently robust to make this dataset usable to derive reliable EU level analysis on the use of woody biomass for energy, and checks with MS are needed to clarify some of the issues identified.

As a general, albeit partial, estimate considering as datasource only the JFSQ, in 2021 fuelwood removals were about 127 Mm^3, while the apparent consumption was roughly of the same amount, since the EU is self-sufficient for this commodity. As anticipated, this amount is smaller than what could be derived from the *nrg_cb_bm* data. These removals are used directly for energy production, either as roundwood or as wood pellets and other agglomerates. However woody biomass for energy from industrial residues and from recovered post-consumer wood, again burnt as is or as agglomerate, counts, but these data are not available in the JFSQ.

3.2.3.2 Wood-based material production

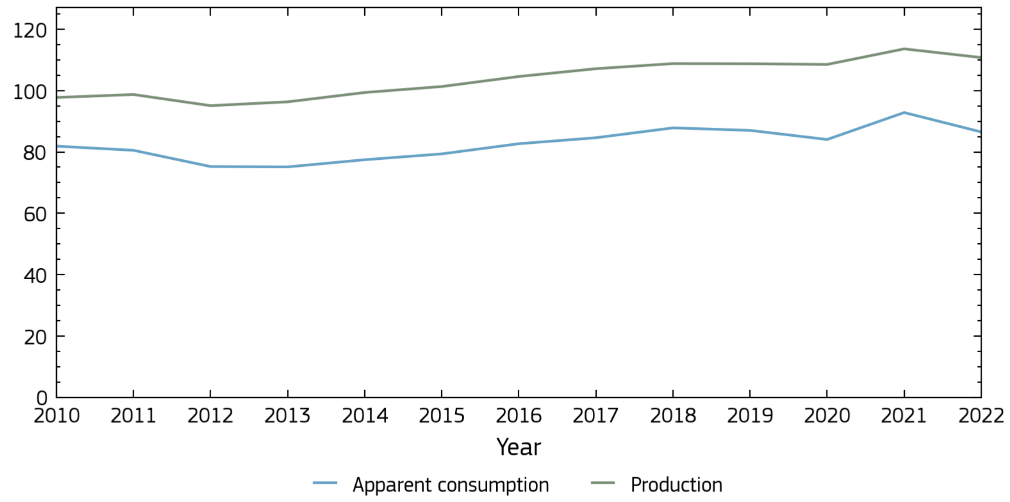
According to JFSQ, which is the datasource for the material sector, the apparent consumption of industrial roundwood was 389 Mm^3 in 2021. This roundwood is used in all the macro-categories of semifinished wood products: sawnwood, wood-based panels and wood pulp

As for the production and consumption of wood-based semi-finished products, from the JFSQ data, it is possible to highlight an increase for both sawnwood and panels (Figure 30 and Figure 31). Specifically, the produced sawnwood increased by 13.3% (from 97.7 to 110.8 Mm^3 product volume) in the time span 2010 to 2022, while the apparent consumption has increased by 5.7% (from 81.8 to 86.5 Mm^3 product volume).



[15] https://unece.org/forests/data-forest-products-production-and-trade

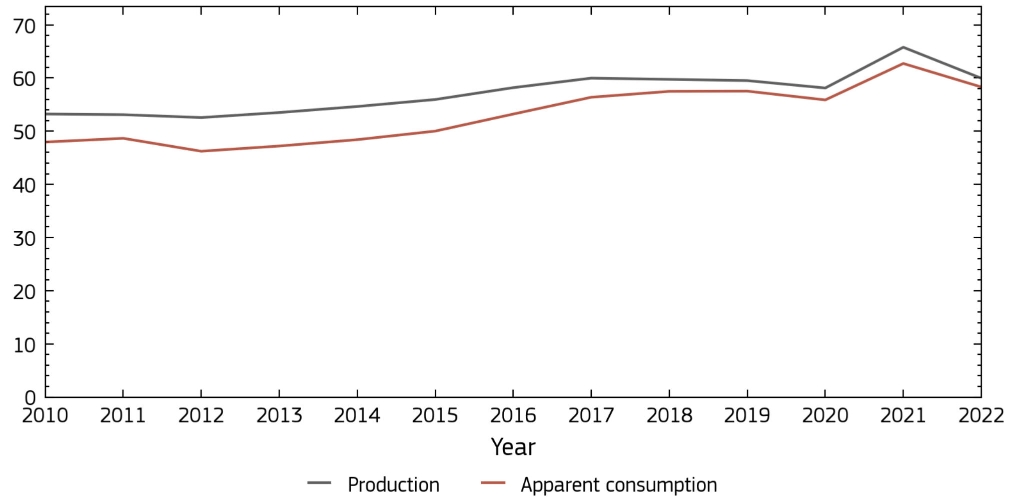
Figure 30. **Apparent consumption and domestic production of sawnwood in the EU, in Mm^3 solid volume.**



Source: JRC elaboration of JFSQ 2023 data.

The produced panels increased by 21.6% (from 48.0 to 58.3 Mm^3 product volume) in the time span 2010 to 2022, while the apparent consumption increased by 12.6% (from 53.2 to 59.9 Mm^3 product volume).

Figure 31. **Apparent consumption and domestic production of wood-based panels in the EU, in Mm^3 solid volume.**

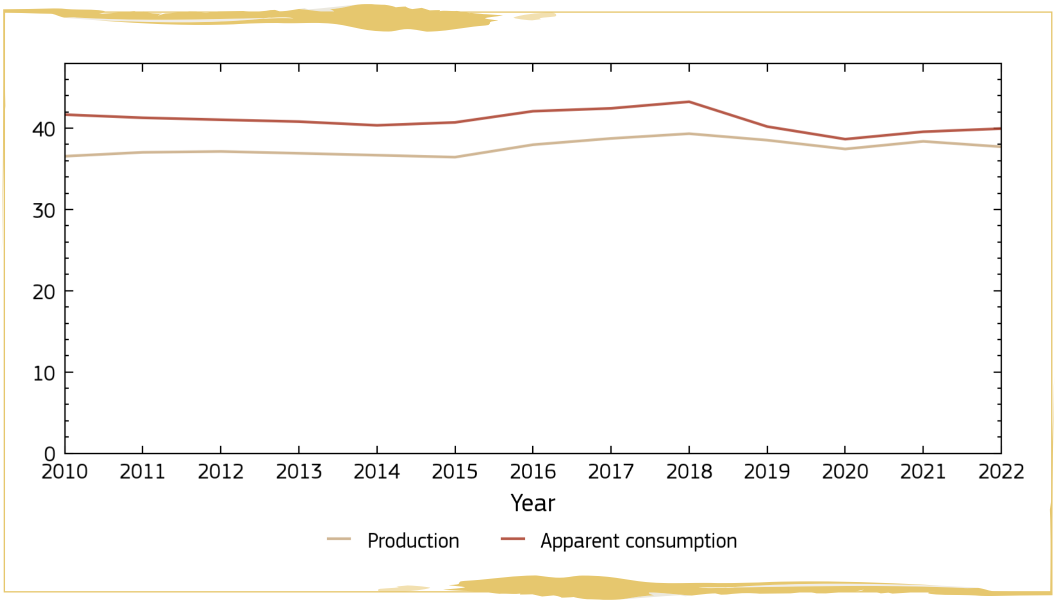


Source: JRC elaboration of JFSQ 2023 data.

From the same figures, it is evident that the EU is a net exporter of both sawnwood and panels. The net-exported quantities of sawnwood increased from 15.9 to 24.3 Mm^3 product volume while net-export of panels decreased from 5.3 to 1.6 Mm^3 product volume.

On the contrary, the EU is a net importer of wood pulp (Figure 32). The domestic production has remained quite stable in the studied time interval, with an increase of only 3.2% from 34.3 to 37.3 Mt, while the apparent consumption decreased by 4.1% from 41.7 to 39.9 Mt. Also, the net import of wood pulp decreased in the last years, from 5.1 9 Mt in 2010 to 2.2 9 Mt in 2022.

Figure 32. Apparent consumption and domestic production of wood pulp in the EU, in Mt.



Source: JRC elaboration of JFSQ 2023 data.

3.3 Fisheries and aquaculture biomass

3.3.1 Safe fishing thresholds

Jordi Guillen, Michael Gras

In most economic sectors, input increases such as labour and capital (i.e., investments) are often considered virtuous, indicating confidence in the future and expected growth. In fisheries, however, investments and increases in inputs are often harmful (Carvalho et al., 2020). Unlike the production of manufactured goods, but also of aquaculture and other biomass sectors, where the production can increase by increasing investments and inputs, fisheries production in general cannot increase sustainably (in the long run) by increasing investments and inputs (i.e. fishing vessels, gears, fuel). This is due to fisheries production (total available catch) being biologically limited, and over-investing does not lead to a more sustainable catch; instead, the fishery would produce either the same or lower catch at higher costs (investments).

Historically, people have had free access to marine fisheries resources, which had no individual property, partly due to the mobility of the resource and the impossibility of their assignment to a fixed territory, as well as the general belief that marine fisheries resources were inexhaustible. This lack of resource ownership complicated the management of fisheries, since fisheries tend to reach an overfishing state, as illustrated by Hardin (1968)'s in the 'Tragedy of the commons'. The use of the 'common' fishery resource is typically shared but never perfectly assigned to individual 'owners'. This imperfect ownership of the fish resources provides little incentives for users to act self-restrained in their exploitation. By increasing exploitation, users fully benefit from increased production, while the loss from the reduced productivity of the fish stocks is shared between all users. Hence, self-centredness leads all users to increase their production seeking further profits, resulting in a worse situation for all.

It is well known in traditional fisheries management that in any fishery as fishing intensity increases, catches increase to a long-term maximum (maximum sustainable yield, MSY[16]). From this MSY point on, if fishing intensity continues to increase driven by the hope to increase individual profits by increasing individual inputs, overall catches and profits will be reduced in the long-term. Thus, overfishing takes place in poorly managed fisheries, where fishing intensity is higher than required by the MSY principle. This results in spending more to catch less fish than at the MSY level (Clark, 1990; Pauly et al., 2002; Berkes et al., 2006; Willman et al., 2009; Worm et al., 2009).

Fish stocks exploited beyond MSY and MEY (maximum economic yield[17]) are thus producing less in biological and economic terms than what could be obtained if optimally managed (Guillen et al., 2013). Adequate fisheries management leads to bigger catches of fish or rents in a sustainable exploitation over time. Therefore, an appropriate management should lead to greater income (rents) over time, as it allows to reduce unnecessary expenses and to limit the inputs into an optimal yield.

The EU Common Fisheries Policy (CFP) is the EU regulation for sustainably managing European fishing fleets and conserving fish stocks (see Box 14). With the latest reform from 2013 (Regulation (EU) 1380/2013), the CFP features i) environmental,

[16] MSY can be defined as the maximum annual catch which on average can be taken year after year from a fish stock on a sustainable way—without deteriorating the productivity of the fish stock (Beverton & Holt, 1957). So, the MSY should correspond to the catch of an optimally managed fishery (at equilibrium) aiming at maximizing production. On an output managed fishery, the quota should be set equal to the catch at equilibrium; while, on an input managed fishery, it is the total fishing effort that needs to be set to the level necessary to harvest the optimal catch.

[17] MEY can be defined as the sustainable catch that maximizes profits -the difference between total revenues and total costs of fishing (Huntsman, 1949; Gordon, 1954). Accordingly, the MEY should correspond to the catch of an optimally managed fishery (at equilibrium) aiming at maximizing profitability.

economic and social objectives in fisheries, ii) fish stock management at maximum sustainable yield by 2020 for all managed stocks, iii) gradual introduction of a landing obligation by 2019, iv) continued application of the multiannual plans (MAPs) to manage more specifically fisheries in different sea basins, v) regionalisation to allow EU countries to propose detailed measures, and vi) fleet capacity ceilings per EU country in combination with the obligation for EU countries to ensure a stable and enduring balance between fishing capacity and fishing opportunities over time.

According to Article 2 of the CFP: “The CFP shall ensure that fishing and aquaculture activities are environmentally sustainable in the long-term and are managed in a way that is consistent with the objectives of achieving economic, social and employment benefits, and of contributing to the availability of food supplies”. However, the CFP gives certain predominance to the biological objective by managing fish stocks at maximum sustainable yield. This implies trying to maximise production rather than profits and using resources in a more efficient way at the MEY. At MEY, the fishing pressure tends to be lower than at MSY, which implies a lower use of fuel and thus reduced CO_2 emissions, and a larger biomass of fish at sea that would imply that fish stocks are managed more precautionary.

In the Northeast Atlantic Ocean (including e.g., the North and Baltic Seas), main commercial fish stocks are managed using Total Allowable Catches (TACs). These TACs are the maximum amount of fish in weight that can be harvested for each stock. The TAC proposals are based on scientific advice from the International Council for the Exploration of the Sea (ICES) and sometimes slightly corrected to incorporate socio-economic considerations based on scientific advice from the Scientific, Technical and Economic Committee for Fisheries (STECF) supported by the JRC. These proposals are then negotiated and agreed at the Council of Ministers, between ministers from the different EU countries. The TACs are split in fishing quotas among countries using the Principle of Relative Stability, a fixed proportion by stock and country derived from historical track records. Fishing opportunities from shared fish stocks are negotiated with third countries, such as the United Kingdom and Norway.

In the Mediterranean and Black Seas, most fish stocks are predominantly managed with effort limitations i.e. establishing the maximum number of vessels and fishing days that can be fished. However, fisheries management that adjusted total effort to the situation of the resource has often not been really in place. In recent years, with the establishment of multiannual management plans (MAP) in the Mediterranean a more proactive approach has been followed, in great part due to the high number of depleted fish stocks in the area.

Box 14. Marine ecosystem condition

Coastal regions, seas and oceans harbour complex, rich and highly fragile marine ecosystems. These are essential for the climate, planetary and human health and they provide for food security and livelihood.

The European Union has in place a holistic framework to protect and conserve its coasts, seas, and the ocean, and ensure their sustainable use under the remit of the Marine Strategy Framework Directive (MSFD), Maritime Spatial Planning Directive, the Common Fisheries Policy (CFP) and the Sustainable Blue Economy Communication.

The Commission is committed to support the preservation of marine ecosystem services by driving the implementation of the MSFD and the CFP forward and by fostering a new approach for a sustainable blue economy in the EU. This is further laid down in the basic regulation underpinning the CFP ((EU) 1380/2013), the Action Plan of the Communication on the Sustainable Blue Economy (DG MARE)[18] and the Action Plan to implement the Marine Strategy Framework Directive (DG ENV)[19].

Mitigating the negative human impacts on the environment helps to preserve its capacity to provide ecosystem services, which are essential for securing resilient social, economic and financial capital for future generations (Dasgupta, 2021).

Since the standard adoption of the System of Environmental and Economic Accounting – Ecosystem Accounts (SEEA EA) in 2021[20], there is growing attention and interest in natural capital accounting (NCA) worldwide (see also section 7.3 of this report). Many applications are currently undertaken for terrestrial ecosystems, and while the importance of the marine ecosystems is concretely acknowledged and endorsed through the organization of ad hoc global partnerships, such as GOAP[21].

Unlike terrestrial ecosystems, which can be more easily monitored, marine systems pose significant challenges due to their dynamic and three-dimensional nature, resulting in a scarcity of spatial data (Townsend et al., 2014). In response, mapping marine ecosystem services has emerged as a crucial tool for translating ecosystem services into practical applications, while modelling offers a valuable resource for assessing these services.

A recent study by Addamo et al. (2024) highlights the limitations and lack of harmonisation in evaluating ecosystem services in European marine and coastal areas. Most research has focused on general assessments, with only a few studies conducting in-depth analyses of habitat-specific ecosystem services, such as those found in coastal lagoons, seagrass, and meadows. This imbalance is not only evident in the types of habitats studied but also in the categories of ecosystem services considered.

The monetary and non-monetary valuation of marine ecosystem services is a critical component in promoting the conservation of marine habitats and resources, as well as ensuring sustainable development of maritime activities. However, the methodology for socio-economic valuation of marine assets is still under discussion, primarily due to the inherent complexities of the marine environment (Addamo et al., 2024; Ascioti & Moraci, 2024).

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[18] COM/2021/240 final (*https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2021:240:FIN*)

[19] COM(2023) 102 final (*https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52023DC0102*)

[20] *https://seea.un.org/content/ecosystem-accounting-news*

[21] *https://www.oceanaccounts.org/*

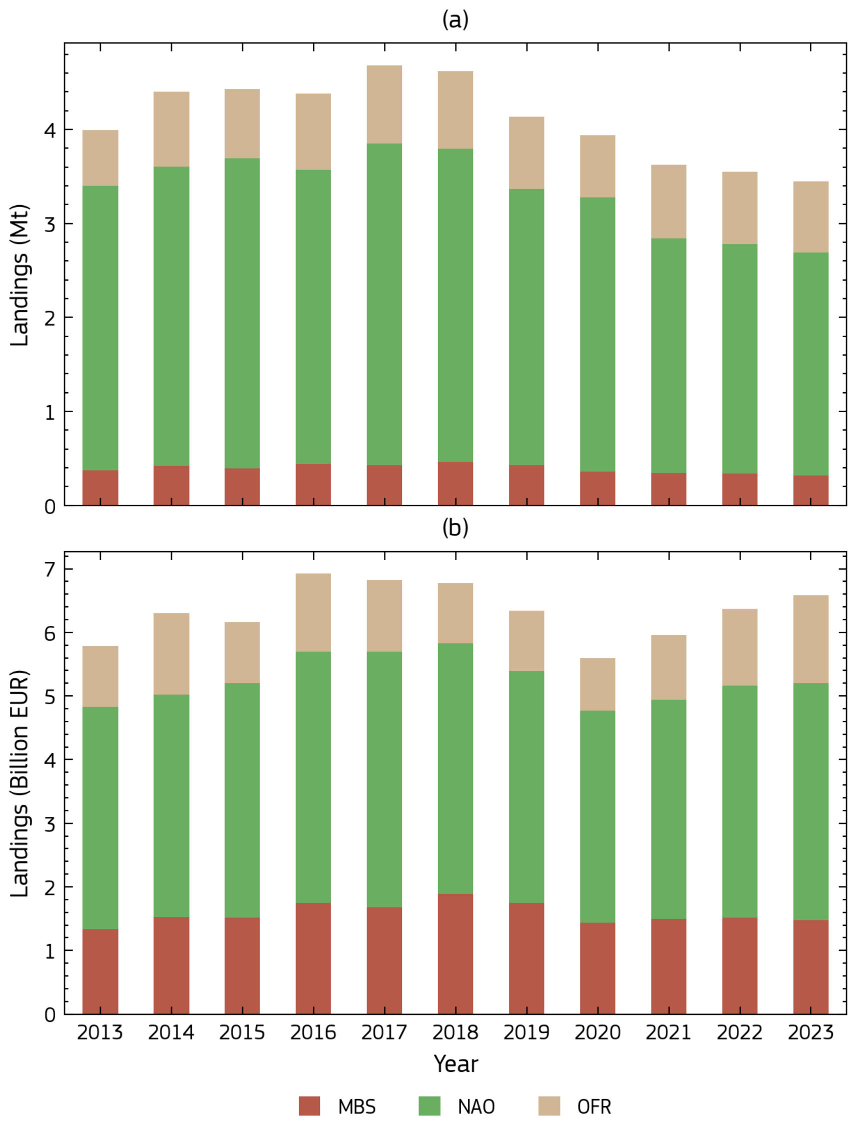
3.3.2 Fisheries production and supply

Zeynep Hekim, Michael Gras, Jordi Guillen

In 2022, the EU-27 fishing fleet numbered 70 986 vessels with a combined gross tonnage of 1.32 million and engine power of 5.26 M kW (million kilowatts). Of these vessels, there were 52 830 active vessels in 2022 offering direct employment to 119 702 fishers, corresponding to 75 816 full-time equivalents (FTEs) (STECF, 2024a).

The EU fleet landed 3.45 Mt (million tonnes) of seafood in 2023, decreasing by 2.8% compared to 2022 (Figure 33a). The value of landings reported was €6.6 billion in 2023 and remained stable compared to 2022 (STECF, 2024a) (Figure 33b). To do so, the EU fleet spent roughly 5 million days at sea and consumed 1.8 billion litres of fuel (STECF, 2024a,b).

Figure 33. (a) Evolution of the EU landings weight and (b) value, by sea region (NAO (North Atlantic Ocean[2]), MBS (Mediterranean and Black Seas), and OFR (Other Fishing Regions)) for the period 2013-2023.



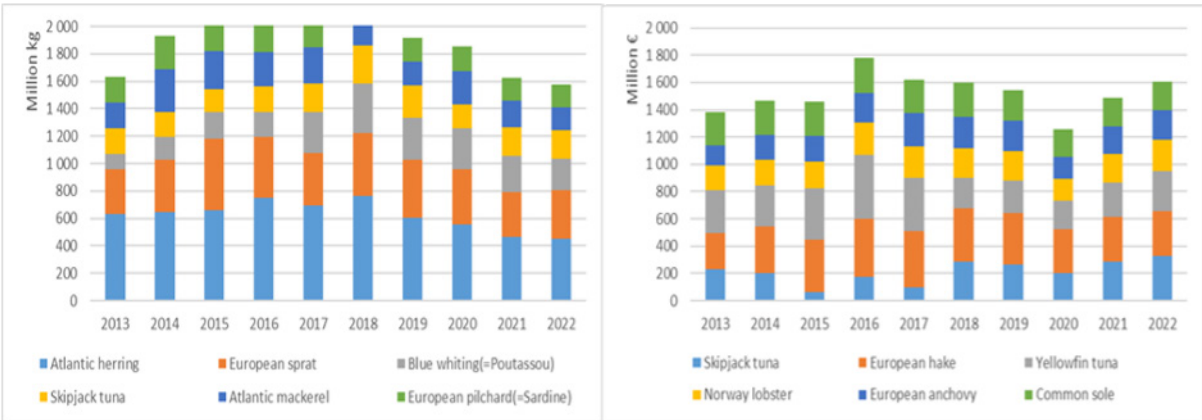
Source: STECF (2024b).

The Spanish fleet accounted for 22% of the total weight of landings in 2023, followed by Denmark (15%), France (14%), the Netherlands (8%), and Ireland (5%). In terms of value of landings, the picture is slightly different, with the top 3 countries (Spain, France and Italy) being responsible for more than 60% of the value landed (STECF, 2024 a, b).

3.3.2.1 Top species landed

Atlantic herring, at 455 000 tonnes, continued to be the most landed species (in weight) by the EU fleet in 2022, followed by European sprat (348 163 tonnes), blue whiting (234 553 tonnes), skipjack tuna, Atlantic mackerel and European pilchard. In terms of volumes landed, together with sandeels and Atlantic horse mackerel, these eight species account for more than half of the landings weight by all EU vessels (51.2%) (STECF, 2024 a, b) (Figure 34).

Figure 34. Trends for the top six species landed in weight and in value.



Source: STECF (2024a); monetary values adjusted for inflation; constant prices (2022).

Skipjack tuna at €331 million, was the top species landed in value, followed by European hake, yellowfin tuna, Norway lobster and European anchovy. Those six species account for almost a quarter of the value landed by European vessels in 2022 (STECF, 2024a).

3.3.2.2 Main factors impacting EU fisheries production

Total landings at EU level (in weight) increased over the years 2013-2017 before following a decreasing trend until 2023 (Figure 33a) with some stability over the last 3 years (2021-2023). Landings in values and weights followed similar trends up until 2021. After that year, landings in values have increased while volumes remained stable.

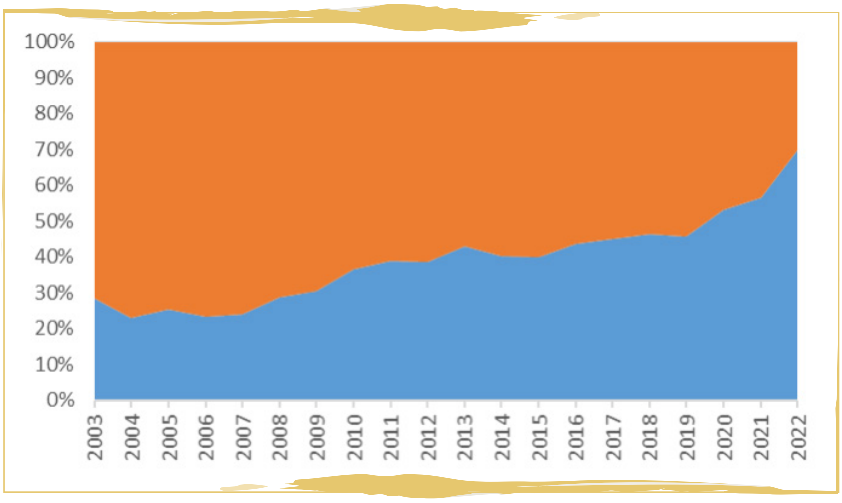
Over the last decade, several external shocks (such as the COVID-19 pandemic, high-energy prices, and BREXIT) had an impact on the fisheries landings at the European level (see for instance, Carpenter et al., 2023; Guillen et al., 2023).

One of the main objectives of the Common Fisheries Policy (CFP) is to bring stocks at or below Maximum Sustainable Yield (MSY). In order to monitor the progress towards this objective, the JRC annually computes a set of indicators primarily based on fishing mortality (F) and Biomass (B) outputs from quantitative fisheries assessments. The time series of these indicators cover the period 2003-2022 or 2003-2021 upon data availability. The indicators presented in this section cover fish stocks in EU waters from the Northeast Atlantic (NEA) and the Mediterranean and Black Sea (MBS).

In EU waters, fishing mortality (F) was estimated for 147 stocks (83 for the Northeast Atlantic and 64 for the Mediterranean and Black Seas). From 2003 to 2022, the percentage of stocks fished at or below the MSY reference point (FMSY) have increased from 28% to 70% (Figure 35).

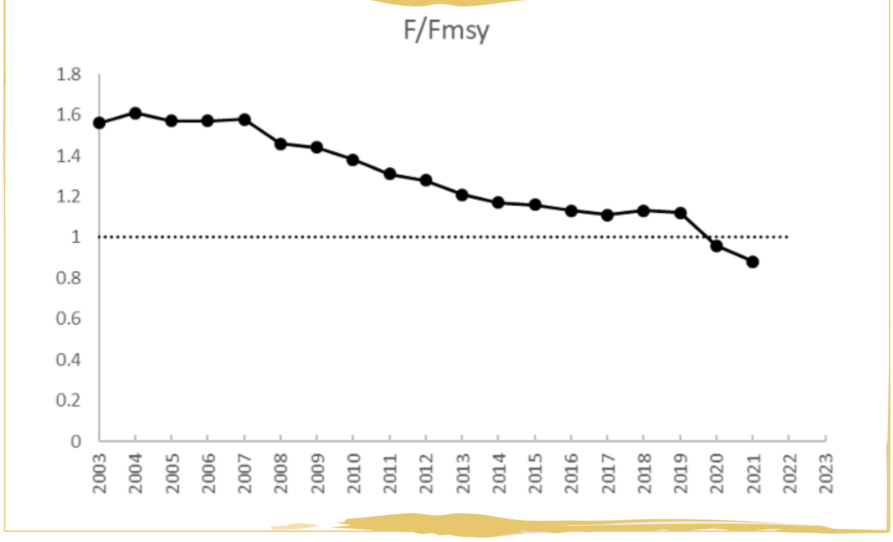
Because F is not available for every stock identified in both sea basins (NEA and MBS) and to quantify the average level of fishing mortality relative to the reference point (FMSY), a trend in F/FMSY was also modelled. For stocks in EU waters, the F/FMSY indicator exhibited a decreasing trend in average from 1.56 to 0.88 over the period of 2003-2021 for which data are available (Figure 36). The results highlight that the objective of all EU stocks being exploited at or below FMSY has not yet been reached. However, progress towards a more sustainable exploitation has been made.

Figure 35. **Proportion of European fish stocks that are overexploited ($F>F_{MSY}$ orange) or sustainably exploited ($F\leq F_{MSY}$ blue). It is to be noted that 2022 data do not consider MBS.**



Source: STECF (2024c).

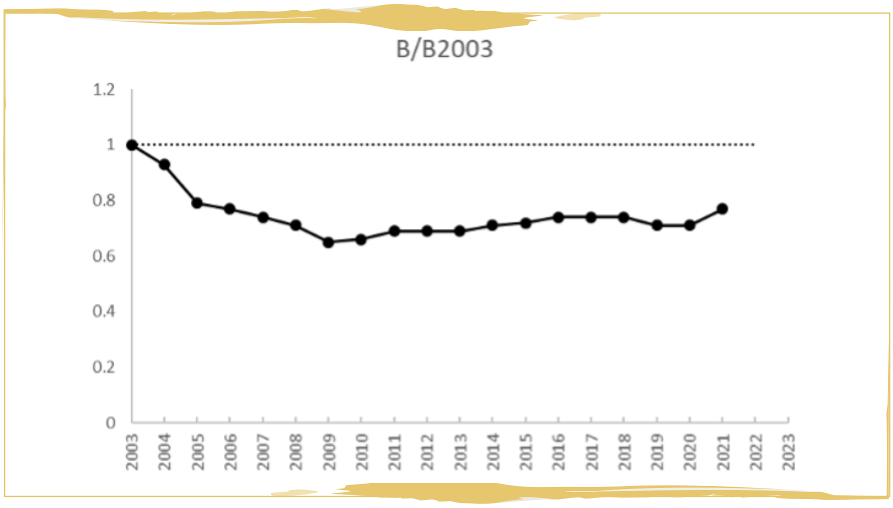
Figure 36. **Modelled trend in F/F_{MSY} for EU waters stocks for which an F time series and an associated F_{MSY} are available (122 stocks).**



Source: STECF (2024c).

The objective of the indicator "trend in relative biomass" (Figure 37) is to track the trend in absolute fish biomass compared to the biomass at the start of the time series (2003). The biomass has first followed a decreasing trend over the years 2003-2009. This decrease is due to the lack of biomass information for several small stocks in the Mediterranean and Black Seas. Their inclusion in the series has artificially decreased the average biomass during those years. From 2009, when the dataset is complete, the average relative biomass of exploited stocks has increased from 0.66 to 0.77, i.e. an increase of 18%. Therefore, concurrently to the reduction in fishing pressure on EU stocks, the average biomass of assessed stocks has increased.

Figure 37. **Trend in biomass compared to the estimated biomass in 2003 for EU waters stocks.**

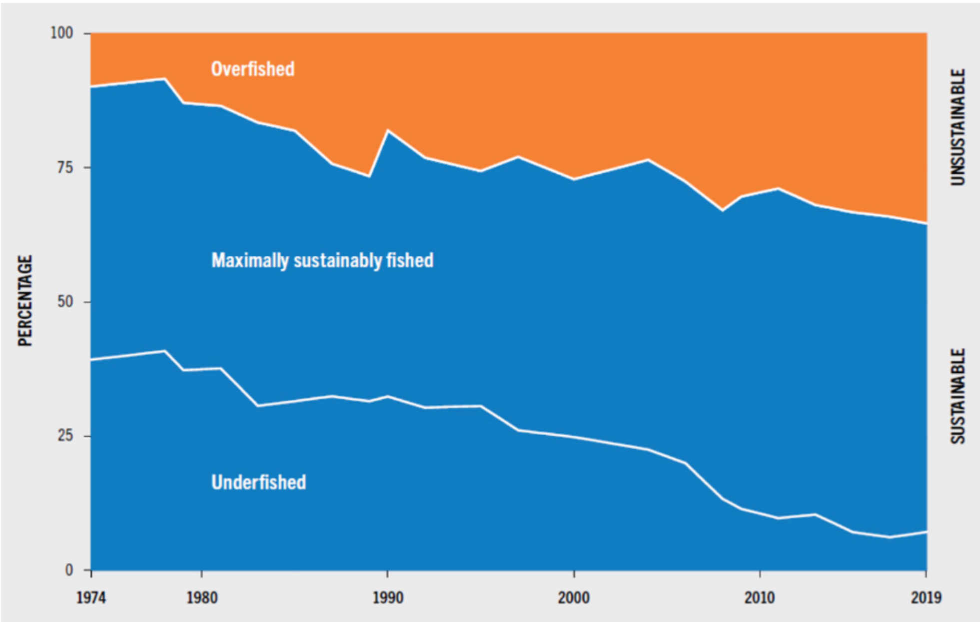


Source: STECF (2024c).

The three indicators presented in this section highlight an improvement in the status of fish stocks in EU waters for which a quantitative assessment is available. The proportion of fish stocks that are overexploited (F>FMSY) has reduced over the years as well as the average F/FMSY which was below 1 in 2021. Concurrently, and since 2009, the biomass of assessed stocks have increased. This increase does not appear as pronounced as the decrease in fishing mortality. This might be due to the lag required by fish stocks to rebuild.

These indicators can be put into a more global perspective and compared to the indicators that the FAO produces at a global scale. Figure 38 shows that worldwide, the proportion of fish stocks that are overexploited has increased over the years 1974-2019 (Figure 38; FAO 2022), i.e. an opposite trend to the exploitation pattern observed in EU waters.

Figure 38. Global trends in the state of the world's marine assessed fish stocks for the period 1979-2019.



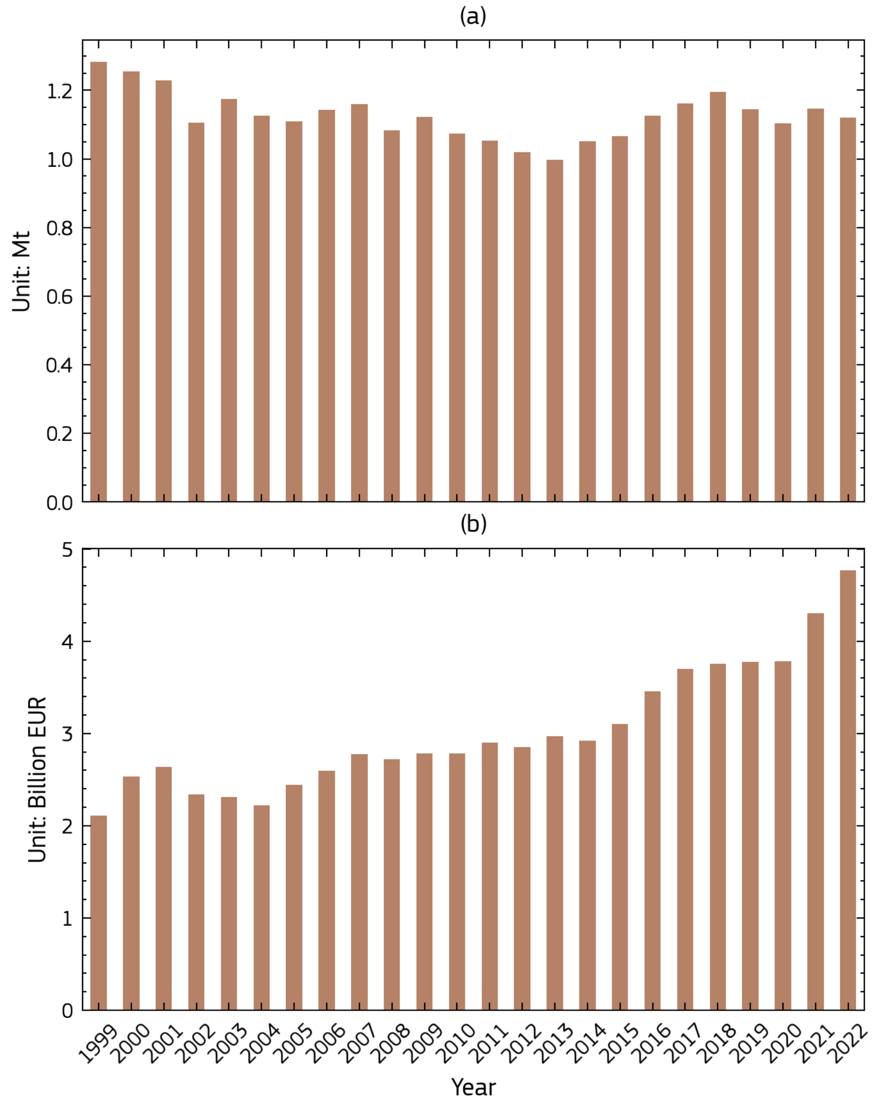
Source: FAO (2022).

3.3.3 Aquaculture production and supply

Jordi Guillen, Jarno Virtanen, Montse Tardy Martorell

EU aquaculture production achieved 1.12 Mt and a value of €4.77 billion in 2022 (FAO, 2024), resulting in a first-sale price of 4.3 € kg^{-1} (Figure 39).

Figure 39. (a) Evolution of the EU aquaculture production in weight (in million tonnes) and (b) value (in billion Euro) for the period 1999-2022.



Source: Own elaboration from FAO (2024) data.

STECF (2023) estimates that the EU aquaculture sector was composed of about 14 thousand companies, with about 57 thousand persons employed in 2020.

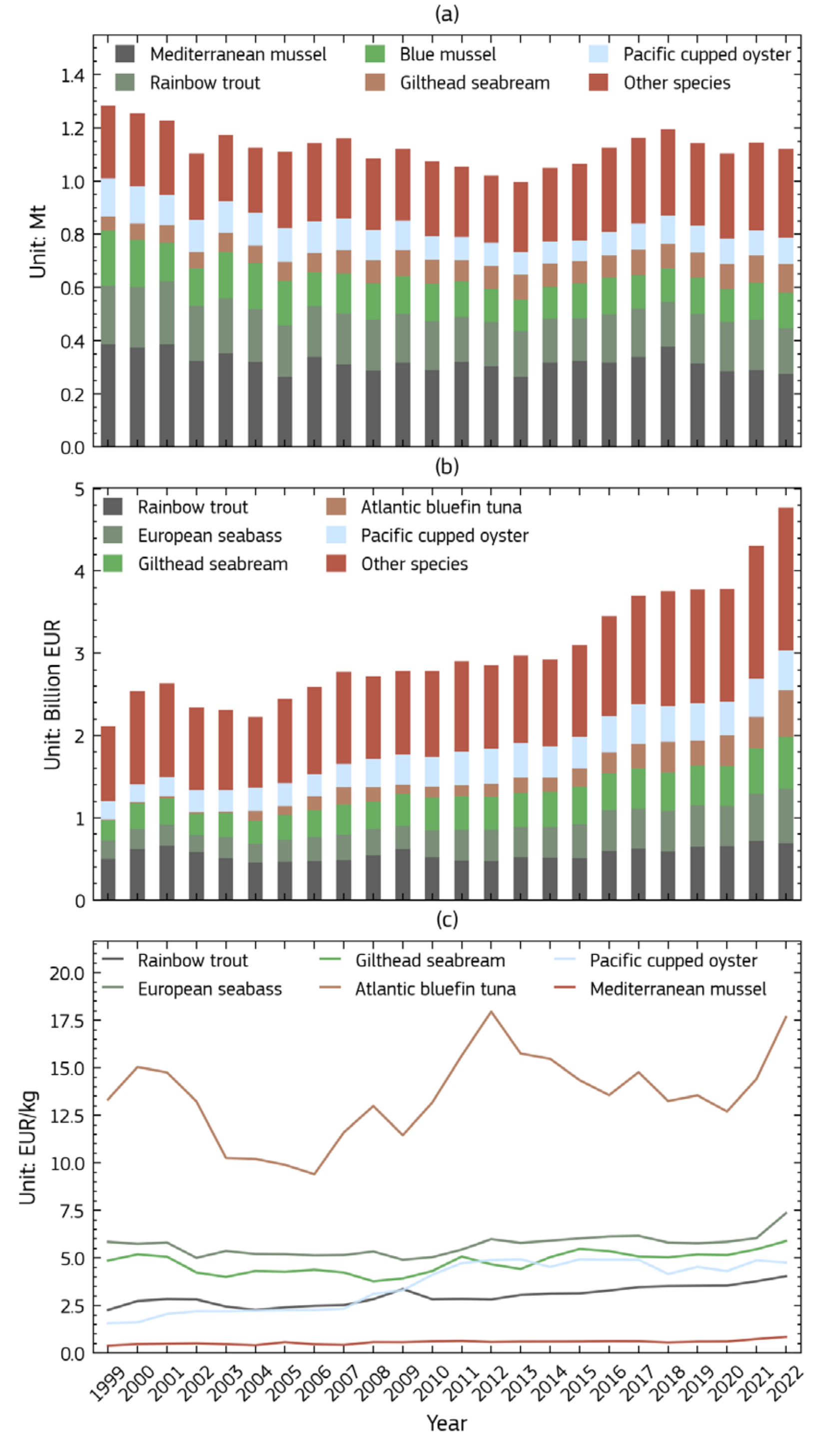
The Spanish aquaculture production in weight represented about 24.6% of the total EU aquaculture production in 2022 (17.1% in value), followed by France (17.9% in weight, 16.3% in value), Greece (12.7% in weight, 17.9% in value) and Italy (11.8% in weight, 10.5% in value). Thus, these four countries –Spain, France, Greece and Italy- accounted 67% of the EU aquaculture production in weight and 62% in value (FAO, 2024).

3.3.3.1 Main species produced

Mediterranean mussel (*Mytilus galloprovincialis*), at 275 thousand tonnes, was the most farmed species in weight by the EU aquaculture sector in 2022, followed by rainbow trout (170 thousand tonnes), blue mussel (*Mytilus edulis*) with 136 thousand tonnes, gilthead seabream and Pacific cupped oyster. These five species accounted for more than 70% of the production weight of the EU aquaculture sector in 2022 (FAO, 2024) (Figure 40a).

Rainbow trout, at €686.4 million, was the top species farmed in value, followed by European seabass, gilthead seabream, Atlantic bluefin tuna and Pacific cupped oyster. These five species accounted for almost 64% of the value produced by the EU aquaculture sector in 2022 (FAO, 2024) (Figure 40 b, c).

Figure 40. Evolution of the EU aquaculture production by main species (a) in weight (in million tonnes); (b) in absolute value (in billion Euro) and (c) in Euro per kilogram for the period 1999-2022.



Source: FAO (2024).

Of the 1.12 Mt produced by the EU aquaculture sector in 2022, shellfish (mainly mussels) represented the 49%, freshwater fish 26%, marine fish 25%, while aquatic plants and aquatic invertebrates, such as crustaceans, are comparatively negligible accounting for less than 0.1% and 0.3%, respectively, of the total EU aquaculture production (FAO, 2024).

This composition differs significantly from global aquaculture trends, where freshwater fish represent 41%, aquatic plants 28%, shellfish 24%, and marine fish 6%, of global production (FAO, 2024). Notably, aquatic plants are primarily produced for non-food industrial purposes, contributing to their lower value share (5%) compared to their quantity share (28%).

3.3.3.2 Main factors impacting EU aquaculture production

While both global aquaculture production and its value have been growing rapidly for thirty years, EU production growth was slow until the beginning of this century, and since then it has remained stagnant between one million and 1.2 million tonnes. The overall EU's aquaculture production in weight grew about 7% in the last decade (2010-19) and negative (-11%) in the previous one (2000-09). This is a strong contrast to the 54% increase in global aquaculture production during the last decade (Guillen et al., 2025).

An examination of the trends in EU aquaculture production by main species shows that the sector is highly heterogeneous. In particular, the production of molluscs has been decreasing (as shown in Avdelas et al., 2021), the production of freshwater fish has been rather stable, while the production of marine fish has been increasing significantly.

As explained by Tacon et al. (2009) and Garlock et al. (2020, 2024), the situation in the EU is not unique and in many high-income countries, aquaculture production is focusing on high-value species and more intensive production practices where there is more scope for productivity growth, with more traditional and extensive aquaculture production stagnating or growing slower. This trend is reflected in the EU's increasing marine fish production, which commands a higher average price than molluscs and freshwater fish (Figure 40).

The EU aquaculture industry on the one hand faces challenges due to stricter environmental regulations, prioritising sustainability over production growth on the other hand the quality of shellfish waters is of utmost importance for the sector. Consequently, the sector would benefit from a more stringent implementation of the EU water aquis[22], which would also help to achieve the objectives of the "Strategic guidelines for a more sustainable and competitive EU aquaculture for the period 2021 to 2030".

While these regulations promote more sustainable production methods, they increase production costs and hinder competitiveness (Abate et al., 2016; Guillen et al., 2019; van Senten et al., 2020; Hedge et al., 2023; STECF, 2023). In contrast, producers in developing countries benefit from more lenient regulations and lower costs, granting them a competitive advantage (Engle & Stone, 2013; Abate et al., 2016; Garlock et al., 2024).

Hence, European producers face stiff competition from low-priced imports, often of lower trophic level species (van den Burg et al., 2016; Bak et al., 2018). The production of high-value species may be a revealed comparative advantage for the EU aquaculture sector, as it often requires more capital and knowledge-intensive practices (Afewerki et al., 2023; Landazuri-Tveteras et al., 2023). Innovation and productivity growth have been key factors in driving the blue revolution, particularly for complex species (Asche, 2008; Kumar and Engle, 2016).

3.3.4 Aquatic biomass demand and uses

Jordi Guillen

The EU is the eighth largest producer of fisheries and aquaculture products (behind China, Indonesia, India, Vietnam, Peru, the Russian Federation and the United States of America), covering around 2% of global production. However, when looking at total fish consumption, the EU ranked third after China and Indonesia, with 11.57 Mt (million tonnes) (EUMOFA, 2023). About 92% of the fish consumed in the EU are

[22] For example related to the implementation of the Urban Wastewater Treatment Directive (UWWTD), the Water Framework Directive (WFD) and the Marine Strategy Framework Directive (MSFD) in relation to shellfish production areas.

for human food consumption, and the rest is for non-food uses such as animal feed, but also the medical and pharmaceutical (i.e., blue biotechnology) uses.

Blue biotechnology is defined as the application of science and technology to living organisms from marine resources, as well as parts, products and models thereof to produce knowledge, goods and services. The total value of sales of the EU blue biotechnology sector are estimated at €868 million in 2021, with Germany and France making slightly more than half of the total EU turnover. Bioengineering, Genomics, Vaccine Development and Drug Discovery applications made 85% of the total turnover of the EU's blue biotechnology (MRFR, 2024; European Commission 2024).

The EU's 2022 imports of fisheries and aquaculture products reached €31.9 billion and 6.1 Mt (average price of 5.2 € kg^{-1}), representing a 23% increase in value but a 3% decrease in volume compared with 2021. Similarly, the value of the EU's exports increased by 19% reaching €8.1 billion (average price of 3.5 € kg^{-1}), but its volume decreased by 5% to 2.3 Mt.

EU trade flows in 2022 were influenced by several key factors. The primary driver was a surge in inflation, partly linked to the COVID-19 recovery, which sparked an increase in demand and subsequent price hikes. In addition, the Russian invasion of Ukraine had a profound impact, as it drove up energy and production costs, exacerbating global inflation and affecting currency exchange rates. Furthermore, supply constraints resulting from quota reductions and intensified competition for raw materials contributed to a decline in trade volumes, which in turn, contributed to rising prices.

The EU's apparent food consumption of fisheries and aquaculture products was estimated to be about 10.60 Mt in 2021, resulting in an average consumption per capita estimated at 23.71 kg (measured in live weight equivalents), representing a 2% increase from 2020 (EUMOFA, 2023). In 2022, household expenditure on fisheries and aquaculture products in the EU reached €62.9 billion, representing an 11%-increase from 2021 (EUROSTAT, 2024). EU citizens can maintain and increase high consumption levels of fisheries and aquaculture products by importing them from other regions of the world. According to EUMOFA (2023), the EU's self-sufficiency has reached a historical low level of 38.2% in 2021. Self-sufficiency is the capacity of EU countries to meet the consumption of their citizens from their domestic fisheries and aquaculture production. Thus, for each 10 kg of fish that EU citizens eat, more than 6 kg are imported.

Most EU consumption of fisheries and aquaculture products consists of wild products (about 70%) and, more specifically, of imported fisheries products. Likewise, the EU fish processing industry strongly relies on imports from third countries: salmon and cod from Norway and the UK, Alaska pollock from China, shrimp from South and Central America and South-East Asia, sardines from Morocco, squid, tropical tuna, etc.

3.4 European and Global macroalgae production and supply

Céline Rebours & Javier Sánchez López

This chapter provides an update from the previous report published in 2023 and presents the latest and best available data on macroalgae biomass production to identify the main gaps, uncertainties, future developments and recommendations for the development of the algae sector in Europe.

3.4.1 Methods

The FishStatJ workspace of the FAO Global Fishery and Aquaculture Statistics was downloaded and analysed, including the datasets on global production by production source (species, country, production area, production source, and year (1950-2022)) (FAO, 2024), value source (species, country, production area, and year (1984-2022)) (FAO, 2024), global commodities production and trade referring to quantity (commodity, country, trade flow and year (2021-2022)) (FAO, 2024). Data on economic value are available only for macroalgae aquaculture production. For the data and analysis provided in this chapter, the production values (harvest and farmed) for the macroalgae species coded in the FAO database were selected, thus filtering out the categories of microalgae species (e.g., *Dunaliella salina, Chlorella vulgaris*), the cyanobacteria *Arthrospira* spp. (also coded as Spirulina) as well as the generic category "Aquatic plants nei" that, according to the FAO database, are farmed in freshwater or are captured from inland waters. Thus, the category "Aquatic plants nei" produced in marine and brackish environments and captured in marine areas were included, as they were considered to most likely include macroalgae species. Data on trade only consider macroalgae biomass and derived products. In the last version of the FishStatJ FAO database (v4.04.00), *Saccharina japonica* (Japanese kelp) is coded with its correct name, while in previous version it was mentioned under the name *Laminaria japonica*.

For statistical purposes, those aquatic organisms that are harvested by an individual or corporate body that has owned them throughout their rearing period are considered as aquaculture production. In contrast, aquatic organisms exploitable by the public as a common property resource, with or without appropriate licenses, are considered as the harvest of fisheries. The production of aquatic plants is given in wet weight (W.W). Quantities are given in tonnes (=1000 kg). The value of aquaculture, converted from local currencies, is reported by FAO in thousands of US dollars using appropriate exchange rates and is expressed in nominal terms. For the present report, economic values are expressed in Euro using a 0.95 EUR/USD conversion rate. In this chapter, the price of the macroalgae biomass (EUR per tonne) is estimated by dividing the value of aquaculture by the amount of macroalgae biomass farmed. More detailed market prices (business to business and business to consumer) of macroalgae specific species in Europe were provided by Araujo et al. (2021).

The data used for the analysis of the algae biomass production, trade, and flows presented in this report were based on the information published in scientific and grey literature and on the use of the available datasets on algae biomass production and trade. These datasets are the official statistics made available by Eurostat and the FAO that include the reporting by national authorities. All European countries (including non-EU countries) with available statistical data were considered relevant and included in the analysis, as some of the main European producers are not part of the EU-27. Thus, the results present a comprehensive overview of the sector at the European level. Analyses at the global level were also conducted for comparative purposes.

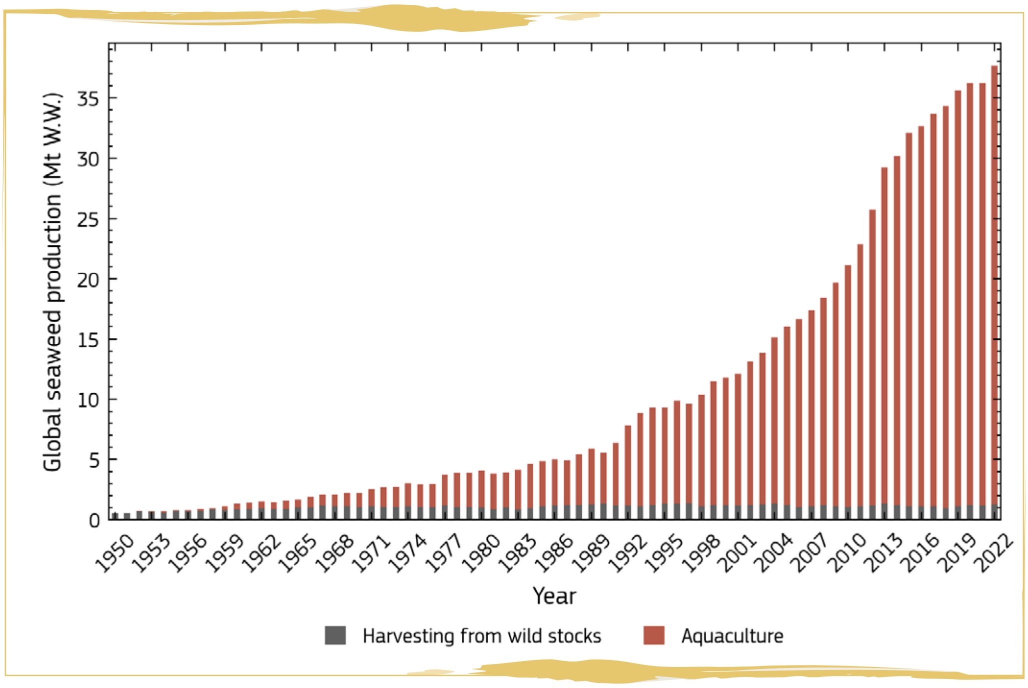
For reporting purposes, when data are not shown at national level in this study, they are aggregated and presented for the EU-27 and /or for other European countries. For comparison purposes between biomass production and trade, 2022 will be taken as a reference year.

Countries that are known to be producers of seaweed but are not covered in the databases used for this study (e.g., Israel) were not included.

3.4.2 Macroalgae biomass production

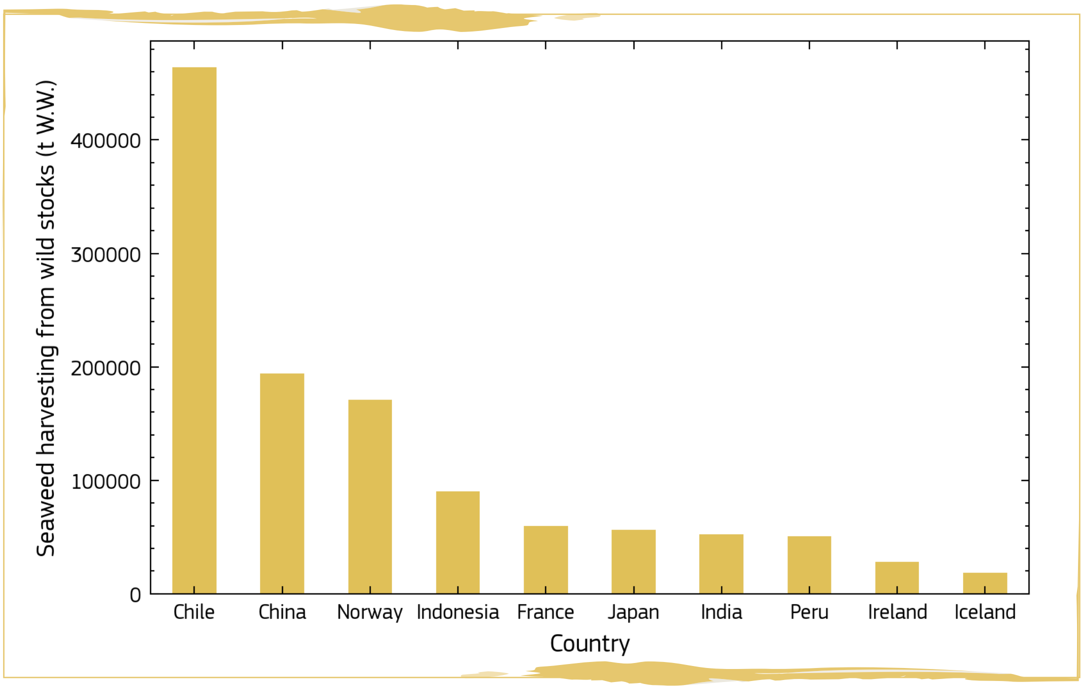
The annual global macroalgae production reported an increase worldwide since 1950 (Figure 41). Until 1970, the biomass was mainly harvested (wild catch). In 2022, the reported seaweed biomass harvested from wild stocks in 29 countries, as shown in Figure 41 (see Table A4.1 in Annexes to Chapter 4), amounted to a total of 1,252,237 tonnes (wet weight, hereafter referred as W.W.). The top 5 countries harvesting seaweed from their wild stocks were Chile, China, Norway, Indonesia and France, which account for over 78.2% of the world's seaweed harvest (Figure 42). The biomass harvested from wild stocks in the EU-27 in 2022 represented 7.5% of the global harvest while other European countries represented 15.1% (Figure 42).

Figure 41. **Global seaweed production in million tonnes wet weight farmed and harvested from wild stocks from 1950 to 2022.**



Data source: FAO, 2024.

Figure 42. **Top 10 countries in wild stock seaweed harvesting in 2022.**



Data source: FAO 2024.

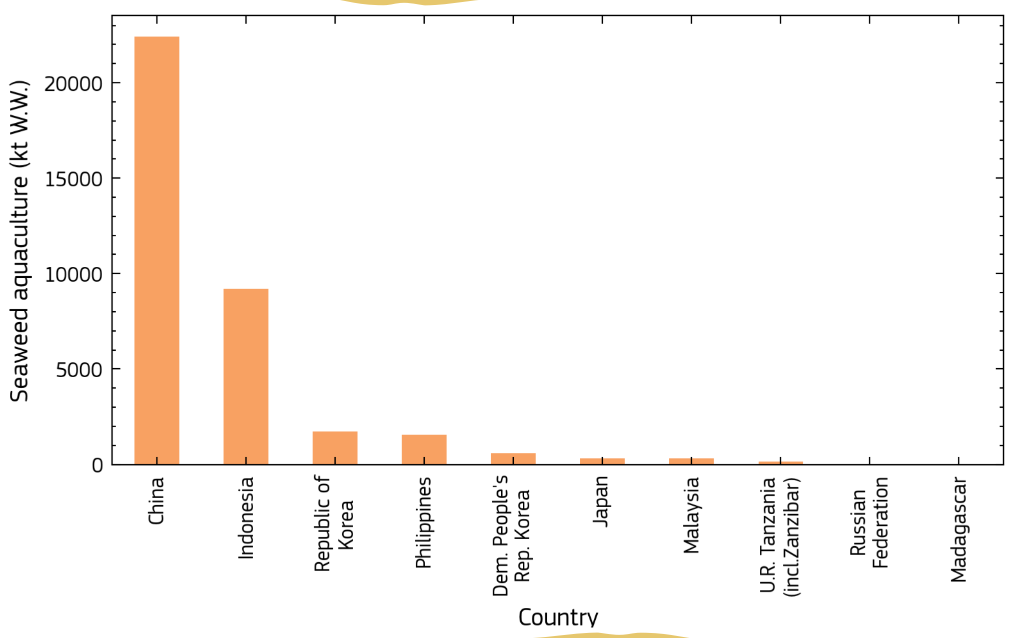
It must be noted that all the biomass reported by China as harvested from wild stocks referred to the generic category "Aquatic Plants", and that part of it (1,530 and 60 t W.W. in 2021 and 2022, respectively) was excluded as they were being harvested in inland waters, according to FAO 2024.

The class Phaeophyceae was the dominating group reported with *Lessonia nigrescens* and *Lessonia trabeculata* in Chile, and *Laminaria hyperborea* in Norway, which was also the species the most harvested in Europe with 172,099 t W.W. (2022 data). In Europe, a variety of seaweed were reported to be harvested in 2022, yet the brown seaweeds, *L. hyperborea*, *Ascophyllum nodosum* (60,025 t.w.w.) and *L. digitata* (44,459 t.w.w.) represented the highest volume (almost 98% of all seaweed harvested). Other brown and red seaweed species were collected in Europe: *Himanthalia elongata*, *Undaria pinnatifida* (invasive), *Gelidium corneum* or Gelidium sp., *Furcellaria lumbricalis*, *Porphyra linearis, Alaria esculenta*. The green seaweeds were solely reported as Chlorophyceae with no mention of species.

The aquaculture production increased steadily until the year 1999 to reach over 10,000,000 t W.W. (Figure 41). In the following 20 years, the production worldwide was reported to more than triple and reached 36,398,334 t W.W. for a value of almost €16 billion in 2022 (Figure 41,Table 10).

The main countries producing farmed seaweed in 2022 are China, Indonesia, Republic of Korea, Philippines, Democratic People's Republic of Korea, and Japan. These countries accounted for almost 98% of the world's aquaculture production (Figure 43, Table 10). The red and brown seaweeds were estimated to be over 99.9% of the total production, in which almost 56% of the total production were Rhodophytes. These results are to be taken with precaution as production quantities are not always reported under a species name (Table 10). The highest price seems to be obtained by the red algae *Meristotheca senegalense*.

Figure 43. Top 10 countries in seaweed aquaculture in 2022.

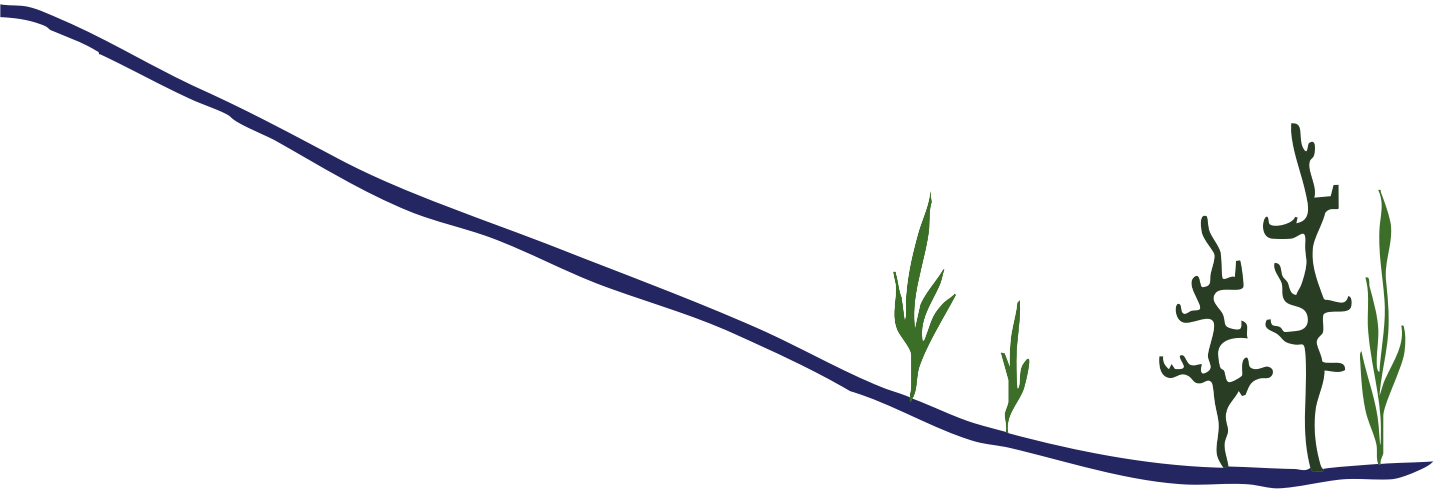


Data source: FAO 2024.

Table 10. Quantity (tonnes wet weight) and value (thousands of Euro) of seaweed species produced worldwide by aquaculture. Biomass from non-identified species highlighted in bold.

ASFIS species (Scientific name)	**2022 Production**	**2022 Value**	**Price**
	(t.w.w)	**(*000 EUR)**	**(EUR per t.w.w)**
Saccharina japonica	10,861,335	3,849,502	354.42
Eucheuma spp.	7,803,037	2,464,722.4	315.87
Gracilaria spp.	7,568,868	3,464,439.9	457.72
Undaria pinnatifida	2,694,578	1,801,812.3	668.68
Porphyra spp	2,176,580	1,261,328.1	579.50
Kappaphycus alvarezii	1,804,133	338,712.3	187.74
Pyropia tenera	785,622	989,572.5	1,259.60
Fusiform sargassum	347,163	271,104.4	780.91
Eucheuma denticulatum	235,310	8,368.1	35.56
Monostroma nitidum	6,283	3,793.6	603.75
Ulva spp.	3,699	1,074.4	290.41
Codium fragile	2,462	1,189.2	483.01
Sargassum spp.	802	658.9	821.73
Caulerpa spp.	641	585.9	913.53
Gracilariopsis longissima	271	38.1	140.28
Saccharina latissima	253	621.7	2,456.58
Caulerpa sertularioides	225	71.8	319.88
Gracilaria gracilis	174	16.3	93.47
Cladosiphon okamuranus	100	20.4	204.06
Alaria esculenta	80	200.6	2,503.03
Meristotheca senegalense	16	243.7	15,230.28
Eucheuma isiforme	16	67.7	4,230.47
Macrocystis pyrifera	11	14.6	1,330.00
Laminaria digitata	10	33.6	3,356.35
Phaeophyceae	2,080,356	1,459,857.1	701.73
Algae	16,384	29,224.8	1,783.73
Rhodophyta	5,310	368.1	69.32
Chlorophyceae	905	235.5	260.27

Data source: FAO 2024.



Seaweed cultivation is still a nascent sector in Europe and has been focused mostly on the kelp species: *Saccharina latissima, Undaria pinnatifida* and *Alaria esculenta*. Few other species such as the green alga *Ulva spp*., the red alga *Palmaria palmata* are also produced on a pilot scale and most of the time in the land-based system and in some cases under the IMTA system (Araújo et al., 2021; Barbier et al., 2019).

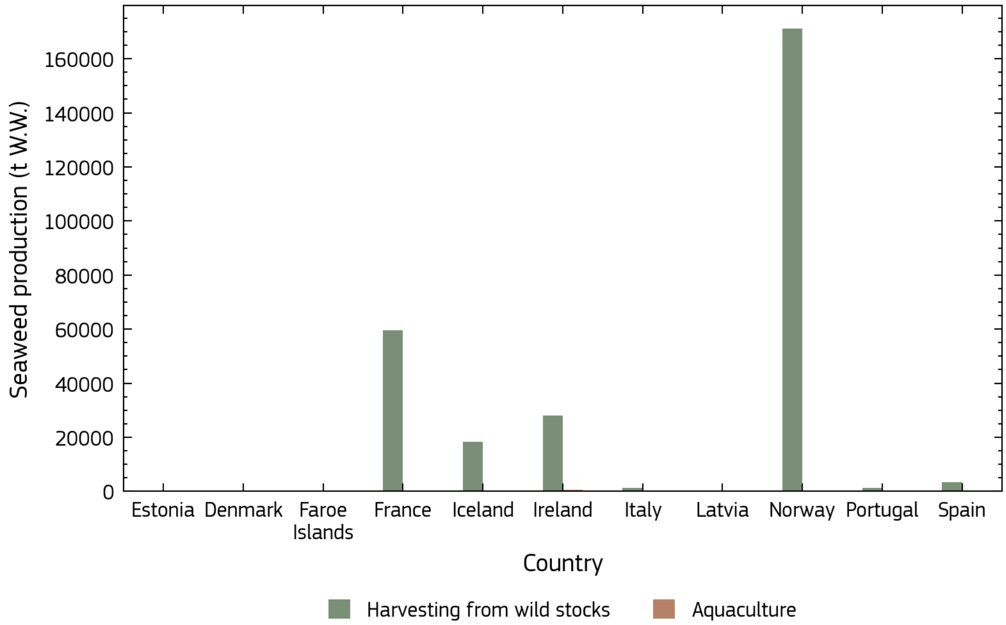
According to FAO data (FAO, 2024), from the total seaweed produced in the EU-27 in 2022 (94.5 thousand tonnes wet weight), only 0.7% (704 t W.W.) was produced by aquaculture. The seaweed farmed in the EU represents 0.00193% of the global seaweed aquaculture (375 t W.W. or 0.001% in 2021), while the rest of European countries contributed with an additional 336 t W.W. or 0.0009% (Table A4.2) (356 t W.W. – 15.5% in 2021). In fact, the European production from both wild harvest and aquaculture is led by Norway and France, supplying more than half (81%) of the total European macroalgal biomass production in 2022 (Figure 44). In the EU-27 and other European countries, the production of macroalgae is still dominated by the mechanical harvest of wild stocks of kelp and the hand-picking of a variety of species. In the EU-27, seaweed aquaculture started only in 1985 with a stronger development from 2006 while in other European countries aquaculture was reported only since 2015 (Figure 45). France reported the first seaweed cultivated biomass in 1985, followed by Italy in 1990. Italy stopped seaweed farming reporting in 2000, while Spain started in 2006 followed by Ireland and Denmark (including Greenland), respectively in 2007 and 2008. Then the countries that started the latest were Portugal in 2014 and Norway and the Faroe Island in 2015 (Figure 46).

In terms of economic value, the seaweed aquaculture production in the EU-27 represented 0.00003% (€5.5 million) of the global seaweed aquaculture in 2022, while in the rest of European countries it represented 0.00001% (€0.8 million) (Table A4.2).

However, it is important to note that the data reported to FAO originated from the national data reported and represented the biomass that was commercially exploited. Such data do not always reflect the on-site production efforts. For example, in Norway producers produced more than they reported to sale and, since 2023, the Norwegian Directorate of Fisheries collected also the quantity of the seaweed biomass farmed (768 t W.W.) and of the biomass sold (137 t W.W.)[23]. Such data are key for assessing the ecological sustainability and economic feasibility of a nascent seaweed sector and to develop good management plan for the production.

[23] *https://www.fiskeridir.no/English/Aquaculture/Statistics/Algae*

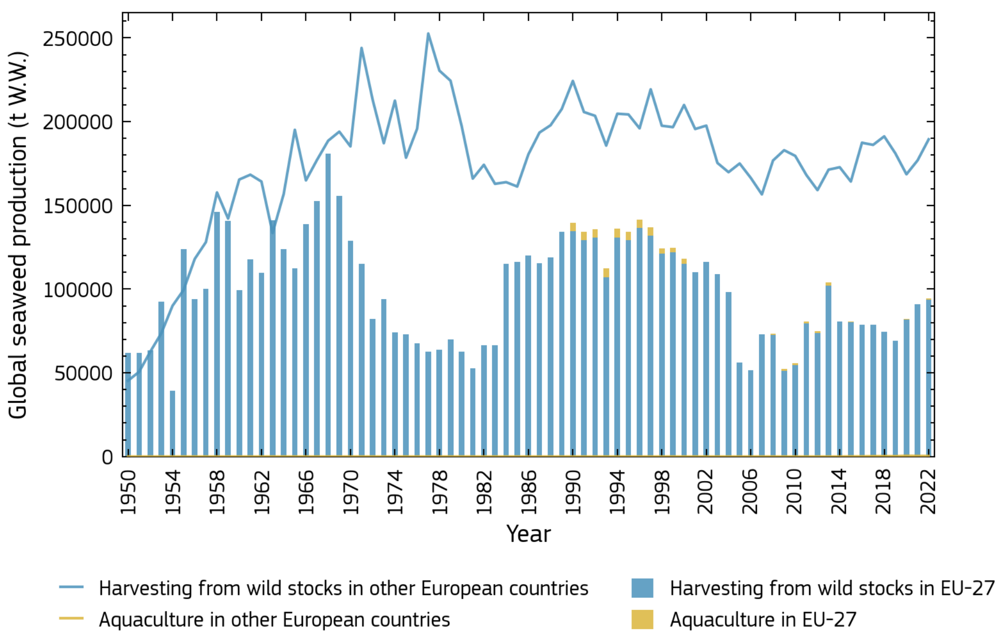
Figure 44. **Seaweed production in tonnes of wet weight for some European countries in 2022 by aquaculture (brown bar) and harvesting from wild stocks (green bar).**



It should be noted that for EU-27, only 7 Member States reported seaweed production values in 2020 (DK, EE, ES, FR, IE, IT, PT) while for other European countries these values refer to 3 countries (FO, IS, NO). It should also be noted that during 1990 to 2000 Italy was reporting between 3,000 and 5,000 t.w.w of seaweed produced by aquaculture but stop reporting after 2000.

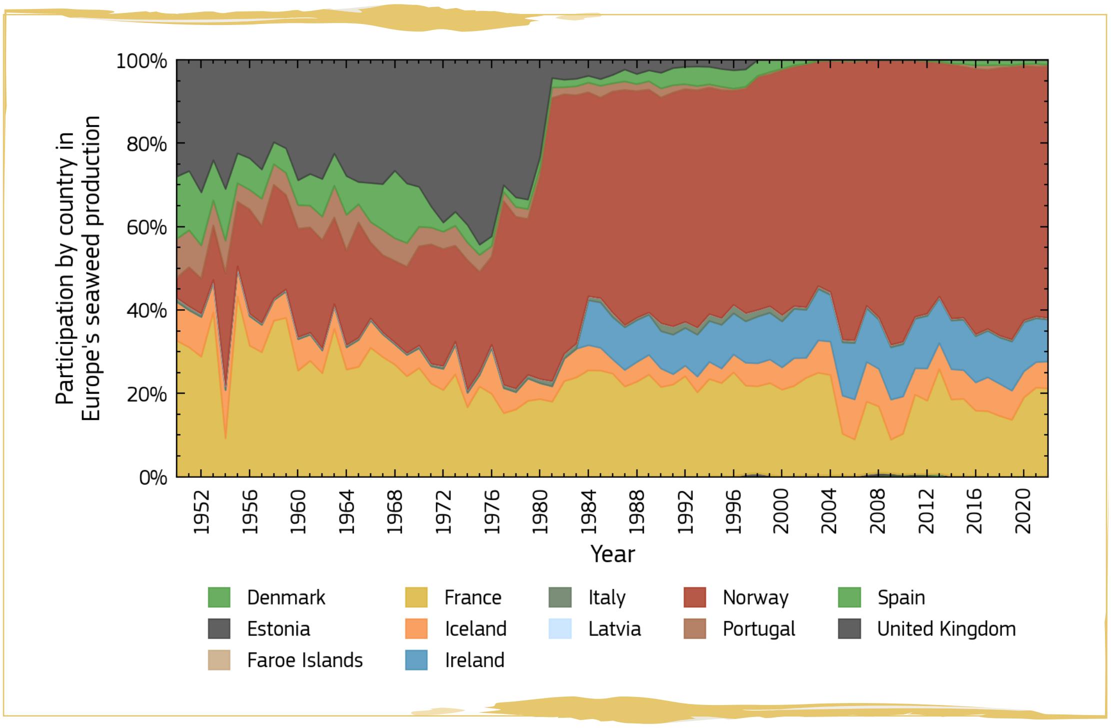
Data source: FAO 2024.

Figure 45. **European seaweed production in tonnes wet weight of farmed and harvested from wild stocks from 1950 to 2022.**



Data source: FAO 2024.

Figure 46. Countries percentage (%) participation in the total European seaweed production (wild harvesting and aquaculture) from 1950 to 2022.

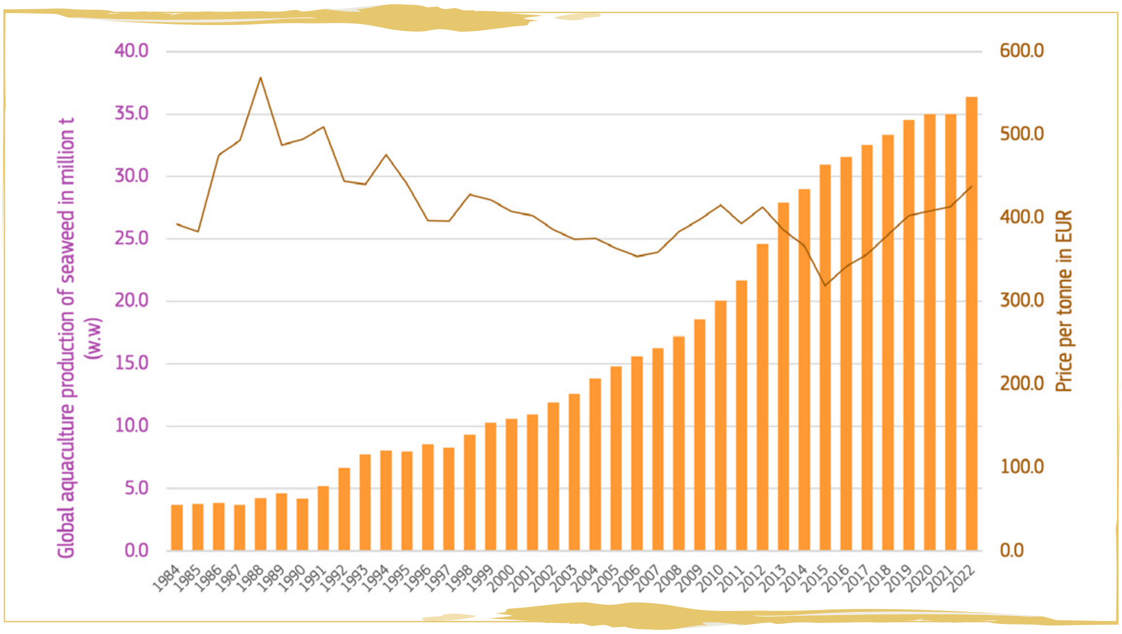


Data source: FAO 2024.

3.4.3 Macroalgae supply

Worldwide, the average price for farmed seaweed, derived from the absolute values of aquaculture and the quantity produced, has not changed since the 1950´s and fluctuates around €412 per tonne (Figure 47). However, there is a high variability in prices between the producer's country and the species sold (Table 10). Seaweed commodities are exchanged under a variety of names in the FAOSTAT and UN Comtrade data.

Figure 47. Global seaweed aquaculture production and seaweed price EUR per tonne from 1984 to 2022.



Data source: FAO 2024.

Table 11. Seaweed commodity name and quantity in tonne of product weight traded worldwide in 2021 and 2022.

Commodity (Name)	2021	2022
Agar agar in powder	781	907
Agar agar in strips	63	62
Agar agar nei	31,929	32,087
Green laver	76	55
Hizikia fusiforme (brown algae)	5,551	5,548
Laver, dry	17,838	19,946
Laver, nei	1,413	1,801
Other brown algae (laminaria, eisenia/ecklonia)	11,110	11,245
Other red algae	159,635	173,411
Other seaweeds and aquatic plants and products thereof	15,389	18,502
Seaweeds and other algae, fit for human consumption, nei	280,293	300,125
Seaweeds and other algae, unfit for human consumption, nei	650,122	693,473
Undaria pinnafitida (brown algae)	40,504	35,154
Total	1,214,704	1,292,315

Data source: FAO 2024

In 2021 and 2022, 205 countries are reporting to export seaweed, 199 were importing seaweed products and only 20 countries were re-exporting. In 2022, the 10 main exporting countries, in order of volume, were Indonesia, Ireland, Chile, Peru, Republic of Korea, China, Philippines, Iceland, United Rep. of Tanzania, France, and Canada. In terms of imports, the 10 main importing countries in 2022 in order of volume were China, Ireland, France, Japan, United States of America, Australia, Spain, Taiwan Province of China, Republic of Korea and the United Kingdom (Figure 48 and Table A4.3). Out of the 20 re-exporting countries, only 9 are producers (United States of America, Canada, United Arab Emirates, Sri Lanka, Bahrain, Jamaica, Trinidad Tobago, Mauritius, the United Kingdom, and Domenican Republic) and 3 (Republic of Moldova, Fiji and Macao) do not report export but only import-re-export. The fact that the quantities traded between countries are much lower than the global production indicates that most of the seaweed commodities are sold as extracts or consumed mainly in the country of production.

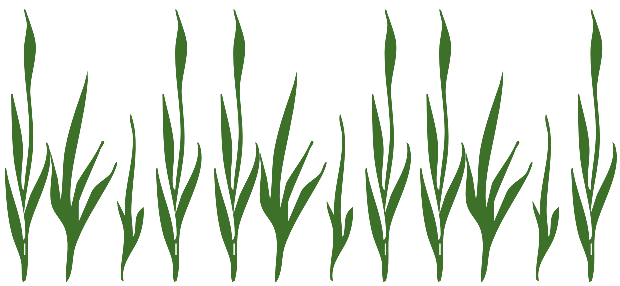
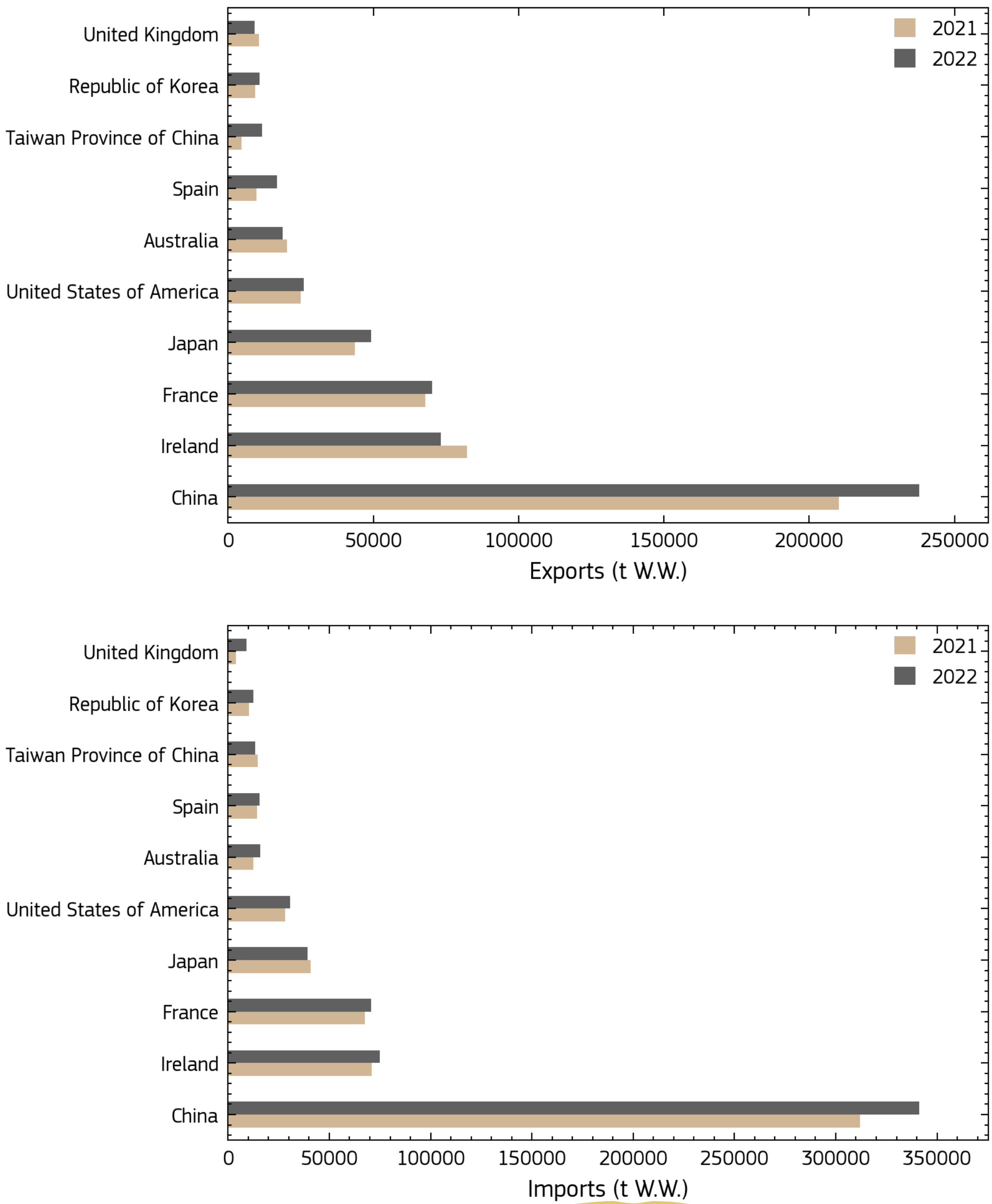


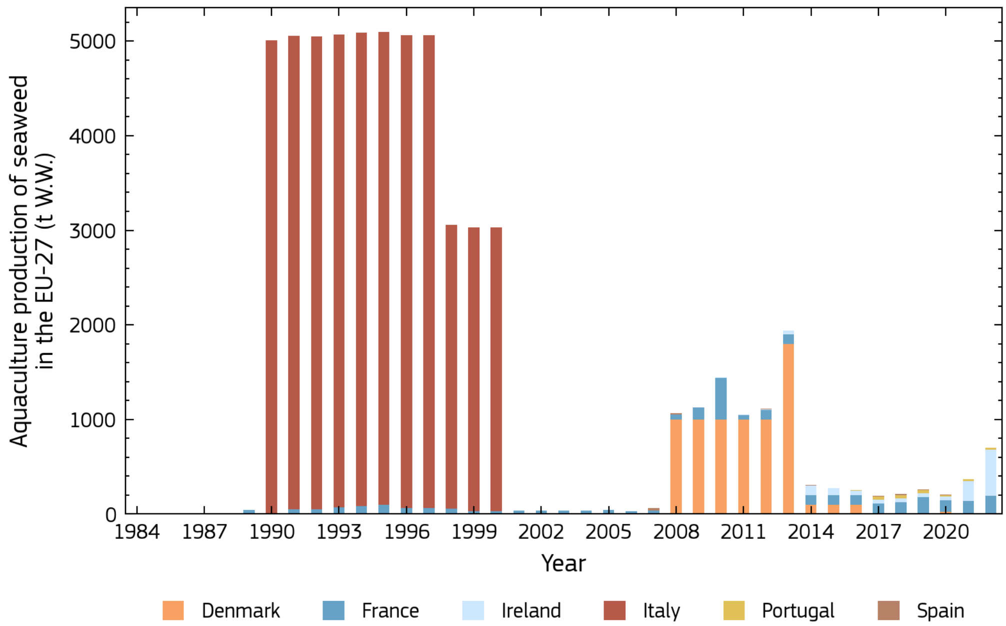
Figure 48. **The top 10 countries with the largest seaweed exports (top) and imports (bottom) in 2021 and 2022.**



Data source: FAO 2022.

In Europe, larger variations in the quantity of farmed seaweed are observed according to FAO data (Figure 49). Italy reported an annual production of seaweed from aquaculture between 3,000 and 5,000 t.w.w. in the period 1990-2000 but stoped reporting after that date. A similar case is found for Denmark, which was reporting between 1,000 and 1,800 tonnes of farmed seaweed between 2008-2013 while the value reported in the last 8 years decreased to the range 9-100 tonnes.

Figure 49. **Seaweed aquaculture production in the EU-27 from 1984 to 2022.**



Data source: FAO 2023.

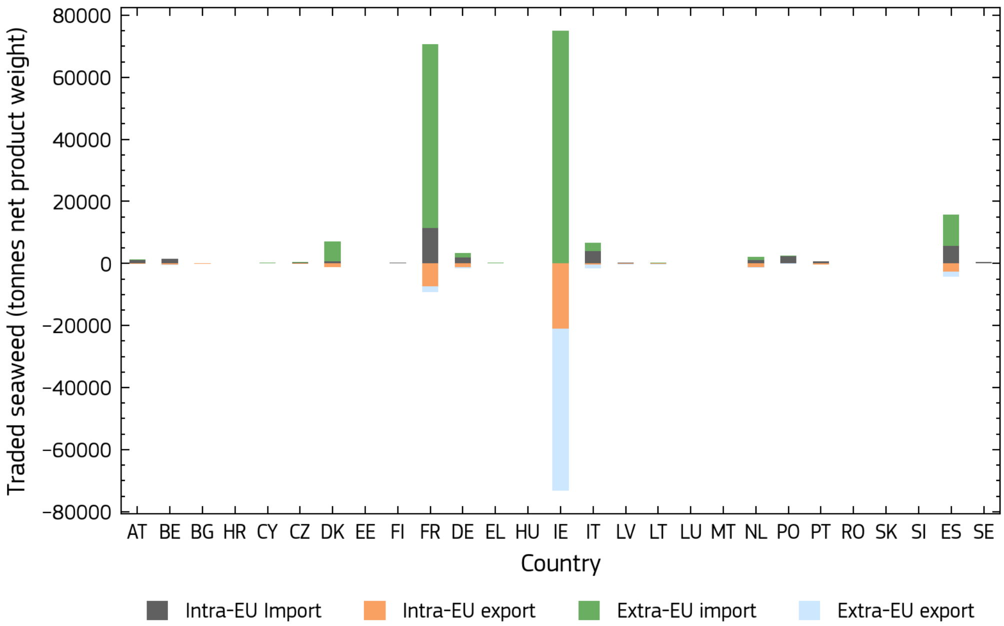
The trade of seaweed is a global market. European countries (as listed in Table A.4.3) export seaweed products to 156 countries worldwide. At the same time, Europe imports seaweed from 101 countries worldwide for which 76.4 % are within the European region.

According to FAO data (FAO, 2024), in 2021 the EU-27 Member States imported from outside the EU (extra-EU imports) a total of 148.0 thousand tonnes of seaweed products (measured in net product weight) while the intra-EU imports amounted to 32.5 thousand tonnes. Regarding the exports of seaweed products, the EU-27 Member States in 2021 exported outside the EU (extra-EU exports) a total of 65.1 thousand tonnes and 41.0 thousand tonnes to EU-27 Member States (intra-EU exports). In 2022, the trade of seaweed products slightly decreased, except for the extra-EU import: 157.4 thousand tonnes of seaweed products were imported from outside the EU together with additional 32.3 thousand tonnes of intra-EU imports; at the same time, 58.3 thousand tonnes of seaweed products were exported outside the EU while 36.1 thousand tonnes were intra-EU exports.

In 2022, the Member State that recorded the largest quantity traded seaweed products among the EU-27 Member States was Ireland with 75.1 thousand tonnes imported (99.9% from outside the EU) and 73.3 thousand tonnes exported (71.4% outside the EU), followed by France (70.6 thousand tonnes of net product weight imported, 83.9% of which from outside the EU, and 9.2 thousand tonnes exported, 20.0% of which outside the EU) as shown in Figure 50.

In the EU-27, the seaweed products most traded in 2022 are those categorised as 'seaweeds and other algae, unfit for human consumption, nei', both for imports (92.1%) and exports (89.7%).

Figure 50. **Extra-EU and intra-EU imports and exports of seaweed products in 2022 by the EU-27 Member States.**



Data source: FAO, 2022.

3.4.4 Gaps, uncertainties, future development and recommendations

Worldwide the biomass harvested and cultivated is reported annually to the Food and Agriculture Organization (FAO). Unfortunately, despite some efforts to improve the data collection, the national reporting systems still vary yearly and across countries, leading to mistakes and errors in the data, such as species not being correctly recorded or recorded under generic and / or higher group names (e.g., “Phaeophyceae”, “Plantae aquaticae”, “Rhodophyta”, “Chlorophyceae” or “Algae”).

Recommendation: specific harvest recording approaches by species might be implemented in Europe. Training programmes for harvesters, producers and personnel recording and processing the data would help ensure the correct identification of the species.

Reporting systems are not detailed enough in the reporting units, importantly in the water content, i.e. dry and wet biomass are reported indistinctly or biomass reported in wet weigh does not detail the moisture content. Furthermore, the reported quantities do not specify the loss that happens during harvesting or pre-processing of the product before the first transaction, making it complex to accurately evaluate the volume farmed in Europe.

Recommendation: The national reporting systems could be aligned across Europe to ensure harmonisation (e.g., units of measure, species classification used, time, location) in the reporting of seaweed biomass collected from both wild and farms.

Some national reporting systems do not regularly report data, or stop reporting for some time, leading to large data gaps in the historical data that prevent from doing a sound assessment of the sector and of the natural seaweed communities. For example, Italy reported the same quantity of farmed *Gracilaria* spp. for a specific period of time (5,000 tonnes per year from 1990 to 1997 and 3,000 tonnes per year from 1998 to 2000) and then stopped reporting (Figure 49).

Recommendation: Time continuity in the national reporting systems of all European countries should be ensured by, e.g., developing a user-friendly system to easily record the quantity of seaweed produced by harvesting from wild stocks or aquaculture.

The food balance statistics (FAO, 2022) and the statistics on the production of global fish processed products (FAO, 2024) do not yet include aquatic plants (nor seaweed).

Recommendation: Similar data collection systems of fish, crustaceans and molluscs already existing could be developed for Aquatic plants to facilitate the analysis and understanding of this sector and contribute to a well-managed development.

The online Global fish trade statistics report for two years at a time, making it difficult to analyse the trends. The commodity list seems not to be reporting on all known algae products or species.

Recommendation: All the products containing seaweed could be reporting its content in seaweed with more details (species, quantity) to facilitate understanding of the trade patterns of seaweed worldwide.

Some countries report larger exporting quantities than the ones they produce and import, which could be due to the different systems used to measure the quantity of seaweed (either in bulk or pre-processed) and of seaweed extracts.

Recommendation: A homogenous system to measure the seaweed biomass flow could be established.

Finally, the European Commission, following its initiative to strenghenintg a sustainable EU algae sector (COM/2022/592) and its action plan, is articulating its effors to tackle the lack of algae-related data, for instance by a mapping of EU-Funded Algae Projects[24] (Carboni et al., 2025). Additional initiatives to improve the algae data collection systems for the provision of accurate, robust, consistent and complete data on algae biomass production should still be implemented.

Recommendation: The implementation of the action plan from the Commission's communication COM/2022/592, to tackle the lack of robust and reliable data on the algae sector should be ensuredto improve data quality and coordination with the EU Data Collection Framework.

3.4.5 Conclusions

Algae play an important role in marine ecosystems contributing to the global primary production and supporting complex food webs in the coastal zone. At the same time, algae biomass is a valuable resource for Europe, mainly for the food and chemical industries. The global production of seaweed is mainly based on aquaculture cultivation, but in the European context wild harvesting is the main production system. The European aquaculture sector represents an alternative to meet the global increasing demand for high quality sustainably produced algae biomass but still needs to overcome several barriers, mainly related to knowledge gaps and access to the market.

Furthermore, management guidelines are needed to ensure the sustainable exploitation of algae resources considering climatic and anthropogenic pressures on the marine environment and the ecological and economic viability of the biomass production sector.

However, the low quality and availability of data on seaweed production and uses prevent from an overarching approach to assess the potential use and

[24] *https://maritime-forum.ec.europa.eu/mapping-impact-eu-funded-algae-projects-insights-and-innovations_en*.

value of this biomass. Despite the several initiatives ongoing to improve the quality of the available information, an improvement on the reporting systems at national level is needed as well as a harmonisation of such systems at the European level (in terms of e.g., units of measure, species, time, origin, seaweed content of processed products).

3.4.5.1 Key messages

- Algae play an important role in marine ecosystems by contributing to the global primary production and supporting complex food webs in coastal zones. They are also key in certain coastal bio-based economies by serving as a source of fertilisers, cattle feed, and human food. In the European bio-based economy, their use by the food and chemical industry is of growing interest;

- Global seaweed biomass production has increased exponentially in the last decades as a result of market demands in new sectors for algae biomass-based applications (feed and food supplements, nutraceuticals, pharmaceuticals, third generation biofuel, and bioremediation);

- Globally, the production is mainly based on aquaculture cultivation, reaching 36.4 million tonnes of farmed seaweed (96.7% of total production) in 2022 while in Europe, harvesting from wild stocks still supplies 99.6% of the macroalgae biomass (283 thousand tonnes of seaweed harvested from wild stocks). Management guidelines are therefore needed to ensure the sustainable exploitation of algae resources considering climatic and anthropogenic pressures on the marine environment and the ecological sustainability and economic feasibility of the biomass production sector;

- The EU-27 produced a total of 94.5 thousand tones of seaweed in 2022, of which only 0.7% (704 t W.W.) was produced from farmed seaweed. The European aquaculture sector is reinforcing its efftors to overcome several barriers, mainly related to knowledge gaps and access to the market, to become an alternative to meet the increase in the market demand for high quality sustainably produced algae biomass;

- Latest data shows a large variation among seaweed producing countries. In the global context China was the largest producer of seaweed in 2022 (22.6 million tonnes, 60% of global production) while in the European context, Norway was the largest producer (171.4 thousand tonnes, 60% of European total production);

- The low quality and availability of data about macroalgae production, flows, and uses still prevent an overarching approach to assess the potential utilization and value of this biomass in the bio-based European economy. The improvement of the quality and quantity of the available information is critical to support policy and the algae sector in Europe.

3.5 Waste Biomass

3.5.1 Biowaste availability: food waste and other biowaste streams

Valeria De Laurentiis, Sarah Mubareka, Selene Patani

Box 15. Definition of bio-waste

The Waste Framework Directive (WFD) defines bio-waste as “biodegradable garden and park waste; food and kitchen waste from households, restaurants, caterers and retail premises; and comparable waste from food-processing plants” (European Parliament and of the Council, 2018). Waste biomass has a significant role in the transition to circular economy and contributes to the sustainable use of natural resources (EEA, 2020; European Commission, 2018). Here we report on food waste and other organic waste.

3.5.1.1 Food waste generation

The European Commission has identified reducing food waste as one of the priority areas of its Circular Economy Action Plan and Farm to Fork Strategy, both important components of the European Green Deal. To accelerate the EU's progress towards Sustainable Development Goal Target 12.3, the Commission is proposing to set legally binding food waste reduction targets to be achieved by Member States by 2030, as part of the revision of the Waste Framework Directive, adopted by the Commission on 5 July 2023. Member States are required to take the necessary measures to reduce food waste by the end of 2030: by 10% in processing and manufacturing and by 30% jointly at retail and consumption.

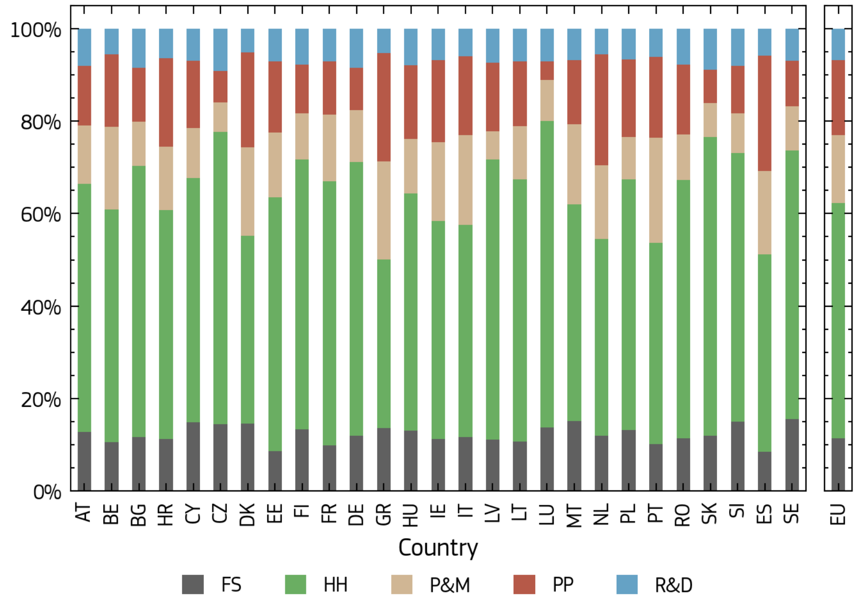
To monitor the progress towards the achievement of targets, MSs are required to monitor and report food waste levels, following a common methodology established by the EC (Commission Delegated Decision 2019/1597). In order to cross-check the amounts reported by MSs, the JRC has developed an independent model estimating food waste generation by developing yearly material flow analyses of the food system of each MS (De Laurentiis et al., 2021, further updated in De Laurentiis et al., 2023 and De Laurentiis et al., 2024). The model uses as starting point statistical data on food production and trade, complemented with data collected from the industry to model the manufacturing stage, and with sales data and food waste coefficients to estimate food waste generation at each stage of the food supply chain.

In its last update, the model estimated a generation of 73 Mt of solid food waste and 11 Mt of liquid food waste across the supply chain in the EU-27 in 2021. Across all countries, the largest share of food waste is generated at household level (Figure 51). Perishable food groups such as fruit, vegetables and dairy tend to be the largest contributors, although there are significant variations across Member States (Figure 52).

It is worth mentioning that the quantity of solid food waste estimated by the model is roughly 25% higher than the total amount estimated by Eurostat based on the quantities reported by MSs in the same year[25]. If quantities are compared at Member State level and at food supply chain level (e.g., household food waste in France), there is however no clear trend (i.e. the quantity modelled is in some cases higher and in other lower than the quantity reported), so no systematic overestimation is observed. Reasons underlying this difference are related to the methodological approaches used to estimate these quantities, as the results here presented are the outcome of a model based on material flow analysis, while the quantities reported by MSs are obtained via a combination of measurement approaches and extrapolation techniques.

[25] *https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Food_waste_and_food_waste_prevention_-_estimates*

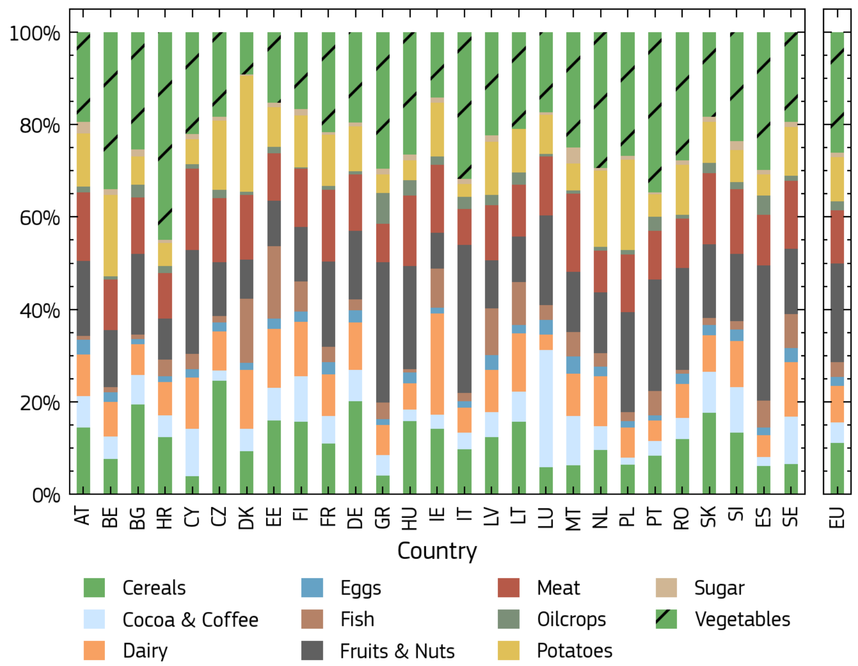
Figure 51. Relative contribution of food supply chain stages to the total food waste generated (solid and liquid components) in EU MSs in 2021.



PP: primary production, **P&M**: processing and manufacturing, **R&D:** retail and distribution, **HH:** households, **FS:** food services

Source: JRC own elaboration.

Figure 52. Relative contribution of food groups to the total food waste generated (solid and liquid components) in EU MSs in 2021.



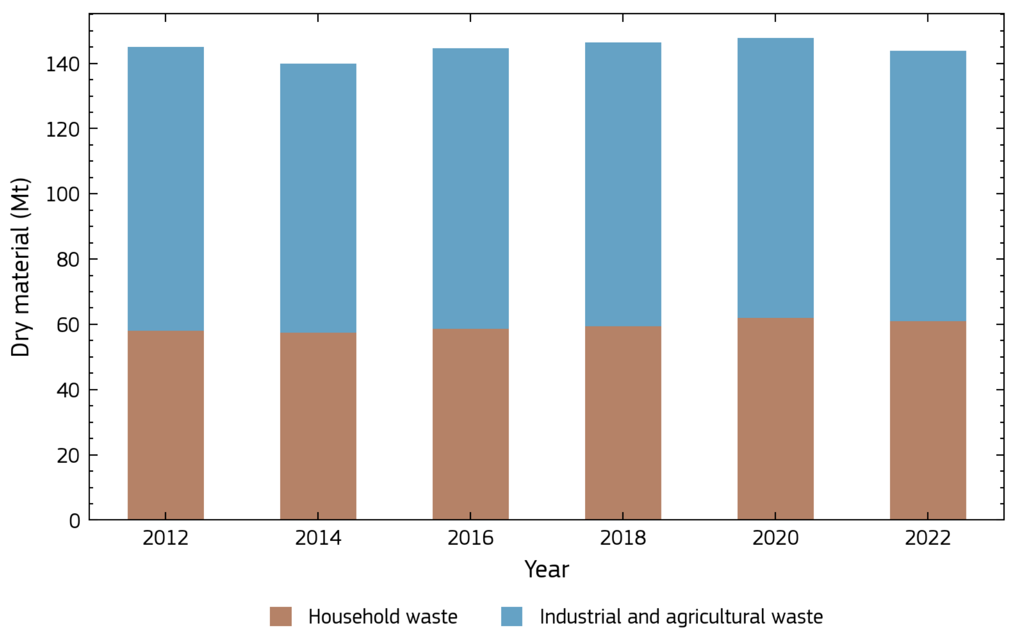
Source: JRC own elaboration.

3.5.1.2 Biowaste, re-use/recycling and recovery

Data on waste generation is collected from EU Member States in a framework set up by the Waste Statistics Regulation and published by Eurostat based on Regulation (EC) No 2150/2002 on waste statistics. This data includes a mix of organic and inorganic wastes generated from various economic activities (including households) but does not distinguish the biodegradable component in the different waste categories. For example, certain waste categories such as textile or rubber waste contain a mix of biodegradable and synthetic wastes, and the two components are not reported separately. Similarly, the biodegradable fraction in generic categories such as "household and similar waste" is not estimated. In fact, some studies in EU MSs have tried to estimate the share of biodegradable waste in municipal solid waste using empirical evidence (Edjabou et al., 2015; Horttanainen et al., 2013). The data presented here builds on the existing statistics and empirical evidence available to estimate the quantities of biodegradable waste generated in the EU and in each MS. Details of how this is computed are provided in the Annex of the previous JRC Biomass Report (p. 277, Caldeira, De Laurentiis & Sala, 2023).

The analysis of the biowaste generation in the EU, based on waste statistics, showed how the generation of biowaste has been relatively stable since 2012, no clear trend can be detected for the timeframe 2012-2022 (Figure 53) for overall waste generation, whether specifically from households or from industry and agriculture.

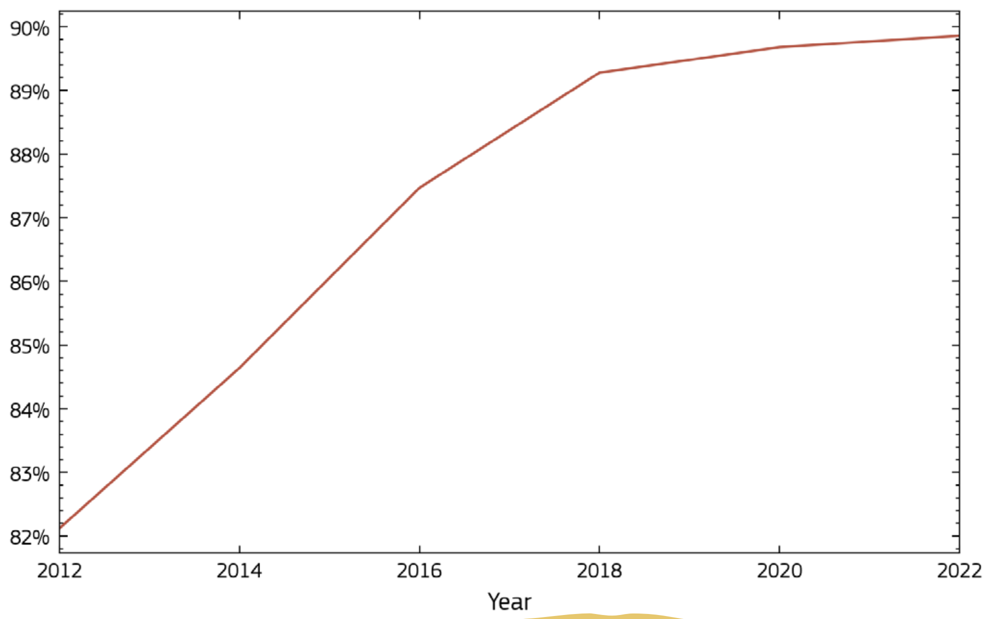
Figure 53. **EU-27 Trends in household and industrial and waste.**



Source: JRC 2024, https://knowledge4policy.ec.europa.eu/bioeconomy/monitoring_en

The amount of biowaste that is recovered (i.e. used for recycling or energy recovery) and the amounts disposed (landfill or incinerated) were computed, building on EU statistics on waste treatment. Industrial biowaste that is used in integrated processes is not included as the data on waste generation is obtained from waste statistics, therefore not capturing biowaste that is utilised in the industry. The recovery rate, corresponding to the share of biowaste recycled or used for energy recovery, had been steadily increasing from 2012 to 2018, but has since stabilised at around 90% (Figure 54). A vast majority of the recovered waste is paper and cardboard wastes (both from households and industry) and wood wastes (mainly from wood-based industries) (European Commission et al, 2024).

Figure 54. **EU-27 trends in recovery of biowaste, 2012-2022.**

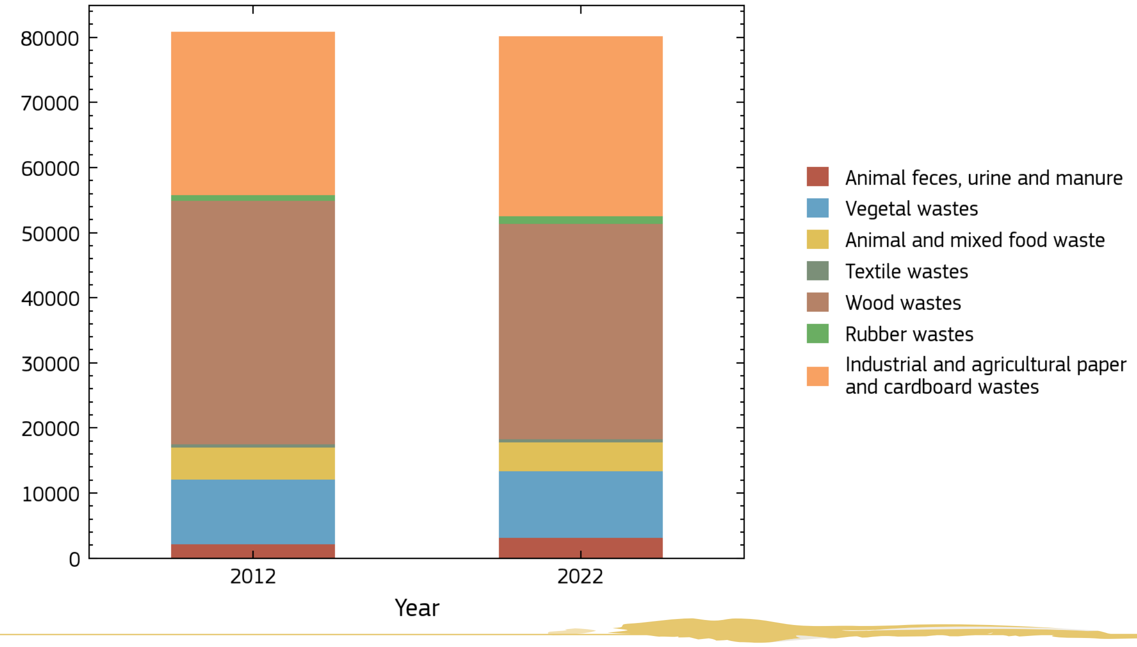


Source: JRC 2024, https://knowledge4policy.ec.europa.eu/visualisation/eu-bioeconomy-monitoring-system- dashboards_en?indicatorId=3.1.c.6

The amount of each type of biowaste (e.g., paper and cardboard waste) differentiated by waste treatment option (e.g., landfill, incineration, recycling) is provided in the database "Treatment of waste by waste category, hazardousness and waste management operations [env_wastrt]" (Eurostat, 2014). These data were retrieved for the EU and each MS for each year.

Figure 55 shows a breakdown of the biowaste recovery from industry and agriculture as reported in 2012 and in 2022. There is an overall slight decrease in recovery (from 80,839 Kt dry weight in 2012 to 80,131 Kt dry weight in 2022) due to a decrease in wood waste recovery according to the statistics.

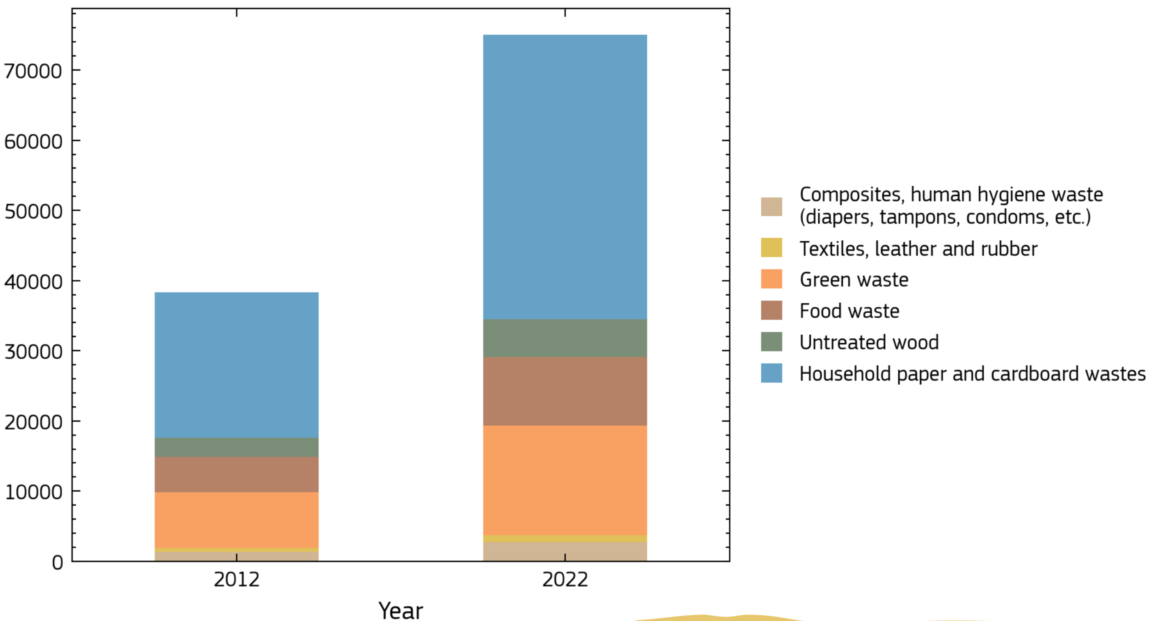
Figure 55. EU-27 Recovery of biowaste in industry and agriculture, comparative 2012 and 2022.



Source: JRC 2024, https://knowledge4policy.ec.europa.eu/visualisation/eu-bioeconomy-monitoring-system- dashboards_en?indicatorId=3.1.c.6

Waste recovery from households in the EU-27 has increased significantly between 2012 and 2022, roughly doubling for all categories of household waste, which means the most significant category, in terms of quantities, is due to recovery of paper and cardboard (Figure 56).

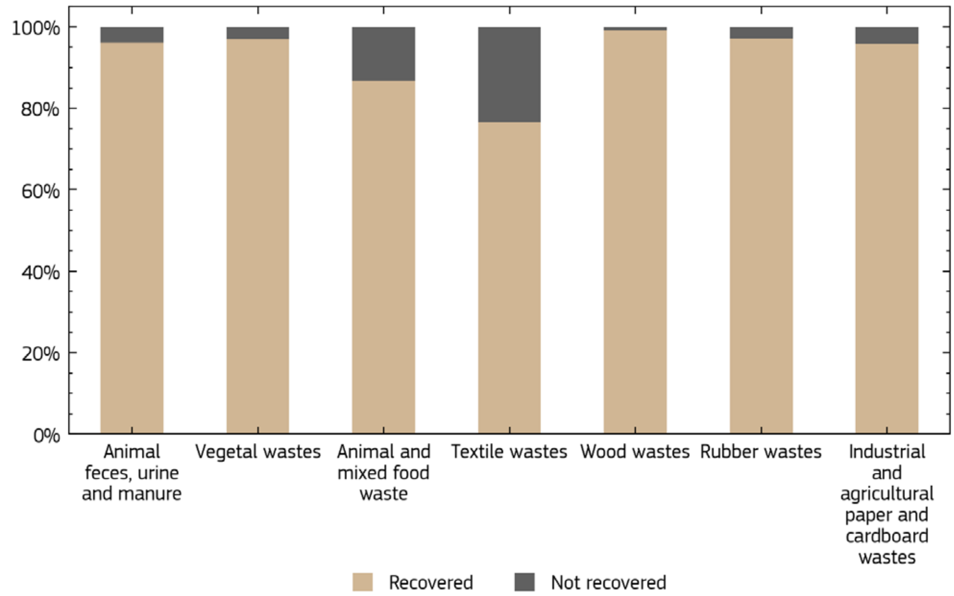
Figure 56. EU-27 Recovery of biowaste in households, comparative 2012 and 2022.



Source: JRC 2024, https://knowledge4policy.ec.europa.eu/visualisation/eu-bioeconomy-monitoring-system- dashboards_en?indicatorId=3.1.c.6

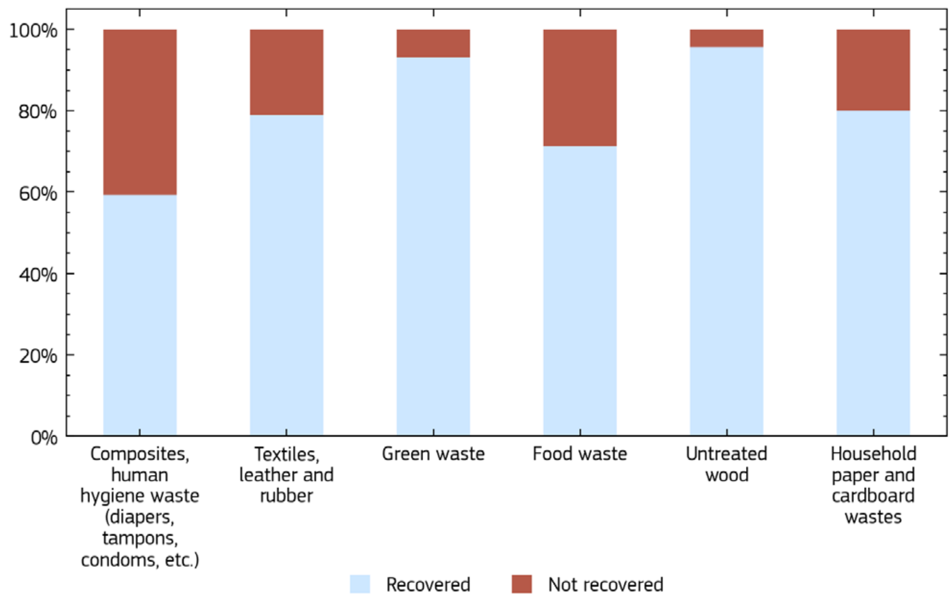
The only categories of waste from industry and agriculture below the 90% mark are animal and mixed food waste and textile waste (Figure 57). For households, recovery is less impressive, with only two categories exceeding the 90% mark: Green waste and untreated wood (Figure 58).

Figure 57. EU-27 Share of recovery of biowaste from industry and agriculture, 2022.



Source: JRC 2024, https://knowledge4policy.ec.europa.eu/visualisation/eu-bioeconomy-monitoring-system- dashboards_en?indicatorId=3.1.c.7

Figure 58. EU-27 Share of recovery of biowaste from households, 2022.



Source: JRC 2024, https://knowledge4policy.ec.europa.eu/visualisation/eu-bioeconomy-monitoring-system- dashboards_en?indicatorId=3.1.c.7

All data reported here can be viewed in the Knowledge Centre for Bioeconomy's Bioeconomy Monitoring System.

3.5.2 Waste biomass and residues' uses for energy

Vincenzo Motola, Nicolae Scarlat, Michele Canova

Various forms of biomass can be used to produce multiple forms of energy. RED defines biomass as the biodegradable fraction of products, waste and residues from biological origin from agriculture, including vegetal and animal substances, from forestry and related industries, including fisheries and aquaculture, as well as the biodegradable fraction of waste, including industrial and municipal waste of biological origin. RED also recognises waste as defined by the Waste Framework Directive (WFD) 2008/98/EC as any substance or object which the holder discards or intends or is required to discard. Since RED makes reference to the waste from biological origin, WFD also defines bio-waste as biodegradable part of garden and park waste, food and kitchen waste from households, restaurants, caterers and retail premises and comparable waste from food processing plants. While solid biomass has no specific definition in the RED, the word "solid" covers solid organic materials of biological origin before energy conversion and it includes solid products, by-products, and wastes (sometimes also reported as residues under this general heading) from both agriculture and forests. While residues are not waste per se, for the sake of providing a more complete picture in this section, we report them as well under this general heading.

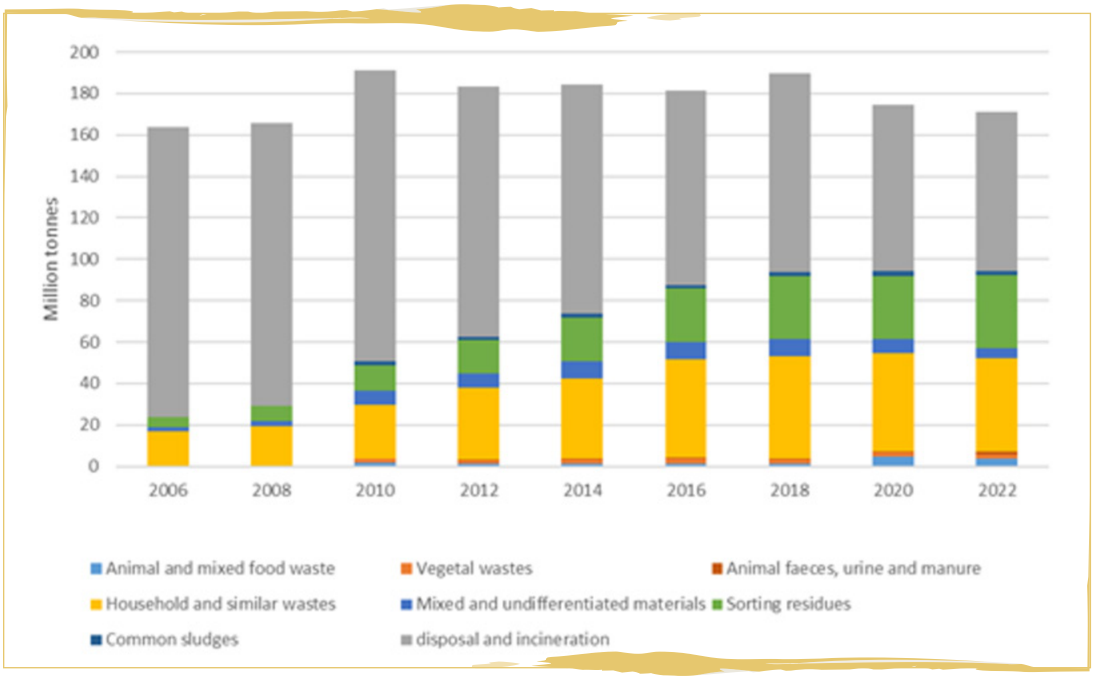
Biogas is mostly generated by anaerobic digestion of organic material (waste and residues such as manure, biowaste, food waste etc.), but another used and growing technology is gasification; in both cases often the feedstock used is waste biomass. Biogas is currently used either for the generation of heat and electricity or it is upgraded to natural gas quality as biomethane, and used as a perfect substitute of fossil gas. Biogas and biomethane can also be upgraded to biohydrogen via methane split (plasma or thermo-catalytic electrolysis). Biomethane is also used in transport.

Bioliquids generate electricity and heat (and possibly cooling); they include types of vegetable oil or pyrolysis oil. Black liquor, a liquid residue from pulping process is recorded under 'Primary solid biofuels' in Eurostat. From a chemical and physical point of view, bioliquids could be the same as biofuels, only they are used in a different application.

Finally, biofuels, which could also be produced from waste biomass streams, can replace fossil gasoline, diesel, or other fossil energy carriers in transport.

See section 6.2 for power and heat production using mostly biomass fuels (i.e. primary solid fuels), with a minor share of waste feedstock. The use of waste and residues for energy production could have a major role in covering energy demand, lowering the impact on environment, greenhouse gas emissions, land use/land use change or competition between the alternative uses of biomass. As result of the waste and renewable energy legislation, a significant increase in the energy generation from waste has been achieved. In the case of biowaste, Figure 59 below shows that the use of various biowaste for energy increased over time, to reach almost 120 million tonnes of waste, coming as animal and mixed food waste, vegetal waste, manure, household waste, sludge and other mixed waste. At the same time, the amount of biowaste sent to disposal (landfilling) or for incineration without energy recovery has decreased over time.

Figure 59. **The use of various biowaste for energy.**

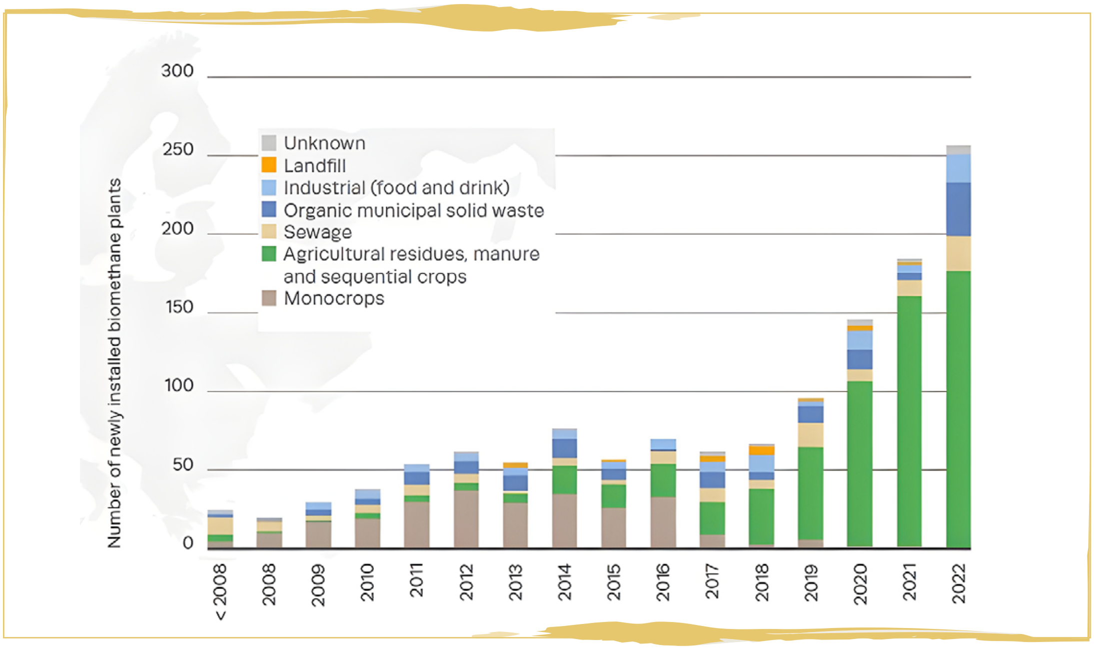


Source: Eurostat, 2024.

3.5.2.1.1 Biogas and Biomethane production

The share of feedstock used for biomethane production in Europe EBA Members (EU, Norway, Switzerland and UK), by adding new plants in the last years, has shifted toward an increased share of agricultural, organic industrial waste and municipal solid waste (Figure 60).

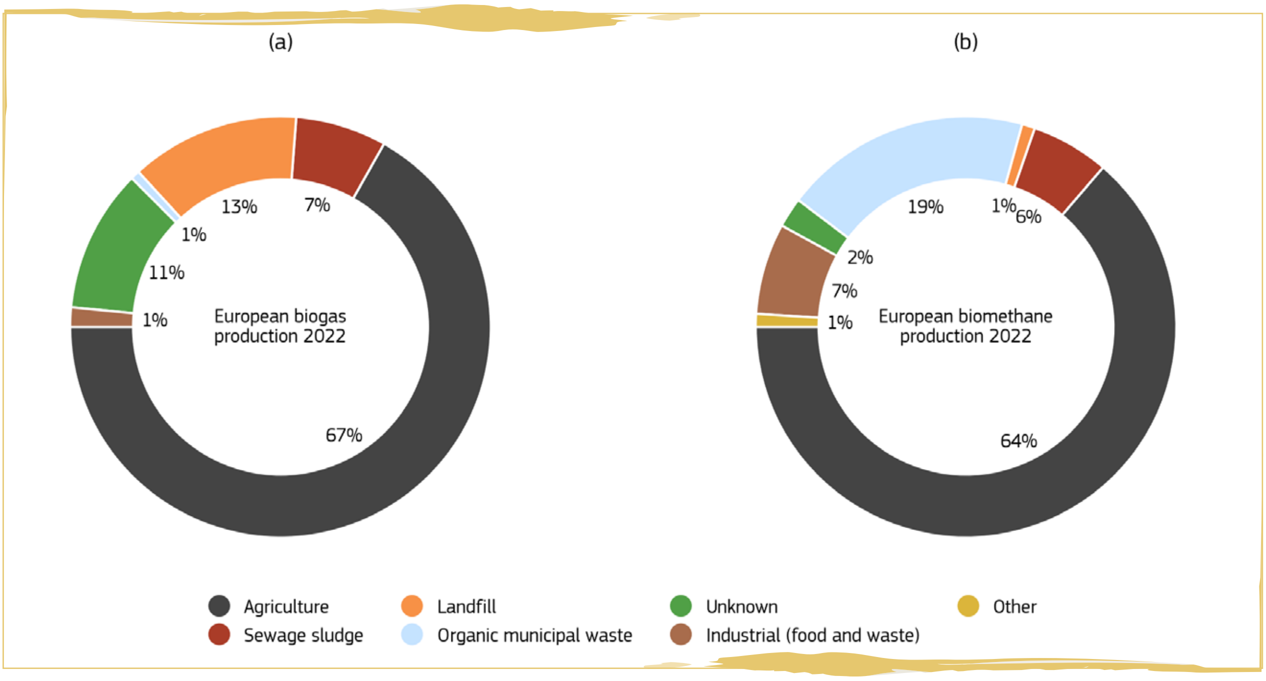
Figure 60. **Share of newly installed biomethane production plant in Europe per feedstock used.**



Source: European Biogas Association, 2023.

The last survey conducted by EBA showed that in 2022 biogas and biomethane operating plants still heavily rely on agriculture crops and residues, with 67% and 64% share respectively. The next source for biogas is landfill gas produced in landfill sites through anaerobic digestion of municipal waste at 13% share, and organic municipal waste for biomethane at 19% share. See Figure 61.

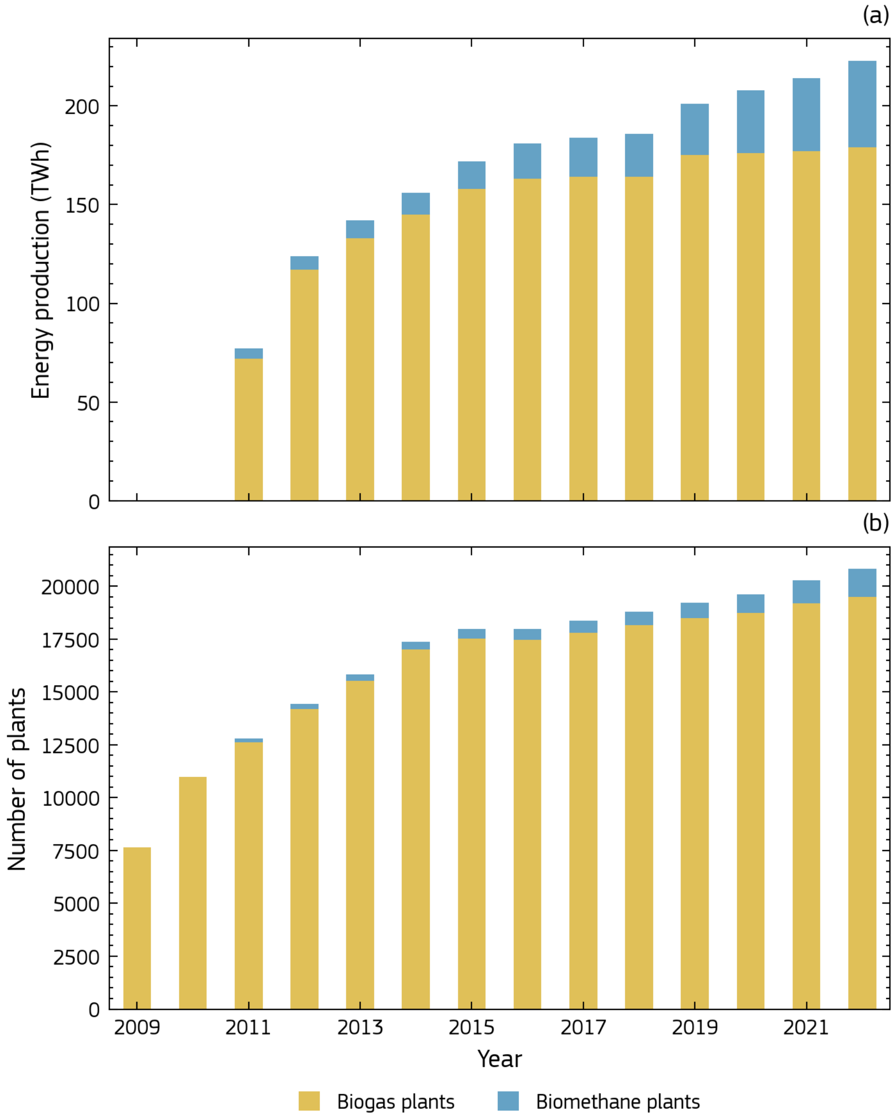
Figure 61. Share of feedstock used in biogas and biomethane production in Europe, 2022.



Source: Adapted from European Biogas Association, 2023.

The biogas production in EU-27, UK, NO and CH more than doubled from 2011 to 2015, increasing from 72 TWh to 158TWh, while biogas production was almost steady in the following years. The combined biogas and biomethane production grew up thanks to biomethane increase (331%) from 14 TWh in 2015 to 44 TWh in 2022 (Figure 62a), with UK having 11% in Biogas production and 16% in Biomethane production. The same trend is visible concerning the evolution of installed biogas and biomethane plants in Europe, with UK having 1111 Biogas plants, 5.7% of total and 133 biomethane plants representing 10% share (Figure 62b).

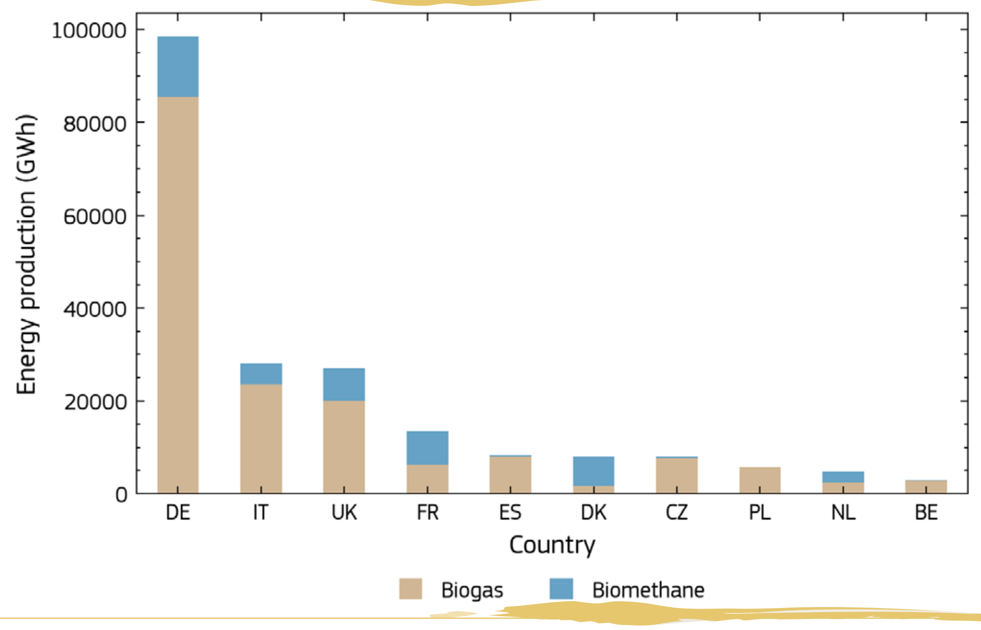
Figure 62. **Evolution of biogas and biomethane production in the EU + UK, NO, and CH (a) in TWh; (b) in installations.**



Source: Adapted from European Biogas Association, 2023.

Looking at the deployment of biogas supply in different Member States, Figure 63 (EU plus UK, NO, CH), the leading MS in 2022 was Germany that had a share of about 53% into the biogas production with 98,623 GWh. Other MSs with high deployment are Italy, France, Spain and Denmark.

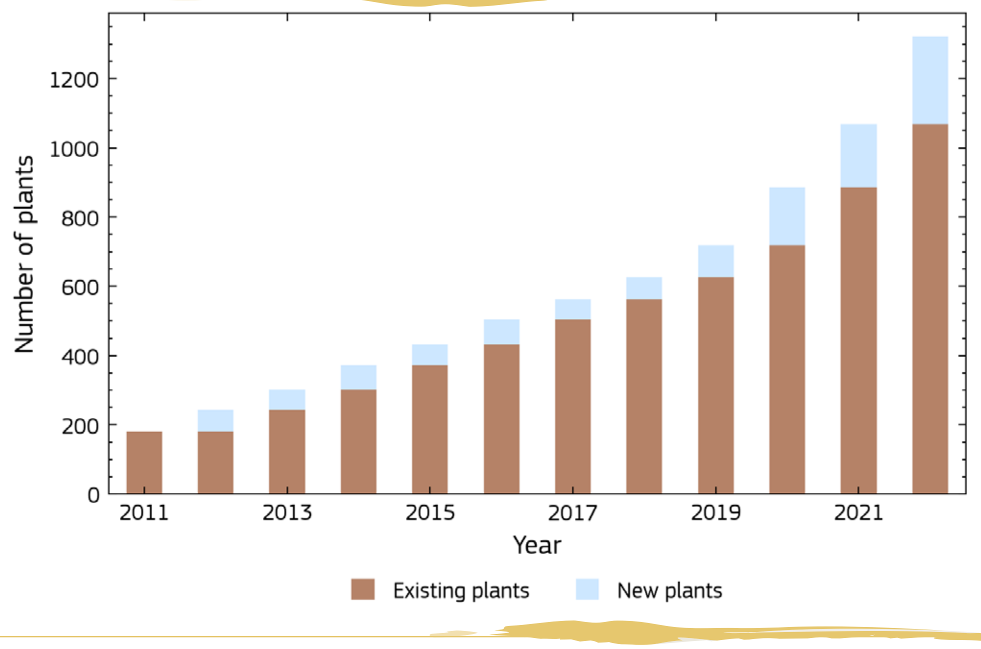
Figure 63. Biogas production in European countries (EU plus UK, NO, CH) in 2022.



Source: Adapted from European Biogas Association, 2023.

The number of new biomethane plants in Europe increased rapidly from 2019, with 254 additions in 2022, see Figure 64.

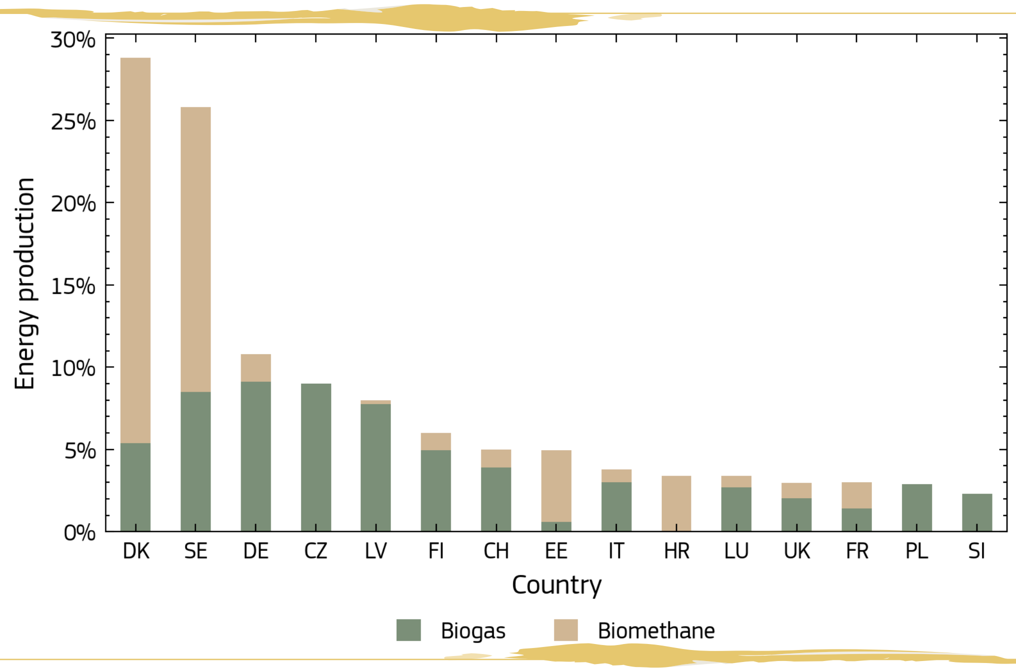
Figure 64. Biomethane plants in European countries (EU plus UK, NO, CH).



Source: Adapted from European Biogas Association, 2023.

When comparing to the natural gas use in various MS, biogas has a significant contribution in Denmark (29 %), Sweden (26 %), and Germany (11 %). See Figure 65.

Figure 65. **Natural gas replacement by biogas and biomethane.**



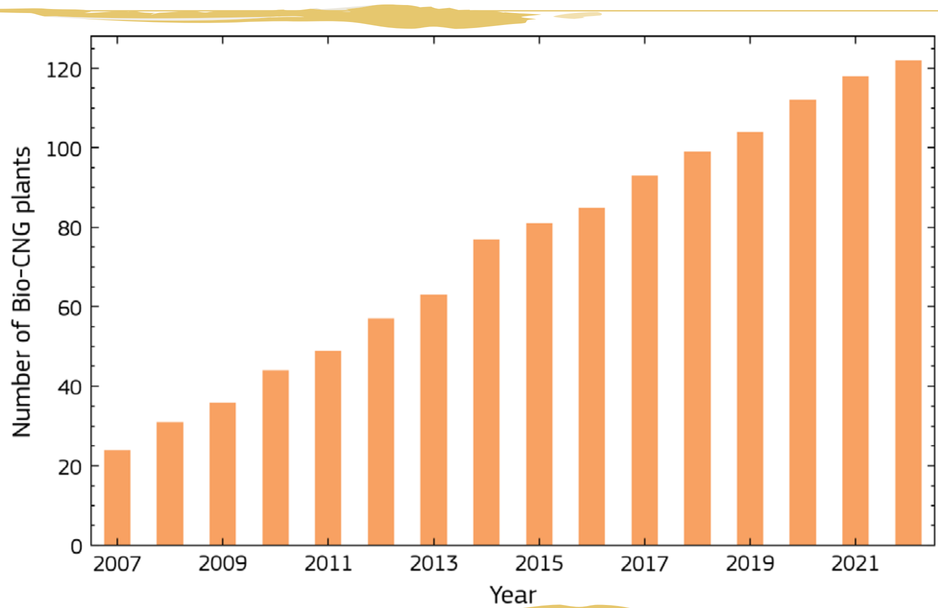
Source: Adapted from European Biogas Association, 2023.

3.5.2.1.2 Bio compressed natural gas (CNG) and liquefied natural gas (LNG) production and trends

According to EBA (European Biogas Association, 2023), there were 27 active Bio-LNG producing plants in the EU plus UK, NO, CH by the end of 2022, and their number sharply increased in the years 2023 (+ 28 plants), 2024 (+ 47 plants) and 2025 (+ 11 plants), bringing the total production capacity from 1.4 TWh in 2022 to a projected 15.4 TWh in 2025.

Out of the 1,222 biomethane plants active in EU plus UK, NO, CH by the end of August 2022 according to EBA, 122 plants are known to compress biomethane on-site to produce Bio-CNG, see Figure 66. This solution has a particular interest in countries with less developed NG grid.

Figure 66. **Number of Bio-CNG plants in EU plus UK, NO, CH.**



Source: Adapted from European Biogas Association, 2023.

Bio-LNG and Bio-CNG fueling stations were already in service in EU plus UK, NO, CH, in August 2022 the EBA report says there were 4,181 CNG filling stations and 576 LNG filling stations. The EU AFIR (alternative fuel infrastructure Regulation) (European Union, 2023) states that until 31 December 2024, Member States shall ensure that an appropriate number of publicly accessible refueling points for liquefied methane are deployed, at least along the TEN-T core network, in order to allow heavy-duty motor vehicles using liquefied methane to circulate throughout the Union, where there is demand, unless the costs of doing so are disproportionate to the benefits, including environmental benefits.

3.6 Biomass trade of food-related commodities potentially linked to deforestation

Teresa Armada Bras, Selene Patani, Mirco Migliavacca, Guido Ceccherini, Valeria De Laurentiis, Vasco Orza, Sarah Mubareka

3.6.1 Introduction

Biomass trade is a fundamental component of the global economy, shaping agricultural and forestry-based supply chains that serve diverse industries and consumer markets. While trade dynamics between highly industrialized nations may often exhibit patterns of relative parity, the exchange of commodities and products associated with deforestation and forest degradation (also called forest-risk commodities) — such as soy, palm oil, coffee, cocoa, cattle, rubber, or timber — frequently reflect systemic imbalances. These imbalances are particularly observable in trade relationships that exhibit structural factors contributing to disparities, often seen in the context of historical trade patterns between regions categorized as less advanced economies and more advanced ones (Amin, 1974; Marini et al., 2022). Such dynamics can lead to the concentration of economic benefits in certain regions while potentially externalizing environmental and social costs onto others (see section 7.1.4 Towards systemic change: addressing structural challenges in international trade). These systemic imbalances contribute to environmental challenges, with deforestation and forest degradation being critical consequences of biomass trade. These are among the most pressing environmental challenges of our time. The loss of forests not only contributes to global warming due to its strong implications in the global carbon cycle (IPCC, 2021), but also leads to biodiversity loss (Qu et al (2024), Hua Fangyuan et al (2024)), while also generating social-ecological impacts (Boillat et al (2020)). Globally, over 5.5 million hectares of forest are lost annually, resulting in the release of 1.9 GtCO2 greenhouse gas (GHG) emissions; this deforestation is primarily driven by the expansion of cropland, pastures and tree plantations for commodity production (Pendrill et al. (2019b), Sigh and Persson (Preprint)).

The deforestation driven by agricultural and forestry activities is significantly more prevalent in tropical countries compared to non-tropical regions. In tropical countries, these activities represent 42% of all deforestation, while in non-tropical countries, they account for 10% (Sigh and Persson (Preprint)). This disparity highlights the particularly severe impact of agriculture and forestry on deforestation in tropical areas. Southeast Asia is particularly affected, with 84% of the carbon emissions from the agricultural and forest commodities production driven deforestation occurring in this region (Sigh and Persson (Preprint)). Across the tropics, pasture expansion for cattle meat production is the most significant driver of agricultural and forest commodities production driven deforestation, accounting for 50%. Oilseed and oleaginous crops, such as soy and palm oil, represent 20% of it, while six other crops (i.e., rubber, cocoa, coffee, rice, maize, and cassava) account for most of the remaining, with significant regional variations and higher levels of uncertainty (Pendrill et al., 2022).

The demand for some agricultural commodities significantly contributes to deforestation through forest clearing for their production, and these products are then traded (Henders et al 2015, Curtis et al 2018). International trade accounts for 26 to 30% of global agroforestry-driven deforestation (Pendrill et al (2019b), Sigh and Persson (Preprint)). The EU-27 represents 14% of global trade of certain products considered to be linked to deforestation (Sigh and Persson (Preprint)). Recent studies show that this figure is surpassed by China and followed by the United States, India and Japan (Sigh and Persson (Preprint)). This consumption pattern contributes substantially to the carbon footprint of European diets, with tropical deforestation estimated to account for approximately one-sixth of these emissions (European Commission, 2023).

In this context, the EU Regulation on Deforestation-free products (EUDR) was established to reduce global deforestation and forest degradation, thereby reducing GHG emissions and biodiversity loss. By requiring that selected commodities imported into the EU-27 market originate from deforestation-free land that was not deforested after December 31st, 2020 (the cut-off date), the EUDR seeks to address the environmental impacts of trade for products related with cattle, cocoa, soy, palm oil, coffee, timber and rubber (EU, 2023). The EU Observatory on Deforestation and Forest Degradation (EUFO) was established in 2021 to support the implementation and monitoring of the EUDR, thus allowing to monitor the state of deforestation and forest degradation, production, and trade at country scale.

This chapter analyses the EU-27's environmental impacts of the EUDR food-related commodities as listed the in the Annex I of the regulation (EU, 2023), i.e. cattle, cocoa, soy, palm oil, and coffee, therefore excluding timber and rubber-based products. It first presents key results on production statistics (section 3.6.2.1) and on the bilateral trade flows (section 3.6.2.2). The EU-27 environmental impacts of trade-driven demand of EUDR food-related commodities are assessed in terms of (a) land footprint (i.e., the land area needed to produce the products imported (or consumed) by a country or region, section 3.6.2.3), as well as, in terms of (b) EU-27's contribution to deforestation and (3) estimated biomass loss for each commodity (section 3.6.2.4). Section 3.6.3 outlines the methodology and section 3.6.4 concludes. The key messages are enumerated in section 3.6.5. To note that the work described in this chapter is without prejudice to the ongoing Commission work under the EUDR implementation.

3.6.2 Key results

This section reports key results on the EUDR food-related commodities, i.e. cattle, cocoa, soy, palm oil, and coffee. All the food-related products listed in the Annex I of the EU Regulation on Deforestation-free products are considered in the analysis.

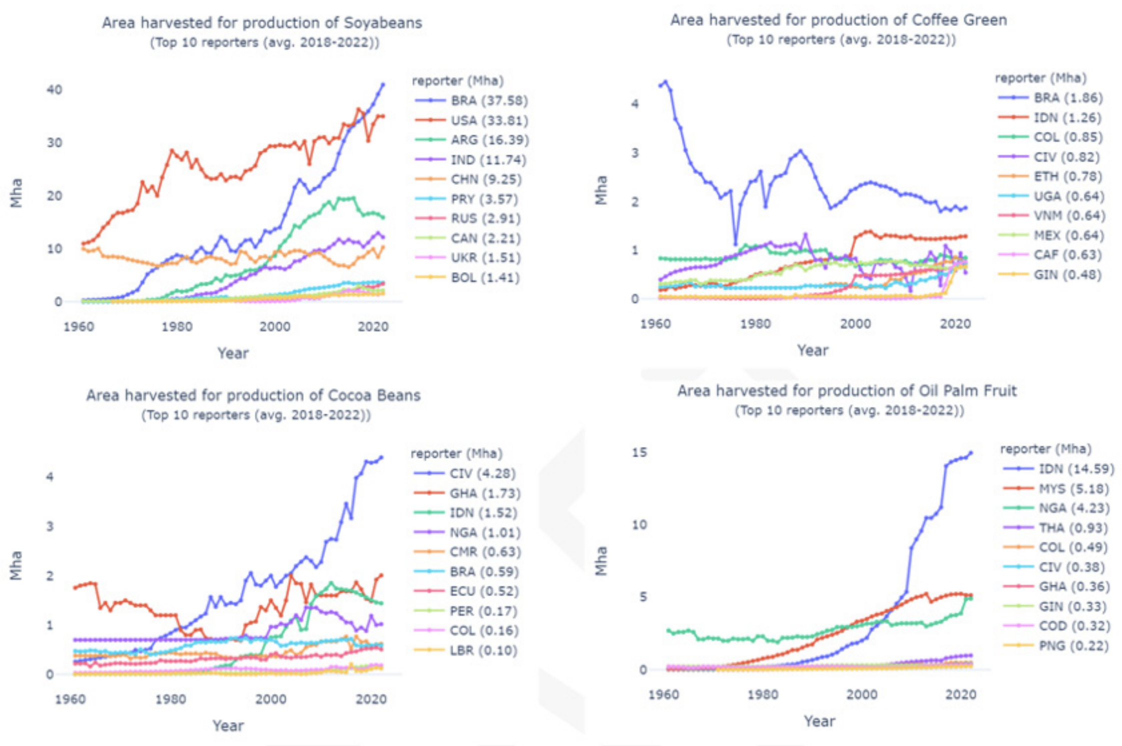
3.6.2.1 Production of food-related EUDR commodities potentially linked to deforestation

We report the key figures calculated from the FAOSTAT dataset regarding the production ('quantity', millions of tonnes - Mt) and land area needed for the production ('area harvested', Mha) of the agricultural commodities considered in the European Union's regulation for deforestation-free products. It should be noted that the area harvested does not refer to deforestation, but it is the total area of land required to produce the commodity, including the land area that did not experience recent land use change.

The time series of the harvested area by country for the main commodities is shown in Figure 67, which also displays the average harvested area over the five-year period 2018–2022. Brazil and the United States reported the highest area harvested to produce soybeans, and show also a strong increasing trend of harvested area. For coffee, the two major producers are Brazil and Indonesia. While Indonesia is showing a relatively stable or slight increase in the harvested area, Brazil has shown a negative trend in the last 20 years. Côte d'Ivoire is the country with the highest area harvested for cocoa production, followed by Ghana, and in both countries, there is an increasing trend on the area harvested. Indonesia is the country with the highest area harvested associated with the production of palm oil, followed by Malaysia and Nigeria, where we observe an important positive trend.

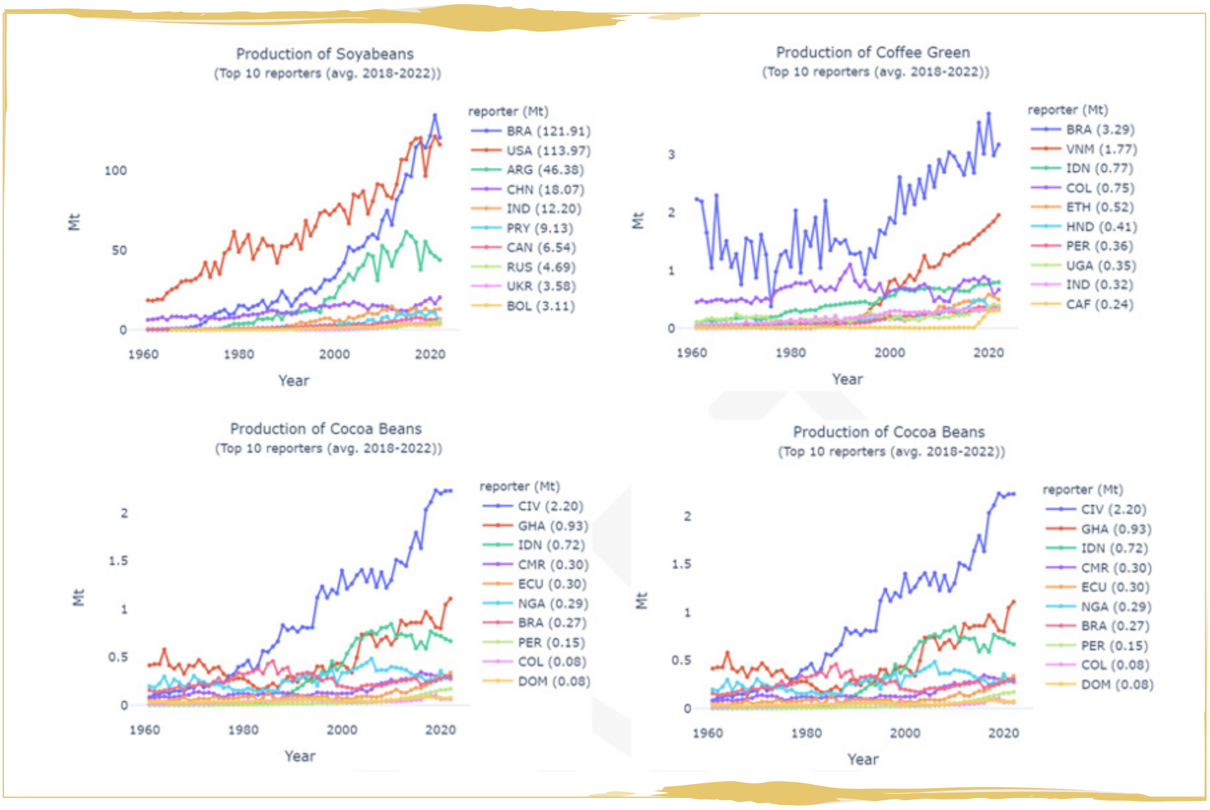
The time series of the production (Mt) of the crop commodities and the ones of cattle-based products are shown, respectively, in Figures 68 and 69. The time series of production (Mt) resemble the time series of the area harvested (Figure 67). Regarding cattle, Brazil and India are the most important producers of live cattle, while the United States, Brazil, and China are the most important producers of meat of cattle and of raw hides and skin of cattle. While the United States is the most important producer of cattle meat, the production in Brazil and China is increasing and showing a positive trend. The same is valid for raw hides and skins of cattle, with China showing the most important positive trend, followed by the United States and Brazil. However, it should be verified if the high production of hides in China is generated by cattle actually grown up in China or imported (for instance, from South America).

Figure 67. **Time series of harvested area by country (ISO alpha 3 code) for the main crop commodities, showing the average harvested area over the five-year period 2018–2022 (FAOSTAT data).**



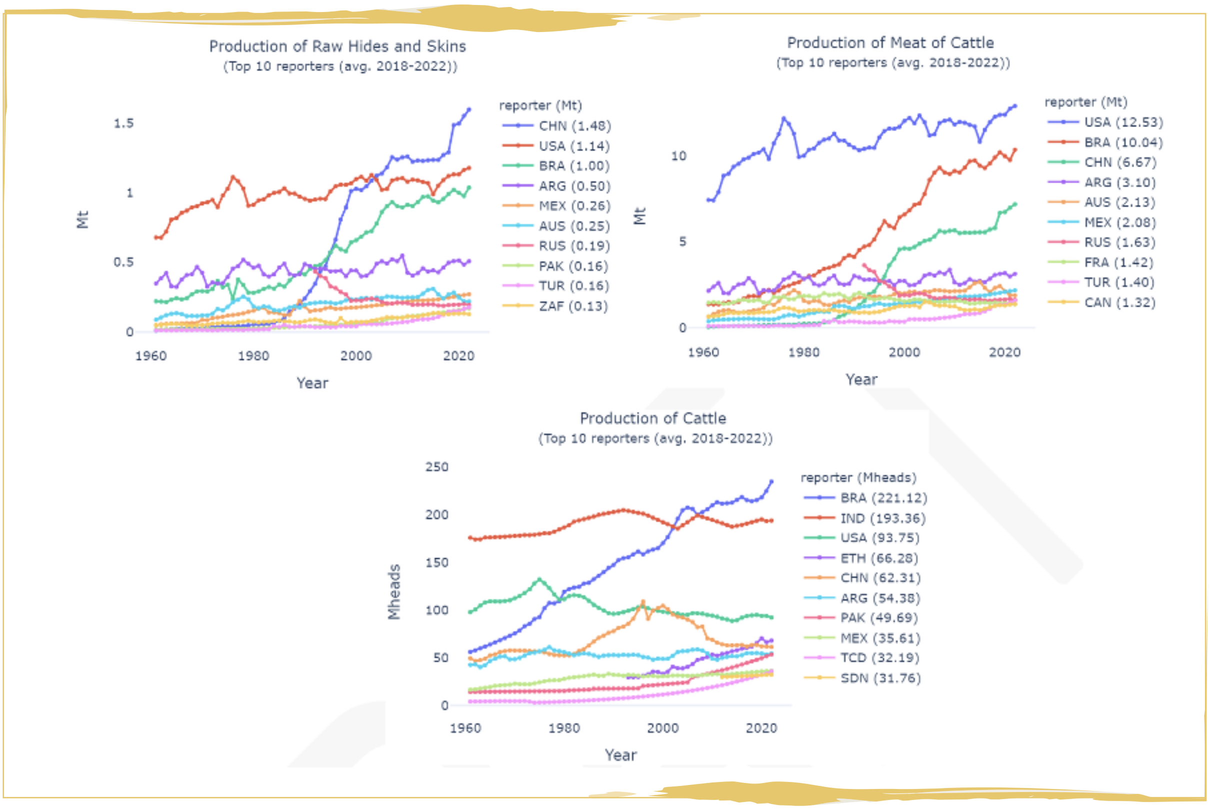
Source: JRC, own elaboration.

Figure 68. Time series of production by country (ISO alpha 3 code) for the main crop commodities, showing the average production over the five-year period 2018–2022 (FAOSTAT data).



Source: JRC, own elaboration.

Figure 69. Time series of production by country (ISO alpha 3 code) for the main cattle-based commodities, showing the average production over the five-year period 2018–2022, (FAOSTAT data).

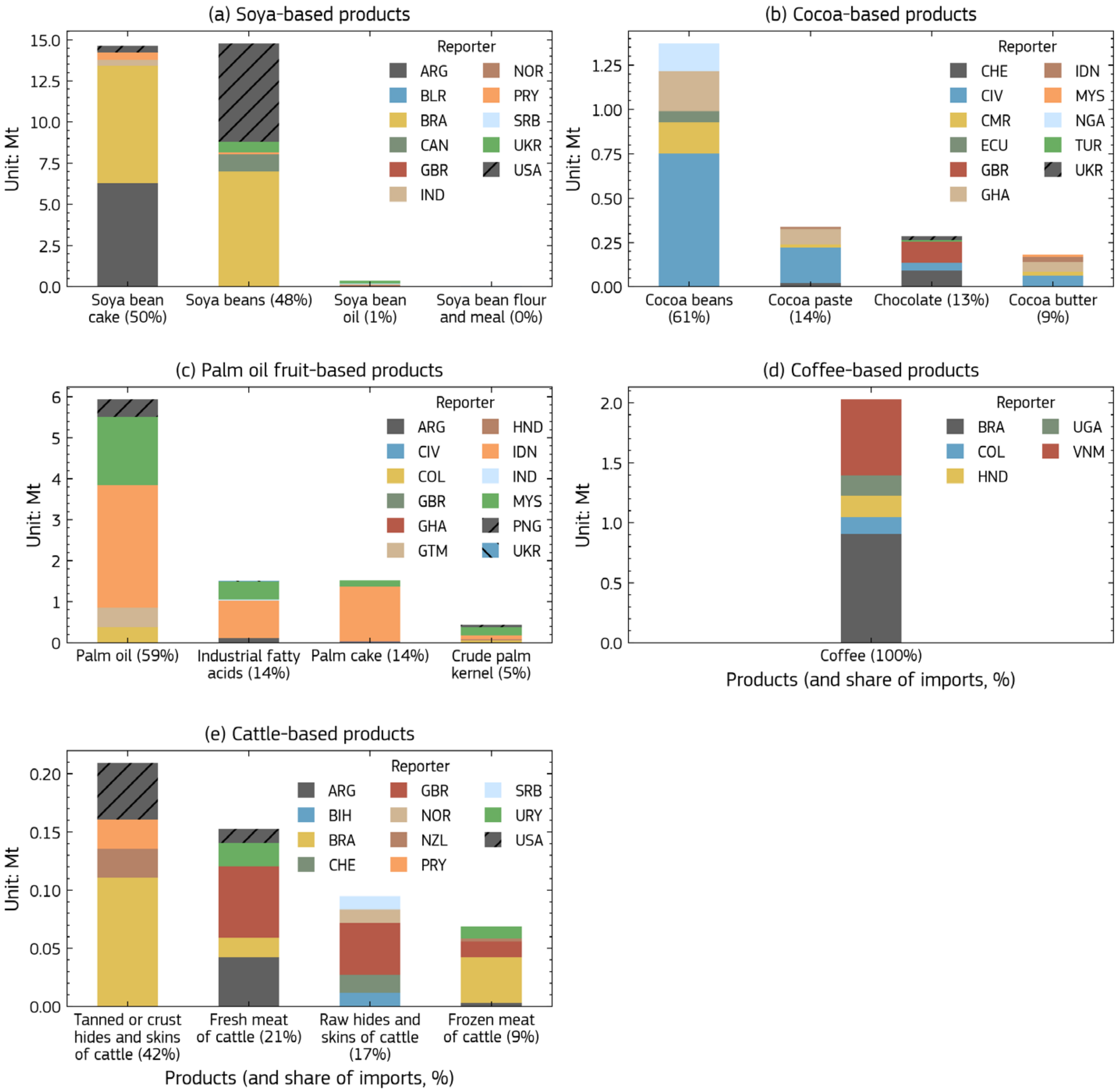


Source: JRC, own elaboration.

3.6.2.2 Trade of food-related EUDR commodities potentially linked to deforestation

In Figure 70, we report the quantity of products derived from soybeans, cocoa, palm oil fruit, coffee, and cattle that were, on average, imported by the EU-27 between 2018-2022. For each product, we show their share in terms of the primary commodity and the five top exporters to the EU-27 (source United Nations COMTRADE data). Cake of soybeans (typically used to feed animals and cattle) and soybeans are the most imported soy products (in total up to 98%) by the EU-27. It is worth to note that for cake of soybeans, Brazil and Argentina are the most important trade partners, while for soybeans, it is Brazil and the United States (and interestingly not Argentina). Cocoa beans represent nearly 60% of the EU-27 imported cocoa-based products, with Ivory Coast and Ghana as the main EU-27 providers. Palm oil, industrial fatty acids from palm oil, and palm cake represent 87% of EU-27 imports of all palm oil-based products, with Indonesia and Malaysia as the main exporters. Brazil and Vietnam are the main coffee exporters to the EU-27. Tanned or crust hides and skins of cattle is the most imported cattle-based product by the EU-27, representing 42% of those, and being mainly exported from Brazil, the United States, Paraguay, New Zealand and the United Kingdom. Fresh meat of cattle, and raw hides and skins of cattle are the second and third most imported cattle products, followed by frozen meat of cattle. Key partners are the United Kingdom and Southern American countries.

Figure 70. Stacked bar chart illustrating the top five countries (ISO alpha 3 code) exporting food-related EUDR commodities to the EU-27, based on five-year average from 2018-2022. Each chart corresponds to a primary commodity (i.e., soybeans, cocoa, palm oil fruit, coffee, and cattle), depicting EU-27 import volumes of up to four associated products, from each of the five leading partners (COMTRADE data).



Source: JRC, own elaboration.

3.6.2.3 Land footprint embodied in EU-27 imports of food-related EUDR commodities potentially linked to deforestation

In this section, we report on the results of the land footprint embodied in the EU-27 imports (i.e., the land area needed to produce imported products) calculated using the land footprint physical-based approach described in section 3.6.3.2. Results refer to the land footprint of imports recorded between 2018 and 2022. This section also provides an overall overview on the shares of embodied harvest area in imported food-related EUDR products not only from the EU-27 but also from other major worldwide importers. Note that a trade reallocation method is employed to attribute the land footprint to the actual producers rather than to intermediate trade partners, who are often large trade hubs but not commodity producers (see methods).

The results show that the EU-27 land footprint of imports of food products covered by the EUDR is larger for soy, cattle, and cocoa-based products, each representing around 18-35% of the total EU-27 land footprint (Figure 71). In absolute terms the EU-27 annual average land footprint for imports of the EUDR food-related commodities is approximately 27 million hectares, being primarily concentrated within specific regions (Fig. 72 and 73). The EU-27 imports of soy-based products, primarily soybeans and soybean cake, are estimated to require nearly 10 million hectares of land, mostly from South America and the United States. Cocoa, primarily cocoa beans, requires around five million hectares, concentrated in Central and Western Africa. Coffee-based products have a land footprint of nearly three million hectares, distributed across the tropics. Palm oil-based products, mainly from Indonesia, Malaysia, and Papua New Guinea, accounts for nearly two million hectares. Cattle-based products have a land footprint of approximately eight million hectares, including both cropland for feed and grassland for grazing, mostly due to imports of tanned hides and skins of cattle used to produce leather products, and fresh meat. These imports originate mostly from Brazil, Argentina, Paraguay, Uruguay, the United Kingdom, the United States, and Australia

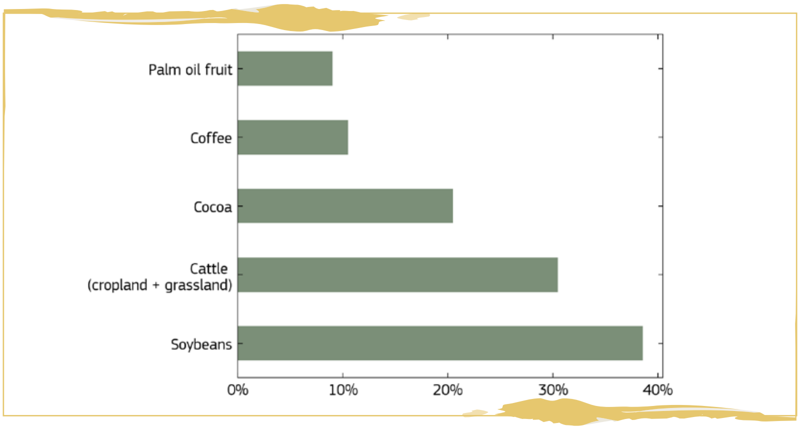
The share of land embodied in the import of food-related EUDR products by major trade partners is presented in Figure74 for crop products. The results are expressed as a percentage of the harvest area in the producer country. The global embodied land footprint of forest-risk products varies significantly across countries. For major trade partners, the share of land embodied in the import of food-related EUDR products is substantial.

Cocoa and coffee producers in West Africa, South America, and Southeast Asia virtually export a large portion of their harvested areas to the EU-27, the United States, and Malaysia (for cocoa), and Japan (for coffee). For cocoa, the market in Ghana, Ivory Coast, and Cameroon is highly concentrated in the EU-27, accounting for 40-63% of the cocoa harvest area. For coffee, Brazil, Colombia, Indonesia, and Vietnam virtually export significant shares of their coffee harvests primarily to the EU-27 and the United States, with smaller exports to Canada and Japan.

The soy and palm oil markets are more diversified, with China, the EU-27, and India being major importers. Brazil's soy production is particularly dependent on these markets, with China accounting for nearly 50% of its embodied land footprint. In Argentina, China, the EU-27, and India each have a significant share of the soy market.

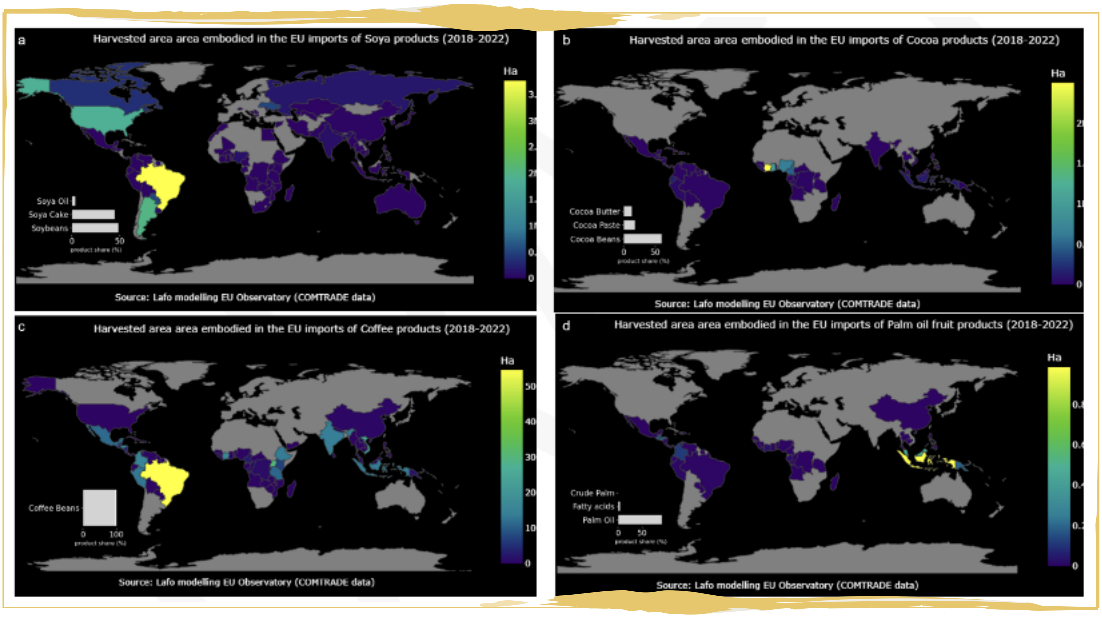
The environmental footprint of imported food-related EUDR products, measured by the land used for their production, varies across different importer countries. Each country's relative contribution to the total land use associated with these imports also differs significantly. This highlights the need for collective action and underscores the importance of regulations like the EUDR in promoting sustainable supply chains. The demand for these imported products can indirectly contribute to deforestation in other regions to meet consumer needs and, consequently, production requirements. This highlights the hidden environmental costs of global trade. The following section will discuss the deforestation linked to EU-27 imports of food-related products covered by the EUDR.

Figure 71. Share of the EU-27's land footprint of imports for each commodity, relative to the sum of the EU-27 land footprint of imports for the considered food-related EUDR commodities. The EU-27 land footprint of cattle refers to the sum of cropland and grassland. Data averaged over the five-year period 2018-2022.



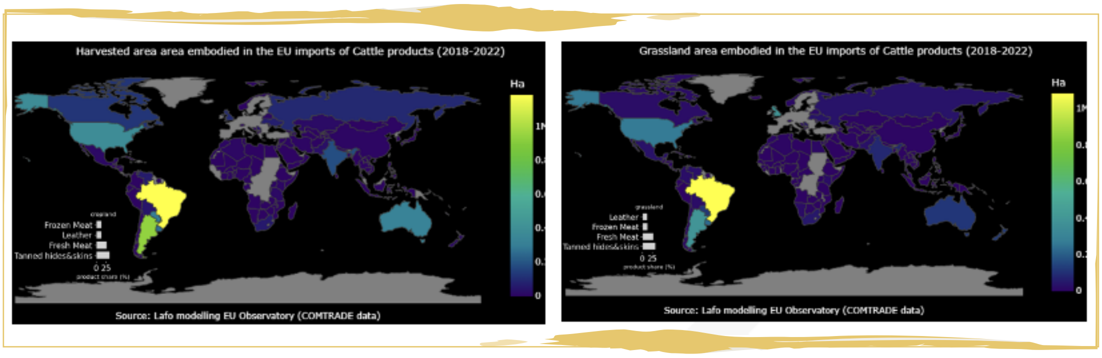
Source: JRC, own elaboration.

Figure 72. EU-27's land footprint for imported crop-based products (averaged 2018-2022) regarding, (a) soy, (b) cocoa, (c) coffee, (d) palm oil fruit-based products. Grey bars show the EU-27's land footprint shares for the three crop-based products with the largest footprints.



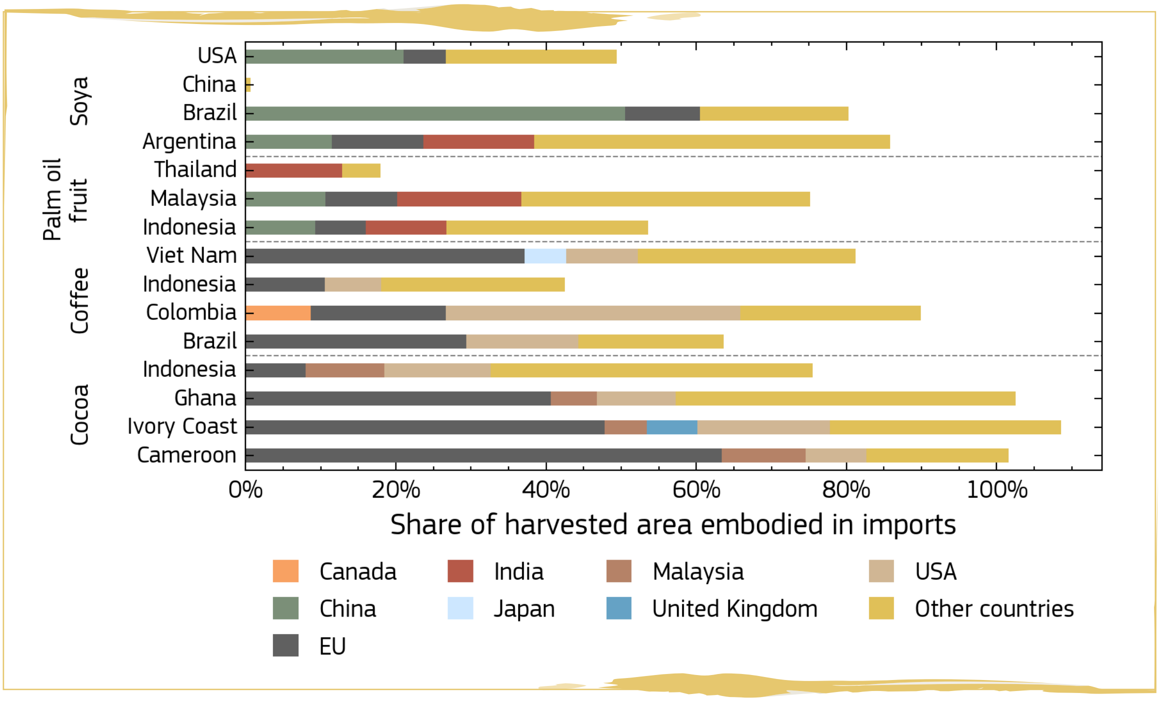
Source: JRC, own elaboration.

Figure 73. EU-27's land footprint for imported cattle-based products (averaged 2018-2022). Results are shown in terms of (a) cropland, and (b) grassland. Grey bars show the EU-27's land footprint share for the four cattle-based products with the largest footprints.



Source: JRC, own elaboration.

Figure 74. Share of harvested area embodied in imported food-related EUDR products (2018-2022) from the top world producers of soy, palm oil fruit, coffee and cocoa. The share is calculated by dividing the land footprint of imports by the harvested area in the country of origin for each crop (obtained by FAOSTAT).



Source: JRC, own elaboration.

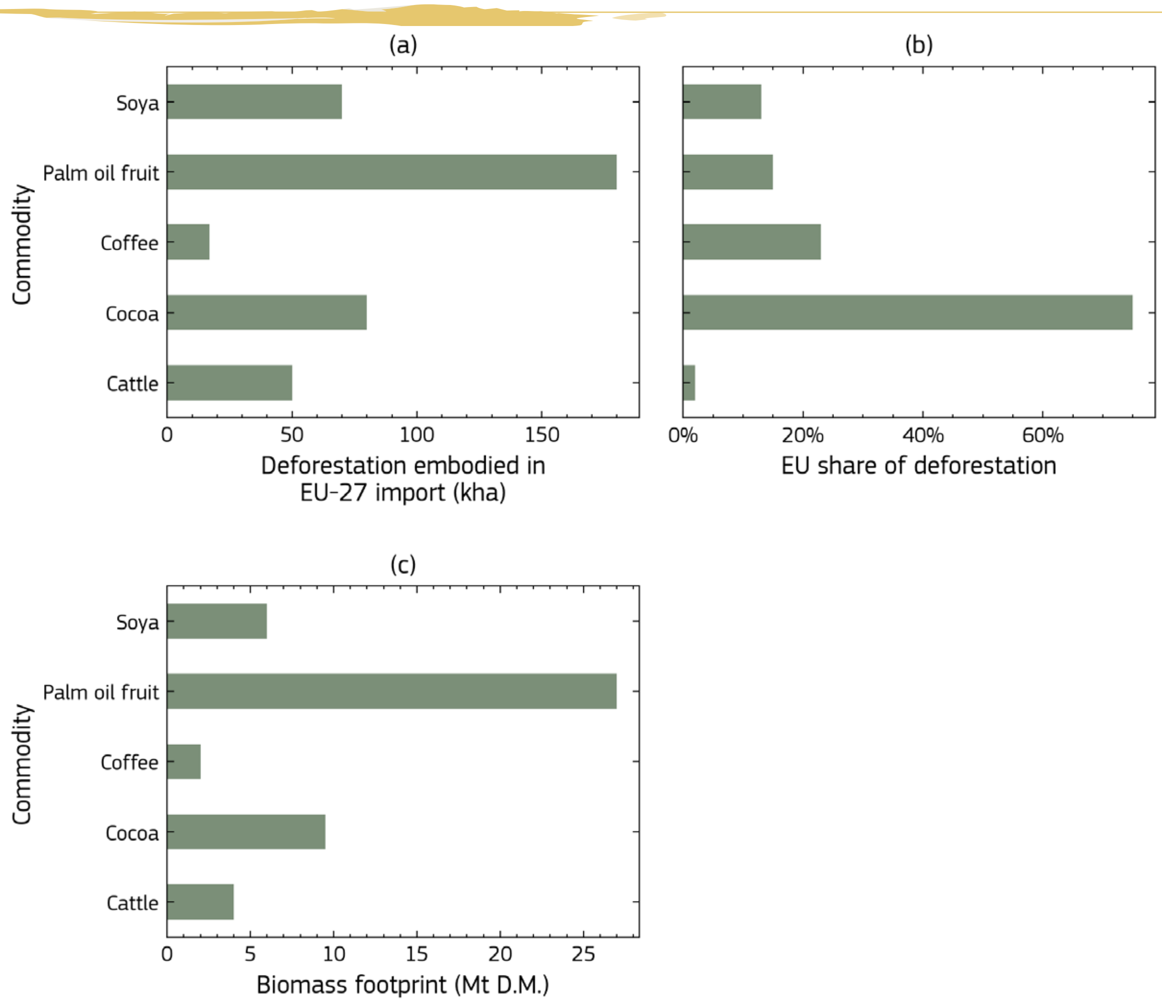
3.6.2.4 Deforestation and biomass loss embodied in EU-27 imports of food-related EUDR commodities potentially linked to deforestation

In this section, we report on the calculation of the deforestation embodied in the EU-27 imports calculated using the land use balance approach described in section 3.6.3.3, and the land footprint from imports from the previous section. The data refers to the deforestation that occurred in the period 2010-2015 and related to the trade between 2014 and 2019. To note that here in this report, the deforestation embodied in imports (and therefore it cannot be directly compared with the one of consumption) is based on the land footprint prior to any reallocation, thus not accounting for re-exports from the calculation, and FAOSTAT land use statistics on land use and land use change (latest access January 25th, 2023). Current efforts are ongoing to include Earth Observation data for forest loss attribution.

The results show that the EU-27 contribution to deforestation in the producing country compared to the rest of the world is very variable depending on the commodity (Fig. 75a). For commodities such as cocoa and coffee, the imports of EU-27 are a driver of deforestation, being the share of deforestation attributable to the EU-27 74.2% for cocoa, and 23.7% for coffee (Fig. 75b). For palm oil and soybeans, the share of deforestation due to EU-27 imports is 15.9% and 13.6%, respectively. Cattle is the commodity that shows the lowest share of deforestation, as the EU-27 is not a major partner of the producing countries for this commodity. The biomass losses per year are reported in Figure 75c, larger for the import of palm oil products (27.02 million tonnes of dry matter, Mt D.W.), followed by cocoa beans (9.72 Mt D.W.), soybeans (5.50 Mt D.W.), cattle (4.42 Mt D.W.), and coffee (1.39 Mt D.W.).

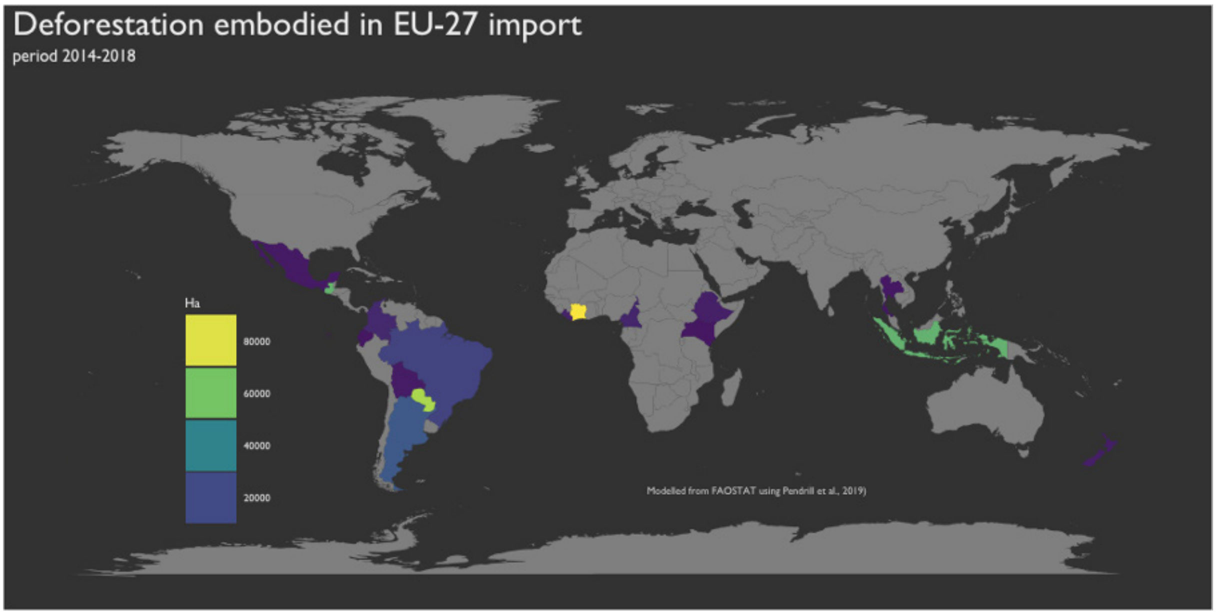
The geographical impact of the EU-27 imports is shown in the maps in Figures 76 and 77 where the deforested area per country due to the import of all the selected food-related EUDR commodities is reported. The EU-27 imports of the selected commodities and products impact mostly in South America (mainly through the soybean and cattle supply chain), central western Africa (due to cocoa production), and South East Asia (where palm oil is produced) (Figure 76). The relative impact of the EU-27 imports on deforestation is shown in Figure 77. The map shows that central American and Central Western Africa are the regions where the consumption of the EU-27 impacts the most in relative terms, and it is associated to the consumption of cocoa and coffee. The map of biomass loss per year (t D.W.) is reported in Figure 78 and broadly resembles the map of the deforestation embodied.

Figure 75. a) Figure 75. a) Total deforested area (2010-2015) embodied in mean annual trade volumes (2014-2019) of the selected food-related EUDR commodities and related products; b) EU-27 share (in percentage) of deforestation per commodity; c) total biomass lost for the production of product imported by the EU-27 (t D.W.) of deforestation per commodity (own calculation). To note that in this exercise, the deforestation embodied in imports is based on the land footprint prior to any reallocation, thus not accounting for re-exports from the calculation, and FAOSTAT statistics on land use and land use change (latest access January 25th, 2023)



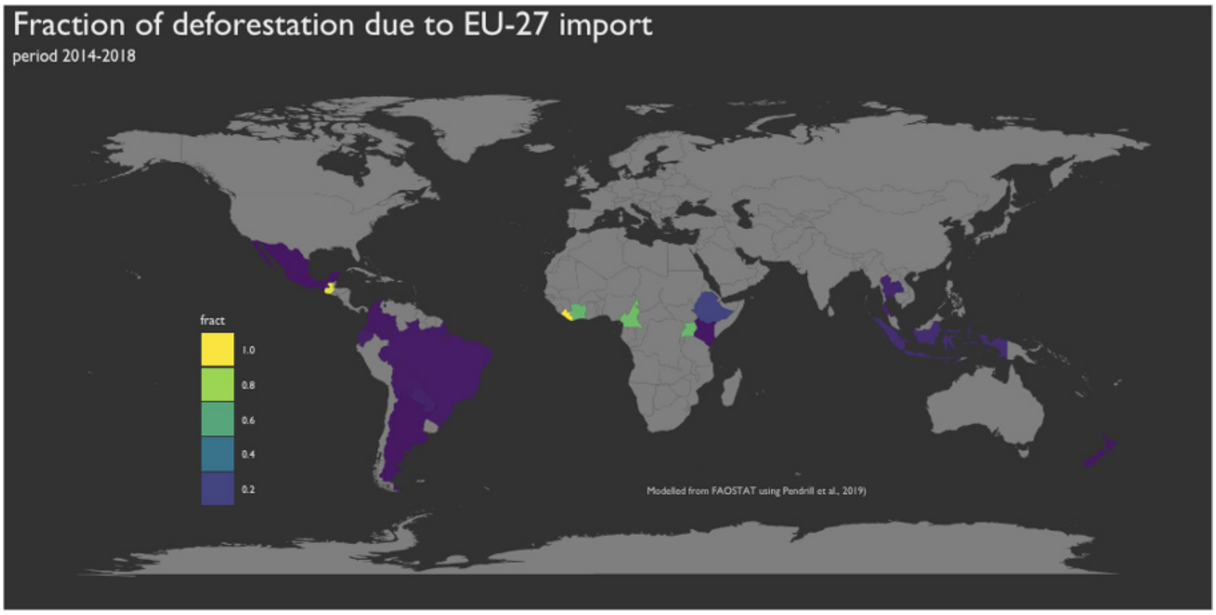
Source: JRC, own elaboration.

Figure 76. Deforestation embodied (expressed in hectares per year) in the EU-27 imports of cocoa, coffee, cattle, palm oil and soybeans products. To note that in this exercise, the deforestation embodied in imports is based on the land footprint prior to any reallocation, thus not accounting for re-exports from the calculation, and FAOSTAT statistics on land use and land use change (latest access January 25th, 2023).



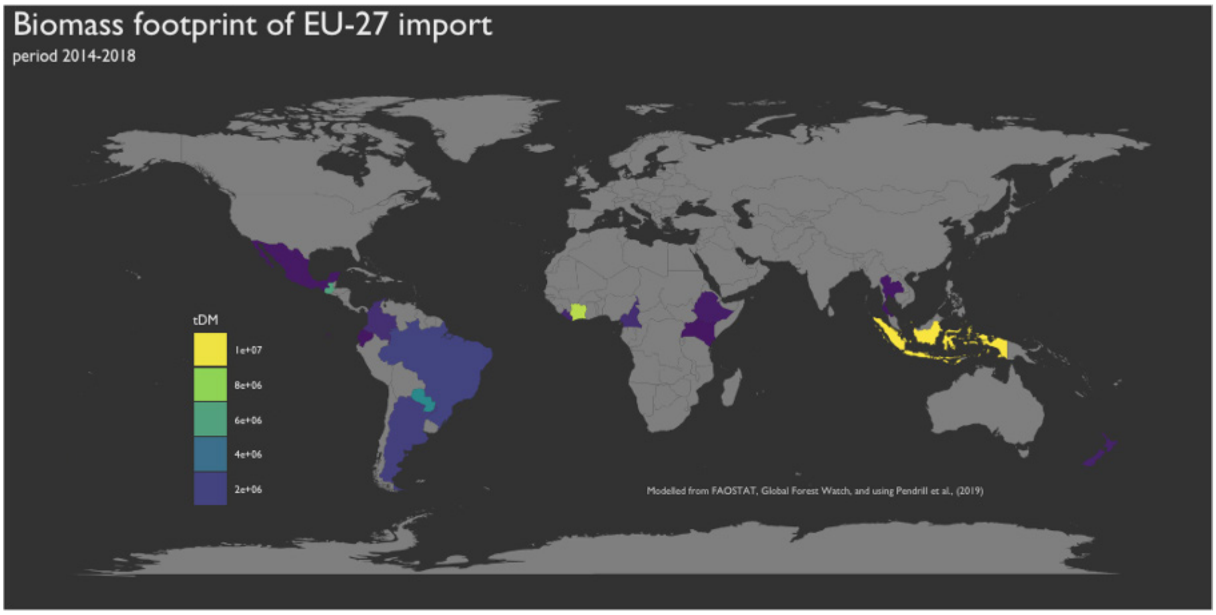
Source: JRC, own elaboration.

Figure 77. Share of deforestation due to EU-27 imports of cocoa, coffee, cattle, palm oil and soybeans products. To note that in this exercise, the deforestation embodied in imports is based on the land footprint prior to any reallocation, thus not accounting for re-exports from the calculation, and FAOSTAT statistics on land use and land use change (latest access January 25th, 2023).



Source: JRC, own elaboration.

Figure 78. Biomass lost (t D.W.) related to the deforestation per year to produce cocoa, coffee, cattle, palm oil and soybeans products imported by EU-27. To note that in this exercise, the deforestation embodied in imports is based on the land footprint prior to any reallocation, thus not accounting for re-exports from the calculation, and FAOSTAT statistics on land use and land use change (latest access January 25th, 2023).



Source: JRC, own elaboration.

3.6.3 Data and Methodology

3.6.3.1 Data on agriculture production and trade used for the land footprint land use change models

This section details the data sources and datasets used to calculate the land footprint and deforestation associated with the imports of the EU-27 EUDR food-related products, i.e. cattle, cocoa, soy, palm oil, and coffee -based products. While the primary focus regarding cattle is on food products, this analysis also includes leather derived from cattle hides. This inclusion is based on the following considerations: (a) leather production is an economically significant co-product of the cattle industry. Its inclusion provides a more complete picture of the environmental footprint associated with EU-27 imports related to cattle, and (b) the environmental impacts associated with cattle raising are inherently linked to the entire animal, including its hide used for leather production. Excluding leather would underrepresent the total environmental burden. The land footprint calculated refers to trade flows between 2018 and 2022.

The following data were used:

- UN COMTRADE time series[26]

  - Annual and country level data on international trade of food and agricultural products (2000-2022), namely import and export quantities, livestock numbers, and monetary values.
  - This data was used as input for the land footprint model to calculate the harvested area embodied in trade.

- FAOSTAT Agricultural Production

  - Annual and country level statistics on agricultural production (2000-2022), namely quantities of commodities produced (tons), harvested area (ha), and annual yield (ton/ha).

[26] Available at: *https://www.fao.org/faostat/en/#data/* and accessed through Rougieux et al (2023)

- This data was used as input for the land footprint model to calculate the harvested area embodied in trade, namely to reallocate imported quantities to the countries that actually produce the primary crop, according to the production of the primary crop.

- FAOSTAT Land Use:

- Annual and country-based statistics on land use for agricultural and forestry activities for the selected land uses: "Cropland", "Land under permanent meadows and pastures", "Planted Forest", and "Forest Land".

- We calculated the changes between 2015 and 2010 for each land use from this dataset. This data was used as input for the land use balance model to calculate the deforestation embodied in trade.

- Technical coefficients were used for the land footprint calculation:

- From FAOSTAT (2011)

  - Commodity tree for cocoa and palm oil fruit-related products.

- Technical conversion coefficients, i.e., extraction rates to convert quantities of processed products into equivalent quantities of the primary product. This data was used at the country level (based on FAO Technical Conversion Factors for Agricultural Commodities[27]), otherwise if not available, we used global coefficients (De Laurentiis, et al 2024), representing an averaged value of the main worldwide producers of the respective product.From De Laurentiis et al. (2022, 2024)

- From De Laurentiis et al. (2022, 2024) Grassland yields by region of origin (t/ha)

  - Technical conversion coefficients

  - Grassland yields by region of origin (t/ha)

[27] https://www.fao.org/3/cb2466t/cb2466t.pdf

- Feed conversion ratios for livestock products (input of dry mass feed per kg of live weight)

- Regional share of ruminant livestock biomass fed by grazing used to calculate the share of ruminant animals (and products) fed by grazing (beef, sheep, milk products)

- Diet composition for livestock (e.g.,: fodder types: wheat, wheat pellets, molasses, soy flour)

- Conversion coefficients from wet to dry mass

- Commodity trees (i.e. tree-schemes of the relations between traded products for each commodity) used to calculate the primary commodity equivalent (i.e. the quantity of primary commodity needed to produce the traded products) from traded products.

The production and land use datasets from FAOSTAT, and the trade dataset from UN COMTRADE was accessed through the self-developed 'BIOTRADE' python package (Rougieux et al, 2023).

3.6.3.2 The land footprint model

The land footprint model calculates the land area required to produce imported goods in a country or region. This is a crucial step in evaluating the deforestation embedded in the EU's imports. Three primary methodologies exist for land footprint modelling (as described in De Laurentiis et al., 2022):

- *Physically-based approach:* This method is selected for its timeliness and comparability with the state-of-the-art literature. It involves calculating land use based on production quantities, trade flows, and technical coefficients. It involves tracking the flow of physical units of materials from production to imports (or consumption) and estimating the corresponding land requirements. This method uses yield data for primary crops and conversion coefficients to convert processed products into crop inputs. It also models the land embedded in trade based on trade statistics and country-specific coefficients, accounting or not for re-exports. Additionally, physical accounting allocates land use to co-products based on factors like economic considerations or protein content.

- *Multiregional input-output models:* These models consider the broader economic relationships between sectors and land use. It links land use from production activities to final demand, considering the trade relationships between all economic sectors of the world. This method allows for the quantification of land footprints for all sectors, including indirect land use, and considers all upstream flows. It often involves using multi-regional input-output (MRIO) databases and official data sources. These models offer a more comprehensive view of the supply chain but rely on datasets that may not be regularly updated.

- *Hybrid approach:* This combines the strengths of the physically-based and multiregional input-output approaches. It is particularly useful for commodities with sufficient data for physical accounting and highly processed products or services that require environmental input-output. By integrating the two approaches, the hybrid method provides a more comprehensive and accurate assessment of land footprints.

The physically-based approach was chosen for this assessment because it offers timely results that are comparable to current research. We used land footprint method developed by the JRC (De Laurentiis et al., 2022, 2024).

The land footprint model (Figure 79) converts imported quantities of processed products into their primary commodity equivalents (PCEs) to determine their land footprint. For example, imported chocolate is converted into cocoa beans. For co-produced goods like soybean oil and soybean cake, technical coefficients are weighted based on monetary values to avoid double-counting (Cuypers et al, 2013). A trade reallocation method (based on Kastner et al 2011) is employed to attribute the land footprint to the actual producers rather than intermediate trade partners. Without this implementation the model attributes a certain amount of land footprint impact to countries that are large trade hubs (e.g., for instance countries with large ports), but that are not producers of the commodities. This involves:

- Determining production and bilateral trade shares: The imported PCEs are divided between domestic production and imports from partner countries.

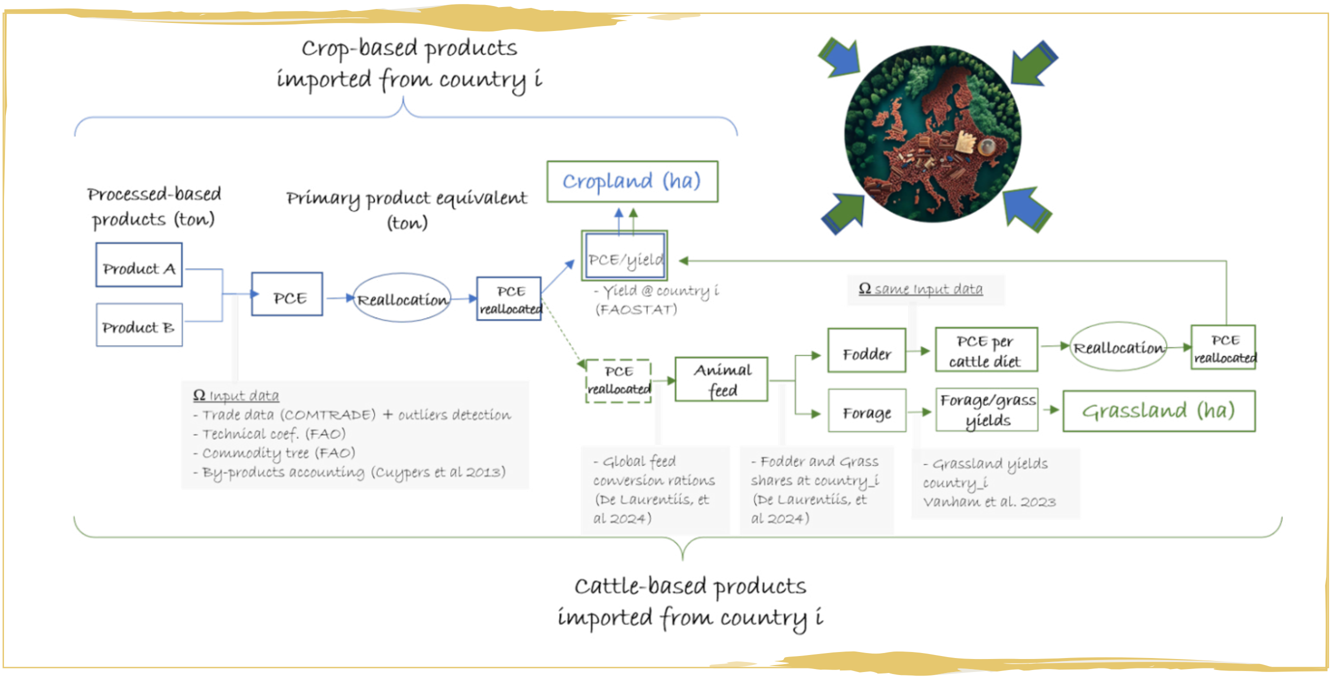
- Reallocating PCEs: A fixed share of imports between trade partners is calculated and used in each reallocation step. Only imports actually produced in each partner country are attributed to that country, while the remainder are reallocated to other partners based on their import proportions.

- Iterative reallocation: This process is repeated for each level of trade partners to ensure that PCEs are attributed to the original producers.

For crop-based products, the reallocated PCE is then divided by the yield of the primary product in the country of production to obtain the land footprint. A moving average of five years of yield is used to reduce the year-to-year fluctuations in the data.

For cattle-based products, the land footprint is calculated in terms of cropland (directly related with the cattle dietary requirements in the fodder), and in terms of grassland (calculated from the forage used in the diet). Trade data, production statistics (i.e., heads of cattle), commodity tree and technical coefficients are used to estimate the quantity of livestock equivalents, which is then reallocated. Feed conversion ratios are used to convert reallocated livestock equivalent quantities into animal feed requirements, which are decomposed into forage and fodder requirements (by using dry mass coefficients provided by region or country of origin). Fodder inputs are assigned to four fodder types considering the shares of cattle's diet types by place of origin (i.e., wheat, wheat pellets, oilseed meal, and molasses), which are then converted into PCE and reallocated using the same reallocation method and by adding the trade matrix of the crop-based products related with the fodder types. Grazed biomass from forage is converted into grassland by using global grassland yields (Vanham et al. 2023).

Figure 79. **Flowchart of the methodology for calculating the land footprint of imported crop and cattle-based products, i.e. cropland and grassland (the flowchart is based on the methodology from De Laurentiis, et al 2022, 2024).**



Source: JRC, own elaboration.

3.6.3.3 Calculation of the deforestation embodied in EU-27 imports

The land balance model used in this analysis attributes deforestation to agricultural production and trade, following the methodology of Pendrill et al., (2019a, 2019b). The model first attributes deforestation to major land-uses (cropland, pastures, forest plantations) based on land use changes and expansion rates. It relies on FAOSTAT statistics on land use and land use change (latest access January 25th, 2023) and provides results at the national level. Second, the model calculates the forest loss embodied in trade. The land footprint of imported commodities is calculated from the bilateral trade, and the portion of forest loss (due to crop and pasture expansion) attributable to EU-27 imports is determined. The model is based on two assumptions:

- Land use conversion: Cropland expansion is assumed to occur through pastures and then forests.
- Forest replacement: Pasture and forest plantation expansion directly replace forest land.

These assumptions are based on the land use patterns in the tropics, namely on the fact that forests and other native vegetation are primary sources of new agricultural land; forest plantations often replace natural forests; and pastures are a significant source of new cropland (see Pendrill et al., 2019b for more details).

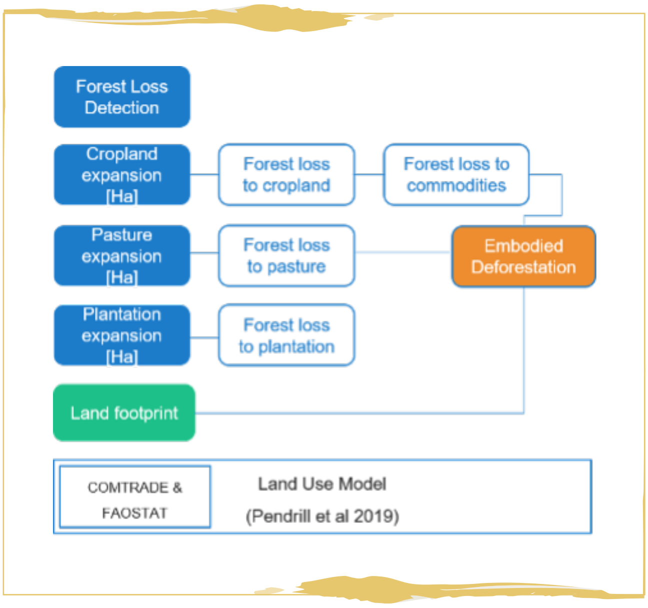
The model attributes forest loss in a given country proportionally to the expansion of cropland, pasture, and forest plantations, capped at the total estimated forest loss in the region. The forest loss attributed to cropland expansion is further distributed to individual crops based on their area expansion. For example, if, for a given country, the expansion of cocoa growing areas accounts for half of the total cropland expansion, then half of the country's cropland deforestation will be attributed to the country's cocoa production. A time lag is considered to account for the time between deforestation and having the product in the market. While deforestation is a one-time event, agricultural and forestry commodities will take a few years to grow and be traded. This is referred to as "amortisation time" and we consider five years. Therefore, the total amount of deforestation embodied in the production of a given commodity in a given year is calculated as the mean of the annual total deforestation attributed to the land use producing that commodity in the five previous years. The amortisation time is a critical parameter of the model. Pendrill et al. (2019b) showed that an amortisation period of five years yields similar results to one and ten years. As a result, in this chapter we calculated the deforestation embodied in the average trade flows between 2014 and 2019. This deforestation occurred in the time period 2010-2015.

We calculated the deforestation embodied in bilateral trade of the selected products for the EU-27 and a given country that produces that commodity, as follows (Fig. 80):

- 'percentage of imported harvested area', which is the ratio between the land footprint for the import of the given commodity divided by the area harvested in the origin country to produce that commodity. It is important to note that the 'percentage of imported harvested area' in this report reflects the land footprint prior to any reallocation, thus not accounting for re-exports from the calculation.

- 'embodied deforestation', calculated from the 'percentage of imported harvested area' that was then multiplied by the forest loss attributed to the expansion of the selected commodity in the producing country. In the case of cattle, the percentage of the imported harvested area was multiplied by the forest loss due to crop pasture expansion.

Figure 80. Flowchart of the methodology used for the calculation of deforestation embodied in the trade of the EUDR selected products. Abbreviations list: Tropical Moist Forests (TMF) dataset; Tropical Dry Forests (TDF) dataset; Climate Change Initiative (CCI); European Space Agency (ESA); United Nations Comtrade database (COMTRADE); Plantations (Plant); Pasture (Past); Croplands (Crop); Hectares (Ha).



Source: JRC, own elaboration, created with BioRender.com.

The biomass loss as consequence of deforestation embodied in the import of the selected commodities in the EU-27 is calculated following these steps:

- for each country, we calculated the deforested area using the forest cover changes from the Global Forest Change (GFC) maps recorded at 30-m spatial resolution from Landsat imagery (REF). We used the "Forest Cover Loss" that is defined as the complete removal of tree-cover canopy at the Landsat pixel scale (natural or human-driven) and is reported annually;

- we aggregated the map of the deforestation area from the native resolution of 30 m at the resolution of the European Space Agency (ESA) Climate Change Initiative (CCI) Biomass product (Santoro et al., 2021) for the year 2010, which is 100 m;

- we then calculated the mean and the median biomass per area [tons DM ha-1] in the deforested areas using the ESA CCI Biomass map and the deforestation area embodied derived from the GFC map;

- we then calculated the biomass footprint of the EU-27 import of product derived from the EUDR selected products by multiplying the deforestation are embodied in EU-27 import for the biomass per ha derived from ESA CCI Biomass map.

3.6.4 Conclusions

Deforestation and forest degradation are significant threats to global forests, impacting the carbon cycle, forest biomass, and biodiversity. Since 1990, global forest loss has amounted to 420 million hectares due to land use conversion (FAO, 2020). Tropical deforestation is primarily driven by agricultural expansion and commodity production (Curtis et al., 2019; Pendrill et al., 2019a, 2022).

The EU-27 has been identified as an important contributor to tropical deforestation through the consumption and trade of deforestation-related products and commodities (Pendrill et al., 2019a). This is primarily driven by the import of soy, cattle, cocoa, coffee, and palm oil, which have high land footprints and are associated with deforestation in producing countries. The EU-27's land footprint for imported EUDR food-related commodities is substantial, amounting to approximately 27 million hectares annually. Key regions from where the EU-27 has larger land footprints include South America, Central and Western Africa, and Southeast Asia. The global shares of virtually imported harvested areas for food-related EUDR products vary significantly across countries and commodities. This indicates that the EU-27's import patterns have a disproportionate impact on certain regions and producers. This is due to the high concentration of bilateral trade between EU-27 and few producing countries. For example, as Ghana, Ivory Coast, and Cameroon are the main exporter in the EU-27 market for cocoa. In those countries the EU-27 land footprint accounts for 40-63% of their harvest areas for cocoa production. In contrast, the soy and palm oil markets are more diversified, with China, the EU-27, and India being major importers. Brazil's soy production is particularly dependent on these markets, with China accounting for nearly 50% of its embodied land footprint.

The EU-27's contribution to deforestation varies by commodity: palm oil, cattle, and soybean are the commodities with the highest deforestation embodied in EU-27 imports between 2014 and 2019, followed by cocoa and coffee. The share of deforestation embodied by EU-27 imports compared to the rest of the world shows a large variability between commodities:74.1% for cocoa, 23.7% for coffee, 15.9% for palm oil, 15.6% for soybeans, and <1 % for cattle. The total forest biomass loss in 2010-2015 of the products traded in 2014-2019 was 48.04 million tonnes of dry matter (this study). To note that in this exercise, the deforestation embodied in imports, as well as the corresponding biomass loss, are based on the land footprint prior to any reallocation, thus not accounting for re-exports from the calculation, and FAOSTAT statistics on land use and land use change (latest access January 25th, 2023).

These findings highlight the significant contribution to deforestation from the EU-27's imports of food-related EUDR products, while also stresses the potential disproportionate contribution to deforestation burdens. This demonstrates the critical role of regulations like the EUDR in driving systemic transformations towards sustainable supply chains and mitigating deforestation.

3.6.4.1 Key messages

- The EU Regulation on Deforestation-free Products does not allow that soy, cocoa, coffee, palm oil, cattle, timber and rubber-based products entering in the EU-27 were produced on deforested or degraded land after 31st December2020, were not legally produced according to the relevant laws of the country of production, and are not covered by a due diligence statement (EU, 2023, art 3).

- The EU-27 has been identified as an important contributor to deforestation through the imports of food-related EUDR products, mostly linked to coffee and cocoa beans, palm oil, soybeans and cake of soybeans.

- The EU-27's annual average land footprint for imports is approximately 27 million hectares, with soy, cattle, and cocoa accounting for the majority, primarily sourced from South and North America (for soy and cattle) and Western and Central Africa (for cocoa-based products).

- The share of land embodied in the global imports of food-related EUDR products varies significantly across countries and among major trade partners: cocoa and coffee producers virtually export larger shares of their harvested areas to EU-27 and the United States; and soy and palm oil producers export larger shares to China, EU-27, and India.

- The imports of EU-27 between 2014 and 2019 contributed to 74.2% of the deforested area between 2010 and 2015 related to the production of cocoa, 23.7% for coffee, 15.9% for palm oil, 13.6% for soybeans, and less than 1% for cattle.

- The total forest biomass loss in 2010-2015 associated to products imported by the EU-27 in 2014-2019 was 48.04 million tonnes of dry matter.

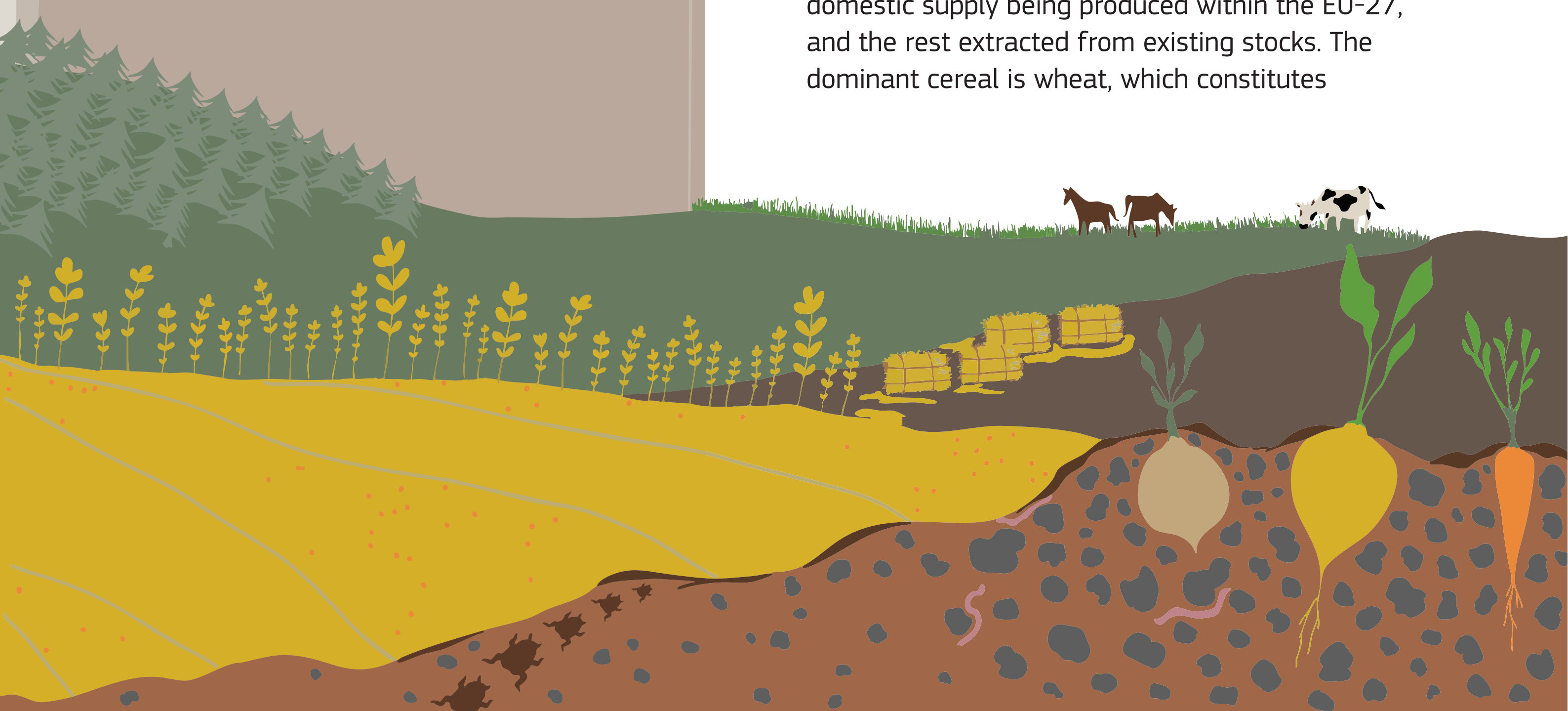
4 A future look into agriculture and forest biomass

4.1 Agricultural medium-term outlook

Patricia Gurria

4.1.1 Cereals

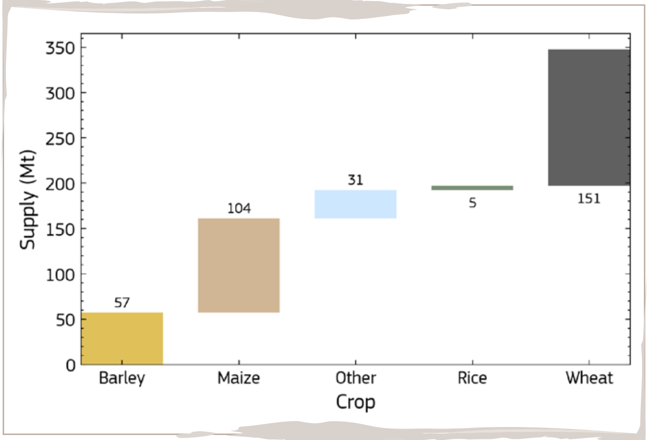
The Agricultural Medium-term Outlook published by the European Commission (DG AGRI), projects a total cereal supply of almost 348 Mt (million tonnes) of cereals for 2035 in the EU-27 (Figure 81). Of these only 9% are sourced as imports, with 79% of the domestic supply being produced within the EU-27, and the rest extracted from existing stocks. The dominant cereal is wheat, which constitutes



over 43% of the domestic production. Maize, however, accounts for the highest share of imports at 64%.

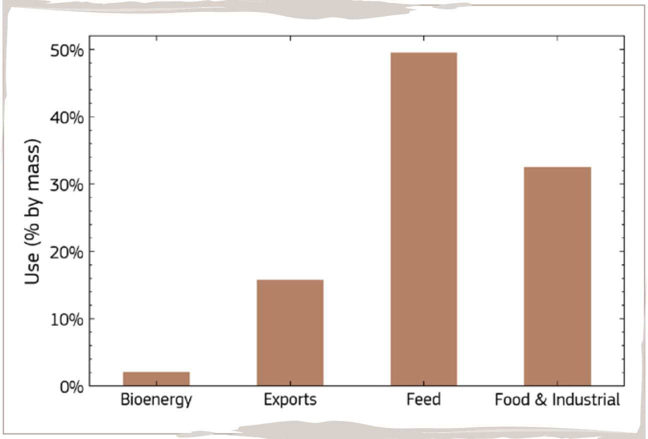
Most of the cereal supply (83%) is used for the production of feed, food and industrial uses (Figure 82). Feed production alone uses almost half of the available cereal. Approximately 16% of the cereal is exported, while bioenergy production remains a minor part (2%) of the cereal uses in the EU-27.

Figure 81. Cereal supply for the EU-27, estimated for 2035.



Source: JRC own elaboration with data from the EU Agricultural Outlook and the JRC Medium-term outlook commodity flows

Figure 82. Cereal uses for the EU-27, estimated for 2035.



Source: JRC own elaboration with data from the EU Agricultural Outlook and the JRC Medium-term outlook commodity flows

4.1.2 Oilseeds and products

The EU-27 is expected to have an estimated 45 Mt of oilseeds available for further processing in 2035. Of these, 62% are produced domestically or taken from built-up stocks. More than half of the domestic production is rape seed. After crushing, 65% of the available oilseeds become meal, while 35% is used in vegetable oil production. Oilseed meal imports are an important share of the EU-27 supply, representing 41% of the total available meal. Almost all of the meal (95%) is used for feed and feed products.

The domestic vegetable oil production is complemented with imports of vegetable oil, of which most (60%) are of oils not commonly produced in the EU-27 such as palm, palm kernel, coconut or cottonseed oil. Food and energy production are the most common uses of vegetable oils.

4.1.3 Milk and dairy products

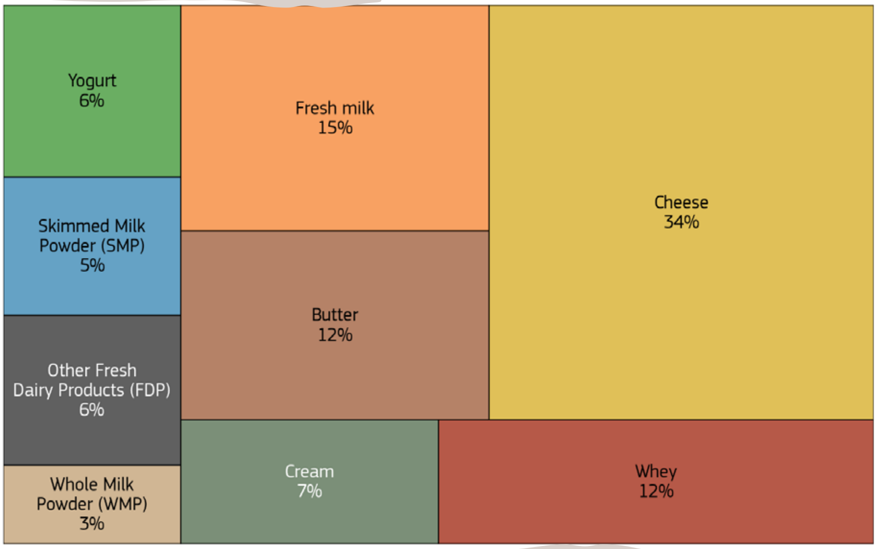
According to 2035 estimates, the EU-27 is expected to produce 151 Mt of milk. Most (95%) of this milk is delivered to dairies for further processing into fresh or manufactured dairy products. Measured in milk equivalents, 26% of the delivered milk is processed into fresh dairy products (drinking milk, cream, yogurt or other fresh dairy products), while 62% is turned into manufactured dairy products, such as cheese, butter, skimmed or whole milk powder or whey. The remaining 12% are unclassified in the current statistics (e.g., lactose products, infant formula).

The EU-27 is self-sufficient in milk and dairy products, with only a very small quantity of imports of manufactured dairy products (mostly cheese and whey). The EU market remains the dominant user of domestically produced milk as the share of dairy products that are exported is relatively small.

In terms of milk equivalents, the highest share of the expected available milk supply in the EU-27 is used to produce cheese, more than twice the quantity consumed as fresh milk.

As for consumption, 66% of the milk and dairy products consumed are manufactured, with only 34% of the total milk equivalent production being consumed fresh (Figure 83).

Figure 83. **Dairy product domestic consumption (thousand tonnes of milk equivalent), estimated for 2035.**



Source: JRC, own elaboration with data from the EU Agricultural Outlook and the JRC Medium-term outlook commodity flows

4.1.4 Meat

Most of the approximately 41 million tonnes of carcass weight equivalent of meat expected to be produced in the EU-27 will be used domestically, either for direct consumption or for further processing by the meat and processed food industry. Pigmeat is the most produced 49% of the total meat) and consumed (47%) meat type. It also accounts for 55% of the meat exports.

4.1.5 Selected fruits and vegetables

Of the 39 million tonnes of these commodities estimated to be produced in the EU-27 (usable fruit), it is expected that 56% will be consumed fresh and 44% will be further processed. As expected due to the perishability of fresh products, a higher share of the processed fruit is exported than is the case for fresh produce.

4.1.6 Key messages

- 348 Mt (million tonnes) of cereals are expected to be available in the EU-27 in 2035, most of which are produced domestically. Wheat is the most common cereal harvested in the EU-27, followed by maize. The cereal supply is primarily used to produce feed (50%) and food (33%).
- The production of oilseed meal utilises 65% of the projected 45 Mt of oilseeds available for crushing. Imports are an important source to supply the internal market of oilseeds, vegetable oils and oilseed meal.
- It is estimated that the EU-27 will produce 151 Mt of milk in 2035, being self-sufficient. In terms of milk equivalent, the highest share of this milk is used to produce cheese.
- 41 Mt of meat are expected to be produced in the EU-27 in 2035. Pigmeat is the most produced and consumed meat type and also accounts for over 52% of the meat exports.
- The main reported categories of fruits and vegetables produced in the EU-27, namely apples, tomatoes, oranges and peaches and nectarines, are consumed in roughly equal proportions as fresh produce and as processed products. 30% of the processed fruit is exported.

4.2 EU forest sink: scenario analysis

Paul Rougieux, Roberto Pilli, Viorel Blujdea, Anu Korosuo, Julia Tandetzki, Sarah Mubareka

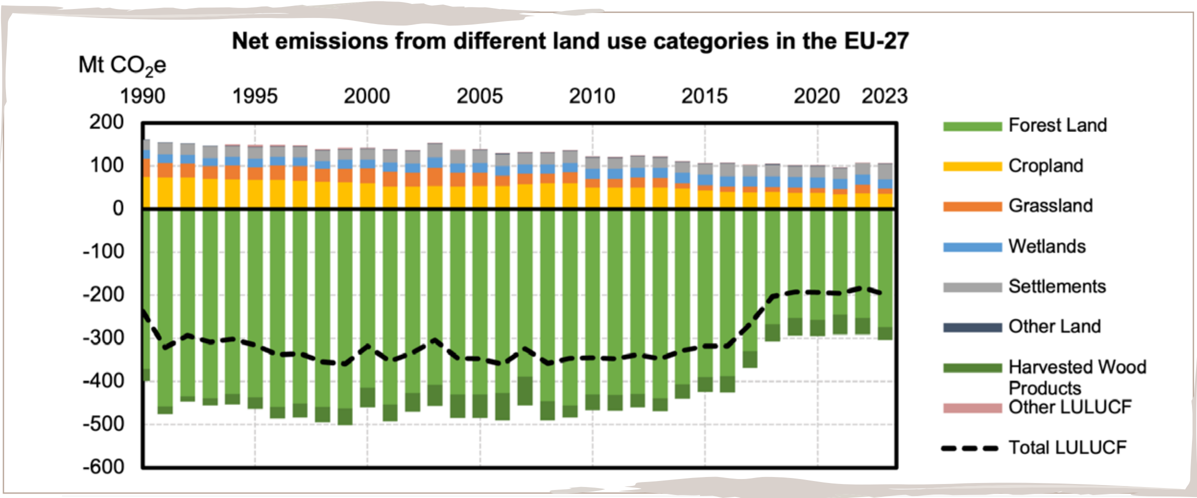
4.2.1 Background of the EU forest sink

EU forests are currently net carbon sinks: each year, there is more carbon stored in living biomass, dead organic matter, soils, and/or harvested wood products. This means that the carbon stock in the forests is continuously increasing. The largest part of the sink is reported to be in living biomass (living trees), which currently absorb more CO_2 through photosynthesis than is released through cell respiration, or removed in harvests or natural mortality of trees. In contrast, the largest carbon stock is in forest soils, even if its change is reported smaller than that of the living biomass.

For climate change mitigation, it is important to remove as much CO_2 from the atmosphere as possible and limit the emissions to the minimum. Harvested wood has climate benefits through storing the carbon in long-lived products such as sawnwood, and may substitute fossil feedstocks as material or fuel. However, trade-offs exist: In the short-to-medium term (up to several decades), in the EU the mitigation benefits of wood use do not compensate for the loss of carbon sinks in the forests (Schulte et al. 2022; Skytt et al. 2021; Soimakallio et al. 2021; Kalliokoski et al. 2020; Jonsson et al. 2020; Valade et al. 2017). Therefore, for climate change mitigation the key is balancing the need to preserve and enhance the net forest sinks, while increasing the climate benefits of wood use. This can be achieved by extending the longevity of wood products, enhancing the substitution effects of wood products, increasing the value added of wood products, and promoting the cascade use of wood over direct energy use (Korosuo et al. 2023). In the long-term perspective, even climatic benefits of material substitution are expected to decrease, as a larger share of energy-intensive materials is replaced by renewable sources and less energy-intensive materials (Brunet-Navarro et al. 2021; Hurmekoski et al. 2021).

On average, the EU forests have been a net carbon sink of ca. 430 Mt CO2e during 1990-2015 (Figure 84). However, in recent years, the forest sink has turned into a clear decline and was reported to be –274 Mt CO2e for the year 2023 (EEA 2025; excluding harvested wood products). Reasons for the decline of the sink vary between Member States, but in general there is a clear trend of increasing harvests, decreasing increment of forests, and increasing occurrence and severity of natural disturbances (Korosuo et al. 2023). The knowledge on the sink development is also continuously evolving. In the latest greenhouse gas inventory (2025), many Member States have used updated national forest inventory data. The new results reveal that the droughts in 2018 led to a much stronger decline of the sink than what was reported in earlier inventories (e.g., Thuenen Institut 2025; Naturvårdsverket 2024).

Figure 84. **The development of the net emissions in the different land use categories of the Land Use, Land Use Change and Forestry (LULUCF) sector, as reported in the EU greenhouse gas inventory 2025.**



Source: JRC own elaboration, based on data from EEA (2025).

4.2.2 Modelling the EU forest sink

The forest sink development is closely linked to forest harvest levels. Each year, roughly 500 Mm^3 u.b. (million cubic metres under bark) of wood are harvested in the EU (see section 3.2.2 for exact figures). This harvested volume is about one percent of the standing stock volume. Considering the large stock, one could argue that there is an abundance of forest biomass available in the short term. However, as we see already in the reported forest sink development, we may be approaching the limits of harvest levels that are compatible with the land sink targets embedded in the EU climate legislation.

Forward-looking forest-growth and management models are valuable tools to simulate long-term forest dynamics and the resulting forest sink, including those resulting from silvicultural treatments, afforestation or natural disturbances. Forward-looking studies for the forest sector supply and demand dynamics focus on wood production and use and are typically not designed to handle environmental and ecological interactions, such as climate change-related natural disturbances or other environmental changes (e.g., CO_2 fertilisation, seasonality). This said, coupling the knowledge of forest growth with that of forest economics provides insights into cause-effect relationships and may help to hint at forthcoming challenges such as the long-term effect of an increasing demand for wood products on the forest sink under different forest management approaches.

In this chapter, we report on the results of a Business-as-Usual (BaU) scenario for the forest sector, whereby the demand for wood follows a middle-of-the-road Shared Socioeconomic Pathway (SSP2), and observed forest management is projected to continue. SSP2 scenario is one of the pathways developed for analysing future global developments in the context of climate change and sustainability (Fricko et al. 2017). It represents a world where trends and challenges continue along historical lines, without extreme outcomes in terms of sustainability or development. Under SSP2, moderate economic growth occurs (roughly 2% annually), with slow but steady improvements in education and technological progress. Global inequalities persist but do not worsen dramatically, and although environmental degradation is attended to, it is not significantly reversed.

We also remain in a BaU scenario for forest management, meaning we maintain the status quo in terms of silvicultural interventions in the EU's Member States and regions. For this purpose, we first assessed the forest management practices applied, at country level, within the historical period 2010 - 2020 (Pilli et al., 2024). We then assume the same management regime and silvicultural practices to continue from 2021 onward, to satisfy the amount of harvest expected under the SSP2 pathway. Separate demands for IRW and FW are implemented based on the statistics on industrial roundwood (IRW) and fuelwood (FW) production. The BaU scenario also assumes afforestation and deforestation to continue the trends of the national reporting to the UNFCCC, i.e. generally both decreasing over time. BaU also assumes that the occurrence of natural disturbances emulates past magnitude and frequency (Rougieux et al., submitted)

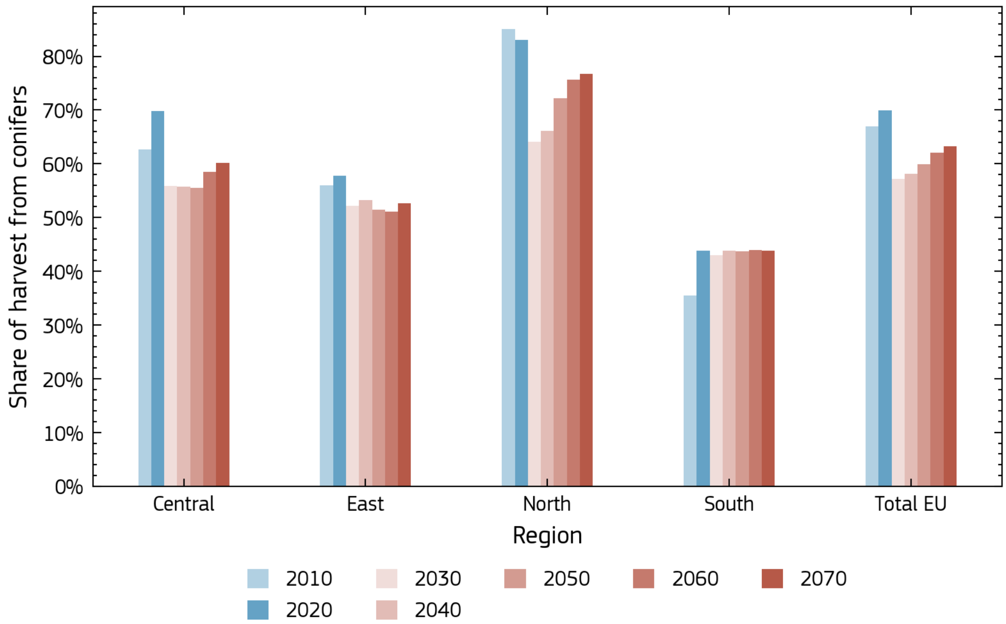
Between 2018 and 2022, harvest removals stayed above 500 Mm^3 u.b. on the EU level. In 2023, there was a slight decrease, with harvest levels reported at 481 Mm3 u.b. Northern and Central European countries contribute to around 74% of the total roundwood harvests at the EU level. As described in Chapter 3.2, there is a distinction in felling rates between coniferous and broadleaf species[28]. For conifers, the felling rate has increased over time, from 70-75% of the net annual increment (NAI) in 2010 to around 80-89% in 2020, and according to FAOSTAT, this rate was maintained through 2021 and 2022. The main reason for this development was the vast barkbeetle infestations that affect mostly spruce. For broadleaved species, the felling rate has remained stable at 56-59% of the NAI over the period 2010 to 2022. The historical felling rates are also quite different between regions. While Southern European countries remove about 70% of the NAI

[28] The fellings rate is given from the ratio between total fellings (including removals and logging residues, even due to salvage logging) and net annual increment. As a consequence, this ratio is generally < 1. Please also note that harvest statistics, such as FAOSTAT, are mostly referred to net removals (over or under bark, depending on data sources), given by fellings minus logging residues.

for broadleaved species, within Northern and Central European countries, the fellings rate for broadleaved species is about 50% of NAI. On the other hand, within Southern European countries, the average felling rates estimated for conifers is around 50% of NAI, while within Northern and Central European countries it is approximately 80% of NAI.

Even if we assumed a BaU management scenario, within our exercise we tried to partially compensate for this unbalanced harvest demand between species, moving part of the total harvest demand projected by the economic model from coniferous to broadleaved species (Figure 85).

Figure 85. **Share of harvest of coniferous species within the historical period (2010 and 2020, as inferred by FAOSTAT) and assigned to these species within the model scenario at EU level and at regional level. The future harvest is based on a scenario following an SSP2 trajectory where an annual increase of roughly 2% in GDP is foreseen, chosen for the purposes of understand the impact of a hypothetical increase in harvest on the EU forest sink.**



East: Bulgaria, Croatia, Hungary, Poland, Romania, Slovenia; Central: Austria, Belgium, Czechia, Germany, France, Ireland, Luxemburg, Netherlands, Slovakia; North: Denmark, Estonia, Finland, Lithuania, Latvia, Sweden; South: Cyprus, Spain, Greece, Italy, Malta, Portugal.

Source: JRC, own elaboration.

4.2.3 Model descriptions

Three models are integrated for this exercise. The future of wood consumption is projected using the Global Forest Products Model (GFPMx). The EU Forest Carbon Model (EU-CBM-HAT) simulates forest carbon stocks and fluxes as determined by tree growth, harvest, natural turnover rate and natural disturbances. Finally, a HWP module based on the IPCC Production Approach (IPCC, 2006), calculates the CO_2 emissions and carbon stored in harvested wood products.

The Global Forest Products Model GFPMx (Buongiorno, 2021) equations were reimplemented in Python for the purposes of this study. GFPMx simulates 3 products (sawnwood, wood panels and paper), an intermediate product (pulp) and 2 primary products (industrial roundwood and fuel wood). The model covers all major regions and countries involved in forest products markets, accounting for the flows of woodand forest-derived materials across international boundaries. The model and its reimplementation are described in Rougieux et al. 2024.

The EU-CBM-HAT model (European Union Carbon Budget Model-Harvest Allocation Tool) is an open-sourced forest carbon accounting tool designed to assess carbon dynamics in forest ecosystems across Europe. It is based on the Carbon Budget Model (CBM, Kurz et al., 2009) framework and harmonises forest management activities to generate projections of carbon stocks, fluxes, and emissions. The model and its reimplementation are described in Blujdea et al., 2022. The model integrates empiric data on forest growth, natural disturbances, harvests, and land-use changes (afforestation, deforestation), allowing for detailed simulations of carbon sequestration and release under various management scenarios. The assumptions behind the simulations are based on the particular forestry approach and data availability of each of the 25 countries (i.e. all EU 25 countries except Malta and Cyprus), updated to the most complete national forest inventories available within the calibration period 2010 – 2020. This is ensured by model calibration and continuous updating of the model's database to the latest available data (Pilli et al., 2023). The harvested wood products pool (HWP), not considered within EU-CBM-HAT, is accounted for separately through the production approach, also used by all EU countries. The production approach is based on the definition of the share of feedstock originating from domestic forests, further combined with the total production of each semi-finished commodity, distinguished between sawn-wood, wood-based panels and paper and paper boards (IPCC 2006, 2014), based on country reported data to FAOSTAT. For each commodity, the annual carbon stock and CO_2 fluxes are determined through a first order decay function, including constant decay rates derived from default half-life coefficients (IPCC, 2014).

Forestry science, given the interest of owners and the broader society, has developed rules to ensure sustainable forest management over a long historical period. These rules are followed in forest management plans regulated in the different EU jurisdictions. To project future forest conditions, our forest dynamics model represents these rules in the form of limits in rotation age and minimal return time between thinning operations. It is a simplified representation of those constraints. There are many other factors which are not captured by the models. Within one country, some protected areas will have more stringent requirements than others in their forest management plans. On top of these legal constraints, forest managers choose a combination of silvicultural practices.

4.2.3.1 Demand for wood

The SSP2 scenario, where GDP increases for all European countries, leads to a 32% increase in total roundwood production between 2020 and 2050, quite equally distributed between various geographical regions (Table 12).

Table 12. **Historical (until 2020) and simulated future roundwood production . The roundwood production is based on a scenario following an SSP2 trajectory where an annual increase in GDP of roughly 2% is foreseen, chosen for the purposes of understanding the impact of a hypothetical increase in harvest on the EU forest sink.**

Region	2000	2010	2020	2030	2040	2050	2060	2070	2050/2020
Central	169,284	175,289	199,961	202,342	230,678	259,979	291,455	326,931	1.30
East	56,566	68,133	78,286	84,467	94,526	103,139	111,681	121,001	1.32
North	150,371	152,433	170,041	189,723	210,849	231,887	252,954	276,760	1.36
South	41,156	35,778	44,982	46,375	50,205	54,282	59,185	64,525	1.21
Total	417,377	431,632	493,270	522,907	586,258	649,287	715,275	789,218	1.32

All values reported as m^3 10^3 under bark.

East: Bulgaria, Croatia, Hungary, Poland, Romania, Slovenia; Central: Austria, Belgium, Czechia, Germany, France, Ireland, Luxemburg, Netherlands, Slovakia; North: Denmark, Estonia, Finland, Lithuania, Latvia, Sweden; South: Cyprus, Spain, Greece, Italy, Malta, Portugal.

Efficiency improvements in recycling rates are not simulated.

Source: JRC, own elaboration

The SSP2 scenario sees wood panel consumption increase by 31%, paper by 21% and sawnwood by 22% between 2020 and 2050 (Table 13). As a result, industrial roundwood demand is expected to increase by 27% at EU level by 2050 (see Table 12). On top of that, fuel wood consumption increases by 46% over the period. Forest management constraints, linked to the specific silvicultural activities defined at country level (i.e., minimum rotation length for final cut, intensity and frequency of thinnings, etc.) applied within the biophysical model prevent 6% of that demand to be satisfied at the EU level in 2050.

Table 13. **Historical (until 2020) and simulated future consumption of sawn wood, wood-based panels and paper, between geographical regions. The future consumption of these commodities is based on a scenario following an SSP2 trajectory where an annual increase in GDP of roughly 2% is foreseen, chosen for the purposes of understanding the impact of a hypothetical increase in harvest on the EU forest sink, including the harvested wood products pool.**

	Region	Unit	2000	2010	2020	2030	2040	2050	2060	2070	2050/2020
Sawnwood	Central	1000 m³	47,613	46,685	46,418	50,512	52,520	54,622	56,914	59,342	1.18
	East	1000 m³	6,452	7,624	12,568	11,616	12,387	12,997	13,604	14,247	1.03
	North	1000 m³	16,259	15,765	16,514	19,598	21,981	24,261	26,264	28,643	1.47
	South	1000 m³	18,982	11,787	8,834	10,798	10,799	10,803	10,810	10,817	1.22
	Total	1000 m³	89,306	81,861	84,334	92,525	97,687	102,684	107,591	113,049	1.22
Panel	Central	1000 m³	23,250	22,519	23,119	24,421	25,570	26,756	28,041	29,405	1.16
	East	1000 m³	5,764	11,055	16,116	19,823	22,679	24,855	26,960	29,346	1.54
	North	1000 m³	3,696	4,586	5,711	6,839	7,816	8,708	9,383	10,234	1.52
	South	1000 m³	11,929	9,775	10,464	10,992	11,528	12,138	12,883	13,663	1.16
	Total	1000 m³	44,639	47,935	55,410	62,075	67,593	72,457	77,267	82,648	1.31
Paper	Central	1000 t	41,126	40,514	35,222	37,079	38,487	39,951	41,459	43,045	1.13
	East	1000 t	4,356	7,836	10,990	13,865	15,950	17,550	19,086	20,801	1.60
	North	1000 t	6,159	5,748	3,058	2,944	3,095	3,217	3,286	3,378	1.05
	South	1000 t	20,393	20,192	18,978	20,083	20,790	21,556	22,478	23,411	1.14
	Total	1000 t	72,033	74,290	68,247	73,971	78,321	82,274	86,309	90,635	1.21

East: Bulgaria, Croatia, Hungary, Poland, Romania, Slovenia; Central: Austria, Belgium, Czechia, Germany, France, Ireland, Luxemburg, Netherlands, Slovakia; North: Denmark, Estonia, Finland, Lithuania, Latvia, Sweden; South: Cyprus, Spain, Greece, Italy, Malta, Portugal.

Source: JRC, own elaboration.

By 2050, in the SSP2 scenario, the EU increases its net export of secondary products: sawnwood, paper and wood panels. It remains a net importer of pulp and of industrial roundwood, net exports of secondary forest products increase by 40% for sawnwood, 279% for panels and 143% for paper in the SSP2 scenario between 2020 and 2050 (Table 14). The overall number of imports of primary or intermediate products are small compared to the net exports of secondary products.

Table 14. **Historical (until 2020) and simulated future total trade of primary (industrial roundwood), intermediate (pulp) and secondary (sawn wood, wood-based panels, paper) products. The future trade is based on a scenario following an SSP2 trajectory where an annual increase in GDP of roughly 2% is foreseen, chosen for the purposes of understanding the impact of a hypothetical increase in harvest on the EU forest sink, including the harvested wood products pool.**

Category	Trade	Unit	2000	2010	2020	2030	2040	2050	2060	2070
Industrial roundw.	Exp	1000 m³	33,576	34,301	61,054	48,338	52,760	56,069	58,324	60,257
	Imp	1000 m³	55,943	48,104	57,302	56,241	56,934	57,683	58,544	59,561
	Net trade	1000 m³	-22,368	-13,804	3,752	-7,903	-4,174	-1,614	-220	695
Sawn wood	Exp	1000 m³	46,030	46,429	60,952	73,636	84,657	95,280	105,847	117,244
	Imp	1000 m³	37,251	30,543	36,724	45,982	50,811	55,575	60,374	65,721
	Net trade	1000 m³	8,779	15,886	24,228	27,655	33,847	39,705	45,473	51,523
Wood panels	Exp	1000 m³	20,845	27,919	32,904	42,253	53,136	65,238	79,453	96,609
	Imp	1000 m³	16,991	22,625	30,436	36,578	41,693	46,972	52,709	59,151
	Net trade	1000 m³	3,854	5,295	2,468	5,675	11,444	18,266	26,743	37,458
Paper	Exp	1000 t	50,708	61,626	55,860	67,815	81,828	97,737	116,354	138,180
	Imp	1000 t	39,243	44,899	41,803	46,087	50,685	55,174	59,947	65,187
	Net trade	1000 t	11,465	16,728	14,057	21,728	31,142	42,562	56,406	72,993
Pulp	Exp	1000 t	9,339	12,946	15,052	16,196	18,040	19,671	21,162	22,675
	Imp	1000 t	14,594	18,064	16,264	17,142	18,632	20,231	22,036	24,089
	Net trade	1000 t	-5,254	-5,119	-1,213	-946	-592	-560	-874	-1,415

Source: JRC, own elaboration.

These projections ar emade for the purposes of this study and are not intended as an outlook study (see Box 16)

Box 16. Outlook studies and long-term modelling in forestry and the forest sector

Forest sector analysis can broadly be categorised into short- to medium-term outlook studies and long-term scenario modelling. While both approaches may use similar modelling tools, such as the Global Forest Products Model (GFPM), Global Timber Model (GTM) or the Global Biosphere Management Model (GLOBIOM), their objectives, assumptions, and application differ.

Short-to medium-term outlooks, typically covering 10 to 30 years (e.g., FAO, UNECE (2021), FAO (2022), Held et al. (2021)) are primarily designed to reflect foreseeable developments based on current economic, political and market trends. These studies help policymakers and stakeholders anticipate future demand, production, and trade patterns under defined base line assumptions. They typically rely on recent empirical data, macroeconomic projections, and structured expert input.

In contrast, long-term scenario modelling explores deeper transformation over extended time horizons (e.g., till 2100), focusing on complex socio-economic, environmental, and technological interactions. It facilitates the simulation of systemic transitions and specific objectives over extended periods, e.g., global decarbonisation pathways or the interaction with biophysical and economic feedback under different climate scenarios or shifts in bioeconomy demand. This approach is particularly useful for assessing long-term system dynamics, including structural uncertainties, potential thresholds effects, and the extended consequences of current policy pathways (Daigneault et al. 2022; Favero et al. 2022).

Despite overlapping model structures, the modelling requirements and data inputs differ. Outlook studies focus on policy- sensitive indicators like trade, production or consumption. Scenario modelling often relies on e.g., Shared Socioeconomic Pathways (SSPs), linking forest sector dynamics to address sustainability questions.

Limitations exist for both approaches. These include uncertainties in the underlying input data, scenario assumptions and structural differences between models. Outlook and long-term modelling do not aim to replicate reality in full detail, but rather to represent essential system relations in a simplified and consistent framework.

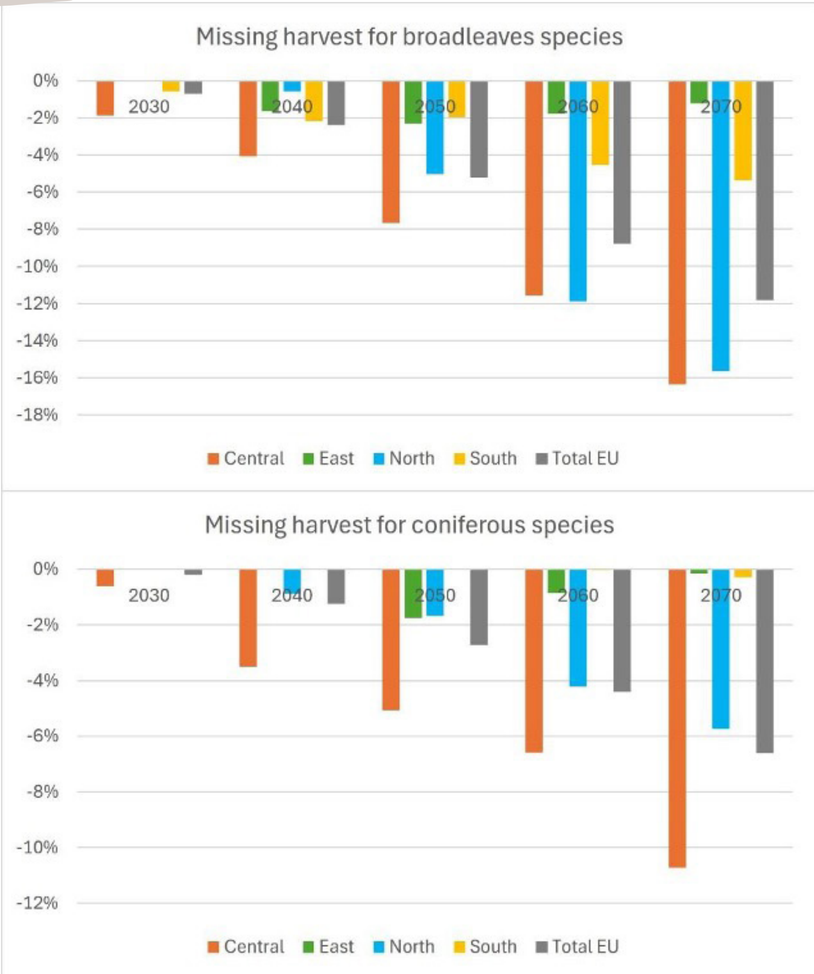
While both approaches provide relevant insights into the forests and forest sector's future development, they are based on different conceptual approaches, serve distinct purposes, and address different stakeholders.

4.2.3.2 Forest sink development

Forests are dynamic systems in which tree growth and natural mortality respond variably to different harvest scenarios and silvicultural regimes. Past and current harvesting practices have consequences on future productivity and the silvicultural practices applicable. The long-term evolution of the net annual increment (NAI, i.e., the annual volume increment of all trees, including the increment of trees that have been felled or have died during the reference period, minus natural losses) is driven by the balance between tree growth and natural mortality, while further loss (e.g., harvest) determines the annual net carbon uptake of the living biomass pool[29].

Under the SSP2 economic pathway, harvest demand surpasses the available supply by 6% and 9%, in 2050 and 2070, respectively Figure 86).

Figure 86. Percentage difference between the harvest demand expected by the economic model, as reported on Figure 90, and provided by the forest model, for each geographical region and group of species. The differences between harvest expected and provided, largely varying between countries (see Rougieux et al. 2024), are due to the fact that silvicultural constraints applied within the forest model (e.g., minimum rotation length applied for final fellings or time interval between consecutive silvicultural treatments, or even the share of area available for wood supply), prevails on the harvest demand, when this would exceed management criteria defined within the calibration period 2010-2020 (see Pilli et al., 2024).



East: Bulgaria, Croatia, Hungary, Poland, Romania, Slovenia; Central: Austria, Belgium, Czechia, Germany, France, Ireland, Luxemburg, Netherlands, Slovakia; North: Denmark, Estonia, Finland, Lithuania, Latvia, Sweden; South: Cyprus, Spain, Greece, Italy, Malta, Portugal.

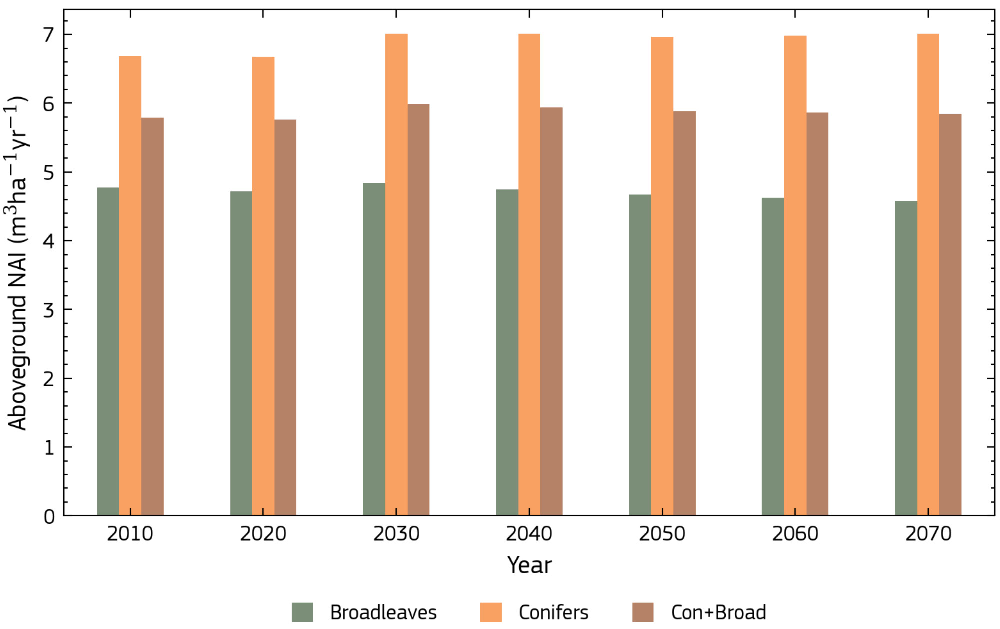
The future harvest demand is based on a scenario following an SSP2 trajectory where an increase in GDP is foreseen, chosen for the purposes of understand the impact of a hypothetical increase in harvest on the EU forest sink

Source: JRC, own elaboration.

[29] The annual C sink is given by the arithmetic difference between NAI, and fellings plus natural disturbances. Therefore, assuming that NAI does not vary in time and excluding the impact of natural disturbances, an increasing amount of fellings reduces the net C uptake of living biomass, even if the total biomass (or carbon) stock can still increase.

As the EU forests are maturing and passing from the age of the fastest growth, a decrease in NAI is projected. This slowed growth is partially compensated by the simulated annual afforestation rate equal to 362 kha yr^{-1}, applied within the entire model run since 2021 and distributed between all EU countries. As a result, the overall NAI per unit of area at EU level is quite stable over the period 2020 – 2070 (Figure 87). At species level, however, conifers' NAI increases from 6.7 to about 7.0 m^3 ha^{-1} yr^{-1}, while broadleaves NAI, since 2040 onward, slightly decreases in time. Part of the reason for this result is the increasing fellings rate applied by our scenario on broadleaves species, at least on some regions, combined with a relatively older age structure compared to conifers. In contrast, for conifers the historically higher felling rate has contributed to rejuvenating the age structure.

Figure 87. Aboveground net annual increment (NAI) estimated by EU-CBM-HAT for broadleaves and coniferous species. The average NAI per ha is determined from the model output, starting from the total NAI estimated at country level, further distinguished between broadleaves and coniferous forest types (as defined in Pilli et al. 2024), divided by the corresponding forest area. The aboveground NAI is given by the net annual aboveground biomass stock change estimated by model for each annual time step, plus annual biomass losses due to fellings and natural disturbances.

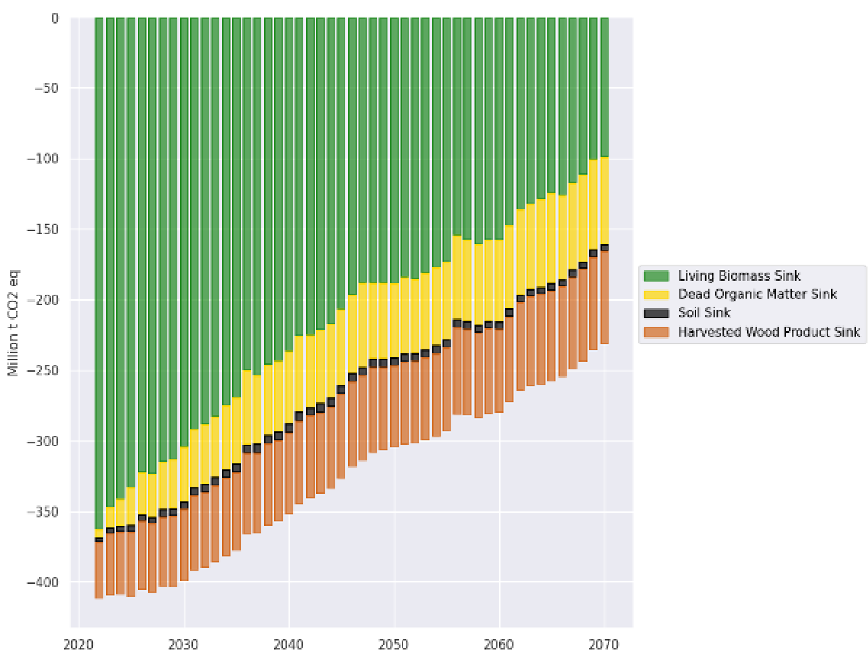


The future net annual increment is based on a scenario following an SSP2 trajectory where an annual increase in GDP of roughly 2% is foreseen, chosen for the purposes of understand the impact of a hypothetical increase in harvest on the EU forest sink

Source: JRC, own elaboration.

Different harvesting practices may alter the forest age structure, which influences the long-term evolution of NAI. For instance, when other wood components (OWC) beside stemwood, such as treetops and branches, are not collected and fuelwood demand remains constant, more forest area is subject to harvest operations, resulting in younger age classes and higher growth rates (Rougieux et al., 2024). However, under the SSP2 scenario, due to the increasing harvest demand and the ongoing ageing process, the living biomass sink initially increases from –268 Mt CO_2-eq in 2020 to –300 Mt CO_2-eq in 2030, then decreases to –168 Mt CO_2-eq in 2050. Considering the additional contribution of DOM and HWP pool, as well as the increased forest area provided by afforestation, the SSP2 scenario projects the total EU forest sink to evolve to -389 Mt CO_2-eq in 2030 and -252 Mt CO_2-eq in 2050 (Figure 88 and Annex 4). Following the assumptions underlying the 2030 targets for LULUCF, the expected contribution of forests to the 2030 EU target was assumed to be -416 Mt CO_2-eq yr^{-1} (Korosuo et al 2023). Despite the increasing C sink provided by HWP pool, this target would not be reached in the SSP2 scenario. Moreover, under this harvest scenario, the expected forest C sink would rapidly deteriorate after 2030, being equal to –191 Mt CO_2-eq in 2070.

Figure 88. **Composition of the EU sink in Mt of CO_2-eq on an annual basis. Colours represent 4 main carbon pools: living biomass, dead organic matter (DOM), soil and harvested wood products. Between 2020 and 2030, when the total harvest expected by model increases by 0.6% per year, the biomass C sink is slightly decreasing. Within the following years, when harvest demand increases on average by 1.1% per year, while NAI is mostly stable, the living biomass sink rapidly decreases. This is only partially counterbalanced by an increasing net carbon sink attributed to HWP pool. The increasing C sink attributed to DOM pool, is determined by: (i) the increasing total carbon stock on living biomass (which is continuously increasing in time), determining an increasing inflow of wood material from living biomass to DOM pool; (ii) the increasing amount of harvest, associated to the continuation of the management practices defined within the calibration period, moves an increasing fraction of living biomass to DOM pool, through logging residue (i.e., the fraction of non-merchantable living biomass components not removed from forest site with silvicultural treatments). Due to the combined effect of these drivers, the net C stock change associated to DOM pool increases in time, while the relative stock change attributed to living biomass decreases. This pattern, however, may change if the share of logging residues associated to harvest activities, vary respect to the calibration period 2010-2020 (see Rougieux et al., 2024).**



Source: JRC, own elaboration.

4.2.4 Conclusions

In 2020, forest growth corresponded to 2.04 m^3 per capita and per year in EU forests, wood harvest was 1.29 m^3 over bark (o.b.) per capita, while the carbon sink over the total forest area was -0.75 t of CO_2-eq per capita (including the HWP pool). By 2050, under an SSP2 scenario where moderate economic growth occurs with slow but steady improvements in education and technological progress, forest growth is estimated to be 2.14 m^3 per capita and per year in EU forests, and if wood harvest is estimated to be 1.55 m^3 o.b. per capita as simulated in this exercise, the carbon sink over the total forest area will decline to -0.68 t of CO_2-eq per capita (including the HWP pool). By 2070, under the same scenario, forest growth is estimated to be 2.28 m^3 per capita and per year, wood harvest to be 1.85 m^3 over bark per capita, while the carbon sink over the total forest area was -0.54 t of CO_2-eq per capita (including the HWP pool).

In conclusion, this simple exercise assessed the impact of an increase in harvest, on the overall EU forest C sink, showing that this would rapidly deteriorate under and increasing harvest scenario. It is likely that this would be further exacerbated when, considering the expected, increasing impact of natural disturbances and climate change (with this latter component, not considered within the present study), thus moving further away the forest C sink from the expected LULUCF target. Also, policy measures, not considered within the present exercise, may have an impact on the medium to long-term evolution of the forest biomass stock. Increasing, for example, the share of the forest area not available for wood supply, or modifying forest management practices (i.e., regarding the use of non-merchantable wood products), the expected evolution of the biomass stock, within the different forest carbon pools, may vary in time (see Rougieux et al., 2024).

Although the results are aggregated by regional grouping and for the EU, the assumptions behind the simulations are based on the particular forestry approaches and data available for each of the 25 countries. This is ensured by model calibration and following the approach described in Pilli et al., 2023.

The simulations assume a stable forestry regime during the simulated period, as a continuation of the current ones. This involves the best possible representation of applicable silvicultural practices, namely: intensity and frequency of thinnings and length of rotation cycles; harvesting efficiency, including residues left after fellings and harvesting; and harvest allocation across standing availability. According to the country's forestry long-term objectives, sustainability is implemented as spatially nested, i.e., the fundamental unit in building sustainability is the local one, and temporally, i.e., the schedule of interventions and fellings consider the short- and long-term objective of forestry. The model mimics this approach, although the optimisation of forestry interventions and harvest allocation during the projections assumes national boundaries rather than local ones, due to data availability constraints. This results in differences between past (pre-2020) and future (post-2020) allocations, as shown in Figure 88. Specifically, the larger standing availability of broadleaved trees generates larger contributions to harvest during the projection compared to the historical period. Other shortcomings of the model is the lack of explicit representation of degradation, due to the lack of clear definitions of what degradation entails and the consequent lack of adequate data.

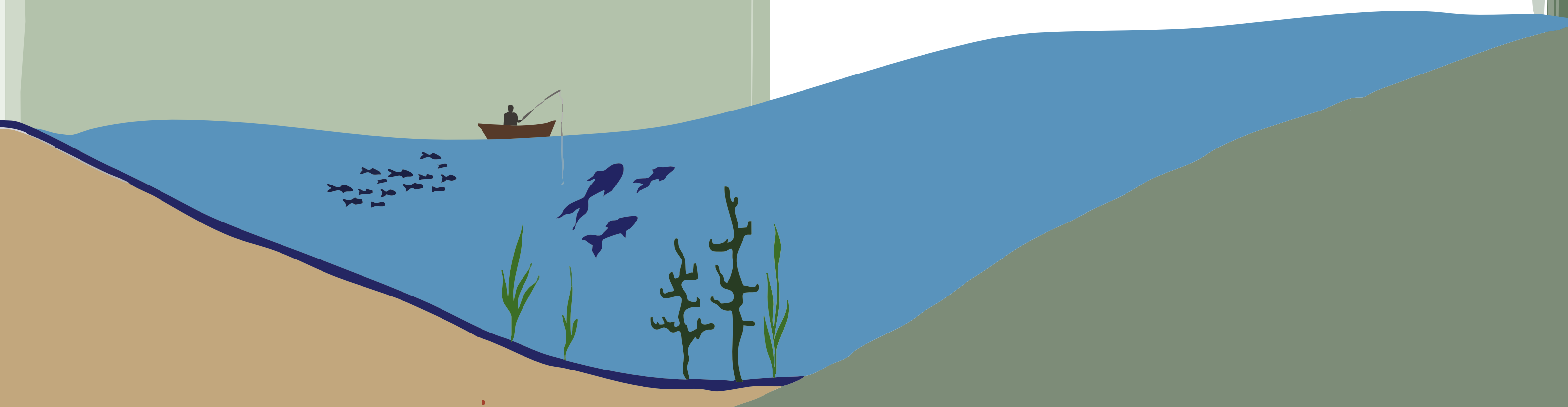
The differences between the demand and supply towards the end of the simulated period, as shown in Figure 86, associated with the SSP2 scenario, may not occur in real life, especially given its small value, e.g., a maximum of 11% and 16% in 2050 and 2070 respectively, for the Central region. This is because of the flexibility of silvicultural practices and their further developement, on one hand, and market fluctatiuons or technical delopments or cascading use of wood, on the other, which may anticipate or postpone harvesting. Indeed, a caveat is that the model does not implement an adjustment of the increment based on future climate (i.e., CO_2 fertilisation, droughts), which attaches significant uncertainty to the differences between the demand and supply as well.

Representing sustainability constraints by time intervals between thinnings and rotation age is overly simplistic. To improve the policy discussion on a possible harvest gap, an improved representation of what constitutes sustainable harvest level is very much needed. This can be done through more complex models that provide a better representation of the multiple dimensions of sustainability. Behind that there are many more considerations related to changes in forestry regime and changes in long term objectives, choices related to enhanced biodiversity conservation or other technical aspects such as resource accessibility, safety net in expectation of future natural disturbances. A policy discussion on these topics requires that there is a clear and consistent definition and interpretation among all stakeholders of what constitutes a sustainable harvest level.

5 Land and ecosystem-based management approaches

When announcing the EU Green Deal, Commission President, Ursula von der Leyen, said: “We need a strong economic and recovery model that **gives back to our planet more than it takes away from it**”.

In this chapter, we propose different regenerative actions. This is a bottom-up effort from the JRC, based on our collective knowledge within the JRC Biomass Mandate. The intention is twofold: first to illustrate the point that many different regenerative actions are neededto address the pluricrises of today and that there is no blanket solution, and second, because there is no universal solution, to invite dialogue and ideas to regenerate our productive systems and our uses of biomass. It is not meant to



be an exhaustive list of actions because it is limited by our knowledge, but it is meant to trigger a broader thought process on how to seek multiple solutions that go beyond sustainability by actively restoring ecosystems, enhancing biodiversity, and improving soil and water health while producing biomass. These actions aim to create a positive environmental impact by regenerating natural resources rather than depleting them.Chapter 5 is meant to stimulate our thinking regarding how we manage our natural resources in a nature-positive manner. The sections are elaborated according to the preference of the authors, however each section begins with a description of the issue the action is meant to address, and all sections defend the ideas within the text.

5.1 Earth-Centred land stewardship

Marcela Velasco Gómez, Garry Merkel, Sarah Mubareka, Nicolas Mansuy, Viviana Ferrario, Elle Merete Omma, Claudette Labonté, Rufino Acosta Naranjo

More than half of the natural resources and ecological processes critical to society's survival and quality of life have been unintentionally damaged (Millennium Ecosystem Assessment MEA, 2005; the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services IPBES, 2019). This degradation is not always the result of deliberate actions, but as an unintended consequence of efforts to meet human material needs and desires.

We are now facing an ecological crisis which is the result of the way we perceive and manage natural resources, demonstrating our capacity to alter the life-support systems of the planet.

Mackensi (2023) argues that the root cause of the current ecological crisis is the cultural separation from nature. In contemporary society, this connection with the land has been fractured. In general, people no longer see themselves as part of nature but rather as superior to it, believing in human control over natural processes. While some advocate for relying on technological advancements to address environmental degradation, this perspective is perilous, potentially leading us down an unsustainable path that ignores the Earth's finite resources and our dependence on nature.

In this section we describe the benefits of developing a close relationship with nature, rejecting a view of nature as property to be exploited in favor of one founded on respect and non-exploitative, non-dominant practices that supports human well-being in a world characterised by uncertainty and change. Earth-centered stewardship acknowledges that society's use of resources must align with the capacity of ecosystems to sustain the services they provide, which are ultimately constrained by the planet's life-support systems. Although often overlooked in modern culture, this is not a new approach; it is an ancient, widely practiced perspective that has been neglected in contemporary society.

Several compelling examples of successful environmental stewardship are found within Indigenous territories. Although Indigenous peoples represent only 6% of the global population, they manage at least 28% of the Earth's land (Garnett et al., 2018). Indigenous lands are often more biodiverse and have lower deforestation rates compared to other protected areas (Schuster et al., 2019; WRI, 2021; Walker et al., 2014; FAO, 2021; Sze et al., 2022). The success of Indigenous stewardship arises from a deep understanding that humans are part of a larger ecological whole, an understanding that is carried over from generation to generation.

Earth-centered stewardship is common among surviving Indigenous communities, whose worldviews often emphasise respect for nature (Kohsaka & Rogel, 2019; Redvers et al., 2020; Gratani et al., 2016; Redvers et al., 2023). However, these principles are not unique to Indigenous communities; and while many Indigenous cultures came and went because they did not have this discipline and outstripped the land's ability to support them, other (non-indigenous) rural societies are practicing ecological stewardship fruitfully worldwide nowadays (Bennett et al., 2018; Enquist et al., 2018; Nikolakis, 2016).

Some examples of communities within the EU-27 that used to practice or are still practicing Earth-centred land management are developed below.

These communities recognise that their survival depends on maintaining a balanced, reciprocal relationship with the environment—one based on mutual benefit and cooperation. This intimate connection to the land is a defining characteristic of Indigenous and other communities practicing Earth-centred stewardship. For these groups, this relationship is not only practical but also deeply woven into their culture and identity, where the health of the land is inextricably linked to the well-being of their communities (Jones, 2019; Taylor et al., 2021; Nikolakis et al., 2023; Garnett et al., 2018).

Sections 5.1.1-5.1.4 below are written by the land practitioners themselves.

5.1.1 A description of the Saami stewardship approach

The Sámi people are the nomadic indigenous people of Europe. Sápmi has been their home since time immemorial and spans the northern parts of Norway, Sweden, Finland, and Russia Kola Peninsula.The Sámi has long practiced land stewardship philosophies that align with Earth-centered principles. Their traditional livelihoods—such as reindeer herding, fishing, gathering, trapping, and hunting—reflect sustainable practices deeply connected to the land. The Sámi governance model, known as the "siida," designates family territories, fostering stewardship and sustainable use. This relationship is guided by principles of modesty—taking only what is needed—and respect for all beings, ensuring actions do not endanger species or cause unnecessary harm.[1]

Sámi land stewardship is guided by a belief that humans are an integral part of nature, not separate from it. The land, waters, animals, and plants are seen as interconnected and equally important parts of a greater whole. This perspective fosters a sense of responsibility to care for the land in a way that maintains its balance and ensures its health for future generations. In essence, Earth-centred land stewardship in a Sámi context is a living philosophy that combines Sámi indigenous knowledge, cultural identity, and environmental ethics to maintain the health and vitality of the land, ensuring it supports both human and non-human life for generations to come.

Reindeer herding is a cornerstone of Sámi culture and a practical expression of Sámi land stewardship. Reindeer herding governance models are based on the siida-system which relies on careful management of pastures and understanding of ecological limits to avoid overuse of the resources while at the same time secure the well-being of the siida. The practice demonstrates respect for the natural rhythms of the landscape, allowing reindeer to follow their instinctual migrations while minimising human interference.

Sámi Earth-centred stewardship is also an act of resistance against colonial land use practices that prioritise resource extraction and industrial development over the health of nature. In recent years, Sámi rightholders often advocate for their rights to self-determination and land management, challenging projects like mining, deforestation, and renewable energy production that threaten their environment and way of life. To address the combined challenges of climate change and loss of nature in Sápmi, partnership with Sámi and the self-determination of the Sámi people in ownership and management of lands, territories, and resources are fundamental pieces in building, maintaining, and strengthening resilience for the Sámi people.[2] Currently, there is no EU internal Indigenous Peoples Policy that addresses the rightsholder perspective in EU policymaking (Keskitalo and Götze, 2023).

5.1.2 A description of the chagras, practiced by the Kali'na Tileuyu, Lokono, Pahikweneh, Wayãpi,Teko and Wayana people in French Guiana

Indigenous communities in the Amazon have developed a profound and meaningful relationship with their surrounding environment over centuries. Living in remote areas, they have relied on their traditional knowledge and practices to maintain self-sufficiency (Velez, 1992, 2007). In general, Amazonian ethnic groups operate under a subsistence economy focused on self-consumption, relying on the availability and complementarity of hunting, fishing, gathering from the forest and cut-and-burn agriculture (chagras).

The chagras is a traditional agroforestry system based on shifting cultivation, grounded in ancestral knowledge. Establishing these systems requires an in-depth understanding of soil, water, plants, fruits, animals, and the overall features of the rainforest. This knowledge ensures that resources are not overexploited, and that the system remains sustainable (Hernandez et al., 2021). The intricate interdependence of all living organisms is recognised within this system. In the *chagras*, the underground ecosystem is seen as equally important, forming an integral part of their holistic approach to nature. A core belief among these communities is that everything has a rightful place and an equal right to exist, and therefore, everything must be preserved to maintain balance—though some populations, such as predators, may require management.

The process of creating a *chagra* begins with a careful selection of the site, based on soil quality and spiritual negotiations with the land, often led by community leaders or shamans. Once the site is selected, the clearing process begins. Crops such as cassava, bananas, sweet potatoes, and medicinal plants are planted. The system's uniqueness lies in the balance of temporary and permanent crops, which ensures continuous food production while preserving the health of the forest. Crop selection is driven by the community's needs, including self-consumption, commercialisation, medicinal purposes, and cultural or ritual uses. All crops are native species, and the seeds are harvested from previous years.

One of the key features of the *chagras* is its agrobiodiversity. The system preserves genetic diversity by passing down high-quality seeds through generations. Additionally, wild species are allowed to grow, contributing to the overall biodiversity and stability of the ecosystem.

The Chagras cycle follows seven basic steps:

1. Site selection and spiritual negotiation
2. Clearing (Socola) and felling trees (Tumba) – a community-wide activity
3. Burning to prepare the soil for planting
4. Sowing and planting, typically carried out by women
5. Weeding and crop maintenance
6. Harvesting, beginning with staple crops like cassava
7. Abandonment and restoration, – once the land has completed its productive cycle, it is abandoned to allow for natural restoration

This system is under threat due to the lack of land rights for indigenous communities in French Guiana. The colonial principle of "terra nullius" led to the French government claiming indigenous lands, and even today, indigenous groups are only allowed limited use of their traditional lands. These zones, known as Zones of Collective Use Rights (ZDUC), restrict traditional practices to designated areas. Outside these zones, practicing traditional methods like Chagras can result in legal prosecution.

Despite these challenges, Chagras continue to play a vital role in indigenous culture, food security, and biodiversity conservation. They are not just agricultural systems but cultural landscapes that reflect the cosmology and social structures of indigenous communities

5.1.3 A description of Coltura Promiscua stewardship approach

An important place in the realm of traditional knowledge is occupied by traditional agricultural systems (Koohafkan, Altieri, 2017), and among them intercropping (the concurrent cultivation of more than one crop species in the same field) and agroforestry (combining woody perennials with agricultural crops, animals, or both on the same unit of land). "Coltura promiscua" agricultural system, which used to be largely practiced in some regions in Italy and has now almost disappeared, integrates intercropping and agroforestry. A closer examination of coltura promiscua allows us to identify some principles that can inspire innovation in new agricultural systems.

What distinguishes coltura promiscua from other traditional agroforestry systems is the presence of grapevine. The grapevine/tree combination used to be practiced in other regions in southern Europe, characterised by very wet winters and hot summers: in northern Portugal, in the Basque country and in some other areas of southern France, in Anatolian peninsula. Nevertheless, Italy was seen as being the country of coltura promiscua *par excellence*, as witnessed by the large use of the Italian term internationally (e. g. Grigg, 1974). The grapevine cultivation gives the system a high degree of spatial/temporal complexity. Not two, but at least three elements, grassland or arable land/pollarded trees/grapevine, were laid out in the space at different heights, each with their own growing times and rhythms. The field could be planted with cereals, vegetables, or flowers, even associated together, for example, maize, and sustaining beans; the grapevine was generally trained on pollards used as a living support (they said the vine was “married” to the tree); the field was dotted, or divided into regular strips, by different species of trees, exploited for timber (elm, ash tree, walnut tree), leaf (maple, mulberry), or fruit (olive tree, cherries, peach, apple tree); these elements positively interacted with one another and with livestock farming and wild animals.

In addition to grapes, wine, and grains, coltura promiscua guaranteed a series of secondary products: the strip of lawn under the rows of trees excluded from ploughing constituted a reserve of forage for the animals; the leaves of the trees, collected to reduce the shading of the crops, were used as supplementary fodder; mulberry leaves nourished silkworms; the trees provided fruit, timber, firewood, and poles for agricultural work. The leaves of the vine and the other pruning residues were used as fertilisers, thus integrating the limited animal production. Pollards are reported to protect both the vine from the tempest and the grains from excess solar radiation in summertime. The grapevine trained in height was protected from the winter frost. Lastly, the coltura promiscua acted as protection for small wild mammals and birds, thus providing a kind of minimal hunting reserve.

At the end of the eighteenth century, coltura promiscua began to be questioned by the nascent science of agronomy, as well as the very principle of associating different crops in the same field. Coltura promiscua was then accused of irrationality and underwent a socio-technical delegitimisation. Specialisation, intensification, mechanisation, use of synthetic fertilisers and pesticides, and drastic reduction of agricultural jobs affected coltura promiscua that almost disappeared from the Italian Peninsula (Tirone, 1975). Nonetheless, the radical decline of the coltura promiscua could not completely erase this landscape from the Italian countryside. Nowadays, in some regions, it is still possible to observe a few relics that have been preserved and are still in production. One can find some small areas of intercropping, or some single row of vines married to the pollards in Veneto and Friuli in Northeast Italy, in Umbria and Tuscany in central Italy, and in Campania in the South. Coltura promiscua still provide supplementary income or supply, like fruit, wine, timber (economic value); is a way to express a personal ability while practicing an open-air activity (functional value); represent a memory of the family history and a reason to meet the family and friends, for example during grape harvest (social value); is a way to transmit an ancient know-how to the following generation (cultural value). It is important to observe that the choice to preserve the relics of coltura promiscua is not only a personal choice, but it is strengthened by a favorable social/familial context: a cultural association supporting the conservations, an interested next generation, and the family consuming products. In some places, coltura promiscua is being reconstructed for symbolic, cultural, or even tourism or commercial purpose. Moreover, coltura promiscua has been officially recognised as a traditional agricultural practice within the Italian National Register of Historical Rural landscapes. Coltura promiscua products—especially wine—are sold with reference to “agricultural heritage”.

“Coltura promiscua” traditional knowledge contains some lessons to design new sustainable agricultural systems: vertical intensification, spatial multifunctionality, resilience through crop diversity, labour-intensive production, personal/familiar/community attachment (Ferrario, 2021). Taken together, these principles describe a new rationality that seems to adapt to new changed global and local conditions, following the principle of retro-innovation (Zagata et al. 2020). This inheritance seems to have been gathered by modern agroforestry that is now widely recognised as a practice that increases biodiversity, carbon sequestration, and farm revenue (EPRS, 2020). Nonetheless, a lot is still to be done, for example protecting and studying existing relics of coltura promiscua to empirically study how they work to scientifically understand the traditional knowledge they convey.

5.1.4 A description of rozas at dehesa

The dehesa is a multi-use land system typical of the southeast of the Iberian Peninsula that, in its traditional model, integrated crops, pastures, forest and livestock uses. It is a savanna-like or park-like landscape resulting from the thinning of the original Mediterranean forest. By clearing the underbrush and some trees, a landscape of oak trees is created, particularly holm oaks, but also cork oaks and other oaks, under which crops were grown in a rotational manner. Animals (sheep, cows, goats, and pigs) grazed on pastures, stubble, and grains, as well as acorns and tree branches. Currently, there is very little cultivation, leading to an advancement of underbrush in some areas, especially those with steeper slopes. This results in a loss of pastures for livestock and an increased risk of wildfires.

Traditionally, the rotational cultivation of farm plots every five years was a guarantee for controlling the underbrush. Likewise, goats fed on the underbrush and partially controlled it. The “rozas” (clearing) was a system in which underbrush was eliminated by cutting it with tools such as sickles or hoes. The remains of the clearing were burned at the end of summer and the beginning of autumn, and part of the ashes served as fertiliser.

European peasant cultures managed their environment in accordance with the ecological processes of their surroundings, but this system broke down after agricultural modernisation. One of the fundamental milestones in the degradation process occurred when the decoupling of economic and ecological processes took place at the end of the last century. The practice of “rozas” is an example of this, which is no longer carried out but, albeit not with the same techniques, its underlying principles can be recovered for sustainable management and bioeconomy.

5.1.5 The Common Thread

The examples described above are not the only ones that represent an Earth-Centred approach to land management. We selected these because they are quite different one from another, both geographically, culturally, yet they do have common elements that we can learn from.

While the European culture is not expected to radically change in the short term, there are several lessons that can be learned from Indigenous and traditional land management practices that can be applied (indeed are already applied) in Europe:

- Humility / Modesty
- Highly disciplined approach to living within nature’s cycles
- Respect
- Constant attention and care to the reaction of management on nature
- Understanding that humans are an integral part of nature
- Prioritisation of health of nature over our own additional comforts

5.1.5 A just, integrative governance for a healthier planet

Earth-centered approaches, characteristic of most Indigenous cultures, can contribute significantly to our thinking toward land stewardship, and this enlightened thinking could help us greatly improve our management approaches.

The environmental achievements of traditional Indigenous and other Earth-centered cultures, such as preserving healthy forests, maintaining high biodiversity, and achieving low deforestation rates, demonstrate alternative relationships with nature and offer valuable lessons in sustainability and ecosystem resilience. It can help us to rethink our relationship with the natural world and begin implementing principles of Earth-centred stewardship to secure a more sustainable future, one that preserves the integrity and health of ecosystems while ensuring human well-being.

In Europe, for Indigenous-led guidance to be truly effective, it is essential to recognise Indigenous presence (see Box 17), and actively involve these communities in decision-making and policy development affecting their territories (Posey, 1999; Borrini-Feyerabend et al., 2004; Reyes-García et al., 2019). Their approach to land stewardship is regenerative, and conservation initiatives achieve the greatest success when Indigenous communities and peasant communities are fully engaged (Schuster, 2019; Kyle, 2023; Dawson et al., 2021; Posey, 1999; Borrini-Feyerabend et al., 2004; Garnett et al., 2018; Reyes-García et al., 2019).

Box 17. Indigenous peoples in Europe

In Europe, Indigenous peoples are present in both continental regions and overseas territories. These include the Kalaallit people in Greenland, the Sámi people in the Arctic regions of Norway, Sweden, and Finland, and the Kalina Tileuyu, Lokono, Pahikweneh, Wayãpi, Teko, and Wayana peoples in the forests of French Guiana, among others in overseas territories.

Currently, these indigenous communities are facing different challenges that are affecting their habitats, cultures, worldviews and their ability to practice land stewardship. In the case of French Guiana, the constitution of the French Republic does not recognise the specific rights of Indigenous people. This means they do not have land rights or the possibility to decide the land management in their area. The Sámi in the Arctic regions and Indigenous peoples in French Guiana are particularly affected by extractive industries, such as mining, which damage their habitats. Concurrently, they experience land encroachments by governments and companies under the guise of the green transition (IWGIA, 2023). This occurred against the background of climate change where these communities are some of the most affected.

If Indigenous peoples are not involved in policymaking, green initiatives risk becoming counterproductive. The Kunming-Montreal Global Biodiversity Framework (KMGBF) in 2022 emphasised the rights of Indigenous peoples and acknowledged their essential role in biodiversity protection and restoration. This framework could drive a significant shift in international conservation efforts. However, well-intentioned initiatives addressing the global ecological crisis continue to overlook the importance of Indigenous participation. A current example is the European Green Deal's push to expand renewable energy projects, such as wind farms and the extraction of critical raw materials, which has adversely impacted Sámi territories. Despite good intentions, these projects have polluted ecosystems, threatened biodiversity, and diminished reindeer grazing areas, which are vital to Sámi livelihoods and cultural practices (Nutti, 2023).

5.1.7 Concluding remarks and moving forward

In this chapter we have hopefully made a compelling case for adopting an Earth-centred land approach, but that desire could easily fade without some direction on how to translate this approach into reality. Before offering recommendations on action, it is important to recognise that the success of any stewardship approach depends on the level of discipline dedicated to developing and maintaining the collective underlying thinking and understanding that supports that approach – a fact that is especially true for Earth-centred cultures. Without this underlying thinking leaders generally rely on magic bullets that often fail because they do not have the depth of understanding to consider all implications of these attractive sounding solutions or to effectively react, adjust and grow in response to inevitable changes in circumstances. Implementing discipline to evolve thinking is just as important as the resultant action arising from that thinking if we want to achieve long-lasting legacy results.

The following is a preliminary set of proposals for actions that could help develop the underlying thinking and take action in contributing towards how an Earth-centred land stewardship approach (or elements thereof) can fit within our industrialised society.

5.1.7.2 Support a Shift in Thinking

- Formally recognise that a shift in thinking towards a new ethical framework is an essential component required to foster the collective wisdom and depth of dialogue required for successful implementation of this Earth-centred approach;

- Develop and deliver a wide-scale education program on the fundamentals of Earth-centred thinking and approaches. Initially this education would be targeted towards the senior decision and policy maker levels, i.e., understanding of concepts and key decision factors. This will provide the foundational understanding to begin deeper discussions and planning with a critical mass of key people;

- Create a formal parallel path to further develop both the underlying thinking and the resultant actions through critical dialogue, targeted research, monitoring progress towards established outcomes and other means.

5.1.7.2 Take Action

- Establish an “Earth-Centred Elders Council”. Many of the Earth-centred land stewardship models that support a modern economy are guided by a group of Elders who have demonstrated knowledge, wisdom and expertise in land. These councils are often supported by various scientific and other experts, but the core remains grounded in a senate type role that is responsible for ensuring that the stewardship approach stays true to Earth-centred.

- Adopt a large-scale multi-resource sector regenerative economy approach. A regenerative economy approach is a business model that aims to create a positive impact on the climate, nature, society and economy. These models move away from an extractive approach and a solitary focus (e.g., reduce emissions) to an approach that re-builds nature’s integrity and ensures justice, equity and inclusion within and between societies and economic markets.

- Move towards a more regionally grounded planning and decision-making framework that is well networked amongst the regions, properly supported by a pool of expertise and has a collective monitoring and adaptive management integrated into implementation.

This is a very preliminary list of starting points that will grow and become more and more effective at achieving the desired economic, social and environmental outcomes as the underlying thinking develops and the subsequent action builds experience.

We are at a crossroads where we still have time to choose a path that opens our minds to acknowledge that we are not the only beings on this planet, nor are we stronger than nature. Building bridges between different knowledge systems and cultures that have learned to maintain a better relationship with nature for thousands of years is essential.

"To see from one eye with the strengths of Indigenous ways of knowing, and to see from the other eye with the strengths of Western ways of knowing, and to use both of these eyes together…" (Bartlett et al., 2012)

The environmental achievements of traditional peasant cultures and Indigenous Peoples, such as preserving healthy forests, maintaining high biodiversity, and achieving low deforestation rates, demonstrate alternative relationships with nature and offer valuable lessons in sustainability and ecosystem resilience. It should prompt us to rethink our relationship with the natural world and begin implementing principles of Earth-centred stewardship to secure a more sustainable future, one that preserves the integrity and health of ecosystems while ensuring human well-being. While the shift towards this new relationship may seem challenging and distant, there are communities in the EU, including Indigenous peoples, that are uniquely positioned to contribute to this transition, drawing on their deep knowledge and experience in the subject. This transformative journey must be supported by governance reforms that foster ecologically, economically, socially and culturally viable stewardship policies, which are key to achieving sustainable solutions.

5.2 Agroecology: strengthening farmers' position within food systems

Michele Ceddia

5.2.1 Introduction

Food systems (FSs) play a crucial role in human wellbeing. They are responsible for the production and distribution of food, while at the same time being entangled in the provision of many other essential environmental services. Unfortunately, FSs also find themselves in a critical position with respect to what scientists refer to as a polycrisis, spanning the environmental and social domains (Swinburn et al. 2019; Rohr et al. 2019; Benton et al. 2021; Crippa et al. 2021; Gold et al. 2021; International Labour Organization et al. 2022) and to which the EU is not immune (European Commission: Directorate-General for Research and Innovation 2018; Palumbo et al. 2022; WHO 2022). FSs are crucial to the EU bioeconomy strategy, since they generate about 60% of all biomass demand (European Commission: Directorate-General for Research and Innovation 2018). Overcoming these challenges requires transforming our FSs into more robust, environmentally friendly and equitable models (Strategic Dialogue on the Future of Agriculture, 2024).

This contribution draws (under CC BY 4.0) on a recent publication by the author (Ceddia et al., 2024). The needed transformation in FSs requires an understanding of the systemic drivers of the polycrisis. Without this understanding, the proposed solutions risk to reproduce the status quo. The goal of this contribution is firstly to shed light on the systemic drivers of the polycrisis. Subsequently, this contribution will illustrate how agroecology could provide an important tool to address it, while strengthening farmer's position within FSs. The focus on agroecology follows also from the fact that the EU Bioeconomy Strategy explicitly refers to it as one of the strategies to "supporting sustainable food and nutrition security for all" (European Commission: Directorate-General for Research and Innovation 2018, p. 48).

Over time, many definitions of agroecology have been proposed. Recently, the High-Level Panel of Experts on Food Security and Nutrition (HLPE-FSN) has put forward a synthetic definition, which is today the most widely accepted. Namely, agroecology is not only the "application of ecological principles to the design and management of sustainable food systems…by harnessing natural processes". It is also a social movement set "to build locally relevant food systems…based on short marketing chains" that "supports diverse forms of smallholder food production and family farming…food sovereignty, local knowledge, social justice, local identity and culture, and indigenous rights for seeds and breeds" (HLPE-FSN 2019). This double nature of agroecology, technical and socio-political, is crucial to its transformative potential (Gonzalez de Molina et al. 2020; Anderson et al. 2021).

5.2.2 The integration of food systems within global capitalism

A significant amount of research suggests that the root cause of the polycrisis lies in the complete integration of FSs within global capitalism. For example, a recent publication by the Group of Chief Scientific Advisors to the European Commission, states that "for most people… food is considered predominantly a tradable good" and subsequently "The current system's goal are aligned to this framing: maximising food production…while minimising costs. It is clear that feeding people healthily is just a subordinate goal in this framing, and that viewing food mainly as a commodity is not compatible with a sustainability focus" (Group of Chief Scientific Advisors 2020). The meaning of this statement can be better appreciated when we consider that FSs as a salient element of global capitalism, organised according to its logic. But what is capitalism, and how are food systems integrated into it? Capitalism is a mode of production centred on the accumulation of capital, sustained through the reinvestments of profits. The realization of profits, in turn, requires the production of commodities exchanged on the market. Under capitalism, markets acquire a special importance. As historian Robert Brenner pointed out, (Brenner 2007) within capitalism, producers must engage in market exchanges to survive, as they cannot exist outside of commodity relations. The differentia specifica of capitalism, with respect to other modes of production, is not the mere existence of the profit motive and/or of markets exchanges. Commodities, markets and the profit drive pre-date capitalism. The specificity of capitalism lies in the fact that, the dependence on markets, profit and commodities is generalised. Under capitalism, for the first time in history, the entire social production and reproduction (i.e., survival) is mediated by the market and is tied to profit and hence to capital accumulation.

The integration of FSs within global capitalism happened gradually. We refer the interested reader to the literature on food regimes (Friedmann and McMichael 1989; McMichael and Myhre 1991; McMichael 2009, 2021; Bernstein 2016). Such integration has been necessary to the formation of globalized capitalism. Generalized market dependence at the world scale could have never been established if significant areas of food production, consumption and distribution were not subsumed to the logic of capital accumulation first.

Importantly, this generalised market dependence is achieved by establishing capitalist-specific relations of production. Capitalist relations of production rest on the separation of producers from the means of subsistence (although not necessarily from the means of production). In this respect it is important to distinguish between the upstream sector (e.g., agricultural inputs production, land ownership, finance etc.) and the downstream (e.g., storage, processing, distribution etc.) sectors of FSs on the one side, and farming on the other. The upstream and downstream sectors of FSs have been almost entirely directly appropriated by financial, industrial and merchant capital, a phenomenon known as "appropriationism" (Goodman 2021). In these sectors, producers are separated by the means of production (e.g., land primarily) to become wage-workers employed by capital producing or distributing commodities, and in this process, they generate also a profit for the capitalist. However, farming is for the most part not directly controlled by financiers, processors, distributors or industrialists. In the Global North, family farms using a significant component of family (non-waged) labour are still the prevalent organisational form. For example, in the European Union, in 2020, family farms accounted for 85% of all farms and paid labour represented less than 30% of all labour input. In the Global South, peasant[30] agriculture is still prevalent. Note how both in

[30] The term peasant is not used in a derogatory sense. It refers to units of production that rely prevalently on family (non-wage) labour and that present low levels of capitalisation (e.g., low use of agricultural machinery etc.). Peasant agriculture is prevalent in the Global South and is distinct from family farms in the Global North. These are units of production that also rely prevalently on family (non-wage labour), but typically present higher levels of capitalisation. Note how both peasant and family farms are not forms of subsistence agriculture, since they produce also for the market and not for mere self-consumption. Lastly, peasant and family farms can be contrasted to capitalist units of production, which rely mainly on wage labour, tend to be heavily capitalised, tend to be larger and produce almost exclusively for the market. We refer the interest reader to the relevant literature (van der Ploeg 2014, 2018).

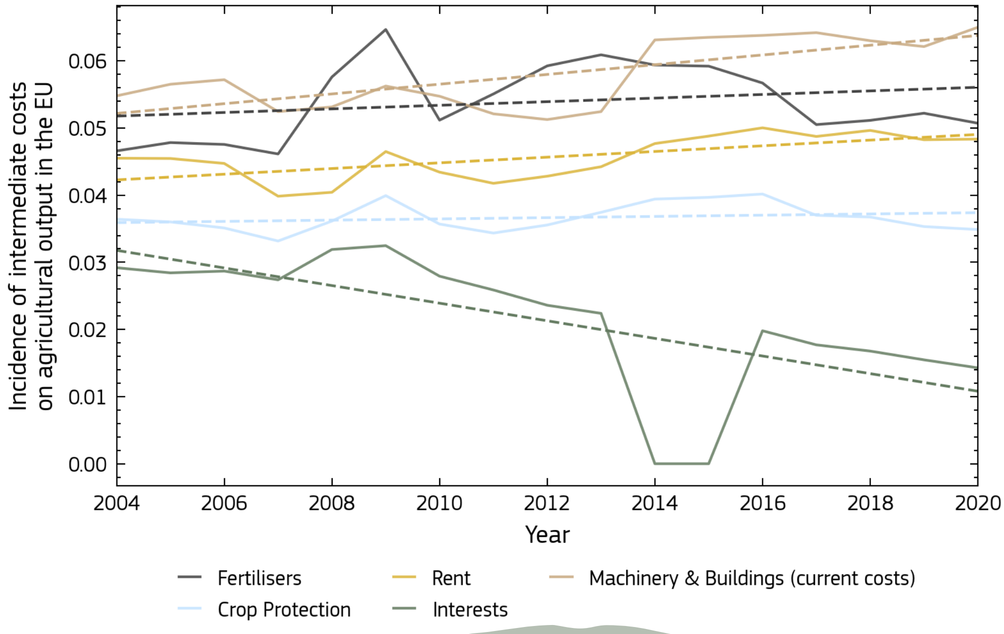
the case of family farms and peasants, unlike in capitalist enterprises, there is no clear separation between ownership (capital) and workers. Moreover, producers formally retain access to the means of production (e.g., land primarily). Nevertheless, the direct control, on the part of processors, financiers and distributors, of the upstream and downstream sectors of FSs, represents a form of indirect control of agricultural activities on the farm in the Global North and in the Global South (Goodman and Redclift 1985; Whatmore et al. 1987a, b). Producers *must* engage in market exchanges to acquire other necessary elements of production and to sell their output. Hence, the market is not a mere opportunity but it is an imperative, and it becomes essential to survival (Meiksins Wood 2002). The integration of FSs into global capitalism today occurs mainly (although not exclusively) indirectly, by integrating farming into the highly capitalised upstream and downstream sectors.

5.2.3 The loss of farmers' autonomy

The direct and indirect control of capital on farming has important consequences in terms of farmers' autonomy. Autonomy can be conceived at least at two levels. Firstly, it refers to the ability of individuals to pursue their own objectives, according to their values, inclinations and capabilities. Secondly, it refers to the aspirations of a collective (society) to achieve self-determination, to choose and decide about their destinies (Böhm et al. 2010; Guimarães and Wanderley 2022). Importantly, autonomy does not reflect the absence of social relations, but rather the quality of these relations. Capitalist relations of production in the FSs will affect the level of autonomy experienced by the producers. We focus particularly on the loss of autonomy among agricultural producers, the foundation of FSs, because it has also consequences for consumers and society at large. In the case of direct control by capital (as in the upstream and downstream sectors), the loss of autonomy on the part of workers/producers is quite evident. For example, a wage worker in agriculture has very little power to determine what he has to do. However, farmers' autonomy is eroded also in the case of indirect control. Financiers, industrial processors, distributors and retailers in upstream and downstream sectors in FSs condition the production process on the farm. The role of increasing rural indebtedness, as a disciplining mechanism in agricultural production, provides an important example (Gerber 2021). Indebted farmers are less free to grow what they want and must produce what is most profitable. The dependence on specific technologies is another example. Certified seeds respond not only to the quality specification of processors and distributors downstream. They also require the application of specific inputs, from fertilisers to pesticides to specialised agricultural machinery, thus matching the needs of upstream operators. Even the dependence on specialised machinery can be problematic. Until 2023, John Deere tractors could be repaired only by authorised traders (Shah 2018). The situation has only changed following a lawsuit. More recent developments, like some forms of digital agriculture, while potentially allowing for the reduction of agricultural inputs, could also have negative consequences in terms of replacing farmers' decision processes with algorithms and perpetuating uneven development (Stone 2022; Fairbairn et al. 2025). Contract farmers, while formally retaining access to land and relying prevalently on family labour, have very little autonomy on the production process (Otsuka et al. 2016).

The high concentration of upstream and downstream sectors, effectively dominated by oligopolies (Howard 2021; Clapp 2021, 2025), exacerbate the loss of autonomy on the part of farmers. As different capitals upstream and downstream collide with each other in the struggle to maximise profit, they exert an increasing pressure on agriculture. This pressure is manifest in the value distribution along the supply chain. In the EU, for example, farming intermediate costs (including, rents, maintenance of machinery and buildings, agricultural inputs) have been steadily increasing (except for interests, due to the steep decline in interest rates) over time. In 2004 these costs absorbed 18% of the value of total agricultural output, while in 2020 they exceeded 20% (Figure 89). Such an increase is truly significant when considering that the value of agricultural output has increased by 70% over the same period. The difficulties faced by farmers are openly acknowledged by the EU, which has recently announced further actions to strengthen their position in the value chain (https://ec.europa.eu/commission/presscorner/detail/en/ip_24_6321).

Figure 89. Incidence of intermediate costs as a fraction of total agricultural output in the EU based on FADN data.



Source: JRC, own elaboration based on FADN data.

Globally, farmers receive a small and declining share of the total value added (Yi et al. 2021). In order to absorb these pressures and stay competitive, farmers must reduce unit costs. This can be done by increasing the productivity of land, via land-saving technology (e.g., improved seeds, fertilisers and pesticides), and/or the productivity of labour, via labour-saving technologies (e.g., machinery) and scale expansion. The pressure to stay competitive and reduce unit costs of production leads to a treadmill effect (Levins and Cochrane 1996) and has also implications in terms of social (e.g., labour exploitation) and environmental (e.g., externalising environmental/health costs of agriculture) dysfunctions within FSs (Magdoff et al. 2000; Gareau and Borrego 2012). Summing up, today, farmers' autonomy is being eroded particularly by the fact that highly concentrated upstream and downstream sectors of the FSs strongly condition farming. In this context, farmers' degree of freedom is heavily reduced.

5.2.4 Agroecology as a solution

The subordination of FSs to profit accumulation, the loss of autonomy of producers, the environmental and social dysfunctions of FS are tightly coupled and must be addressed together.

Agroecology represents an important strategy to simultaneously increase farmers' autonomy, thus reducing the subordination of FSs to profit accumulation, while also addressing some of the social and environmental dysfunctions. The Oxford Research Encyclopedia of Anthropology provides a definition of agroecology that is largely consistent with the one provided by the HLPE-FSN, but it stresses more explicitly its double nature. Namely agroecology is "a) the application of ecological principles to food and farming systems that emerge from specific socioecological and cultural contexts in place-based territories; b) and a social and political

process that centres the knowledge and agency of Indigenous peoples and peasants in determining agri-food system policy and practice" (Pimbert et al. 2021). The double nature of agroecology, concrete/technical and social/political, is in fact crucial to understanding its potential to transform FSs (Gonzalez de Molina et al. 2020; Anderson et al. 2021). Autonomy within FSs resonates strongly with food sovereignty, a concept spearheaded by La Via Campesina. Food sovereignty calls for the democratic control of the process of food production, distribution and consumption (La Via Campesina 2022). Note how within this definition two elements are tightly coupled. The social/political one (i.e., the democratic control) and the concrete/technical one (i.e., the process of production, consumption and distribution of food).

The HLPE-FSN proposes a set of 13 principles informing agroecology. Notably, these principles support resource efficiency and resilience, a concrete/technical dimension, and promote social equity, a social/political dimension. However, concrete/technical practices also have by themselves social/political implications. For example, the activation of synergies within the agro-ecosystems can help to sever the relationship of dependence from external input providers, thus reducing the influence of industrial and financial capital operating upstream. At the same time, agroecological principles operating mainly on the social/political dimension will also act to transform the concrete/technical dimension. For example, evidence suggests that improving women's access and control of productive resources (which includes access to land) strongly correlates with the production of more diverse food crops in Burkina Faso and in India (Connors et al. 2023). Experience from Europe indicates that setting up local distribution networks for agroecological products stimulates the uptake of agroecological production methods (Espelt 2020). We see therefore a sort of dialectical interaction between the concrete/technical and social/political elements of agroecology, which can set in motion a sort of virtuous transformative cycle (see Box 18).

Box 18. **Examples of Agroecological initiatives**

The Northern Frisian Woodland in the Netherlands

The Northern Frisian Woodland (NFW) is a territorial cooperative for agrarian landscape management, operating in the North of Netherlands, with over 1,000 members and covering about 50,000 ha (van der Ploeg 2021; Van Der Berg et al. 2023). The cooperative was formed as a reaction to the designation of the area as acid-sensitive, in the 80s. Local farmers committed to maintain biodiversity and reduce ammonia emission in exchange for the area being declared not at risk of acidification. Farmers started to experiment with reducing nitrogen inputs, both in the form of feed concentrates and soil fertilisers. In particular, they changed the cow's diets to mainly grass and in so doing, they changed the quality of manure and consequent leaching and soil acidification. Better manure further reduced the need for the application of soil fertilisers. This is the concept of closed-loop farming. This new approach allowed farmers to maintain high milk yield, while reducing significantly input costs. Notably, the success follows from farmers'-initiated research. Additionally, the cooperative directly engages in landscape management to maintain biodiversity. Still today, farmers collaborate with research institutes and are directly involved both in the production and in the dissemination of knowledge. The NFW examples illustrates quite well the application of various agroecological principles. From the reduction of external inputs and the activation of natural processes to the production and dissemination of knowledge, to new forms of governance with respect to landscape management.

The Ecovida Agroecology Network

The Ecovida Agroecology Network (EAN) was formally established in 1998, and today includes more than 5,000 family farms in almost 200 municipalities in Southern Brazil. Farmers are organized in 300 community-based groups, forming 30 regional nuclei. EAN also includes several NGOs and cooperatives. The origins of EAN can be traced to the 1970-80s, when various social movements emerged in response to both land concentration and agrochemical-based agriculture (Mier y Terán Giménez Cacho et al. 2018). A further impetus to the formation of AEN occurred in the 1990s, when the Brazilian state attempted to make third party certification schemes for organic products mandatory. Family farmers reacted by pushing their own agenda and allowing for the reliance on participatory guarantee systems (PGS). EAN has its own PGS, which requires farmers to use agroecological methods, and practice non-exploitative working conditions. The EAN goes beyond farming and has allowed producers to create various distribution networks, like the well-known "The Circuit" (van der Ploeg et al. 2023). Importantly, in order to participate to these distribution networks, farmers groups: a) agree to prioritize intra-network circulation of food; b) must also buy (not just sell); c) agree to adopt "fair prices", which do not necessarily follow prevailing market prices (Niederle et al. 2020). The EAN case provides a vivid example of the transformative power of agroecology. Transformation occurs by engaging both the concrete/technical aspects and the social/relational aspects and by acting on both production and distribution.

5.2.5 Trade-offs and co-benefits

Agroecology is often presented as less productive than conventional agriculture. Notably, there are indications that contradict this view. While comparative assessments of all agroecological practices against conventional farming do not exist, there are important indications with respect to some key practices. Meta-analysis indicate that intercropping and legume-based rotations (two key elements of agroecology) significantly increase yields and reduce land requirements (Martin-Guay et al. 2018; Zhao et al. 2022). Various forms of diversification in farming, another central tenet of agroecology, have been shown to be beneficial from both environmental, social and economic point of view (Rasmussen et al. 2024). One critical element, however, pertains to the labour requirements. In terms of farming methods, agroecology relies on the activation of synergies among the various ecosystem processes and is likely to be labour intensive. This aspect, however, calls for clarification. Agroecology can be thought of as a process of labour driven intensification (van der Ploeg 2014). Labour driven intensification draws on the use of skill-oriented technologies, namely simple instruments requiring deep knowledge and skills. Agroecology is based on a deep knowledge of the local agroecosystems and tends to avoid its simplification. The case of the NFW previously illustrated (Box 18) provides a fitting example of skill-oriented technologies. In this sense, agroecology stands in stark contrasts to production methods that rely on the use of "mechanical technologies", here intended as complicated instruments that require little knowledge and are therefore deskilling. The case of digital agriculture, previously mentioned, can serve as an example. On the one hand, the adoption of digital agriculture may require the acquisition of skills by the farmer (e.g., how to operate a milking robot, how to program spraying and weeding bots etc.). On the other hand, these technologies could also lead to deskilling in the sense that they could produce the loss of knowledge, related to the connection between farming and the broader ecological processes occurring on the farm. Additionally, they could increase farmers' dependence on knowledge produced somewhere else (i.e., by the companies developing the technologies), thus further reducing their autonomy (Carolan 2018).

5.2.6 Impact on regenerative economy, society, indirect effects

Food Systems are crucial to the survival of human society, since they provide food and contribute to many important ecosystem processes. At the same time FSs today are also involved in a polycrisis. This polycrisis becomes particularly manifest in farming, a central component of FSs, given its subordination to the upstream and downstream sectors. We already mentioned how, from a strictly economic point of view, the direct control on the part of capital of the upstream and downstream sectors of the FSs, represents an indirect control on farms subjecting them to an increasing pressure. This process, known as farm squeezing, implies that farmers appropriate a small and declining share of food value. Agroecology, through the reduction of external inputs and the reliance on ecosystem processes, enables farmers to distance themselves from upstream markets and reshape social relations of production in a way that strengthens their autonomy. Agroecology, with its focus on the creation of local markets and alternative distribution mechanisms (as illustrated in the case of the EAN in Brazil) allows farmers to regain control of downstream sectors of the FSs. The result is the appropriation of an increasing share of the value added on the part of farmers.

We already noted how the prevalent type of farming in both the Global North and Global South is based on peasant agriculture and family run farms. Family farms and peasants' agriculture mainly rely on family labour (rather than wage labour) and tend to be smaller than capitalist units of production, in both extension and economic dimension. In the EU, for example, data from Eurostat indicate that almost 65% of agricultural holdings are of less than 5 ha, with another 20% being less than 20 ha. Agroecology aligns quite strongly with peasants and family farmers' agriculture. This is an important distinction. Large-scale farms, which tend to be organized as capitalist units of production with a clear separation between ownership (capital) and workers (wage labourers), prevalently pursue the maximisation of profits or returns on invested capital. Family farms and peasants' units of production aim to maximise labour income and generate meaningful employment opportunities for the family members (van der Ploeg, 2014). The different organization of farming labor (waged vs. non-waged) has direct implications for the objectives pursued by the farming unit (maximum profit, return on capital vs. labor income) and consequently for the farming practices. For example, FADN data indicate that in 2021 large farms (with an economic dimension larger than eur 500,000 and an average utilized area of about 250 ha) used 139 eur/ha in crop protection. In the same year, small (family) farms (with an economic dimension smaller than 8,000 eur and an average utilized area of 6 ha) spent about 44 eur/ha. The point is important and worth repeating. The crucial difference does not lie in the size of the farm, but in the reliance on wage vs. family labour.

Agroecology and labour-driven intensification can generate employment opportunities, particularly in rural regions. This could be beneficial in terms of repopulating rural areas while at the same time addressing the farmers' ageing crisis.

Summing up, the promotion of agroecology could be beneficial in ecological, economic and social terms, it would align with the interests of most farmers, boosting their autonomy, and society at large. However, the transformative potential of agroecology can only be realized if both the concrete/technical and socio-political dimension are activated. With these final considerations, the author highlights the importance of maintaining the social and political content of agroecology. While agroecology encompasses an integrated approach that simultaneously applies ecological and social concepts and principles to design sustainable food systems, prioritizing people's well-being and the environment, the author wants to mention the risk of certain interpretations of agroecology being limited to purely technical interventions (Giraldo and Rosset, 2023). For unless social/political elements are engaged, and capitalist relations of production are weakened, the subordination of FSs to capital accumulation will persist. And so will environmental and social dysfunctions.

5.3 Pastureland management strategies

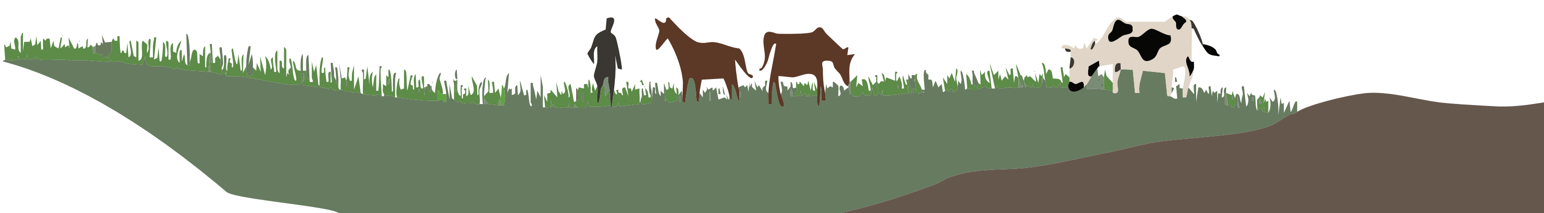
Julien Morel & Mattia Rossi

Grasslands are ecosystems dominated by grasses or other herbaceous vegetation. While their biomass productivity is essential for ruminant meat and dairy production, grasslands provide numerous vital services that contribute to the resilience of agricultural systems as well as to recreation (Schils et al 2022). As diverse habitats for a wide range of insects, small animals and plants, grasslands serve as natural hotspots for biodiversity (Petermann & Buzhdygan, 2021). Their dense and diverse root systems work as a natural water purification system, reducing the leaching of potentially harmful substances to groundwater while minimising runoff and soil erosion. Such well-developed, undisturbed root systems also support the accumulation of soil organic matter, acting as a carbon sink (Bai et Cotrufo, 2017, Conant et al 2017, Hungate et al, 2022) and hence help to mitigate effects due to climatic changes.

5.3.1 Grassland Management in Europe today

Grasslands are managed in several ways ranging from intensive to extensive practices. Extensively managed grasslands are typically found in mountainous or Mediterranean regions or other areas where climate, topography or economic factors do not allow for intensive management.

Intensively managed grasslands include both permanent (grown continuously for more than five years) and temporary (grown for five years or less and often included in a crop rotation) grasslands. Either way, such grasslands management is designed to increase biomass productivity and supports high livestock stocking rates, yet to the detriment of other ecoservices such as biodiversity (Bardgett et al 2021;



Tälle et al 2016). Intensive practices translate into a regular application of fertilisers and pesticides to maximise the growth of grasses while limiting light, water and nutrient competition with other species (Schils et al. 2022). Production maximisation is also reached through various biomass management strategies, such as rotational grazing or regular mowing for forage production, which typically happens two to five times depending on the climatic and topographic context of the region. Intensively managed grasslands can also be regularly reseeded to maintain high productivity, usually every three to five years.

In comparison, extensively managed grasslands show lower levels of input and intervention, such as less intensive grazing or less frequent harvesting and little to no chemical fertilisers or pesticides. Despite being less productive than their intensively managed counterpart, extensively managed grasslands are more efficient in delivering other ecoservices such as greenhouse gas mitigation, erosion control, water purification or increased biodiversity (Klein et al 2020; Petermann et Buzhdygan, 2021; Tälle et al 2016).

Although grasslands are spread throughout Europe, their composition and prevailing management practices differ considerably based on geographical distribution. In northern Europe grasslands are either permanent or, often, managed temporarily as part of the crop rotation, while in most of central and western Europe grasslands are managed intensively in the lowlands in the form of mown meadows or frequently grazed grasslands or a mixture of both. In higher altitudes and mountainous regions grasslands are managed more extensively, due to limited accessibility and shorter growth cycles, and are either mown or used as pastures depending on the slope steepness. Southern Europe grasslands are less intensively managed due to limited water availability as well as heat in summer that provokes dormancy. Here, grasslands are often combined with forestry or shrubland and left in a more natural state as compared to the high output meadows in central Europe. Exceptions to the North – South gradient are Pannonian and steppe-like grasslands in central and Eastern Europe that are managed very extensively as well.

5.3.2 Pasture management and the European Green Deal priorities

Pastures principally contribute to three European Green Deal key priorities (i) “Climate adaptation”, (ii) “The farm to fork strategy” (F2F) and (iii) “Preserving and restoring ecosystems and biodiversity”. These EGD outcomes have different key priorities and outcomes that necessitate different grassland types and management practices (Figure 90).

For “Climate adaptation”, key factors are a high capacity to retain water in the soil and therefore to regulate the runoff and prevent soil erosion through an adequately deep rooting system, which also fosters greenhouse gases fixation in the plants and the soil. These factors lead to a high climate resilience with permanent grassland (older than five years) compared to temporary grasslands.

Concerning “Greening and the farm to fork”, the importance lies on the productivity of grassland as well as the protein content, as highlighted by the EU “Protein strategy” (Albaladejo 2023; Wiesner 2023). The reduced use of pesticides (as compared to annual crops) and high fixation of nitrogen and phosphorous in the ground is advantageous but of slightly less importance. This is true for temporary and intensively managed permanent grasslands while extensive grasslands or mixed forms with other vegetation are usually less productive and therefore less of interest for the Farm to Fork Strategy.

“Preserving and restoring ecosystems and biodiversity” is supported by grasslands with a high species richness and a diverse species composition, especially when supplemented by rare species. Here, both the restrictions in use of pesticides and the presence of pollinators are of key importance. These factors generate a high ecological resilience in permanent grasslands that are extensively managed or in mixed forms with shrubs, bushes or partially with trees, while intensively managed permanent and temporary grasslands are generally negatively impacting this goal set in the European Green Deal.

Figure 90. **Grassland characteristics mapped to EGD priorities.**

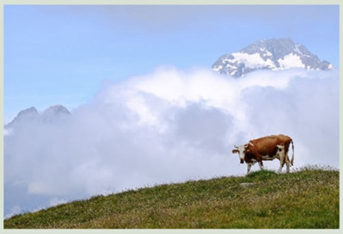
EGD	Key factors and traits	Low benefits	High benefits
01 CLIMATE ADAPTATION	• High water retention • Water runoff regulation • Greenhouse gas sink • Prevent soil erosion • High climate resilience	 Temporary grasslands	 Permanent grasslands
06 GREENING AND FARM TO FORK	• High productivity / yield • High protein content • Limited use of pesticides • Storage of N and P • High social and economic resilience	 Extensive or mixed	 Temporary or intensive
07 ECOSYSTEM AND BIODIVERSITY	• Species richness • Different and rare species composition • Limit use of pesticides • Abundant pollinators • High ecological resilience	 Temporary or intensive	 Permanent extensive or mixed

Photo credits by row, from left to right: Julianne Oliveira, Jan W. Jongepier; Christian Gazzarin, Alan Hopps; Jantine van Middelkoop, João Miguel Catarino all photos except the top left one, courtesy of the SUPER-G project.

Source: JRC, Photo credits as noted.

5.3.3 Key messages

Grasslands play a major role in feeding livestock while having significant impact on climate risk mitigation. While it is important to maximise productivity and to strengthen resilience to climate change and reduce yield losses, it is crucial to preserve the capabilities of grasslands to fulfill ecological functions for different flora and fauna. The balance is important to reduce waste in the feed sector by cutting long supply chains short, reduce losses by combining species in grassland and increase their climate resilience.

- Grasslands are present all over Europe in a range of types and managements, from very extensive semi-natural pastures to highly intensive temporary meadows.
- Grasslands are a cornerstone of feed production for livestock but also provide several environmental-related services.
- Intensively managed grasslands maximise the feed productivity, while extensive grasslands sustain, among other services, water purification, erosion limitation, fostered biodiversity and carbon storage.
- Current studies suggest that it might be best to revert from temporary to permanent grasslands to increase resilience and to service the EGD goals.

5.4 Sharing or sparing of forest land?

Nicolas Mansuy

In addition to traditional wood production, forests are increasingly valued for their multifunctional role, offering European citizens a wide range of economic, environmental, and social benefits. A broad spectrum of EU policies and initiatives is connected to forests and the ecosystem services they provide. The EU Forest Strategy for 2030, the EU Biodiversity Strategy, and the EU Nature Restoration Regulation all aim to address climate change, reverse biodiversity loss, and ensure climate-resilient ecosystems. Furthermore, the EU Bioeconomy Strategy highlights that a sustainable and competitive forestry sector is crucial for advancing the bioeconomy and enhancing rural livelihoods.

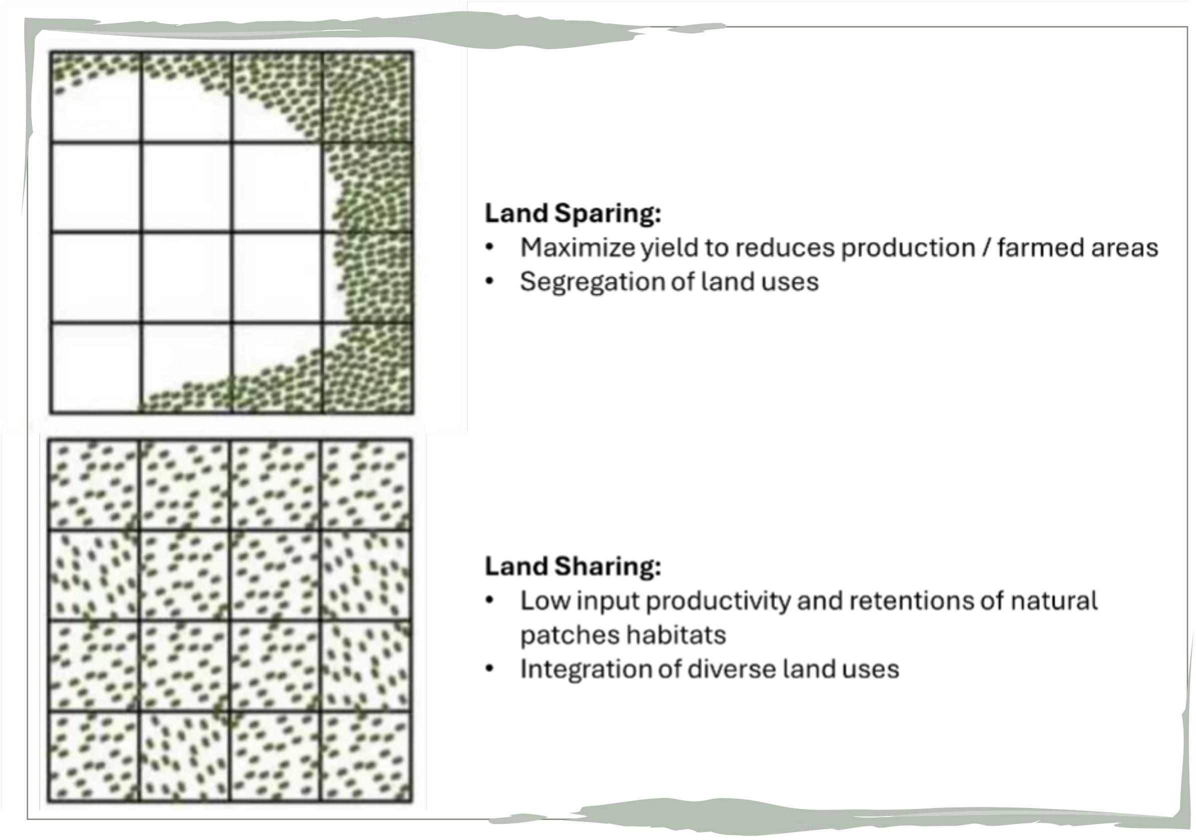
However, as the global demand for biomass is growing rapidly to meet energy and climate targets (IEA, 2023), the capacity of forest ecosystems to sustain their diverse services and functions is questioned (see Section 3.2.1). Integrated biomass management is central to this debate, with the key question being how to balance its multiple uses and values.

In this chapter, we delve into the land sharing and land sparing approaches as potential pathways for reconciling the diverse uses and values of biomass. Land sharing and land sparing can represent complementary approaches for managing landscapes to balance biodiversity conservation with production of wood commodities, including biomass management (Anderson-Teixeira et al., 2012; Kremen, 2015; Grass et al., 2021). Land-sharing sparing approaches have a long-established history in food production systems (e.g., wildlife-friendly agriculture; Phalan et al. 2011; Green et al. 2005) and they have attracted increasing interest in the management of forested landscapes (Edwards et al. 2014). Although these approaches are not new, they deserve further exploration to address competing demands on forest ecosystems, particularly regarding biomass extraction and ecosystem services.

5.4.1 Land sparing vs land sharing

Land sparing refers to an approach where areas are designated exclusively for conservation, or recreation while other areas are designated intensively managed for production (Figure 91). Conversely, other areas would be dedicated to more intensive biomass production, where forest management practices are optimised with high productivity. These areas could be dedicated for intensive sylviculture with even-aged forest structure (Hardy et al. 2023), mono specific species or with fast growing species. Therefore, land sparing requires segregated spatial organisation to reduce the pressure on ecologically sensitive areas by concentrating biomass extraction in areas specifically designated for this purpose, thereby minimising overall environmental disruption.

Figure 91. **Representation of the land sparing and land sharing concepts.**



Source: Modified from Balmford et al. (2012).

In practice, this approach could involve zoning forest landscapes to designate high-biodiversity areas for strict protection, while less ecologically sensitive regions are actively managed for biomass production. Achieving this would require stakeholders to collectively agree on setting aside the largest possible and most contiguous forest areas to maximise biodiversity conservation and enhance other ecosystem service outcomes.

In contrast, land sharing involves integrating conservation and production within the same area (Figure 91). In this approach, forests could be managed in a way that combines forest harvesting with measures that maintain or even enhance biodiversity. The idea is to create multifunctional landscapes where production and ecosystem services coexist in a balanced way.

The challenge lies in finding the right balance between land sharing and land sparing. Both approaches have their advantages and limitations (Table 15). Land sparing can be more effective in preserving biodiversity in certain areas but may lead to intensified pressure on production zones, potentially degrading the ecosystems in those areas. Land sharing, on the other hand, fosters more integrated and multifunctional landscapes but may not provide the level of protection needed for sensitive species or ecosystems that require undisturbed conditions to thrive. Besides, limitations remain due to the difficulty of identifying and finding consensus which areas should be protected versus exploited, and it risks oversimplifying the complex interconnections between different natural ecosystem and socio-economic needs (Phalan et al. 2018).

Table 15. **Example of current management practices and their impacts on the ecosystem.**

Aspect	Land Sparing	Land Sharing
Biodiversity	- Maximises conservation in undisturbed areas, benefiting species requiring intact habitats (Green et al., 2005; Phalan et al., 2011).	- Supports moderate biodiversity across the entire landscape by integrating habitat features into production areas (Kremen, 2015).
Productivity	- High productivity per unit area in intensively managed zones, reducing the overall land needed for resource extraction (Phalan et al., 2011).	- Lower productivity per unit area, as production is balanced with biodiversity considerations and other land uses (Grass et al., 2021).
Landscape Connectivity	- Can lead to isolated protected areas, risking habitat fragmentation and reduced genetic diversity (Williams et al., 2021).	- Can promote connectivity across landscapes, benefiting species requiring transitional or mixed-use habitats (Kremen, 2015).
Ecosystem Services	- Focus on large-scale ecosystem functions like carbon storage but lacks localised multifunctionality (Edwards et al., 2014).	- Provides diverse ecosystem services across landscapes, such as pollination, water regulation, and soil health (Kremen, 2015).
Social Impact	- May displace local communities and restrict access to resources, leading to potential social conflicts (Williams et al., 2021).	- Can support traditional and small-scale livelihoods by integrating conservation and production activities but requires tradeoffs in land use and local functional governance (Grass et al., 2021).
Environmental Risks	- High-intensity production risks soil degradation, water pollution, and dependence on chemical inputs (Edwards et al., 2014).	- Less reliance on chemical inputs, fostering more sustainable practices but requires careful management to maintain productivity (Kremen, 2015).
Implementation	- Requires large, contiguous areas for conservation, which may not be feasible in fragmented or urbanized landscapes or in a context of small private lots (Williams et al., 2021).	- Suitable for fragmented landscapes where strict separation of uses is impractical, but governance is challenging to design and monitor (Green et al., 2005; Grass et al., 2021).
Resilience	- Intensive systems may be vulnerable to pests, diseases, or climate shocks (Edwards et al., 2014).	- Diverse systems offer greater resilience to environmental changes (Grass et al., 2021).

Source: JRC own elaboration.

5.4.2. Overcoming the limitations of the land sharing-sparing dilemma

The limitation of both approaches along with the complexity to put them into practice have fueled the ongoing land sharing-sparing debate (Pichancourt, 2020; Fischer et al., 2013). Fundamentally, the main controversy revolves around the efficient allocation of a finite and valuable resource, land, to balance competing demands for biodiversity, ecosystem services, and production. Framing this issue through the lens of "land scarcity" (Fischer et al., 2013) provides a more practical perspective, particularly in the context of European landscapes where land is both limited and under significant pressure from diverse and often conflicting demands. Forest ecosystems in Europe, for example, are already facing challenges from fragmentation, intensive land use, and the impacts of climate change, which further constrain the capacity to meet conservation and production objectives simultaneously (Maes et al., 2021). This highlights the need for nuanced and context-specific management strategies that account for ecological, economic, and socio-cultural factors while maintaining multifunctional landscapes Therefore, in the context of woody biomass management, land sparing could mean setting aside specific contiguous forest areas for strict conservation areas, allowing natural processes like deadwood accumulation and forest dynamic (natural disturbances) to occur without human interference (i.e., biomass removal). These conserved areas should be identified to maximise biodiversity and ecosystem health, protecting key species and habitats while also contributing to long-term carbon sequestration. For example, increasing the protection and preservation of primary and old-growth forests, which currently represent less than 3% of the total forest area in the EU (Sabatini et al. 2020; Barredo et al. 2021; Barredo et al. 2024), is part of the Biodiversity Strategy and is essential to conserve biodiversity, and ensure resilience to climate change.

A land-sharing approach enables forests to deliver a broad range of ecosystem services—such as carbon sequestration, wildlife habitats, and biomass for energy—without dedicating specific areas solely to conservation or production. This approach promotes the creation of multifunctional landscapes where varying intensities of forest management are applied across small patches within the same landscape to optimise diverse forest uses. Implementing such practices requires careful spatial zoning and a mix of management strategies like uneven-aged forest management and triad forest management (Hardy et al., 2021; Betts et al., 2021), selective logging and minimising or avoiding salvage logging to retain deadwood. For instance, developing clear guidelines on deadwood retention and removal can help balance the biodiversity objectives of the EU Nature Restoration Regulation with the energy targets of the Renewable Energy Directive (RED). With effective local participatory planning and stakeholder engagement, flexible land-sharing approaches can also facilitate the implementation of restoration actions (Meli et al., 2019). By integrating ecological considerations with management practices, this approach aligns biodiversity conservation and ecosystem service provision within a unified landscape framework.

Given the diversity of European forests, both approaches must be tailored to local and regional contexts, taking into account ecological, geographical, cultural, and historical considerations. Furthermore, integrating climate change impacts into biomass management strategies will be essential to ensure the long-term resilience of forest ecosystems (Mansuy et al., 2018).

5.4.3 Key messages

Implementing land sharing -sparing approaches for biomass management presents significant policy implications. The suitability of land-sparing versus land-sharing approaches depends on regional conditions and objectives, and ultimately land availability. Land sparing is typically more effective in regions with high biodiversity value and intact forest landscapes, where strict protection and large areas can deliver significant ecological benefits.
In contrast, land sharing may be better suited to degraded landscapes and areas dominated by smallholder systems, where integrated conservation and production practices can help restore ecosystem functions while supporting local livelihoods. In both cases, effective local governance is critical to design forest management and monitor outcomes.

Ultimately, achieving greater policy coherence—not only between forest-related policies but also across sectors such as the materials sectors, energy, biodiversity, and food systems—is essential. Aligning these policies with broader environmental goals and climate neutrality, will help ensure that forests can continue delivering their multiple ecosystem services, including biodiversity conservation, carbon sequestration, and sustainable resource provision, while addressing climate change mitigation targets.

5.5 Nature-based climate solutions and carbon farming

Mirco Migliavacca, Emanuele Lugato, Tommaso Chiti, Hans Joosten, Aleksi Lehtonen, Lucia Perugini, Ana Rey

5.5.1 Introduction: nature-based climate solutions

Terrestrial ecosystems absorbed about a third of anthropogenic CO_2 emissions during the period 2013-2022 (Friedlingstein et al., 2024) and have long been studied for their significant contribution to mitigating global warming (Novick et al., 2024). Due to the increasing impacts of climate, there is an urgent need to reduce CO_2 emissions as well as to increase the removals of CO_2 from the atmosphere. The enhancement of the CO_2 removals can be achieved by proactively managing terrestrial ecosystems to enhance carbon uptake and storage or minimise greenhouse gas (GHG) emissions (Griscom et al., 2017). This objective can be reached by using Nature-based Climate Solutions (NbCS), defined by the European Commission as "Solutions that are inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social and economic benefits and help build resilience. Such solutions bring more, and more diverse, nature and natural features and processes into cities, landscapes and seascapes, through locally adapted, resource-efficient and systemic interventions". NbCS are promising for climate mitigation but are considered by many scientists to be "not a cure-all" (c.f. Anderson et al., 2019) and must be accompanied by consistent and widespread reductions in CO_2 emissions across all economic sectors.

For this reason, NbCS (e.g., afforestation, peatland restoration and rewetting) have been widely supported and promoted by policy makers, conservation organisations, and the private sector. They consist of voluntary management activities promoted by farmers and land managers aimed at managing ecosystems to enhance the CO_2 removal from the atmosphere and its long-term storage in different carbon pools, and curtail emissions from ecosystems, including other main GHG (e.g., methane and nitrous oxide). In addition, NbCS should also provide other ecosystem services such as biodiversity conservation and water management. NbCS includes a series of activities such as conserving and restoring carbon-rich forests and wetlands, optimising the use of lands for agriculture, forestry, and grassland management. Beyond their environmental benefits, NbCS can also offer economic incentives, and a potential diversification of farmers and land managers' income. For this combination of reasons, they have garnered broad support. Nevertheless, NbCS have been recently debated, largely because their practical implementation has outpaced scientific understanding, in particular - but not only - on the permanence of the carbon removals.

NbCS have become an element of recent European Union (EU) policies. The EU has introduced the concept of 'carbon farming' in the Sustainable Carbon Cycle Communication COM(2021) 800 final, as "any land or coastal management practice that, over a minimum of five years, captures atmospheric carbon and stores it temporarily, or reduces emissions from the soil". The Carbon Removals and Carbon Farming (CRCF) Regulation (EU/2024/3012) was published in the Official Journal of the EU on 6 December 2024, creating the first EU-wide voluntary framework for certifying carbon removals, carbon farming and carbon storage in products across Europe. This certification must adhere to the QU.A.L.ITY criteria, which require accurate measurement and clear climate benefits, along with ensuring that the carbon removal activities exceed normal practices and legal obligations. The QU.A.L.ITY criteria are: quantification (carbon removals need to be quantified accurately); Additionality (the activities must be additional to current standard practices); Long-Term Storage (the storage should be long-term); and Sustainability (to be eligible, carbon farming activities must not harm other environmental objectives and deliver mandatory biodiversity benefits, while they can also support other sustainability objectives such as climate change mitigation, resilience, and water quality).

This chapter presents the scientific understanding behind NbCS and it is divided in 3 sections: 1) the science behind the NbCS, with a particular focus on those that can be applied in Europe; 2) the expected implications in terms of biomass stocks in the EU; 3) a discussion on co-benefits and potential trade-offs.

5.5.2 Carbon stocks and carbon sequestration rates in major European ecosystems

Recent results from the Global Carbon Budget project report an average carbon sequestration of terrestrial ecosystems of -3.2 (standard deviation 0.9) GtC yr^{-1} (negative sign represents removals of carbon from the atmosphere), between 2014 and 2023. In the same period, the emissions from land use change were 1.1 (standard deviation 0.7) GtC yr^{-1}. Therefore, the net carbon sequestration in the same period is about -2.1 GtC yr^{-1}.

According to the national GHG inventories of the EU-27 in 2022 (EEA, 2024), the net removal of the land use, land use change and forestry (LULUCF) sector was -236 $MtCO_2$-eq yr^{-1}, which is equal to about 8% of the EU's 2022 annual GHG emissions. The forestry sector, including harvested wood products, was a net carbon sink (-332 $MtCO_2$-eq yr^{-1}), while cropland (21.7 $MtCO_2$-eq yr^{-1}), grasslands (19.5 $MtCO_2$-eq yr^{-1}), and wetlands (23.2 $MtCO_2$-eq yr^{-1}) were a source (Figure 92a). Note that the new inventory was recently published in the EEA Website.

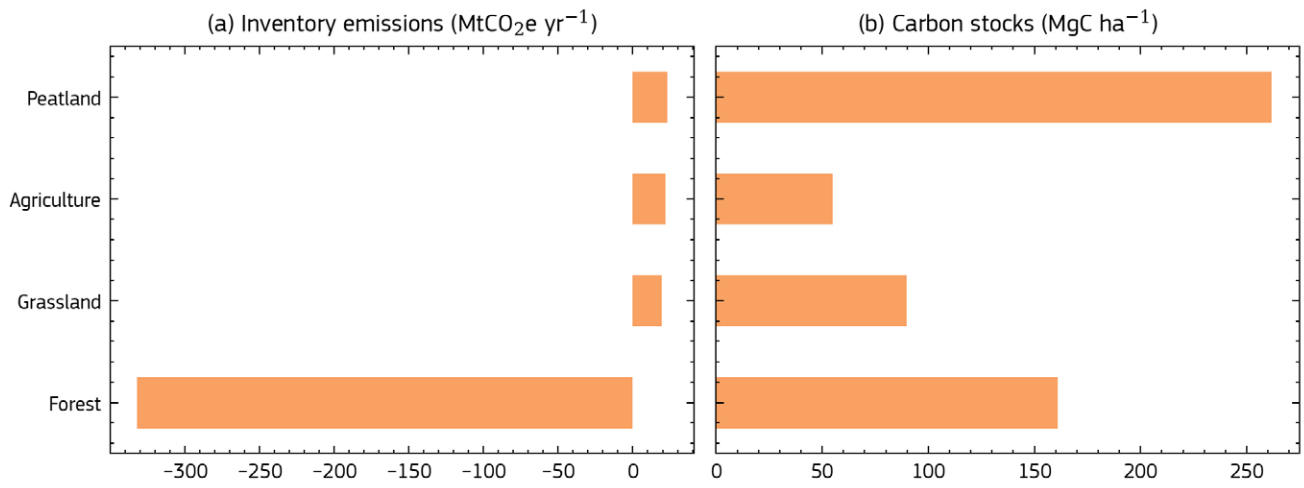
In addition to the natural capacity of ecosystems to sequester carbon, the net CO_2 emissions of ecosystems depend on how these ecosystems are managed (Mäkelä et al., 2023; Mäkipää et al., 2023). Forests have a high potential to store carbon in biomass and soils (Mo et al., 2023; Roebroek et al., 2023) compared to other terrestrial ecosystems. The report on the State of the European Forests 2020 indicated an average annual carbon sequestration of 155 MtC in Europe (including here not only the EU-27). The carbon in the living biomass pool (including aboveground and belowground) is estimated to be 67.4 MtC ha^{-1} (does not include peat soils), while the soil organic carbon (SOC) pool in mineral soils is estimated to be 93.5 (MtC ha^{-1}) (Lugato et al., 2021) for a total of 160.9 MtC ha^{-1}. The total forest biomass for the EU-27+UK is estimated to be 9.8 PtC (SOES, 2020), while, conservatively, 9.1 PgC are stored in the forest topsoils (Lugato et al., 2021). However, in the last decade the forest carbon sink in the EU is declining due to climate change and due to increase of forest harvesting resulting from disturbances and forest age structure (Korosuo et al., 2023). Large uncertainty exists in the quantification and modelling of the impact of forest management practices (in addition to climate effects) on the carbon sink potential of European forests (Naudts et al., 2016), particularly, for the SOC pools (Mäkipää et al., 2023; Mayer et al., 2020).

Agricultural soils are a large carbon reservoir in Europe. The SOC content in cropland (including both arable and permanent lands) is 7.1 PgC at the EU-27+UK, which is 61.3 MgC ha-1 for annual crop and 48.6 MgC ha-1 for permanent crops (Lugato et al., 2021) (Figure 92b). Because of land use changes and agricultural management practices coupled with rising temperatures due to climate change, agricultural soils are becoming a source of atmospheric CO_2 (Bond-Lamberty and Thomson, 2010). In the EU, De Rosa et al. (2024) showed an average reduction of SOC content for continuous cropland a reduction of 0.03 ± 0.005 gC kg^{-1} yr^{-1} between 2009 to 2018, which is equivalent to an annual loss of 7.7 MtC from top soils. Also, part of the agricultural lands in Europe has been recently converted, especially those in Northern Europe, and therefore are losing still carbon that originates from larger C stock of previous land use, namely forestry (Heikkinen et al., 2013). Continuous cropland, especially monocultures, or the conversion of grasslands to croplands, even under conservation agriculture practices, have been identified as major detrimental factors for SOC losses in agricultural systems (Wiesmeier et al., 2019).

Grasslands instead have been shown to act as a carbon sink. De Rosa et al., (2024) showed that continuous grasslands or the conversion of cropland to grassland could contribute to an increase in SOC content of 0.48 ± 0.01 and 0.33 ± 0.04 gC kg^{-1} yr^{-1}, (~1.2 and 0.8 tC ha^{-1} yr^{-1}, respectively) across European pedoclimatic conditions. Lugato et al. (2021) reports a SOC stock in EU-27+UK grasslands of 54.9 MtC ha^{-1}.

Peatlands are the most important carbon pool of all European terrestrial ecosystems (Malak et al., 2021) and hosts the largest carbon stock per hectare in Europe (Figure 92b). According to the national GHG inventories, peatlands are currently an important source of CO_2-eq, with a large variability depending on the management practices, habitat type and condition. The review study carried out by Hendriks et al., (2020) analysed more than 300 datasets from peatlands and reported a mean carbon stock in peatlands and wetland soils of 261.8 tC ha^{-1} (ranging between 1 to 827 tC ha^{-1}), with very variable carbon emissions/removals rates across sites (range: 0.49 – -6.5 tC ha^{-1} yr^{-1}). This variability can be quite high due to the definition of peatlands and the sampling protocol used that may lead to the underestimation of SOC in deeper layers of the soils. Methane and CO_2 are the dominant GHGs emitted by peatlands as a result of SOC decomposition. On average, water saturated, and non-degraded peatlands emit substantially less CO_2 than methane in temperate conditions, and, conversely, peatland drainage reduces methane emissions while increasing CO_2 emissions as a result of SOC transformation. Therefore, while a substantial CO_2 emission reduction can be achieved by rewetting, raising the water table often leads to a re-installment of methane emissions due to the established anaerobic conditions. Yet, recent modelling efforts indicate that methane radiative forcing does not undermine the climate change mitigation potential of peatland rewetting in temperate conditions (Evans et al., 2021; Günther et al., 2020). For boreal forests rewetting provide climate benefits with a time horizon that can be up to 150 years (Ojanen and Minkkinen, 2020). However, rewetting will be a way to conserve a peat storage in those lands and to restore biodiversity and water quality benefits in boreal peatland forests (Palviainen et al., 2022).

Figure 92. Emissions and carbon stocks. a) CO_2-eq emissions from inventory data (EEA, 2024) reported as average of the last five years (2018-2022) including also emissions from activities; b) carbon stocks for the main ecosystems.

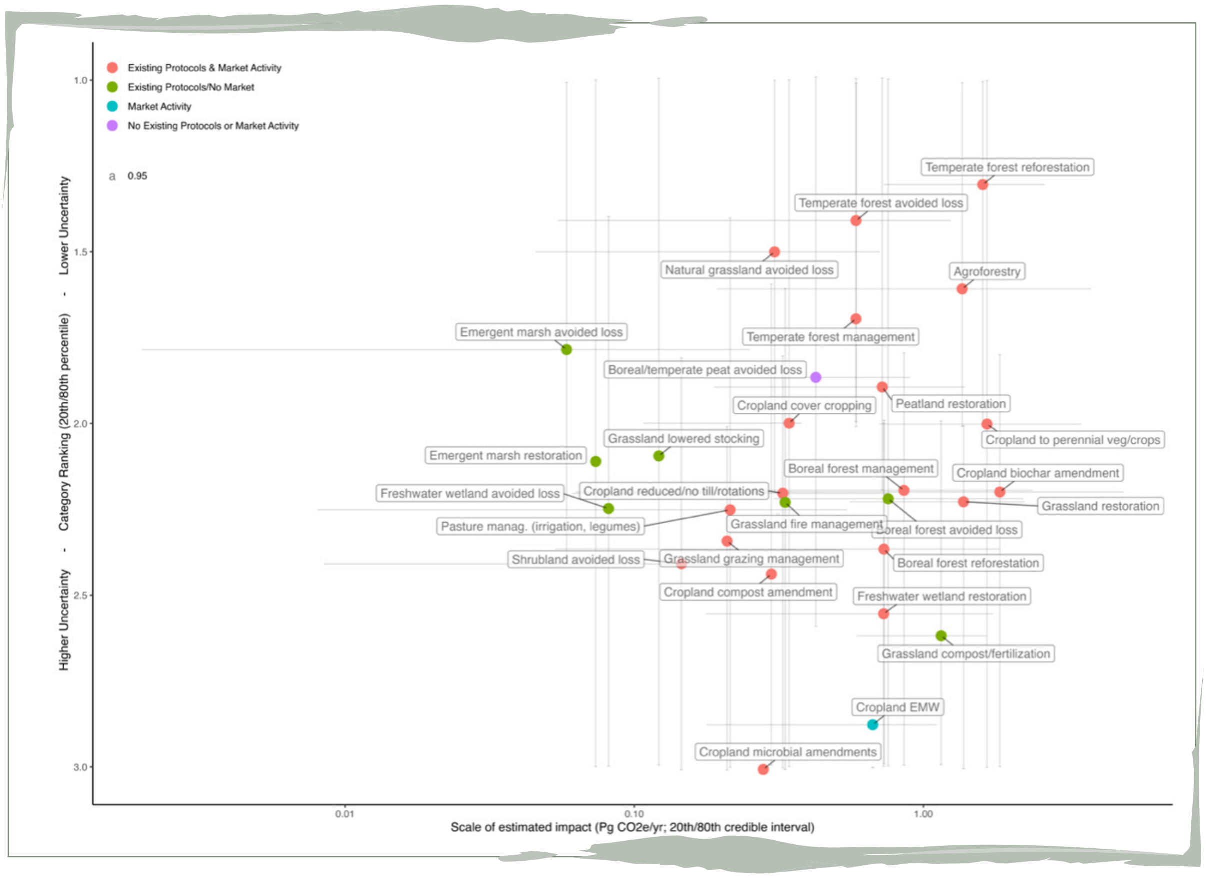


Source: JRC elaboration. Panel b: Forest ecosystems based on biomass data as reported by the State of the European forests 2020 and topsoil SOC in as reported by Lugato et al., (2021).

5.5.3 Expected implications for biomass stocks and soil organic carbon stocks in Europe

Land management activities have a strong potential to improve or reduce the carbon sequestration capacity of terrestrial ecosystems. NbCSs aim at optimising cropland management practices, forest management and afforestation, pasture and wetlands management, with the aim of boosting the CO_2 uptake and cutting GHG emissions from the management activities, including methane and nitrous oxide. A study based on an expert review (Buma et al., 2024) analysed 43 NbCS activities showing that the most adopted, such as tropical forest conservation and afforestation, have a solid scientific basis for climate mitigation. However, this study suggests that several pathways, many with carbon credit eligibility and market activities, remain uncertain in terms of their climate mitigation efficacy. Sources of uncertainty include incomplete GHG measurement and accounting. Figure 93 reports the estimated global impact and associated uncertainty of the NbCS activities from Buma et al, (2024), with a specific focus on the ones that can be applied in the EU.

Figure 93. **Mean categorization of land NbCS activity versus scale of estimated impact. Activities in the upper right quadrant have both high confidence in the scientific foundations and the largest potential global impact; activities in the lower left have the lowest scientific confidence and an estimated smaller potential impact. Designations of carbon credit eligibility under existing protocols and market activity at the present time are noted, the color are reported as in Buma et al., 2024. Bars represent 20th to 80th percentiles of individual estimates, if there was variability in estimates.**



Source: Reproduction of the figure in Buma et al. (2024), with the selection of relevant land NbCS applicable in the European Union.

A key question is to what extent NbCS can increase biomass stocks, soil organic carbon stocks and carbon sequestration rates of EU terrestrial ecosystems. Below, we review the latest scientific literature, and summarise the findings reported in two milestones reports (Chiti et al., 2024; Petersson et al., 2025) to present the latest estimates of the potential of NbCS in the EU for different land uses.

5.5.3.1 Forests

Forest management practices in the EU are diverse, ranging from strictly protected areas to intensively managed monoculture forests for biomass production. In Europe, over 80% of the forest area is managed for timber production, with only 10% under intensive management and a growing 30% of managed forests for multiple uses (Eurostat 2023b; Forest Europe 2020). Therefore, there is a large potential to improve forest management practices to enhance carbon sequestration and by maintaining sustainability, including biodiversity and preserving other ecosystem services besides carbon sequestration. Chiti et al., (2024) collected the last decade of scientific literature (2013–2023) and presented a detailed review of the potential forest management options to enhance carbon sequestration while adapting to climate change in different ecoregions in Europe. These practices include: afforestation/reforestation, silvicultural practices, enhancing species diversity and forest structural diversity, agroforestry, and management of peatland forests.

Afforestation on former agricultural lands and grasslands has a strong climate change mitigation potential with associated long-term benefits and additional environmental co-benefits in some cases. The carbon sequestration potential varies significantly depending on factors such as previous land use, climate, tree species and stand age structure. Estimates for afforestation range between 5 and 25 tCO_2 ha^{-1} yr^{-1} (Chiti et al., 2024). Afforestation impacts carbon sequestration differently across boreal, temperate, and Mediterranean regions. In boreal regions, short-term afforestation based on conifer species can lead to small carbon sequestration rates, in some cases associated to SOC losses (Ťupek et al., 2021), but in the long-term gains are expected in both, soils and tree biomass (Chiti et al., 2024). A study in Canada showed that in Boreal regions, natural regeneration in abandoned agricultural lands can lead to high carbon sequestration and climate mitigation potential (Thibault et al., 2022). The effects of afforestation on former grasslands is less clear, and more studies are needed to better understand the dynamics of SOC. In temperate regions, afforestation primarily increases carbon in tree biomass, with variable effects on soil carbon sequestration and in some cases, even carbon losses (Mayer et al., 2020). In Mediterranean regions, afforestation with fast-growing species results in high carbon sequestration rates, but with negative impact on other ecosystem services and biodiversity (Chiti et al., 2024). Soil carbon accumulation with afforestation in former grasslands varies, with losses in more humid areas, while in dry areas often leads to positive soil carbon sequestration, likely because of increased carbon use efficiency with aridity (Migliavacca et al., 2021). In alpine regions, pasture abandonment presents an opportunity for afforestation. Afforestation in these regions often promotes carbon sequestration rates faster than the one achievable by natural forest succession. Long-term sequestration rates of about 3.5 tCO_2 ha^{-1} yr^{-1} have been reported, with most of the carbon stored in the tree biomass (e.g., Speckert et al., 2023). However, afforestation at high altitudes requires substantial investment and may have unintended consequences, such as a negative impact on biodiversity in alpine meadows or increased soil GHG emissions (Pornaro et al., 2013), and decreased albedo.

The planting of forests with diverse tree species has the potential to enhance carbon sequestration and increase forest resilience to climate extremes in the second part of the century (Mahecha et al., 2024). Still, the effectiveness of tree planting and enhancing tree species diversity is uncertain and it depends on the species, and changes in species niches due to climate change (Wessely et al., 2024), with some afforestation activities failing. Identifying climate-resilient and suitable species is crucial for planning tree plantings, considering the regional context and the tree-species bottleneck given the reduction in the species available for forest management in the future (Wessely et al., 2024). Moreover, it should be considered that in the short-term, increasing species diversity may not be immediately beneficial for carbon removals, given that some species may have lower productivity compared to fast growing species. However, in the long-term increasing species diversity should be beneficial due to the higher resilience of the more diverse forests (Morin et al., 2025).

Extending the rotation period between harvest cycles in forest management, traditionally controlled by economic goals, is now seen as a potential NbCSs strategy to increase carbon sequestration in mature stands (Chiti et al., 2024), although it should be considered in stands that have low disturbance risks. However, the optimisation of the rotation period should be accurately defined to meet climate objectives (increase carbon sequestration and long-term carbon stocks) and, at the same time, maintaining the economic value of the forest and the forest yield (Lundmark et al., 2018). Chiti et al., (2024) reported few literature examples from European forests: a pan-European study in various forest types, boreal, temperate and Mediterranean species, projected an additional sequestration of 2.1 to 4.4 tCO_2 ha^{-1} yr^{-1} by increasing of 20-year the rotation length (Kaipainen et al., 2004). For boreal forests, extending rotations from 100 to 120 years for pine and spruce stands showed an increase in carbon sequestration ranging from 2.1 to 8.1 tCO_2 ha^{-1} yr^{-1} (Stokland, 2021), while a 10 to 30 years longer rotation period enhanced annual carbon sink in Finnish forests by 1.5 to 2.9 tCO_2 ha^{-1} yr^{-1} (Triviño et al., 2017). IIn Mediterranean regions, Chiti et al. (2024) report that extending the rotation period has a high potential for biomass carbon sequestration (~12 tCO_2 ha^{-1} yr^{-1}), but achieved mostly in monospecific plantations, and although effective for carbon sequestration, it may be not compatible with the sustainability criteria of many of the carbon schemes that are promoting NbCS.

Harvest intensity reduction is one of the NbCS with higher potential in terms of carbon sequestration enhancement. This is because harvest reduction can increase the proportion of older, larger trees, thereby enhancing forest biomass carbon stocks (Schütz, 2002). However, it should be carefully considered that the permanence of this carbon may depend on the local disturbance regime: mature and taller trees are more susceptible to disturbances due to the so-called structural overshoot, which can negate or reverse carbon sequestration benefits (Brèteau-Amores et al., 2023; Senf and Seidl, 2021). Additionally, reduced timber harvest intensity can lead to leakage, where demand shifts to other areas, potentially causing deforestation elsewhere (Kallio and Solberg, 2018) and cancelling out any climate mitigation effect. Therefore, a complete halt to forest management is an extreme measure that should not be followed as it carries risks of leakage, as well as economic and ecological impacts, despite potential climate and biodiversity benefits (Langridge et al., 2023; Nagel et al., 2023).

5.5.3.2 Agroforestry

Livestock agroforestry systems, covering 15.1 Mha of European land (den Herder et al., 2017), enhance biodiversity and ecosystem services, such as carbon sequestration. This applies also to crops, where trees serve as windbreaks, shade providers (Ramachandran Nair et al., 2010), and improve soil fertility (Rolo et al., 2023). Carbon sequestration rates in these systems are influenced by various factors including tree species, age, location, and management activities, with positive CO_2 sequestration rates for both, soil (0.4-1.7 tCO_2 ha^{-1} yr^{-1}; (Cardinael et al., 2017) and above-ground biomass (0.5-19.4 tCO_2 ha^{-1} yr^{-1}; (Kay et al., 2019)). Ensuring the longevity of these systems through proper management is essential for sustained benefits.

5.5.3.3 Cropland

In agroecosystems, the main carbon pool is the mineral soil, as the majority of the aboveground biomass is exported to the market, with the exception of pluriannual and perennial crops. Therefore, the increase of SOC and reduction of GHG emissions from agricultural management activities are the main NbCS targets in agriculture. NbCS in agriculture encompass the portfolio of sustainable management practices that can lead to an increase in SOC compared to conventional management practices and critically depends on local pedo-climatic conditions and land use history (Bolinder et al., 2020). These management options include manure applications, aboveground crop residue retention, conservation agriculture, organic amendment, the use of cover crops and nitrogen fertilisation.

Petersson et al., (2025) present the most recent and comprehensive dataset derived from a systematic review of studies that measure annual SOC stock change in topsoil (0-30 cm) up to 150 cm of soil depth in Europe associated to different NbCS. Below, we report the main outcome of Peterson et al., (2025) (Table 16). The list of practices is then grouped in the main categories considered by Petersson et al., (2025).

On average, the practices that increase biodiversity (IB in Table 16)) may lead to a relatively small SOC stock increase compared to continuous cropping systems (CCS). However, more studies are needed and more samples at deeper soil depth should be taken to make the conclusions more robust, particularly for the establishment of edgegrows, silvoarable system, and silvopastoral system (Table 16). Peterson et al. (2025) found that the supposed benefits of reduced soil disturbance (RSD in Table 16) on soil CO_2 emission reductions and thus, climate change mitigation are overestimated. The review shows that no-tillage practices lead to an increase in topsoil SOC but a decrease at deeper layers (subsoil), while traditional ploughing distributes SOC more evenly, with less topsoil gain but increased subsoil carbon due to deeper root growth and lower microbial activity at deep layers. When broader soil depths are considered, the effectiveness of RSD in reducing SOC emissions compared to conventional tillage is questionable. Nevertheless, it should be considered that RSD approaches lead to a reduction in fossil fuel use for machinery operations and benefits for soil erosion reduction. There are evidences that the practice leading to increased SOC inputs (SCI in Table 16) and result in SOC accumulation above both, the initial levels prior to treatment and the business-as-usual scenario, particularly in the case of organic amendments and cover crops (Table 16). This positive effect on SOC is also observed in deeper soil layers, as detailed in Table 16.

Peterson et al., (2025) showed that shifting annual croplands to other uses generally results in increased SOC in the topsoil. This increase ranges from 0.33 tC ha^{-1} yr^{-1} when transitioning to Short Rotation Forestry (SRF), to 0.77 tC ha^{-1} yr^{-1} when converting to grasslands, and 1.08 tC ha^{-1} yr^{-1} when setting aside croplands for 20-years followed by a natural regeneration. In particular, the conversion of annual croplands to poplar plantations, especially in continental locations, leads to a reduction in SOC in both the topsoil and subsoil layers. A broader trend of carbon depletion in the topsoil, in some cases lasting many years, has been observed when permanent grassland is replaced by either natural or planted woody species (Alberti et al., 2011; Chiti et al., 2018). Set-aside has been shown to be the most effective option for increasing C sequestration.

Changes in management, and specifically to organic agriculture management led to a substantial increase of SOC stocks, while conservation agriculture shows a lower increase compared to organic agriculture.

Table 16. List of categories of types of Nature based Climate Solution (NbCS) and list of agricultural practices. We report also the information level, which is the number of studies used to generate the numbers indicated in Peterson et al., 2025. Peterson considered the following 12 practices: 1) cover crops (GM/Mu); 2) organic amendments (OA); 3) crop residues maintenance (R); 4) improved rotations (IR); 5) reduced soil disturbance (RSD); 6) establishment of hedgerows (HEDGE); 7) silvoarable systems (SLA); 8) poplar plantations (SRF); 9) organic management (ORG); 10) conservation management (CONS); 11) set-aside (SET-ASIDE) and 12) conversion of cropland into permanent grassland or pasture (G/P).

Category	Practices	SOC stock changes effects
Improved biodiversity (IB)	improved rotations (IR)	0.26 tC ha^{-1} yr^{-1} (n=5)
	establishment of hedgerows (HEDG)	0.125 tC ha^{-1} yr^{-1} for 100 m linear of natural or planted hedgerow (n=1)
	silvoarable systems (SLA)	0.35 up to 0.56 tC ha^{-1} yr^{-1} up to 150 cm soil depth (n=1)
	Silvopastoral systems (SLP)	−0.16 tC ha^{-1} yr^{-1} at 0–30 cm, while positive at 0–50 cm (0.49 tC ha^{-1} yr^{-1}) compared to meadow (n=1)
Reduced soil disturbance (RSD)	conservation tillage practices characterised by no or shallow non-inversion tillage including no tillage (NT)	0.17 tC ha^{-1} yr^{-1} at 0–30 cm, 0.00 Mg C/ha/yr at 40 cm, -0.15 tC ha^{-1} yr^{-1} at 50 cm
	minimum tillage (MT) at 10 cm depth	
	reduced tillage (RT) at 25 cm depth	
Soil organic carbon inputs (SCI)	crop residues (R)	0.16 tC ha^{-1} yr^{-1};
	organic amendment (OA)	OA vs unfertilised: median = 0.38 tC ha^{-1} yr^{-1}; OA vs nitrogen inorganic fertilised plots: median = 0.29 tC ha^{-1} yr^{-1}; (n = 26)
	cover crops (GM/Mu)	0.32 tC ha^{-1} yr^{-1} in European annual croplands with an average experimental duration of 18 years for the introduction of green manure or mulch cover crops (n = 22)
Land cover-change (LCC)	conversion of cropland to i) grassland/pastures (G/P)	0.77 tC ha^{-1} yr^{-1}
	conversion of cropland to orchards (ORCH)	−0.46 tC ha^{-1} yr^{-1} (n=9)
	conversion of cropland to poplar plantations (SRF)	0.33 tC ha^{-1} yr^{-1}
	Set aside of grasslands (SET-ASIDE)	1.08 tC ha^{-1} yr^{-1}
Combined carbon farming practices (CFP)	Combination of LCC, SCI, and RSD	0.89 tC ha^{-1} yr^{-1} in the 0–30 cm profile (n = 21)
Management change (MN)	organic agriculture (ORG)	0.92 tC ha^{-1} yr^{-1} in the 0–30 cm profile (n = 18)
	conservation agriculture (CONS)	0.70 tC ha^{-1} yr^{-1} in the 0–30 cm profile (n = 10)

Source: The list is taken from Petersson et al., 2025.

5.5.3.4 Peatlands

Rewetting and restoration of peatland/organic soils is one of the main NbCS (Buma et al., 2024). Due to higher emissions per area compared to other land uses, peatland soil restoration requires much less land compared to other mitigation measures and has therefore been prioritised recently (Leifeld and Menichetti, 2018). Peatland rewetting and restoration is already taking place in Europe, reducing the emissions, restoring long-term carbon storage, and potentially carbon sequestration. Peatland rewetting not only increases SOC but also has a strong effect on vegetation biomass, both above and below ground, depending on hydrological and local conditions (Schwieger et al., 2021). In colder climates peatland restoration and rewetting brings climate benefits on agricultural lands in shorter time frame. With drained peatland forest lands climate impacts of peatland restoration depend on site fertility and tree biomass and generally climate benefits are obtained during 100 to 150 years (Laine et al., 2024). Tannenberg et al. (2021) report that rewetting grasslands and croplands on drained peat soils in Europe saves up to 20 and 30 tCO_2 ha^{-1} yr^{-1}.

It should be noted that in many rewetted peatlands no net GHG sink will occur until after 2050, due to the potential offset of initial methane emissions. However, in the longer term (century), the positive effects of GHG emission reductions from rewetted soils dominate (Schwieger et al. 2021). Günther et al. (2020) showed that the radiative forcing of methane emissions does not undermine the mitigation potential of peatland rewetting as an important mitigation option in the land use and agriculture sector (Günther et al., 2020).

Forested peatlands are quite diffuse in Northern Europe, particularly in Finland and Sweden (Chiti et al., 2024). Continuous cover forestry (CCF) is a management option that can help to control peatland water table levels, which plays a role in reducing nutrient loading into waterways over the long term (through reduced nitrogen leaching), especially in Nordic countries, but also in the Baltic states and Poland. Additionally, these practices may help recover original peatland vegetation. The immediate climate benefits of CCF in boreal conditions relate to the avoidance of clear-cuts that have significant GHG emissions (Korkiakoski et al., 2023; Lehtonen et al., 2023). CCF is a management practice potentially relevant for carbon farming in drained peatlands as it has the potential to reduce GHG emissions, but rewetting is the best option for safeguarding peat C storage (Tanneberger et al., 2021).

5.5.4 Co-benefits and potential trade-offs

Sustainable NbCS often focusses on carbon sequestration, which can also yield numerous co-benefits such as biodiversity enhancement and biophysical climate adaptation impacts. However, NbCS might involve negative trade-offs: biophysical impacts, such as changes in albedo, evapotranspiration, and sensible heat flux, nutrient cycle, methane that have varying regional effects on local climate. Current research elucidated the interplay between afforestation/reforestation, carbon sequestration and biophysical aspects in the US and Europe (Naudts et al., 2016; Novick et al., 2024). For instance, Barnes et al., (2024) showed that reforestation in temperate United States regions can provide biophysical climate adaptation benefits by means of the cooling surface and air temperatures. In Europe, a modelling study found a consistent increase in low cloud cover as a consequence of afforestation (about 3.5% on average), with variable magnitude and direction of this effect depending on various factors such as location, seasonality, and forest type (Caporaso et al., 2024).

This is still an area where research needs to provide more information to policy makers (Migliavacca et al., in review), particularly in Europe. The potential tradeoffs of NbCS in Europe are the interplay between the impact of afforestation/reforestation on carbon sequestration and water and nitrogen cycles, food security, and the interplay between reduced forest management and potential disturbance feedbacks. In terms of the effects of changes in forest cover on the water cycle, current research is mostly focused on large scale modelling with contrasting results (Hoek van Dijke et al., 2022; Teuling, 2024). Results point to an increase in precipitation as a result of increased forest cover thanks to higher transpiration, while there is considerable uncertainty in (i) the spatial pattern of this precipitation increase, and (ii) the relation of the increased precipitation water input with the increased transpiration water demand which consequently drives soil water availability. Increased sensitivity of vegetation to water availability is already observed in many regions. The related enhanced water supply to the atmosphere can lead to additional precipitation regionally and positive effects on cloud cover (Caporaso et al., 2024), but elsewhere the net effect on water availability is, however, often negative (Hoek van Dijke et al., 2022). This way, afforestation is only sustainable in places with sufficient water availability, and in regions where this is not jeopardized by climate change.

Beside the biophysical feedback, the potential leakages of NbCS should be considered. For instance, increasing rotation length may support biodiversity and recreation (Başkent and Kašpar, 2023), but risks like potential disturbances and timber harvest reduction, can lead to leakage effects like increasing wood import from other regions and enhancing harvest outside the EU (see Chapter 4). Thus, it is essential to balance extended rotation advantages with environmental suitability and associated risks.

Peatland rewetting is a key NbCS as described above. Rewetting of drained peatlands generally yields an immediate positive impact on climate change mitigation by significantly reducing GHG emissions, encompassing CO_2, nitrous oxide, and dissolved organic carbon fluxes, compared to the previously drained state. However, as methane production in anoxic soils is an unavoidable byproduct of peat carbon preservation and sequestration, peatlands rewetting often leads to an increase in methane emissions, a more potent greenhouse gas than CO_2 (Buzacott et al., 2024). Nevertheless, even with an initial surge in methane emissions post-rewetting, the long-term climate benefits of rewetting surpass maintaining the drained status. This is attributed to the shorter atmospheric lifetime of methane (~12 years, IPCC, 2021) compared to CO_2 and nitrous oxide, which accumulate over time. Continuous methane emissions reach a steady state where atmospheric concentrations stabilise, whereas CO_2 emissions lead to cumulative atmospheric concentrations and increased warming over time. Thus, the long-term climate impact of CO_2 is stronger than that of methane (Günther et al., 2020), emphasising the urgency of reducing CO_2 emissions, even if methane emissions are tolerated. Besides rewetting, afforestation of drained peatland was often suggested as potential NbCS. However, recent literature suggest that this is not a viable option because of the unclear result in terms of long term carbon sequestration because of the trade-off between carbon sequestration of the trees at the cost of enhanced soil respiration (Jurasinski et al., 2024).

5.5.5 Key-messages

- Nature-based climate solutions (NbCS) offer significant potential for climate mitigation while providing incentives, including additional income, for landowners;

- A comprehensive review of various NbCS highlights their potential for carbon sequestration across forests, peatlands, grasslands, and agricultural lands in Europe;

- Potential trade-offs, such as methane emissions and biophysical effects, when implementing NbCS, should be carefully evaluated.

5.6. The benefits of urban green

Kathrin Briem, Grazia Zulian, Sarah Mubareka

More than 70% of European citizens are living in urban areas. (Eurostat, 2022) This number is expected to rise further in the upcoming years to 80% of the European population living in cities, towns or suburbs (UN-Habitat, 2022). The growing amount of people living in urban areas highlights the importance of taking quality of life of urban dwellers into account to improve the quality of life of the vast majority of Europeans.

The quality of urban life is highly influenced by the urban ecosystem that is surrounding its citizens. (Grunewald et al., 2017). Whereas these social-ecological systems are heavily relying on artificial, built infrastructure, they also include biomass in the form of green spaces such as parks, forests, lakes, waterbodies etc., known as urban green spaces (UGS) (Zulian et al., 2022) UGS are widely acknowledged to contribute positively to the urban environment and make cities more liveable (Iungman et al., 2023; Kabisch et al., 2016)

UGS offer a variety of different social benefits. For example, they are spaces for recreation and leisure activities (Belmeziti et al., 2018; Kabisch et al., 2016; Sandström et al., 2006). When it comes to recreation, they are providing an escape of everyday life pressures, offering a place of wilderness and tranquillity within the city (Marafa et al., 2018). Leisure-wise, UGS offer spaces to meet up e.g., on playgrounds, BBQ areas, park benches etc. and therefore are contributing to an increase of social cohesion and cultural exchange (Belmeziti et al., 2018). Furthermore, the proximity to urban green correlates to a lower rate of mental health issues (Nutsford et al., 2013) as well as is contributing to a higher level of physical activity and hereby generally improving citizen's health (Romanello et al., 2023). Finally, yet importantly, from an environmental education perspective urban green spaces are providing early childhood experiences in nature which are then leading to a higher identification with nature and have the potential of laying the foundation for the development of a lifelong environmental concern (Oliver et al., 2022; Strife and Downey, 2009; Wolsink, 2016).

UGS also contribute to climate change mitigation and adaptation (Romanello et al., 2023). For example, UGS are taking over regulating services such as the reduction of heat intensity on a local level (Marando et al., 2022), the reduction of the risk of urban floods (Romanello et al., 2023) and carbon sequestration (Fuller and Gaston, 2009). In addition, with providing a habitat for urban flora and fauna (Chace and Walsh, 2006; Morelli et al., 2016; Pellissier et al., 2012; Tudorie et al., 2019) and therefore helping the conservation of biodiversity (Kabisch et al., 2016; Sandström et al., 2006).

As urban green spaces are more and more recognised as supporters of sustainability, they are also more and more part of international frameworks and EU policies. For example, they are mentioned within the SDGs (United Nations, 2015) and as a Nature Based Solution within the EU Strategy on Adaptation to Climate Change (European Commission, 2021) and the Nature Restauration Regulation (European Union, 2024).

5.7 Seaweed farming

Diego Macias Moy, Chiara Piroddi, Natalia Serpetti, Jean Baptiste Thomas, Céline Rebours

Seaweed cultivation emerges as a potential sustainable solution for meeting the European Union's (EU) biomass production needs without the need of land, freshwater and fertilisers, helping to remove excess nutrients (i.e, reducing eutrophication) and absorbing carbon. This section provides a synthesised analysis of the findings of a recent study (Macias et al., 2025) on seaweed farming, addressing the environmental, economic, and ecological dimensions of its viability as a renewable biomass source. Seaweed cultivation is primarily concentrated in Asian countries, with minimal activity elsewhere (Araújo et al., 2019 and 2021; Buschmann et al., 2017; Hughes et al., 2012). In the EU, 99% of seaweed production depends on wild-stock harvesting, while at global scale there is an opposite trend, with 99% of the production coming from cultivation (see Section 3.4 and Vazquez-Calderon et al., 2022). Hence, while presenting significant opportunities for diversifying and strengthening the EU's biomass portfolio, seaweed cultivation requires a balanced assessment to ensure its role as a sustainable option within the EU's blue economy (van der Burg et al., 2016).

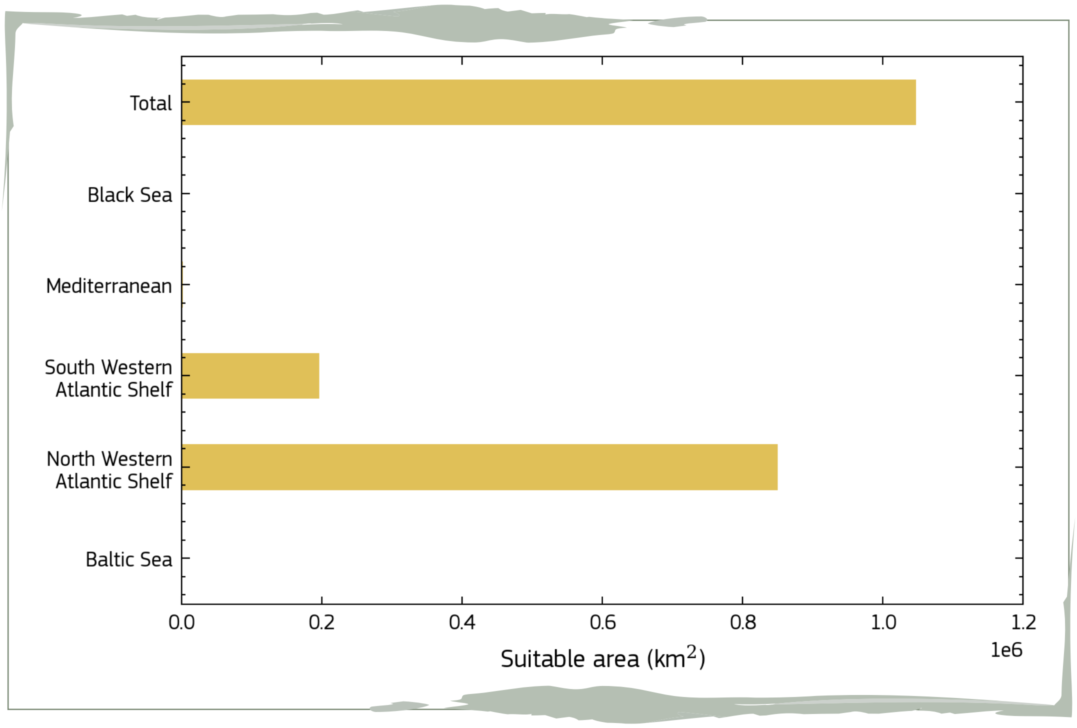
5.7.1 Seaweed as a Biomass Resource: An Overview

The EU's commitment to sustainability and self-sufficiency has spurred the exploration of alternative biomass sources (COM(2021) 236 final). The European Commission has set an action plan for EU that did a gap analysis and identified 23 specific policy actions aiming to unlock algae potential in the EU. Seaweed (or marine macroalgae), with its minimal cultivation requirements and versatile applications, stands out as a promising candidate. As a rapidly growing marine resource, seaweed does not compete for arable land and has a negligible need for freshwater and fertilisers (when cultivated at sea), distinguishing it from traditional terrestrial crops, although proper consideration of other maritime activities is needed (through Maritime Spatial Planning). Seaweeds can be used for food production (Nayar and Bott, 2014; Roleda et al., 2010), feed (Mac Monagail et al., 2018), feedstock for the bio-based economy (Stévant et al. 2017; Helmes et al. 2018), pharmaceutical applications (Kang et al., 2016), cosmetics (Couteau and Coiffard, 2016), bioremediation, i.e.,removing pollutants from the aquatic environment (Elizondo-González et al., 2018), CO_2 sequestration (Zhang, 2012; Alevizos & Barille, 2023; Wu et al., 2023), and alleviation of eutrophication problems (Kotta et al., 2022).

5.7.2 Environmental Suitability for Seaweed Cultivation

The capacity for seaweed cultivation depends on environmental factors that regulate the growth rates of the different species. Hence, a detailed assessment of the suitability of all EU marine regions for seaweed cultivation is crucial for the strategic development of this resource. Macias et al. (2025) utilised the World Offshore Macro Algae Production Potential (WOMAPP) model (Van Oort et al., 2023) to assess the environmental suitability of EU marine regions for seaweed cultivation. The Atlantic-facing regions, specifically the North Western and South Western European Shelves, were identified as the most promising, with over a million square kilometres deemed suitable for cold-water and intermediate-water seaweed species (Figure 94). A conservative estimate suggests that using just 1% of these areas could yield significant biomass contributions in the order of 30 Mt D.W. yr^{-1} (million tonnes dry weight per year), indicating the scalability of seaweed farming for biomass production in the EU.

Figure 94. Area deemed suitable for cold and intermediate-water seaweed species.



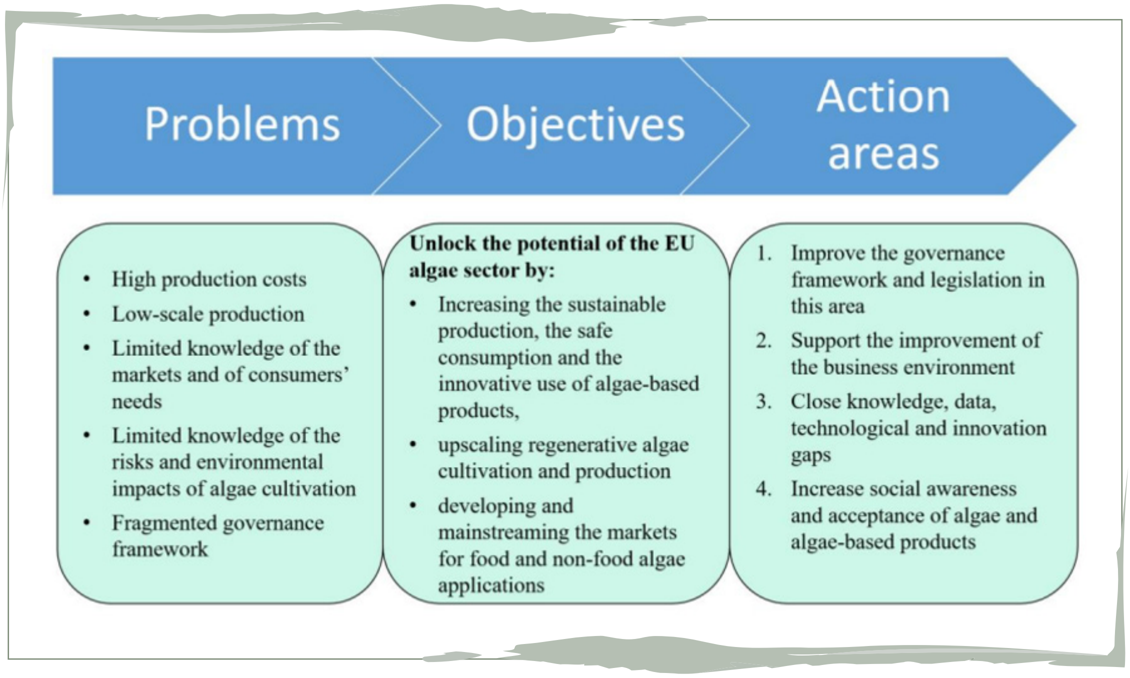
Source: Macias et al. (2025).

Integrating seaweed farming with other aquaculture activities, following the concept of Integrated Multi-Trophic Aquaculture (IMTA, Neori et al., 2004), is also a promising avenue. IMTA presents a synergistic approach to aquaculture, combining the cultivation of seaweed with finfish cultures to utilise the nutrients from fish excretion for macroalgae growth, thereby mitigating eutrophication near farming sites. This integration alleviates, on the other hand, nutrient limitations that restrict seaweed growth, expanding the feasibility of cultivation in nutrient-poor regions such as the Mediterranean or Black Sea basins (results not shown in Figure 94).

5.7.3 Economic Considerations and Market Dynamics

The economic landscape for seaweed cultivation within the EU is characterised by notable challenges, including high production costs and limited market demand prices (van den Burg et al. 2016; Bak 2018; STECF, 2023). See below the main gaps and objectives to address them as identified within the EU Algae Initiative (Figure 95, see also section 3.4)

Figure 95. Problems, objectives and proposed action areas for EU algae-related initiatives as defined by the EU Algae initiative.



Source: EU Algae initiative.

Strategies to improve economic feasibility could include scaling up production to achieve economies of scale, optimising supply chains, and targeting high-value market segments for seaweed-derived products (Gereffi and Lee, 2016; Gereffi and Fernandez-Stark, 2016; van den Burg et al., 2021). Additionally, the environmental services provided by seaweed, such as nutrient uptake and carbon sequestration (up to 600 tC $km^{2\ [-1]}$ $yr^{[-1]}$ (tonnes of carbon per square kilometre per year)), could justify government support, potentially through subsidies or incentives, to stimulate growth in this nascent industry.

5.7.4 Potential Ecological Impacts and Management

The ecological impacts of seaweed farming must be carefully managed and quantified to ensure sustainability and avoid nature-negative effects. The EU approach could be to focus on smaller-scale cultivation while making higher added value products and utilisation of entire biomass (waste-free circular production).

While seaweed farms can provide habitats for marine life and help removing excess carbon and nutrients pollution, the potential for large-scale cultivation to disrupt marine ecosystems cannot be overlooked. Environmental impact assessments, solid data and knowledge are essential for understanding the full range of effects seaweed farming has on marine ecosystems and for ensuring that the industry's development does not compromise the EU's broader environmental objectives. Long term data on biodiversity and ecological impacts of wild and farmed seaweed sectors are still lacking (Cottier-Cook et al., 2016).

5.7.4.1 Impacts on biodiversity

Seaweed farming can have positive effects on local biodiversity as they can increase habitat complexity (offering refuge, nursery and feeding grounds to multiple species) (Buschmann et al., 2017; Heery et al., 2020). Also, by removing excess nutrients from the seawater they can help reducing local eutrophication problems and enhancing water quality (Verdegem, 2013; Thomas et al., 2022)

In some contexts, restoration or expansion of kelp forests and other macroalgal habitats can stabilise coastal ecosystems and support higher trophic levels, forming a basis for improved biodiversity (Eger et al., 2023).

However, seaweed cultivation can pose ecological risks if managed improperly. It can provoke the introduction of non-native strains (with risks for the local genetic diversity) or the transfer of epiphytes and pathogens to local populations (Campbell et al., 2019; Cottier-Cook et al., 2016; Loureiro et al., 2015; Visch et al., 202).

Large farms may, also, alter local hydrodynamic conditions, affecting light penetration to benthic communities and changing sedimentation patterns (Buschmann et al., 2017). Over time, those changes can shift community composition, sometimes displacing native algae and the species dependent on them (Rebours et al., 2014).

5.7.4.2 Disease emergence

High density monocultures can lead to conditions favourable to outbreaks of diseases that can affect nearby wild populations (Cottier-Cook et al., 2016; Gachon et al., 2010). Regular checks and using IMTA approaches (combining multiple trophic levels and different seaweed species) have the potential to limit large-scale pathogen outbreaks (Chopin and Tacon, 2021; Ellis and Tiller, 2019).

5.7.4.3 Management and research gaps

Despite recent efforts in increasing our understanding of the ecological implications of seaweed farming, there remains significant knowledge gaps (Bhuyan, 2023). Long term biodiversity assessments are rare, yet much needed to capture the multi-year population level response to changes in different environments (Spillias et al., 2023). Comparsions between monoculture and IMTA systems are needed to clarify best practices in diverse conditions (Ellis and Tiller, 2019; Alexander et al., 2016). Also, diseases and pathogen interactions demand close examination in potential farming sites, where early detection and advanced biosecurity measures can limit widespread losses (Cottier-Cook et al., 2016; Cain, 2024).

And last, but not least, the socio-economic dimensions of seaweed farming need to be properly assessed, from labour needs and local acceptance to regulatory frameworks, as they play a decisive role in shaping sustainable expansion of the activity.

5.7.5 Conclusions and way forward

This chapter is intended to provide the reader with an overview of seaweed cultivation's potential as a sustainable biomass source within the EU. It translates complex scientific findings into actionable insights, aiding in the formulation of informed policies and investment strategies. For a comprehensive understanding of the scientific methodologies and detailed results, the original research paper (Macias et al., 2025 and references therein) should be consulted.

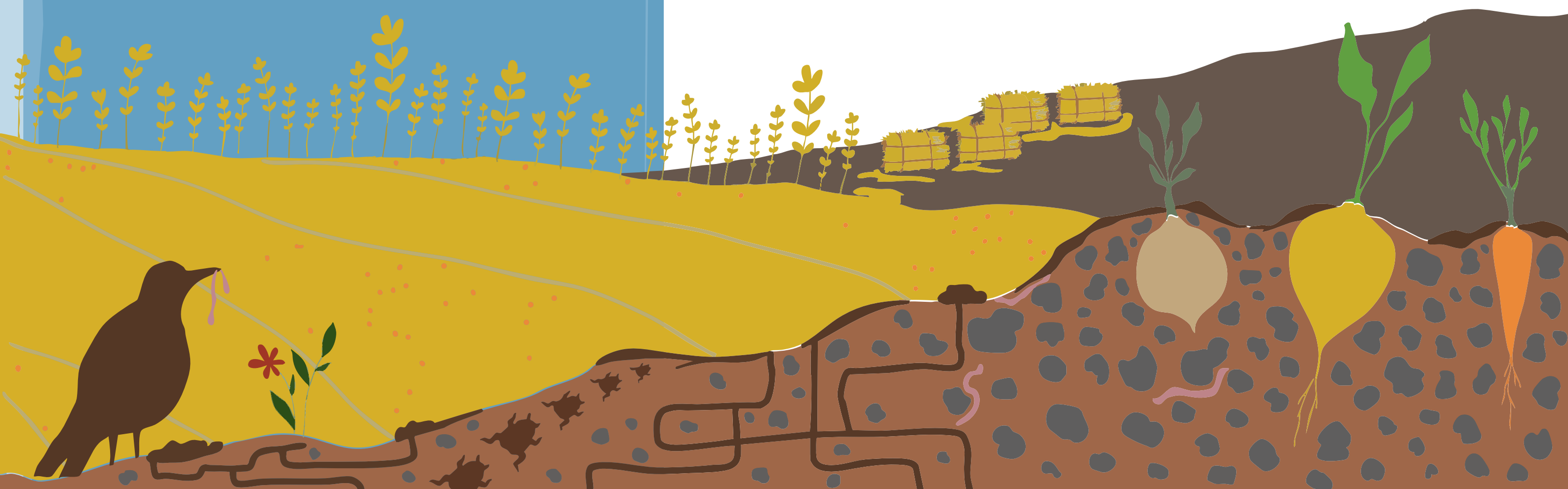
Seaweed cultivation offers a viable pathway for the EU to diversify its biomass sources while improving health of surrounding marine environment sustainably. The findings presented in this chapter highlight the need for a well-informed and cautious yet proactive approach to developing seaweed farming, balancing economic aspirations with environmental stewardship. It is crucial to approach seaweed farming scale-up expansion with careful consideration of both its potential and limitations. This chapter calls for a cautious, evidence-based development of seaweed farming, taking into account its economic viability and ecological impacts. As the EU seeks to augment its sustainable biomass supply, seaweed cultivation stands out as a promising option that requires further investigation, strategic planning (as stablished, for example, in the EU Algae initiative), and responsible management to realise its full potential within the EU's blue economy.

6 Sector-specific opportunities and challenges

6.1 Value added of biomass

Jesús Lasarte-López, Patricia Gurría, Francisco Javier Egea González, Robert M'barek

The European Green Deal (EGD) has set ambitious targets to transform the European Union (EU) into a fair, resource-efficient, and competitive economy. This includes reaching zero net emissions of greenhouse gases by 2050, decoupling economic growth from resource use, and leaving no person or place behind. To achieve this, the EGD foresees actions in different areas, which are specified in a set of strategies and transversal instruments (European Commission, 2019). In this context, the sustainable management



of biomass resources plays a fundamental role in advancing a green and fair transition. Biomass can serve as a source for 'bio-solutions', namely, renewable and more sustainable bio-based alternatives to non-renewable and/or fossil-based products and processes (e.g., biofuels or bioplastics), as well as ecosystem services such as climate regulation through carbon sequestration, water retention or recreational services.

In light of the above, the bio-based economy, understood as the set of activities that produce, transform, and use biomass resources, is indeed recognised in the EGD as a key enabler and result of transitioning to a green and fairer economy (European Commission, 2022), given its potential to offer solutions that promote sustainable production, reduce greenhouse gas emissions, and enhance ecosystem services, while creating economic opportunities and improving human well-being. Consequently, a growing number of public policies and strategies at all levels, from local governments to supranational institutions, are promoting the deployment of the circular bioeconomy model, based on sustainable management of biomass resources, including organic materials such as agricultural residues and food waste. Sustainable management involves efficient use of biological resources, including the cascading principle, and their regeneration. A circular bio-based economic model would enable the fulfilment of targets such as reducing waste, dependence on fossil fuels and pollution, in parallel to promoting economic development and creating jobs (Khanna et al., 2024).

One of the key dimensions of circular bio-based economy models and the sustainable management of biological resources is the value added generated from the utilisation and conservation of biomass. This includes not only economic value derived from its production, transformation and use in production processes, but also the benefits provided in terms of ecosystem services and GHG emissions saving through the potential phasing out of fossil fuels and materials. This chapter focuses on exploring the concept of value added with a focus on the economic benefits that can be generated through the production, transformation, and use of biomass resources. An overview on the value provided by ecosystem services is given in Chapter 7.3.

Although this chapter does not explicitly assess the contribution of ecosystem services or other environmental factors, it is essential to recognise that the relationship between biomass use and the environment is not a zero-sum game. Improving the efficiency in the use of biomass resources, such as through circular and cascading uses or the valorisation of organic residue streams, can increase the economic value added from biomass uses while also potentially generating environmental sustainability gains, like reducing waste. However, biomass valorisation processes are complex and typically involve uncertainties and trade-offs between economic benefits and environmental impacts. These trade-offs must be carefully considered and addressed to ensure that the economic and climate benefits of biomass valorisation are achieved without compromising environmental sustainability or climate neutrality.

6.1.1 Concept and quantification of value-added

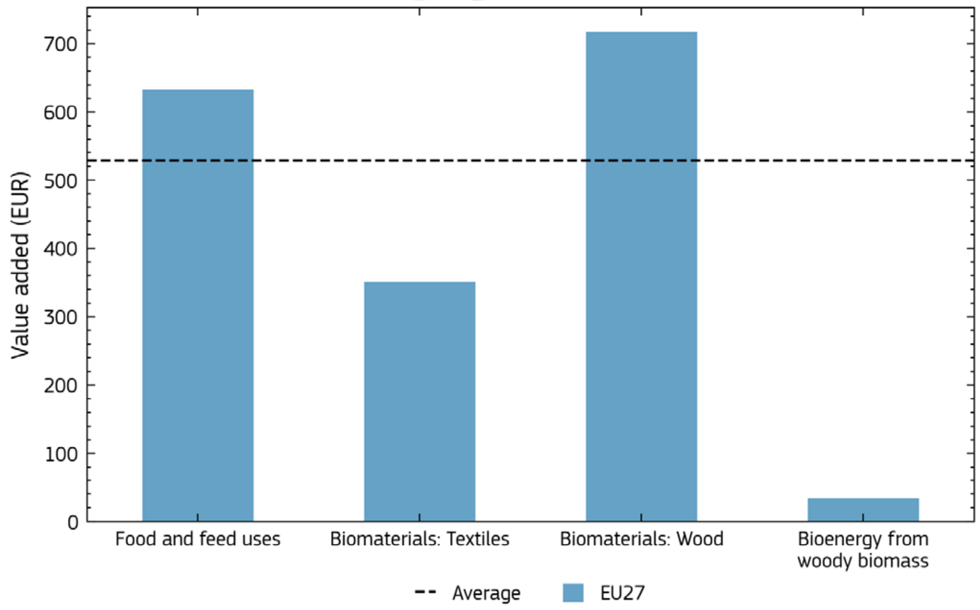
The valorisation of biomass resources from both primary and secondary sources is at the heart of a circular bio-based economic model. This valorisation can come from using bio-based inputs as alternatives to those of fossil-based origin, or from giving new uses (and value) to materials that traditionally had low value, such as residuals from the agricultural sector. Biomass valorisation is an intrinsic aspect of the implementation of bio-solutions, as it conditions their economic viability and, subsequently, their potential for scaling up and developing markets for bio-based products. This enables bio-solutions to become viable alternatives to fossil-based products, thereby addressing environmental and socioeconomic challenges (Khanna et al., 2024).

To give an overview on the current value added of processed biomass in the EU, we can combine data from two publicly available databases: data on biomass flows, extracted from Gurria et al. (2024), detailing origin and destination use, as well as indicators on value added in the bioeconomy sectors obtained from Lasarte-López et al. (2024). The objective of combining these two data sources is to estimate the value added generated per ton of processed biomass in the EU and its Member

States, also differentiating by type of use[31]. In our analysis, value added is related to output from the economic activity, while intermediate consumption (incl. energy) is related to input. We focus on the value added generated by biomass producing and processing sectors, regardless of inputs. This exercise is exploratory and should be understood as a starting point to identify patterns and insights from the main biomass value chains. To the best of our knowledge, this is the first attempt to quantify the value added generated by biomass flows. However, it has some limitations due to data availability, such as differences in biomass quality across sectors and Member States. Therefore, it is not intended as a comparison or competition analysis, but rather as a starting point for further research and discussions on the opportunities and challenges of biomass valorisation in the EU.

Figure 96 shows the value added generated per tonne of dry matter processed biomass in the EU in a selection of economic activities. While the average value per processed tonne of biomass in dry matter is estimated at around €529 in the EU in 2021, this value varies significantly across different applications. Notably, the value added from food and feed uses is above the EU average (€632). Wood used for wood-based materials also yields a high added value around €717. In contrast, the use of biomass for textile materials results in a value added below the average (€351). The lowest economic added value is obtained from biomass used for the generation of energy from woody biomass (€34).

Figure 96. Value added (euro) per tonne of processed biomass (dry matter) by selected uses (EU-27, latest available value).



Note: No differences in biomass quality are considered in the calculations shown in this chart.

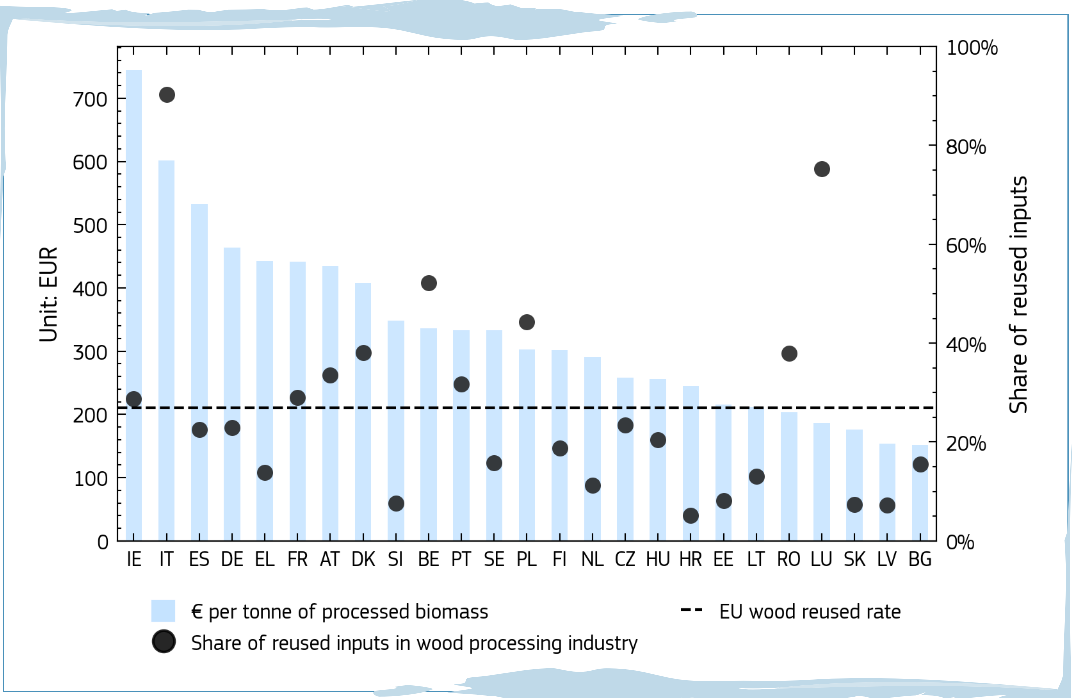
Source: Own elaboration with data from Gurria et al. (2024) and Lasarte-López et al. (2023).

[31] While these calculations allow for providing a general overview of the current value of processed biomass in the EU, some limitations may be acknowledged. The uses of biomass in Gurria et al. (2024) do not have a direct correspondence with the sectoral disaggregation in Lasarte-López et al. (2024), which limits the mapping between the two data sources to only some types of use/sectors. Additionally, many biomass flows have unknown origin or destination. This implies that there are sectors such as bio-based chemicals and pharmaceuticals for which no information is available, as well as other sectors, such as biofuels, for which the reliability of the results may not be representative. Consequently, no calculations are provided for these sectors. Last, the numbers are not adjusted for Purchasing Power Parity, which can affect the comparison between countries.

The activities using wood as input (biomaterials and bioenergy) illustrate very well the potential of a cascading use of biomass in terms of value added besides environmental sustainability. If not looking at the basic needs of biomass use (food and energy), a non-negligible portion of the higher value added of woody biomass processed for biomaterials can be attributed to reused inputs (by-products and, to a lesser extent, postconsumer wood). According to our calculations, the reuses are estimated to be around 16% of wood supply for biomaterials, although there are significant differences across Member States. On the other hand, the low economic value added of energy from woody biomass can be partially explained by lower quality of wood inputs and/or with no other potential uses (e.g., residues or thinning). However, according to estimates from Gurria et al. (2024)[32]approximately 60% of inputs for this use (equivalent to more than 40% of total roundwood supply in the EU) are not recycled from other production processes, but directly used for energy, dominantly as fuelwood. The implications of this fact suggests that there could be room for increasing resource efficiency in the use and valorisation of woody biomass.

Figure 97 illustrates the value added per tonne of dry matter of biomass processed by country. In general, the food and feed uses are the main component explaining the value added from biomass. This means that those countries generating higher value per ton of biomass are also those yielding elevated values from food and feed processing (usually Western countries more specialised in high quality food products, such as Italy, Spain, Germany, Greece or France. In these countries, the food production sectors have the potential to act as the main driver to advance towards a circular bioeconomy model (see Box 19) for a case study on the province of Almería in Spain). Besides the food and feed uses, another important factor is the proportion of reused inputs over total biomass inputs in the wood-processing sectors. Thus, the countries with a higher proportion of reused inputs for biomaterials also tend to generate higher value added from biomass processing. The countries with lower value added per processed biomass also show shares of reused inputs below the EU average, with the exception of Romania and Luxembourg.

Figure 97. Value added (euro) per tonne of dry matter of processed biomass by selected EU Member States, last available year.



Source: Own elaboration with data from Gurria et al. (2024) and Lasarte-López et al. (2023).

[32] Data from 2017 reporting because as described in section 3.2.3.1, there is no usable datasaet at EU level available after that year

The transition to a circular bioeconomy model can have potential benefits for most countries. For this, applying a selective approach to prioritise biomass uses and implement the cascading principle can help increasing resource efficiency, therefore generating higher economic value added from lower net biomass inputs. Additionally, this can create environmental benefits, although uncertainties and trade-offs must be considered (such as energy intensity of the bio-based process compared to its alternative). While some countries may have an initial advantage in generating higher economic value added from biomass due to their existing industrial specialisation, others can still increase their economic value added by adopting practices that promote the reuse of inputs and efficient resource use. In fact, successful cases in countries with different economic and sectoral profiles suggest that there is room for collaborating and sharing best practices between different actors to generate synergies and accelerate the transition across all countries.

6.1.2 Key messages

The development of a circular bioeconomy can be a key driver for achieving the EGD objectives and the green and fair transition. Within circular bioeconomy models, biomass valorisation can increase resource efficiency, reduce waste, and promote the circular bioeconomy, including the utilisation of organic waste streams and residues from agriculture, forestry, and other industries. The information presented in this chapter suggests that there is room for improvement in resource efficiency, both in the agricultural sector (see Box 19) and in the use of woody biomass.
By prioritising sustainable biomass management, promoting the reuse of inputs, and adopting efficient resource use practices, the EU and its Member States can move closer to achieving their targets for a green and fair economy. To achieve this, it is essential to foster cooperation among different stakeholders, including governments, businesses, researchers, and civil society, to share experiences and knowledge. However, despite the potential benefits, the valorisation of biomass also faces some challenges, such as the required investments and technological uncertainty, as well as potential trade-offs between economic costs and environmental and climate impacts that can offset potential benefits, especially in the context of growing global demand for bio-based products (Khanna et al., 2024). In this sense, it is essential to consider that the successful implementation of a circular bioeconomy model in the EU will depend on careful consideration and addressing of the trade-offs between economic, environmental, climate and social factors. The findings of this analysis provide a foundation for further research and policy discussions, emphasising the need for continued innovation and collaboration to unlock the full potential of the circular bioeconomy in the EU.

Box 19. **From horticulture to bioeconomy: Opportunities from biomass valorisation in Southeast Spain**

As bioeconomy clusters and initiatives are becoming increasingly more frequent in Europe, one of many cases that can illustrate the opportunities of a circular bio-based economy is located in the Spanish southeastern province of Almeria. During the last 50 years, this province has developed an efficient agro-industrial complex, with intensive horticultural production being the main economic activity, and with a capacity of generating around two million tonnes of biomass per year. This complex occupies around 3% of the land, creates more than 45% of employment in the province, both directly and indirectly, and exports more than 70% of its production. In recent years, Almeria has been developing a transformation towards a circular bio-based economy model that prioritises the valorisation of biomass and waste reduction. This shift is driven by the need to address major sustainability issues, such as the management of agricultural residues, water scarcity, or adaptation to climate change (Egea et al., 2018).

The province of Almeria is a case study of how representatives of the so-called quadruple helix (including public administration, universities, companies, and civil society) are collaborating to propose and implement innovative solutions that enable advancing towards a circular bio-based economy model that addresses the challenges of sustainability while creating economic opportunities. According to Egea et al. (2021), the main areas of action in this transformation process are (1) biomass valorisation, (2) shift to bioinputs, (3) transition from linear to circular value chains, and (4) societal impact.

The valorisation of biomass is a crucial aspect of the bioeconomy in Almeria. The biomass generated from intensive agriculture, including residues from crops, can be converted into high-value products such as biomolecules or biopolymers, with high potential for innovation and market access. One example are the furanic blocks, such as 5-hydroxymethylfurfural (HMF), which is a major topic in green chemistry given its applications for alternative bio-based chemicals and bioplastics. Another relevant area for biomass valorisation is the production of biofertilisers and biostimulants. Biostimulants are formulated products of biological origin that improve plant productivity, and they can be derived from biomass or other biological sources, such as microalgae. These bio-based products have been shown to increase crop yields and improve plant health while reducing the environmental impact of traditional fertilisers (Egea et al., 2021).

European funding programs for R&D such as Horizon 2020, Horizon Europe, and CBE-JU, have significantly contributed to the advancement of the above-mentioned novel bioproducts. Recently, ongoing efforts are focused on scaling-up technologies for the production of building and insulation materials based on lignocellulosic fibers obtained from the greenhouse plants. This helps connect with initiatives like EU Smart-cities and boosts the link between rural areas and more developed coastal regions.

As a result, a bioeconomy-based territorial cluster is emerging in the province of Almeria, encompassing all economic activities centered on the valorisation of biomass from horticulture for new uses and technologies. This cluster is expected to play a key role in the development of the bioeconomy in the region, given its potential to facilitate collaboration and knowledge-sharing among agents from the quadruple helix, and foster innovation and entrepreneurship. Additionally, the growth of biotechnology laboratories in the province is contributing to the economic diversification of the local economy. Public administrations are actively promoting this new cluster as a means to address the challenges of the province, including environmental issues, socioeconomic development, job creation, and imbalances between urban coastal areas and rural inland ones (Egea et al., 2021).

6.2 Biomass for the energy transition

Vincenzo Motola, Nicolae Scarlat, Michele Canova

6.2.1 Background

6.2.1.1 Biofuels

The RED updated and aligned the RES targets for 2030 with the more ambitious EU climate targets, including the ones for the use of renewable energy in transport. Electrification of road transport is a key objective, biofuels are expected to contribute mostly to sectors that are difficult to decarbonise, such as aviation and maritime.

While biofuels produced currently in the EU are mostly conventional biofuels produced from food- and feed-based crops, their production was limited as response to the concerns related to their potential negative impacts and sustainability constraints. Therefore, to reduce their impacts and the Indirect Land Use Change (ILUC) effects, the ILUC Directive 2015/1513 and the RED limited the share of biofuels produced from food and feed crops and reduced the share of high ILUC-risk biofuels to zero in 2030. The Commission Delegated Regulation identifies "high-ILUC risk" biofuels based on land expansion into high-carbon stock areas with higher than ten percent since 2008 with an annual expansion of more than one percent. Until the end of 2030, the use of high-ILUC risk biofuels shall gradually decrease to zero. Low ILUC-risk biofuels are exempt from the gradually decreasing limit. Low ILUC-risk biofuels are fuels produced from feedstock within schemes that avoid displacement effects through improved agricultural practices and prevent the cultivation of crops on areas which were previously not used for crop cultivation.

The use of bioenergy to decarbonise the transport sector within the low-ILUC boundaries prescribed by the RED could contribute to nature restoration. The cultivation of degraded lands could take place in areas and by adopting techniques that restore soils: by choosing selected energy crops and their subsequent processing for energy use, pollutants could be removed from soils and nutrients can be left into them, thereby enhancing their fertility (e.g., also by adding biochar derived from the energy-crops). A significant part of biofuels will be used in hard to decarbonise sectors, namely aviation and maritime sectors, as RED III extends the scope of 2030 target to maritime and aviation. This leaves little space for an increased use of biofuels in the light-duty road transport sector, especially as the electrification of light-duty road transport is increasing and is supported through the Alternative Fuels Regulation (EU 2023/1804) which ensures minimum infrastructure to support the required uptake of alternative fuel vehicles across all transport modes and in all EU Member States to meet the EU's climate objectives. Overall, while the use of crop-based feedstock to produce biofuels is limited by the production cap, the demand of further advanced biofuel may be driven by the decarbonisation of aviation, maritime and possibly road heavy transport.

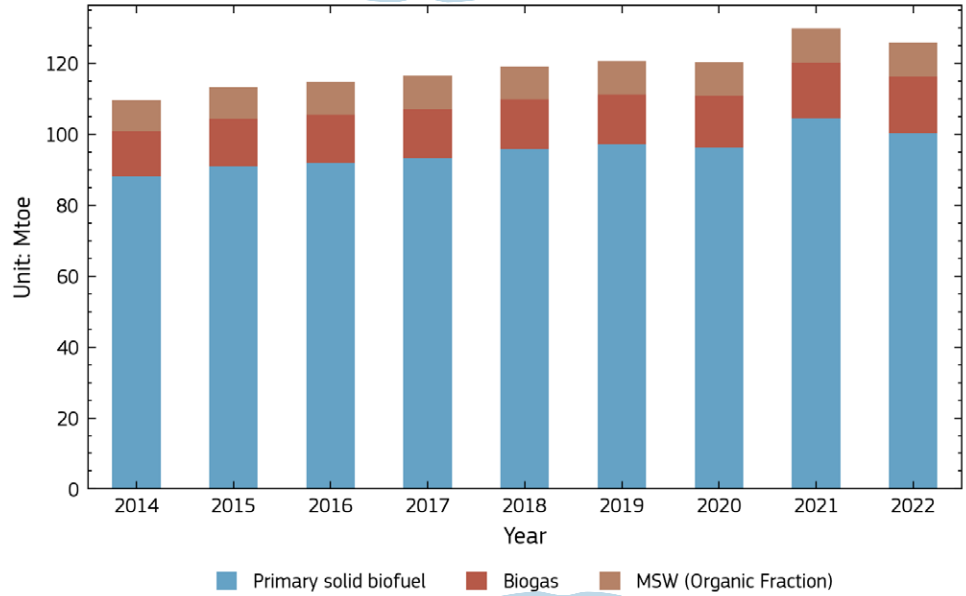
Biofuels are the key option for the decarbonisation of the aviation and maritime sectors and indeed contribute to the targets imposed by the ReFuelEU Aviation and FuelEU Maritime regulations to decrease GHG emissions. ReFuelEU Aviation aims at promoting sustainable aviation fuels through a blending mandate for fossil suppliers to reach an increasingly high level of sustainable aviation fuels into jet fuel, including synthetic fuels. FuelEU Maritime sets a limit on the GHG content of the energy use in ships decreasing over time compared to the fleet average in 2020, where biofuels can play an important role. Eligible biofuels include advanced biofuels (e.g., produced from biofuels produced from waste and residues feedstock listed in Part A of Annex IX of the RED) and biofuels produced from Part B of Annex IX of the RED. The biofuels produced from food and feed crops are not considered eligible for both aviation and maritime sectors. Some residues, waste or ligno-cellulosic feedstocks started to be used for advanced biofuel production.

Biofuels produced from food and feed crops are not eligible to contribute either to maritime or to aviation sectors, under ReFuelEU Aviation and FuelEU Maritime regulations but are eligible under the RED, as amended, and ETS. Biofuels from food and feed crops are produced from starch-rich crops, sugar crops, or oil crops produced on agricultural land as a main crop. Commonly produced biobased fuels are biomethane, biodiesel, other renewable diesel, bioethanol, biogasoline.

6.2.1.2 Heat and power

As for the production of heat and power, the production of bioenergy feedstock (mostly biomass fuels) more than doubled in the EU from 60 Mtoe in 2000 to more than 120 Mtoe in 2022 (Figure 98 shows trend from 2014 onwards).

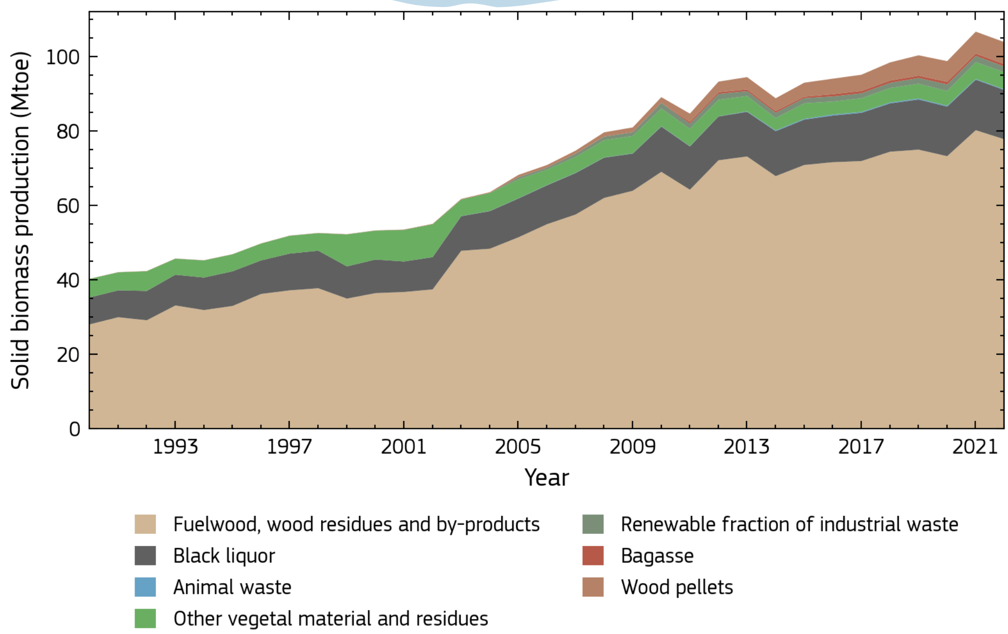
Figure 98. **Bioenergy feedstock used for heat and power in the EU.**



Source: Eurostat, 2024.

Solid biomass bioenergy production and use peaked in 2022 at around 100 Mtoe per year and it is by far the most used bioenergy feedstock used for heat and power. Fuel wood, wood residues/by-products form around 80% (disaggregated data is unavailable) of all solid biomass feedstock used for heat and power (Figure 99).

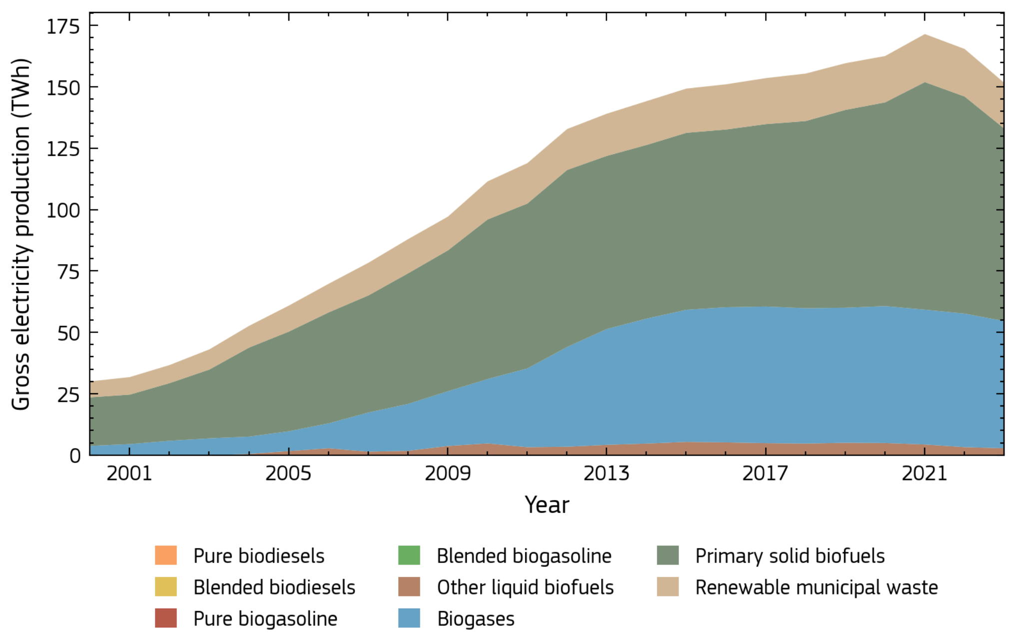
Figure 99. **Solid Biomass bioenergy production share in the EU.**



Source: Eurostat, 2024.

Electricity generation from biomass has increased significantly in the European Union, from 30 TWh in 2000 to almost 175 TWh in 2021. The annual growth rate of electricity generation seems to be decreasing in the last years. Solid biomass, with an increase from 41 TWh in 2005 to 93 TWh in 2021, is the main contributor to biomass electricity generation, with a biomass feedstock share decreasing from almost 66% in 2000 to just above 54% in 2021, due to the strong growth from biogas electricity and from the use of biomass waste. Significant progress has been achieved in biogas electricity from 8 TWh in 2005 to 56 TWh in 2016. The share of biogas electricity increased significantly from 13% in 2005 to 31% of total biomass electricity generation in 2021. Electricity generation from the organic fraction of municipal waste (Renewable Waste) has also increased from 11 TWh in 2005 to 19 TWh in 2021, with a share decreasing from 17% to 11% in 2021 due to higher growth from solid biomass and biogas electricity generation (Figure 100).

Figure 100. **Evolution of biomass electricity production in the EU.**

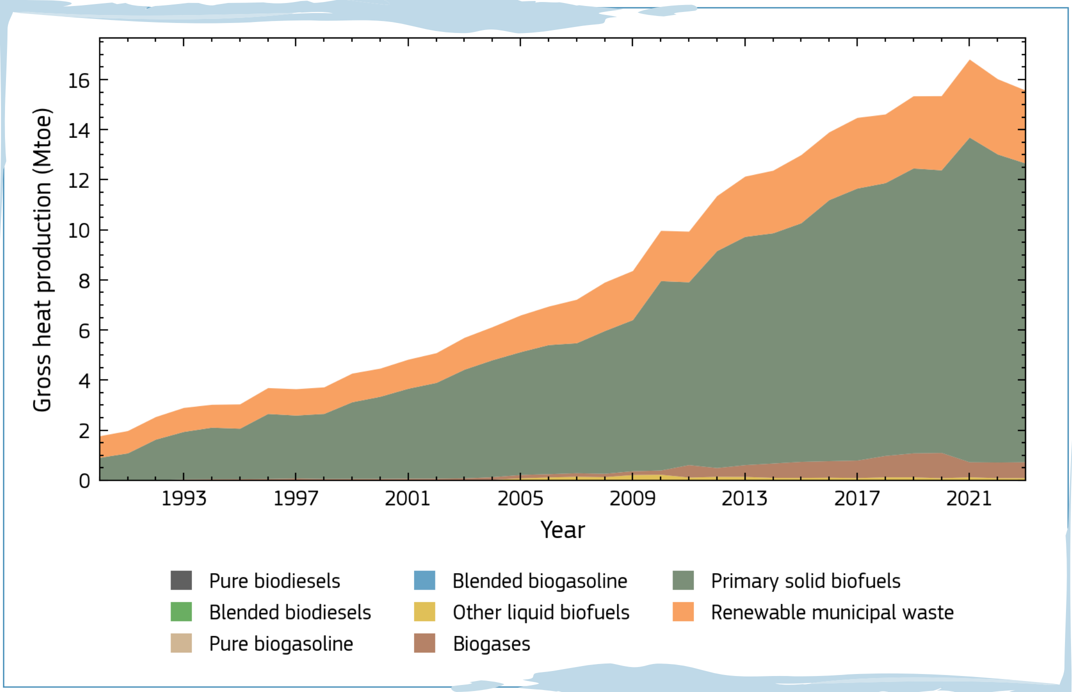


Source: Eurostat, 2024.

Biomass is the largest contributor to renewable heating and cooling. While biomass heating grew from 6.2 Mtoe to above 16 Mtoe between 2005 and 2021, its share in renewable heating decreased slightly from 94% in 2005 to 80% in 2021 due to higher growth of other renewables. The main contributor of biomass in renewable heating is solid biomass (forest and agricultural residues, wood pellets and various waste, including municipal solid waste). Although the use of solid biomass in heating increased, its share in biomass heating decreased from 97% in 2005 to about 80% 2022, compensated by the share increases of biodiesel and biogas. The use of municipal renewable waste also has seen a considerable increase, related to the deployment of waste to energy plants producing combined heat and power. An important increase, in relative terms, came from the use of biogas from a contribution of 1% in 2005 to 5% of biomass heating in 2022.

The use of heat from biogas has increased as result of the need to improve the economics of biogas plants through additional income, or measures to promote the use of heat from CHP plants in the European Union, displaying a slower progress in biogas heat use than in the electricity generation (Figure 101).

Figure 101. Evolution of the gross heat production from biomass in the EU.



Source: Eurostat, 2024.

6.2.2 Description of problem

The current fossil fuels consumption including in the transport sector is contributing greatly to the overall GHG emissions in the EU and in the world. The needed replacement of those fossil fuels in the different transport sectors may occur through a full technology switch, e.g., by switching means of transport in favour of electrified versions or by replacing fossil fuels with renewable or low carbon drop-in fuels, including biofuels, that could be used in existing fleets, possibly after some part replacement (e.g., gasket, nozzles, injection systems, pumps).

In heat and power production, while biomass offers an alternative to fossil fuels to a certain extent, the promotion of the cascading principle is expected to shift partially feedstock uses (Haudenschild, 2023).

6.2.3 Key messages

Biofuels from food and feed crops are transitional biofuels in transport decarbonisation, until advanced biofuels emerge, and they are capped to up to 7% share. Advanced biofuels and low-ILUC fuels (see section 3.1.4), biomethane and bio hydrogen could contribute to replace fossil fuels in the transport sectors and for those means of transport for which the technology switch has not occurred now and is not currently expected to take place massively in the next 15 years. This may mean in particular the aviation and maritime sectors, but also some existing road and railway vehicles which could remain in service until and beyond 2040 (e.g., last cars and vans sold until 2035, trucks, emergency vehicles, ambulances, long-range buses, but also agriculture, logistic, industrial, mining internal-combustion-engine machineries). It would be important to put in place a range of simple check and fix actions to make sure that existing fleets are capable to use alternative fuels without mechanical problems.

A similar reasoning is valid for hard-to-abate GHG emissions from certain energy intensive industries where the electrification may not easily bring the needed high temperatures or where the switch would require and complete (and lengthy) overhaul of the technology. In such a case the needed time for the construction of the new plants may suggest a transition period during which biofuel, biomass fuel, biomethane and bio hydrogen could be part of the solution jointly with other renewable/low carbon fuels.

In terms of feedstock availability, some biomass feedstock could be freed from sectors where electrification is taking place more rapidly (e.g., the power and heat sectors, although it remains to be seen to which extent, also in consideration of the additional energy demand due to emerging needs). Such feedstock could contribute to the energy transition in sectors that are more reluctant to electrification, although non-energy sectors may compete for the same resources until the cascading principle is extensively enforced.

There are a lot of diseases (pine beetle, etc.) and issues (extreme weather events, storms and forest fires) affecting some forests. These issues must be addressed by selective cutting and removal of affected trees or forest residues, whose best use is energy as they cannot be used for materials nor other industrial uses (e.g., chemical industry). This is beneficial for both nature restoration and preservation and bioenergy production as well. However this feedstock cannot be relied upon as it is the by-product of unforeeable natural disasters.

6.3 Biomass and the European Bauhaus

Solene Gautron, Sarah Mubareka, Elena Zepharovich

With 98% market share of the mineral-based materials, our built environment is currently dominated by non-renewable carbon-intensive minerals, such as concrete, steel, asphalt, bricks, sand, and gravel (Trinomics et al, 2021). Timber presents desirable structural, thermal, and aesthetic qualities. It is a highly adaptable material, offering strength and stability while allowing for innovative designs. Wood is also central to many biophilic design principles, notably for its light and warm aesthetic, matched by natural thermal insulation properties that reduce the need for excessive heating and cooling systems.

Together with inclusion, sustainability and aesthetic are two of the core values of the New European

Bauhaus (NEB). The NEB is an initiative that was launched by the European Commission in 2020 as part of the European Green Deal, to promote a more sustainable, inclusive, and aesthetic approach to designing living spaces, cities, and economies. Building on the engagement of a strong community[33] and the active participation of Member States, the New European Bauhaus notably advocates for rethinking our built environment as part of the solution to the climate and biodiversity crises, with regenerative and circular approaches, and quality of experience as a core focus. The initiative supports projects across Europe with the aim of enhancing social acceptance of the green transition and democratic processes at the local level, boosting research and innovation in the construction sector, and enabling change through the emergence of new business and funding models.

6.3.1 Wood for construction

Section 3.2 sets the scene for the forest biomass production and uses, the reader is invited to consult there for data on forest resources, forest ecosystem condition and forest biomass uses. Here we focus on wood for construction.

While wood is a traditional building material in many regions of the world, especially North America and other northern regions, wooden or wood-walled buildings are not characteristic of European architecture. Wood construction in Europe has declined together with the decline of smaller-scale construction in general, as wood is used more extensively in houses compared to other buildings.

Most sawn wood consumed in European construction is used in one- and two-family houses and small buildings. Secondary wood is mainly used for other construction purposes, such as roof structures and joinery (flooring, doors, windows, stairs, cupboards, etc.) and in construction site use.

Data on wood for construction is very heterogeneous. What makes statistics difficult to track, according to Riihimäki (2023), is the versatility of the materials used: they can be used in many places and in different forms in construction. Construction largely consists of hybrid construction, which means that the shares and variables covered with statistics do not fully explain the overall use of materials. The same also applies to other construction materials besides timber. If a building is reported as timber-framed, it may still contain many other materials even in its load-bearing frame. On the other hand, a lot of wood may also be used in other building elements or secondary structures in non-timber-framed buildings (Riihimäki, 2023). Currently only a handful of European Member States collect data indicating the main material used for construction (Table 16). It is in number of houses, so it does not give an indication of how much wood is used. The trends are increasing in all countries (some show a slight decline in the last year). In Austria for example the use of wood in construction doubled in the last 20 years.

[33] Three years after its launch, the New European Bauhaus has a strong membership-based Community of local and international, profit and non-profit organisations, as well as representatives of public authorities, supporting its actions on the ground. The +1500 Community members operate in fields such as culture, education, research, architecture, heritage, forestry, construction and housing, or fashion. Meaningful engagement with the NEB Community is expected to intensify and evolve as the Community expands. The political guidelines for the European Commission 2024-29 include an enlarged NEB Community as one of the objectives for the initiative.

Table 17. **Table of wood for construction resources at Member State Level.**

Country	Years	Indicator	Link
Germany	1993-2023	Number of residential buildings, having wood as predominantly used building material.	*https://www.destatis.de/DE/Themen/Branchen-Unternehmen/Bauen/Publikationen/Downloads-Bautaetigkeit/baugenehmigungen-baustoff-xlsx-5311107.xlsx?__blob=publicationFile* (1993-2021) *https://www-genesis.destatis.de/genesis/online?operation=abruftabelleBearbeiten&levelindex=1&levelid=1721131634796&auswahloperation=abruftabelleAuspraegungAuswaehlen&auswahlverzeichnis=ordnungsstruktur&auswahlziel=werteabruf&code=31111-0006&auswahltext=&wertauswahl=67&werteabruf=Werteabruf#abreadcrumb* (2015-2023) *https://www-genesis.destatis.de/genesis/online?sequenz=statistikTabellen&selectionname=31111#abreadcrumb* Tabelle -31111-0006
Sweden	1995-2022	Dwellings in newly constructed conventional multi-dwelling buildings by materials in the frame of the houses.	*https://www.statistikdatabasen.scb.se/pxweb/en/ssd/START__BO__BO0201__BO0201M/MaterialiStommeFN/*
Finland			*https://stat.fi/*
Czech Republic	2000-2023	Completed buildings by Construction Materials	*https://csu.gov.cz/produkty/bvz_ts* Table 16 Completed buildings by Construction Materials
Bulgaria	2001	residential buildings by construction and material used	*https://nsi.bg/en/content/3135/newly-built-residential-buildings-completed* Only “other materials” online
Austria	2010-2024	Number of residential buildings, having wood as predominantly used building material.	*https://statcube.at/statistik.at/ext/statcube/jsf/tableView/tableView.xhtml*
Belgium		No public data, but private: Embuild (*https://embuildoostvlaanderen.be/nl/contact*) has knowledge Embuild is an “umbrella organisation” representing the interests of all construction companies.	
Denmark	2011-2024	Buildings and their floor area by outer wall material, unit, region and time	*https://www.statistikbanken.dk/BYGB60*
Lithuania	2019-2023	Number of new residential building completed | per cent	*https://osp.stat.gov.lt/en/statistiniu-rodikliu-analize?hash=bbc155f0-8a43-49bd-aaac-3bd4ae6ffc7d#/*

Source: JRC, own elaboration.

In countries where timber use in structures (new construction) is less predominant, the share of timber is accentuated in construction site use and in renovation. The construction site use of timber covers various protective and support structures, moulds, accessways etc. Most of the timber is only used once, but some of it can be used several times. In Europe, the share of new housing in total wood consumption is approximately one fourth. This makes new housing the most relevant category as regards timber product use, particularly in Finland (see Box 20). In renovation, timber products in existing buildings are replaced by new timber elements. However, the amount of wood in buildings typically increases when renovated. In façades, for example, the share of timber increases during the building life cycle as façades are being renovated (Riihimäki, 2023).

Box 20. Wood for construction in Finland

In Finland, approximately 45–50% of timber use in construction focuses on new construction, 30–35% on renovation, 8% on civil engineering and 12% on construction site use, mainly in new construction. In new construction, approximately 60–70% of timber products and volume used in Finland are accounted for by timber-framed buildings, which are classified as wooden buildings. Similarly in renovation, timber use is presumably mainly focused on timber-framed buildings. In Finland, timber use in residential construction accounts for approximately 70% of overall timber use in new construction. This is one third of total wood consumption in construction.

Timber is also widely used in small outbuildings and in the yard in general. In many countries, small outbuildings are excluded from construction statistics, but the timber use related to them is quite notable. In the example figures for Finland (Box 20), timber use in garden construction has been included in renovation even though a part of the use is surely comparable to new construction (Riihimäki, 2023).

6.3.2 The New Euroepean Bauhaus

Demonstrators that “showcase novel sustainable construction systems, like hybrid engineered wood products and building systems, and reused or recycled components and assemblies” are desirable (Schellnhuber, 2022). The New European Bauhaus responds to this need, notably through its annual NEB Prizes supporting innovative projects that could be scaled up and replicated. For the first edition of the NEB Prizes in 2021, the project Vivihouse, based in Austria, was amongst the selected finalists for its adaptable construction system for multi-storey buildings based on a modular timber frames assembled with sustainable materials such as straw bales for the insulation system and lime or clay plasters. Researching the potential market, new technologies (such as the use of AI, IoT sensors or robotics) and processes for the utilisation of primary and secondary bio-based materials (including underutilised hardwoods, low quality, damage, and post-consumer wood) is also key to enable the transformation of the construction ecosystem. To this end, a New European Bauhaus call for the climate-smart use of wood in the construction sector was launched under Horizon Europe in 2023, inviting stakeholders to explore new raw material sources and secondary material, technologies, and designs for wood components and buildings. In February 2024, a second call was launched for projects demonstrating the potential of Nature-based Solutions to contribute to sustainable, inclusive, and resilient living spaces.

6.3.3 Considerations for a future in wood for construction

New skills are needed to research bio-based materials, apply new building technologies, or design for circularity. For timber construction, we need to mainstream knowledge on the properties of wood (durability: fire resistance, humidity, endurance in time), the possibilities for diversification of wood species as well as modular and circular design (design for disassembly, etc). One of the main challenges for skill development in the sector is to scale-up existing knowledge: skill gaps are not the same at all scales of timber construction—SMEs and micro-enterprises hold technical skills applied to small-scale housing which need to be adapted for larger developments. To support the necessary upskilling and re-skilling effort and boost the transformation of the construction ecosystem, the European Commission launched the NEB Academy, a network of Hubs that will deliver online and in-person trainings on sustainable construction throughout Europe. The project, lead by a consortium of 14 partners across 11 Member States, has gathered the interest of many stakeholders at the forefront of education for sustainable construction.

The integrated approach of the New European Bauhaus also invites project developers to ask if building anew is the best solution. When possible, we must prioritise the transformation of our existing building stock over the rapid consumption of new materials and energy required to replace it. Many of the buildings we inhabit today will still be standing in 30 years. Yet almost three quarters of those buildings do not meet our current standard of energy efficiency. The Renovation Wave launched by the European Commission to address this challenge needs to be paired with life cycle thinking and circularity through the cascading use of sustainably sourced, but also affordable, materials. If we maximise our efforts to scale up the circular economy from front-runners to the mainstream economic players, we have a unique opportunity to make Europe a world leader in shaping an economy that is restorative and regenerative by design. This means supporting the construction industry as it develops technologies to clean, reprocess, and reintroduce building materials (including reclaimed timber) to the market in a systemically efficient manner. It also means supporting the industry as it transitions towards new business models, preserving value in the form of energy, labour, and materials.

6.4 Novel foods

Antonio Borriello, Hanna L. Tuomisto, Sarah Mubareka

The global demand for food is expected to increase significantly, driven by the steady growth of the world's population. According to recent projections by the United Nations, the Earth's population is anticipated to reach 10.4 billion by the year 2100. This surge in population will inevitably amplify the need for essential nutrients, particularly proteins.

Several key factors contribute to the rising demand for proteins. First, as economic conditions improve, higher incomes tend to correlate with increased consumption of protein-rich foods. Second, urbanisation plays a pivotal role; as more people migrate to cities, dietary habits shift toward greater protein consumption. Lastly, the ageing of the population further accentuates this trend, as older adults often require higher protein intake to maintain muscle mass and overall health (Andreoli et al., 2021).

As we report in section 3.1.3, approximately 80% of the total of the crop biomass consumed as food and feed in the EU is used as animal feed, for the production of animal-based food.

In this context, novel foods (see Box 21 for definition) such as foods derived from biomass (e.g., plant-based alternatives, insects) or from precision fermentation; and cultured food, are being considered as complimentary to the more traditional sources of food.

6.4.1 Description of novel foods

Novel foods (defined in Box 21), can be classified based on their source (e.g., plant-based, animal-based, or cell-based), production methods (e.g., genetically modified, cell-cultured), and their acceptance by consumers.

Some products, such as plant-based burgers, have been around for decades but only recently have evolved notably to mimic conventional meat closely and attract different categories of consumers.

Box 21. Definition of Novel Foods

Throughout this chapter, the terms "novel food" indicate categories of food that are not consumed to a significant degree in EU, such as insects, algae, plant-based food that attempts to mimic meat, cultured food, etc., and should not be confused with the definition reported by the Regulation (EU) 2015/2283.

Table 18. Examples of novel foods and their intended applications.

Product / Ingredient	Description	Application	Source
Algae (e.g., chlorella, nori, spirulina)	Algae are a diverse group of aquatic organisms rich in proteins, lipids, and bioactive compounds.	Food ingredients, supplements, biofuel, food fortification; dietary supplement, food additive, protein source	Pulz, O., & Gross, W. (2004). Journal of Applied Phycology ; Becker, E. W. (2007). Journal of Applied Phycology
Cultured meat	Meat produced through in vitro cultivation of animal cells	Meat alternatives, environmentally and ethically sustainable protein source	Post, M. J. (2012). Meat Science
Precision-fermented proteins	Bioengineered proteins produced through microbial fermentation	Food (dairy, egg, meat), beverages, nutraceuticals, pharmaceuticals.	Teng et al. (2021). EMBO Reports

Source: JRC, own elaboration.

The development of alternative food products has undergone significant advancements in recent years, with notable improvements in the formulation of plant-based alternatives. These innovations have enabled such products to closely replicate the characteristics of conventional meat, thereby expanding their appeal to a broader range of consumer demographics.

Additionally, certain culinary traditions have long utilised (macro)algae as a means of achieving umami and marine-like flavour profiles. More recently microalgae, such as spirulina, are emerging as an attractive food type due to their high nutritional value.

In the realm of industrial food production, both traditional fermentation and biomass fermentation techniques are employed to efficiently generate protein on a large scale, as exemplified by the production of mycoprotein. Furthermore, precision fermentation is utilised to produce a range of specific functional ingredients, including proteins, enzymes, vitamins, and fats.

Lastly, the emerging field of cultivated food technology involves the propagation of animal cell lines to replicate animal tissue, offering a novel approach to food production.

6.4.2 Environmental implications of novel foods

The monitoring of novel food uptake and environmental impact is essential to align with the EU's sustainable dietary goals. Many novel foods have been evaluated using Life Cycle Assessments (LCA), which show variability in environmental impacts depending on production scenarios (Parodi et al., 2018; Mazac et al., 2022; Tuomisto et al., 2022; Smetana et al., 2023; Box 22).

Box 22. **Environmental and Nutritional Considerations through the Consumption footprint framework**

The Consumption Footprint Framework developed by Sanyé Mengual & Sala (2023) allows the environmental impacts of novel foods to be compared with traditional diets across food categories. Integrating novel foods into this framework offers insights into their potential for reducing environmental footprints.

Plant-based alternatives (e.g., rapeseed powder, mung bean protein) generally have a lower environmental impact compared to animal proteins, although additional processing (e.g., for texture improvements) can raise their footprint (Colantoni et al., 2017; Smetana et al., 2023).

Insects, though variable in environmental impact depending on species and feed, can offer lower impacts if fed on food industry by-products (Halloran et al., 2016; Smetana et al., 2021).

Algae production has low land use but varies in environmental impact depending on species and cultivation methods (Braud et al., 2023). Systems using wastewater for nutrient supply (Calicioglu et al., 2021) offer additional environmental benefits.

Microbial proteins, produced from autotrophic and heterotrophic organisms, also show promise due to low land-use requirements. Gas-fermented organisms, for example, do not rely on agricultural land (Järviö et al., 2021a; Sillman et al., 2020). Notwithstanding the substantial energy requirements associated with microbial protein production (Smetana et al., 2015; Järviö et al., 2021b), the precision fermentation process often generates significant amounts of residual biomass, which can be leveraged as a feedstock to produce renewable energy. Moreover, the adoption of microbial protein as a substitute for traditional animal-derived products could have a profound impact on environmental sustainability, with the potential to reduce annual deforestation and associated greenhouse gas emissions by approximately 50% by 2050, assuming a scenario in which 20% of per-capita ruminant meat consumption is replaced with microbial protein alternatives (Humpenöder et al. 2022).

Only a few prospective LCA studies of cultured meat have been published to date, and the results show a high variation between the different studies. Contributing to this variation are the sources of nutrients and growth factors, the bioreactor design and the cell type (Table 19). Cultured meat production is generally considered to be more land-efficient and less climate-damaging than livestock, though its energy demands are significantly higher (Tuomisto et al., 2022; Sinke et al., 2023), and the source of energy used has a major influence on the climate impacts. Cultured seafood may need more land and freshwater than traditional fisheries but less than conventional aquaculture (Marwaha et al. 2022). LCAs indicate that the global warming potential (GWP) of cultured seafood, particularly when produced with conventional energy sources, may exceed that of both wild-caught and farmed fish. This higher GWP is largely driven by the substantial energy demands of bioreactors, which are crucial for cellular production (Telesetsky, 2023). However, cell-based seafood theoretically requires less energy than meat due to its physical and biological properties, such as the ability to grow at lower temperatures, although this has not yet been confirmed by LCA studies.

Table 19. Comparison of the climate impact and land use of cultured meat based on published life cycle assessments.

Source	Carbon footprint (kg CO^2-eq/kg cultivated meat)	Land use (m^2/kg cultivated meat)	Details
Tuomisto et al. (2011)	1.9–2.2	0.2	Cyanobacteria as a main source of nutrients in the culture medium, stir-tank bioreactor
Smetana et al. (2015)	23.9–24.6	0.4–0.8	Data mainly from Tuomisto et al. (2011), but cyanobacteria produced in bioreactors instead of open ponds
Mattick et al. (2015)	3.0–25.5	1.5–9.5	Chinese Hamster Ovarian cells, standard serum-free culture medium, stir-tank bioreactors
Tuomisto et al. (2022)	4.9–25.2	1.8–6.9	C2C12 cells, standard culture medium with and without FBS, hollow fiber bioreactors
Sinke et al. (2023)	2.9–14.3	2.5	Aggregated data from companies (several cell types and culture medium ingredients)
Kim et al. (2023)	15.4	0.08	Burger patty made of primary bovine cells, standard culture medium, data from a company

Source: Tuomisto & Ryynänen 2024.

6.4.3 Geographical considerations of novel foods

6.4.3.1 Regulations

EFSA has assessed and deemed suitable for human consumption some insect species, such as Acheta domesticus (house cricket) and alphitobius diaperinus (Lesser mealworm), however insects as foods still represent a very small niche market in EU.

Recently, more than 20 new algae species were added to the EU Novel Food Status Catalogue, bringing the total of species that can be sold on the EU market as food or food supplements to 60, covering several species of microalgae and seaweed derived products (such as extracts, or oils)[34]. Cultured food is not yet approved in EU, although EFSA is engaging with scientists and stakeholders to outline a fit for purpose approach for the assessment of animal cultured cells for food consumption (EFSA, 2024). Currently, a few companies have applied for approval to sell cultured meat in the EU (e.g., Gourmey for foie gras, Mosa Meat for beef), although the process will require several years to be finalised.

6.4.3.2 Geographical differences

According to the Good Food Institute database on alternative proteins (e.g., plant-based, cultured, fermentation derived), there are 553 companies with headquarters in EU Member States, covering the entire production chain (e.g., bioprocessing, cell-line development, manufacturing). Of these, about 40% are in Germany (146) and in the Netherlands (84).

[34] DG MARE, 2024. News announcement: *More than 20 algae species can now be sold as food or food supplements in the EU*

Algae production is predominantly concentrated within the European Union. According to the Food and Agriculture Organization (FAO, 2024), in 2022, France was the leading producer of algae, accounting for approximately 60,000 tonnes. Furthermore, France was the primary producer of algae in freshwater environments, whereas Ireland dominated production in marine environments. Additionally, the cultivation of algae in brackish water was exclusively undertaken in Portugal and Spain. While waiting for an official risk assessment of EFSA of cultured food, some European countries have taken divergent actions. For example, Italy approved a bill in November 2023 to ban any production, tasting and marketing of cultured food (Bottini et al., 2023). Shortly after, the French party Les Republicains introduced a bill in the National Assembly to prohibit the "production, import, export, marketing or placing on the market, free of charge or for a fee of [...] synthetic food and meat". At the end of 2024, Hungary has drafted an act to ban the production and sale of lab-grown meat, prompting a response from FEASTS (Fostering European Cellular Agriculture for Sustainable Transition Solutions, a consortium funded by EU), which argues that the ban is unwarranted.

Opposite actions were taken by the Dutch government. In 2023, the Netherlands became the first EU country to make pre-approval tastings of cultured food possible. This action aligned with a €60 million investment plan to create a cellular agriculture hub in the country.

6.4.4 Economic and social considerations of novel foods

6.4.4.1. Consumer acceptance

The ultimate test of a novel food's viability lies in its ability to gain acceptance from consumers. Regardless of its potential benefits, such as being cost-effective, environmentally friendly, safe and nutritious, a new food product will ultimately fail if it does not resonate with consumers and drive sales.

A systematic review by Onwezen et al. (2021) highlighted differences in consumer acceptance of alternative proteins. Plant-based alternatives (e.g., pulses, plant-based meat) are the most accepted, while insects and cultured meat face significant acceptance barriers. Drivers of consumer acceptance include taste, health perceptions, familiarity, and social norms (Tuorila & Hartmann, 2020). The study found that consumers who eat large amounts of meat were more open to cultured meat than plant-based alternatives.

In addition to the organoleptic characteristics, the major drivers of consumer acceptance of cultured food are public awareness, perceived naturalness, and food-related risk perception (Pakseresht et al., 2022). An additional key consideration is the naming and labeling of cultured food. Studies show that the terms used on packaging can greatly influence consumer perceptions and acceptance (Malerich, Bryant, 2022).

6.4.4.2 Industry and Research on Novel Foods

Several key industry and research initiatives are driving the development and market uptake of novel foods:

- The Good Food Institute Europe and Innova Market Insights focus on alternative protein innovations, providing insights into consumer trends and technological advancements.

- GIANT LEAPS is an EU-funded project aiming to reduce knowledge gaps of the various alternative proteins (e.g., plants, microalgae, and single-cell proteins) in terms of environmental aspects, health and barriers to adoption in support to the long-term objective to reduce animal protein consumption in Europe by 50% by 2030.

- Other initiatives like LIKE-A-PRO and ProFuture focus on scaling up production and improving consumer acceptance of alternative proteins. The EU-funded project FEASTS estimates the potential role of cultured meat and seafood in resilient, equitable and sustainable food systems, whereas the EPIC-SHIFT project has similar objectives but focuses on other novel protein sources (e.g., insects, plant-based proteins, algae and microbial proteins).

6.4.4.3 Economic considerations

The introduction of a novel product on a consolidated market can create economic and social disruptions. These include, for instance, revenue shifts from conventional animal farming to emerging protein sectors, as well as a change to the job market, which will shift the search towards higher-skilled workers, such as engineers, biologists and chemists. Potentially, disruption along the entire supply chain can be observed. For example, the advent of cultured seafood may impact the shipbuilding of fishing vessels.

It is important to stress, however, that many novel foods are still at the reach of a very small number of consumers, due to the high costs. This is especially true for novel foods that require large investments in research and development as well as in technology.

6.4.5 Conclusions & Key messages

The impact of novel foods on biomass is complex and depends on various factors, including the type of novel food, production methods, and ecosystem context. Novel foods can provide opportunities for increasing food security and reducing environmental impacts (e.g., reduced land use, lower GHG emissions), however they also require careful consideration of potential unintended consequences, such as competition for resources and introduction of invasive species. Furthermore, careful consideration of dietary shifts from a social and economic perspective, such as rural income, must be carefully considered. This is further discussed in section 7.5 of this report.

A more comprehensive analysis of the opportunities and risks associated with the development of these novel foods is needed to assess their potential impacts on EU food systems at large. For example, comprehensive monitoring frameworks, such as the Consumption Footprint, will play a key role in evaluating the environmental performance of novel foods compared to traditional diets.

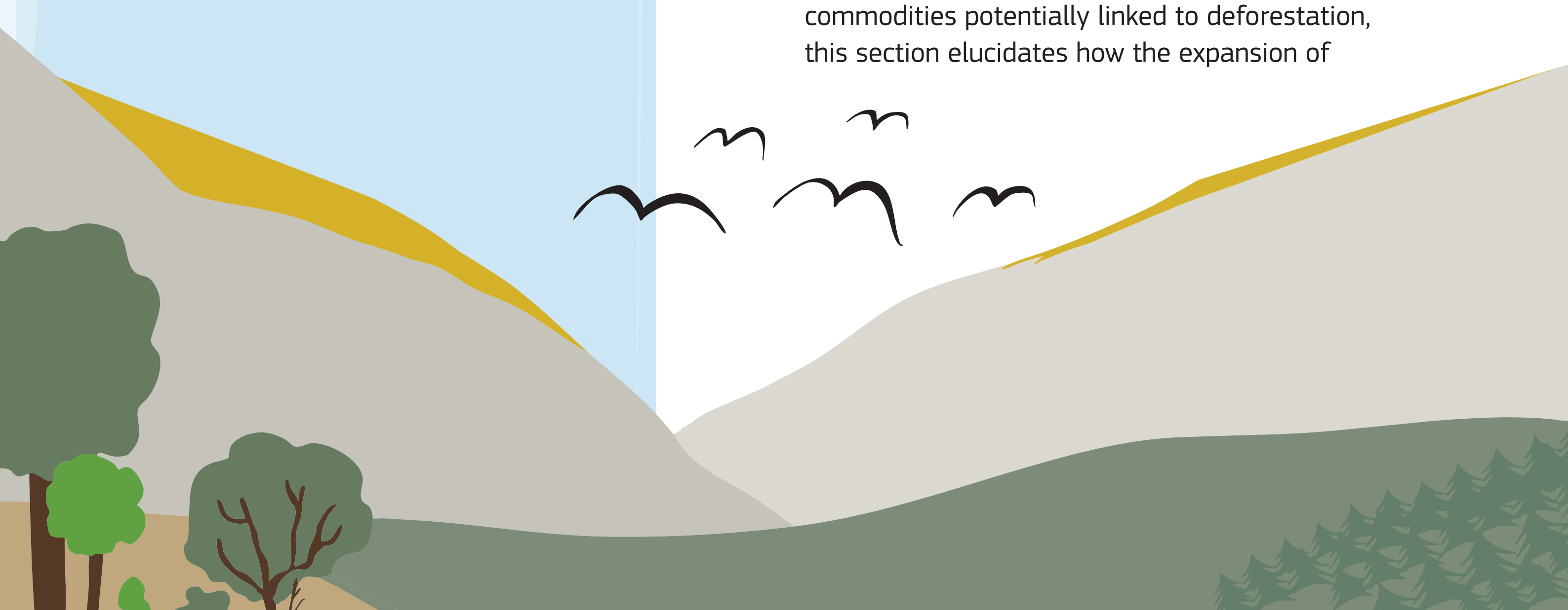
7 Policy instruments and societal shifts

7.1 Responsible trade of commodities potentially linked to deforestation

Teresa Armada Bras, Michele Ceddia, Rene Colditz, Mirco Migliavacca, Nicolas Mansuy

7.1.1 Introduction

This chapter addresses the intricate relationship between global trade and deforestation. The section begins by directly addressing the problem of deforestation in global trade (section 7.1.2). Building on chapter 3.6 Biomass Trade of food-related commodities potentially linked to deforestation, this section elucidates how the expansion of



agriculture and forestry acts as a key driver of trade-related forest loss. It quantifies the impact of global and EU trade on forest loss and greenhouse gas (GHG) emissions, and cites the EU Regulation for Deforestation-free Products (EU 2023, EUDR), highlighting the Union's acknowledgment of EU trade's role in deforestation. Section 7.1.3 discusses the EUDR's potential in achieving sustainable trade. It addresses key concerns regarding the EUDR, drawing upon peer-reviewed literature as well as from reports from governmental bodies and organizations. This section concludes by emphasizing that sustainable trade extends beyond solely preventing deforestation. This broader understanding of sustainable trade encompasses not only deforestation but also systemic issues and sets the stage for the discussion in the section 7.1.4. This section discusses that while the EUDR is a significant step forward in achieving sustainable trade, there are underlying structural challenges that persist.

7.1.2 The problem of deforestation in global trade

The intricate relationship between global trade and forest conservation has become increasingly significant, particularly regarding the so-called forest-risk commodities (FRCs), which are agricultural or natural resource products that are commonly linked to deforestation and forest degradation (Duran and Scott, 2022). These commodities are often produced in regions where forested land is cleared or degraded to make way for agricultural production, plantations expansion, forest harvest, extraction, or other economic activities. Their production can have significant environmental and social impacts, including biodiversity loss, greenhouse gas emissions (GHGs), while also disrupting the livelihoods of indigenous and local communities (Pendrill et al. (2019b, 2022), Sigh and Persson (Preprint), Henders et al (2015), Curtis et al (2018), EC (2023)).

Expanding agriculture and forestry are key drivers of trade-related forest loss. Trade related to deforestation represents 26-30% of global deforestation (Pendrill et al. (2019), Sigh and Persson (Preprint)). Between 2001 and 2023, global forest ecosystems were a net source of GHGs, emitting an average of 9.0 ± 2.7 Gt CO_{2e} per year (Gibbs et al., Preprint). Deforestation alone contributed between 3.3 and 5.0 Gt CO_2 per year to these emissions (Gibbs et al., Preprint). Given that commodity-driven deforestation globally emitted 1.9 ± 0.3 $GtCO_{2e}$ per year from 2001 to 2022 (Sigh and Persson, Preprint), we estimate that these emissions account for approximately 21% of total forest GHG emissions.

The EU is a major driver of global deforestation. From 1990 to 2008, the EU accounted for 10% of worldwide deforestation due to its consumption (EU 2023, recital 18)). Even with a decreasing share, the EU's consumption remains a disproportionately large driver of deforestation. This is acknowledged in the EUDR - the EU Regulation for Deforestation-free Products (EU 2023, recital 18)). The EUDR, in force since June 2023, aims to minimize the EU's contribution to global deforestation, land degradation, climate change, and biodiversity loss (EU, 2023, (18)), specifically targeting commodities and related products listed in its Annex I, i.e., cattle, cocoa, coffee, palm oil, rubber, soy, and wood related products.

Recent estimates show that from the 1.43 million hectares of deforested land attributed to international trade (Pendrill et al (2019)), the EU consumption of food-related commodities (i.e., cattle, cocoa, coffee, palm oil, and soy related products) account for 14% of it (estimations based on data from Singh et al, 2014), whereas EU imports represent up to roughly 28% of it (based on the EU embodied deforestation data from Chapter 3.6), see Box 23. This is primarily attributed to imports of palm oil, cocoa, and soy-related products and also, to a lesser extent, to the EU imports of cattle and coffee-based products (see Fig. 75a in Chapter 3.6 Biomass Trade).

The environmental impact of trade can be measured in terms of land footprint, which is the land area needed to produce the imported products, (Chapter 3.6). To note that here we are focusing on the impact of imported food-related commodities potentially linked to deforestation, and not on the consumption which excludes the exports while also considering the domestic production of those commodities. The EU holds a substantial share of the embodied land footprint for imported food-related products considered in the EUDR (EU, 2023, Annex I), particularly for commodities like cocoa and coffee from Western Africa, Southeast Asia and South America. For instance, the EU imports of cocoa's products is responsible of the 47% of Ivory Coast's harvested area for cocoa production, 30% of Brazil's harvested area for the production of imported coffee products. Similarly, other major importing countries exert significant influence on global agricultural production, such as in soy and palm oil, as illustrated in Figure 74 in Chapter 3.6. For example, soy-based products to China require 50% of Brazil's soy production area. The WWF report (2021), by using data from Pendrill et al (2019) and from TRASE (a not-for-profit initiative jointly led by the Stockholm Environmental Institute and The Global Canopy), estimated that in 2017, the EU contribution to deforestation related to all agricultural and forest commodities production (e.g., cattle meat, soybeans, palm oil and forestry products (from tree plantations), cereals, other oilseeds, pulses, roots and tubers, vegetables, fruits, tree nuts, fiber crops, and other crops) ranked second (16%), after China (24%), but ahead of India (9%), the USA (7%) and Japan (5%). High-consumption countries like Japan (0.11 ha/cap), the US (0.079 ha/cap), and the EU (0.062 ha/cap) have significantly higher per capita land footprints than China (0.054 ha/cap) and India (0.0057 ha/cap; own calculation with averaged land footprint between 2018-2022, considering cattle, cocoa, soy, palm oil, and coffee-based products). This highlights the impact of their consumption patterns on global deforestation, despite their lower overall contributions. Emphasizing the need for these countries to adopt sustainable consumption and support sustainable production and trade policies, these figures underscore the necessity of coordinated global action on supply chains to tackle deforestation.

Motivated by Member States' and the European Parliament's repeated concerns about persistent deforestation and degradation (European Parliament, 2020), as well as the significant link between agricultural expansion and human rights violations, the EU acknowledges the inadequacy of current global efforts (EU 2023, recitals 11, 12, 13). This recognition aligns with the Commission's European Green Deal communication of December 11, 2019, which sets out a strategy to transform the Union into a fair and prosperous society through a modern, resource-efficient, and competitive economy based on sustainable trade, achieving net-zero emissions by 2050, decoupling growth from resource use, and ensuring no one is left behind (EU 2023, recital 10).

Box 23: The EU share on deforestation embodied trade

The estimation of the EU share of the deforestation embodied in imports of food-related products is based on data from (a) the total deforested land attributed to international trade, which Pendrill et al. (2019) estimated to be 1.43 million hectares (calculated as 26% of the total global forest loss of 5.5 million hectares per year between 2005 and 2013), and (b) on the EU embodied deforestation from imports provided in Chapter 3.6, namely using trade data, from 2014-2019, on key food-related commodities (i.e., cattle, cocoa, coffee, palm oil, and soy-related products). The analysis in Chapter 3.6 indicates that the deforestation embodied in EU imports is approximately 397 000 hectares. Therefore, the EU's import-related deforestation share is roughly 28%.

The estimates of the 397 000 hectares relies on the methodology explained in Chapter 3.6, which primarily uses FAOSTAT statistics on land use and land use change (latest access January 25th, 2023). Moreover, the reallocation of land use was not implemented, i.e., re-exports of products were not considered. This methodology is currently under development to improve its accuracy by better accounting for trade flows and incorporating satellite data.

According to the data from Singh et al, 2024, which is linked to the consumption and not imports, the EU embodied deforestation on the consumption of the same food-related commodities is 194 000 hectares (as an average between 2014-2019), thus representing a share of 14%.

7.1.3 The EUDR's transformative role in achieving sustainable trade

The EU's is pursuing various trade-related sustainability efforts, including the EU's Aid for Trade (European Commission, 2024). In this context the EUDR is a decisive and targeted regulatory response to the urgent need to curb deforestation and biodiversity loss from specific commodities placed in the EU market. The EUDR enhances the EU's action to contribute effectively to the achievement of the Sustainable Development Goals and the European Green Deal (EU, 2023). The EUDR aims at minimising the Union's contribution to deforestation and forest degradation worldwide and to reducing its contribution to climate change and biodiversity loss (EU, 2023, recital 18). It does so by prohibiting operators from placing major agricultural commodities and derived products (i.e. related with cattle, cocoa, coffee, palm oil, rubber, soy, and wood) on the EU market if they have been produced on land legally or illegally deforested after December 31st 2020 (the cut-off date) and by imposing mandatory due diligence obligations on companies placing or making available such products (EU, 2023, Annex 1) on the EU market or exporting from it (EU, 2023, article 4).

The EUDR promotes partnerships and cooperation with producer countries to address the root causes of deforestation and forest degradation, focusing on the conservation and restoration of forests, and the transition to sustainable commodity production, consumption, processing, and trade methods (EU, 2023, article 30). It establishes a tier system for a risk classification of countries (EU 2023, article 29), ensuring appropriate transparency and clarity. The EUDR emphasizes the importance of stakeholder participation, including indigenous peoples, local communities, women, the private sector, and smallholders (EU, 2023, article 30). It has a built-in review process to assess, across time, its effectiveness and consider potential improvements, including an evaluation of the EUDR's impact on farmers, in particular smallholders, indigenous peoples, and local communities (EU, 2023, article 34).

The EUDR is a pioneering regulation aimed at tackling global deforestation and forest degradation, with the EU becoming a strong global actor for sustainable trade. This is part of a growing trend of regulatory responses to environmental and social supply chain challenges. However, while other countries are beginning to address deforestation-related issues, they have yet to implement similar comprehensive regulations. The United Kingdom, for instance, has the Environment Act 2021, which includes provisions aimed at reducing deforestation associated with its supply chains. In the United States, although there have been discussions and proposals for legislation related to deforestation, such as the previously considered Forest Act 2023, no comprehensive federal regulation is currently in place. Verhaeghe and Ramcilovic-Suominen, 2024 (in Barclay, 2023) acknowledge the EU's role in minimizing its contribution to deforestation, and also that it demonstrates a commitment to driving transformative change. The EUDR, however, may partially depend on the extent to which it can drive global change. There are concerns that the EUDR may lead to leakage (Amsterdam Centre for European Law and Governance 2024, Azevedo-Ramos et al 2024, Johnston et al, 2025, Muradian et al 2025, Vaccarezza et al 2025, Vasconcelos et al, 2024). Traders could redirect their commodities and products from deforested land to other markets with less stringent regulations (Vasconcelos et al, 2024) while the EU market absorbs most of the sustainably produced commodities, potentially posing serious doubts on the EUDR's additionality (Amsterdam Centre for European Law and Governance, Workshop notes Implementing the EUDR, 2024). Despite these concerns, the EUDR has potential to promote significant changes in producers' attitudes and therefore on global standards and norms, even without direct regulatory authority over non-Member States (Vasconcelos et al, 2024). This is simply due to the EU's market size and the economic incentives for corporations to standardize their practices globally. Doing so allows them to avoid the costs and complexities of adopting different production standards for various markets. This could be the case for cocoa and coffee markets, where the EU has a large and concentrated presence (see Fig. 74 in Chapter 3.6). Specifically, the EU is the primary market for cocoa from Ghana, Ivory Coast, and Cameroon, absorbing a substantial 40-63% of their production. While the United States and the United Kingdom have smaller market shares (8-17%

and 5-11% respectively), their parallel regulatory efforts could significantly reinforce the transition to deforestation-free cocoa in these key producing countries. For commodities such as soy and palm oil, however, the influence of major importers like China and India, alongside the EU, underscores the necessity of their involvement for genuine change (see Fig. 74 in Chapter 3.6). There is the concern that China's dominance along with other emerging economies in these markets will increase the risk of leakage. However, for example the EU's long-lasting bilateral cooperation with China on environmental issues has led to some convergence in standards and regulations (EEAS – The diplomatic service of the European Union, Vasconcelos et al., 2024). Both parties have, for instance, endorsed the Kunming-Montreal Global Biodiversity Framework (adopted in December 2022 at the 15th meeting of the Conference of the Parties to the Convention on Biological Diversity).

The EUDR traceability aims for greater transparency and accountability, making it more difficult for deforestation and other illegal activities to remain undetected. With its emphasis on legal and sustainable supply chains, the EUDR could contribute to better safeguarding the rights of indigenous peoples and local communities, who are often disproportionately affected by deforestation and land grabbing (Borras et al, 2013, Farrel et al 2021, Brito et al 2019). Careful monitoring and international cooperation will be necessary to avoid deforestation shifting to other regions. Moreover, as Strohschneider (2024) recommends in the report – "Strategic Dialogue on the Future of the EU Agriculture - A shared prospect for farming and food in Europe" - a greater coherence between trade and sustainability policies is essential. This, coupled with fostering sustainable consumption within the EU, could positively influence global supply chains and potentially mitigate the risk of deforestation shifting to other regions. The EUDR sets a precedent for enhancing the sustainability of supply chains.

While the EUDR represents a significant step in this direction, the concept of sustainable trade encompasses a broader scope than solely preventing deforestation. Sustainable diets (see Chapter 5.16 Dietary Shifts in this report) and reduced food waste (see Chapter 5.15 Societal Shifts: Food waste reduction) might promote a diverse and nutritious food supply while minimizing environmental impact through optimized production and consumption patterns but also offer a powerful solution to reduce deforestation linked to consumption. Promoting societal shifts towards reduced overconsumption and the production of durable goods is also crucial for a sustainable future.

7.1.4 Towards systemic change: addressing structural challenges in international trade

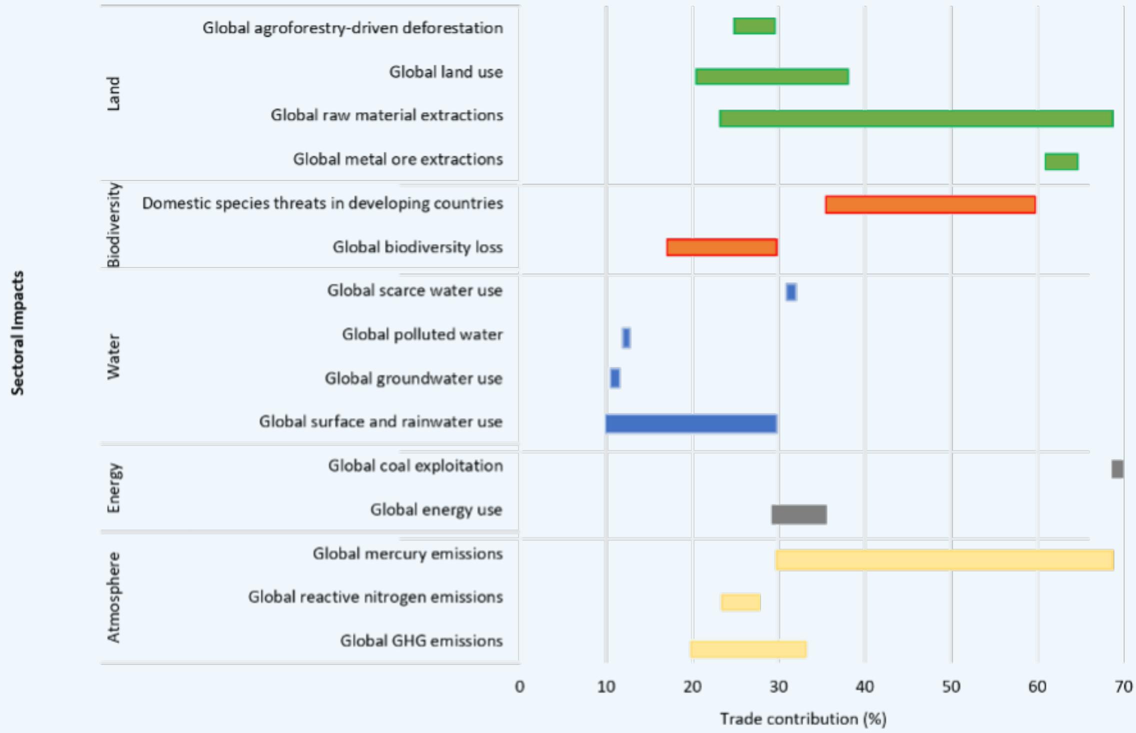
We have already discussed how trade in agricultural commodities is strongly associated to deforestation, particularly in less advanced economies. There are however some structural aspects, which need to be discussed, and that drive the emergence of such a pattern. These structural elements refer to the fact that the configuration of less advanced economies have historically evolved in dependence of the economies of the most advanced ones (Amin, 1974; Marini et al., 2022). Broadly speaking the high-income and advanced economies have a strong advantage in the financial sector and in the advanced technological sectors. This in turn leads to an international division of labour where the low- and middle-income countries and emerging and developing economies -the World Bank classifies countries according to their income level and the International Monetary Fund distinguishes between advanced economies and emerging and developing economies- have few options other than specialising in the export of primary sectors commodities, or low value-added commodities (United Nations Conference on Trade and Development, 2023). The case of cocoa and/or palm oil are typical examples. The same logic extends also to non-forest raw materials, like mineral ores, or to low value-added industrial commodities (e.g., apparel). In this section, we want to broaden the discussion, and bring to the fore exactly those structural elements whose consideration is essential in order to make trade more sustainable. These considerations go beyond trade in deforestation related commodities, but they are pertinent because they apply also to these commodities.

The expansion of international trade is rife with socioeconomic opportunities but also global environmental consequences and contradictions. Indeed, it is often cited for its potential to foster specialization, create mutually advantageous exchange relations leading to lower prices for consumers, and an easier access to a wider variety of products and economic growth (Ohnsorge and Quaglietti, 2023). Moreover, trade can also have positive environmental and social impacts, directly through the diffusion of environmental technologies (Garsous and Worack, 2021), or indirectly, by promoting growth and enhancing governments' capacity to deal with environmental and social challenges. However, while acknowledging benefits, the relationship between integration into global trade and poverty reduction is conditional on many other factors, including public policies and safety nets (Harrison and McMillan, 2007; Stiglitz, 2015). While there is evidence that trade has played a crucial role in narrowing the income gap between economies in the last 30 years, income convergence and global economic integration have been uneven, leaving some economies behind (WTO, 2024). There are different mechanisms that could lead to unbalanced effects. Firstly, net appropriation of labour through large wage differentials that are not explained through differences in labour productivity (Emmanuel, 1972). This net appropriation of labour is spread across all sectors and across all skills levels, and has been estimated at 16.9 trillion € in 2021 alone (Hickel et al., 2024), and represents an important obstacle to the development of low- and middle-income countries and emerging and developing economies. Secondly, given the paucity of capital in less advanced economies (compared to the advanced ones), commodity exports from the former are often performed by operators that are established through foreign direct investments (FDIs). The profit generated by commodity exports is largely repatriated to the more advanced economies, thus subtracting resources from the exporting country (Parnreiter et al., 2024). Given the prominent role of FDIs in promoting the expansion of commodity crops and deforestation (Ceddia, 2020) and given their relationship with commodity flows, it would seem appropriate to treat capital and commodity flows jointly. Lastly, the necessity of less advanced economies to attract FDIs may induce them to a "race to the bottom" in terms of environmental standards (Van et al., 2024). As a result, exports from these countries can be associated with large environmental (see Box 24) and/or social costs, which are not necessarily factored in by the parties involved.

These considerations highlight some fundamental structural factors that shape international trade, including that of deforestation-related commodities. While acknowledging the initiatives undertaken by policymakers to foster mutually beneficial international trade (in deforestation related commodities but not only), the persistence of these problems is likely if these underlying structural causes are not acknowledged and addressed (Longo et al., 2025). A comprehensive strategy that integrates open trade with other key policy areas is essential to make trade more inclusive and spread the benefits of trade to all (WTO, 2024).

Box 24. Global trade's contribution to the environmental footprints

Global trade has led to economic growth but also increased environmental (see Figure in Box) and social challenges. As Wiedmann & Lenzen (2018) note, fragmented supply chains and outsourcing of production from regions with lower environmental standards, poor working conditions and limited labour rights protections, have exacerbated these issues.



Source: adapted from Wiedmann and Lenzen (2018) with Pendrill et al (2019), and Sigh and Persson (Preprint)

7.1.5 Key messages

- International trade of palm oil, cocoa, coffee, soy, cattle, wood and rubber products is partly linked to deforestation.

- The EU, as an important importer of these commodities, contributes substantially to global deforestation.

- By prohibiting the imports and placement of commodities and products linked to deforestation and forest degradation on the EU market, the EU Regulation on Deforestation-free products (EUDR) can directly contribute to the preservation of forests and biodiversity.

- The regulation's due diligence requirements can increase transparency in supply chains, by facilitating the identification and addressing of unsustainable practices.

- The EU's substantial market presence and political influence may catalyse global adoption of similar sustainable trade regulations. The EUDR offers potential for transformative change in supply chains, but its efficacy may be conditional upon effective measures to prevent market leakage, avoid exclusion of smallholders, and promote sustainable production in sourcing countries.

- The impact of agricultural commodities' trade on deforestation reflects a broader set of underlying structural causes, that apply also to other commodities. Attention to these causes is relevant for sustainable and fair development.

7.2 The 'polluter pays' principle and the use of taxation and subsidisation as policy instruments

Jordi Guillen

Taxes and subsidies are tools that governments can use to affect the supply of products and services in the economy. Taxes are mandatory financial charges that can increase the cost of production and so tend to reduce supply. On the other hand, subsidies are financial support aiming at incentivising production or consumption, by decreasing costs and so increasing supply.

Because of their influence in changing the production supply and so on the activity level of industries, taxes and subsidies can mitigate human impacts that degrade the natural capital, as well as encourage those activities with positive impacts on the natural capital, helping to preserve the environment's capacity to provide ecosystem services. To assess the optimal level of taxation and subsidisation, we must look at the economic theory.

An externality is the cost or benefit that affects an economic agent who did not participate in the activity generating that cost or benefit (Pigou, 1920; Coase, 1960; Buchanan & Stubblebine, 1962). In the presence of negative externalities, the cost to society is greater than the cost borne by those undertaking the activity (production or private costs). This results in a non-efficient allocation of resources, with over-consumption of the product causing externalities (Sandmo, 2008). Pollution from fossil fuel consumption is a clear example of an externality, where the whole of society faces environmental pollution and the effects of climate change while only some of its members are benefiting from the consumption of fossil fuels.

Pigou (1920) proposed the creation of a tax, known as Pigouvian tax, equal to the external (non-private) cost, so that governments could pass the external cost to the economic agents incurring in the activity that generates the externalities. This way, the economic agents would have to face the full cost of the activity (the externality is internalised in the costs of the economic agents undertaking the activity), leading to a lower level of the activity generating externalities and an efficient allocation of resources (Baumol, 1972; Barthold, 1994). For example, the optimal taxation level of fossil fuels (i.e., a carbon tax) should internalise the associated pollution and global warming costs, requiring consumers to fully account for them at the point of consumption, so that the socially optimal level of consumption is achieved (Pearce, 2003).

This is completely in accordance with article 191(2) of the Treaty on the Functioning of the European Union that enshrines the polluter pays principle[35]. This principle implies that polluters should pay for the pollution they cause, thus, creating an incentive to avoid damaging the environment at its source and holding polluters accountable (ECA, 2021).

7.2.1 Application to EU aquaculture

Extractive species, such as algae and molluscs, have the capacity to extract carbon, nitrogen, and phosphorous from the seawater; therefore, enhancing ecosystem services of CO_2 sequestration and nutrient reduction to mitigate eutrophication (Zhang, 2021; Kotta et al., 2022; Alevizos & Barille, 2023; Wu et al., 2023). Therefore, selected farming of extractive species, when managed appropriately, has a limited or even positive carbon and environmental footprint.

On the other hand, achieving a sustainable production of carnivorous finfish is a more challenging process due to its high carbon and environmental footprint. Marine ingredients from wild-caught fish – as fishmeal, fish oil or whole – are often an important component of the feed. If the fisheries are not well-managed, this may add pressure on wild fish stocks highlighting the importance of reducing the dependence on fish-to-feed towards a more sustainable socio-technological feeds (Tacon et al., 2009; Tacon et al. 2021). Moreover, the discharge of the uneaten feed and faeces waste from the

[35] "Union policy on the environment shall aim at a high level of protection taking into account the diversity of situations in the various regions of the Union. It shall be based on the precautionary principle and on the principles that preventive action should be taken, that environmental damage should as a priority be rectified at source and that the polluter should pay."

finfish can worsen water quality and even create hypoxic zones when appropriate mitigation measures are not adopted, therefore negatively impacting the environment, depending on the status of the surrounding ecosystem. Waste from feeding and its accumulation on the seafloor has been identified as one potential negative environmental impact of aquaculture (Karakassis et al., 2000; Luna et al., 2019).

Hence, it may be reasonable to financially support those sustainable aquaculture practices that result in positive externalities (e.g., ecosystem restoration by carbon sequestration and extraction of nitrogen and phosphorous); while increase the burden (e.g., through taxes) on those aquaculture practices that are less sustainable and cause negative externalities (e.g., carbon, nitrogen and phosphorous emissions), in line with the polluter pays principle. Theoretically, this will incentivise the production of sustainable aquaculture.

On the other hand, this implies that polluters, as could be the case of fed-aquaculture producers, should pay for the pollution they generate, thus, creating an incentive to further reduce or avoid emissions. However, such a tax could easily result in reductions in the fed-aquaculture production.

There is great uncertainty, and controversy as well, in the estimation of the social costs of the carbon, nitrogen and phosphorous emissions, and so on the economic benefits of sequestering them. The social cost is a measure that quantifies the economic costs associated with an additional tonne of emissions to the atmosphere. There is a high degree of variability in the social cost estimates found in the literature, partly due to different assumptions and methodologies used (see for example for the social costs of carbon, van den Bergh and Botzen, 2015; Nordhaus, 2017; Ricke et al., 2018; Pindyck, 2019).

The US Environmental Protection Agency (EPA, 2022)'s latest central estimate of the social cost of carbon (SCC) is at USD 190 per tonne of CO_2. Despite the EPA's SCC estimate having increased from USD 51 to 190 per tonne of CO_2, this estimate is not without controversy. One criticism being that different values are attributed to human lives, depending on each country's willingness or capacity to pay. Carleton et al. (2022) estimated that the EPA's SCC would approximately double if all lives were valued equally (approx. USD 380 (€360) per tonne of CO_2). Van Grinsven et al. (2013) estimate an average social cost of €18 per kg of nitrogen, in line with Birch et al. (2011). While Gourevitch et al. (2021) estimate an average social cost of $934 (€823) per kg of phosphorus for the period 2016-19.

From Macias et al. (2025) the total amount of C, N and P taken out of the environment will vary depending on the final use of the seaweed. For example, if the seaweed is used as food or feed, then the C, N and P will largely come back to the environment; while if the seaweed was removed and buried, the removal would be larger. This implies that the ecosystem benefits vary from €0.26 to €4.82 per kg depending on its final use. Hence, this could justify financial support seaweed production up to these amounts, which is rather significant as the average farmed seaweed price goes between €2 and €5 per kg (STECF, 2023; FAO, 2024).

On the other hand, bluefin tuna (BFT) aquaculture has been largely criticised by its environmental and ecological impacts. Guillen et al. (2024) show that the high environmental impacts of BFT aquaculture of about €9.55 per kg of BFT produced outweigh its economic and social benefits.

7.2.2 Conclusions

There is a high degree of variability and so uncertainty in the emissions and, especially, the social cost estimates available in the literature, partly due to different assumptions and methodologies used. Yet, assuming a single value social cost per emission covering all EU sea basins is a simplification. The cost of the damages varies depending on the individual emissions and the overall emissions level (i.e., costs may not always be directly proportional), on the site location, the local population preferences, etc.

Moreover, for this taxation to be fair, it would have to cover, at least, all food production systems, including imports, easily leading to an undesired increase in overall food prices, if no corrective actions are taken.

All these points make the traditional implementation of such a tax to compensate for the environmental impacts rather complex and undesirable in a context where it is aimed to improve competitiveness. To be fully efficient, the establishment of such an environmental tax would have to be done globally, requiring a major international agreement.

A less traditional or academic approach would be the establishment of such a mechanism of taxes and subsidies for a given sector, ensuring that the taxes collected in the sector are then invested in the sector, for example, through research programs or supporting investments that improve their sustainability. A system of blue carbon credits could have similar effects.

Alternatively, the need to grow extractive species near big farms of fed-aquaculture to mitigate their environmental impacts could be regulated. A similar solution could be to promote Integrated Multi-Trophic Aquaculture (IMTA) where the bioproducts of a farmed species can be used as inputs (food) for another farmed species (e.g., farming finfish in spatial co-occurrence with bivalve and algae that uptake the excess of organic matter generated from the fish cages). However, to date, there is a lack of a comprehensive understanding regarding economic, social and environmental sustainability and benefits of IMTA and the scale-up of their production.

7.3 Mainstreaming ecological content into the economic context through an integrated environmental and economic accounting system

Alessandra La Notte

The role of the natural environment in providing resources, absorbing waste and generally maintaining the functioning of all ecological processes that support human activities is central to economic activity. Consequently, any economic system that ignores the environment ignores a fundamental component of the functioning of the economic system itself. The System of National Accounts (SNA) is an international standard for the systematic compilation and presentation of economic data that provides the information needed for economic analysis and policymaking at the national level (UN et al. 2009). The SNA encompasses the stock and flows of goods and services employed in production activities, which entails the utilisation of inputs drawn from, and the exertion of effects upon, the natural environment. Such impacts include the depletion of resources and the generation of waste, which is subsequently returned to the environment. The System of Integrated Environmental and Economic Accounting (SEEA), which is led and coordinated by the United Nations Statistical Division, is designed to establish a systematic and structured relationship between the environment and the economy. This objective can only be met if the SNA remains at the core of the system. In fact, the consistency with the SNA guarantees the possibility of comparing conventional economic accounts with all nature related accounts to illustrate how changes in the economic structure affect nature and vice versa.

The SEEA comprises two components. The first is the Central Framework (CF), which encompasses accounts of pollutant emissions, biotic and abiotic natural resources, environmental expenditures, taxes and sectors providing environmental goods and services (UN et al., 2014). The second is Ecosystem Accounting (EA), which includes accounts of the extent and condition of ecosystems and of ecosystem services (ES) (UN, 2024). ES facilitate the integration of ecosystems and socio-economic systems by quantifying the ecological flows on which human activities depend.

Although it may appear that the provision of biomass as such can only be captured by natural resource accounts (SEEA CF), the reality is that, depending on how terrestrial and marine ecosystems are managed, they can generate:

1. not only the provision of biomass, but also many more (or fewer) services that support and protect human activities;

2. not only the provision of biomass in current years, but also its provision in the long (or short) term.

Therefore, accounting for ecosystems and their services (SEEA EA) is necessary to understand the regenerative role of biomass. This is because such accounting captures the perspective of a functioning ecosystem, whereas a resource account does not.

7.3.1 Application to the EU

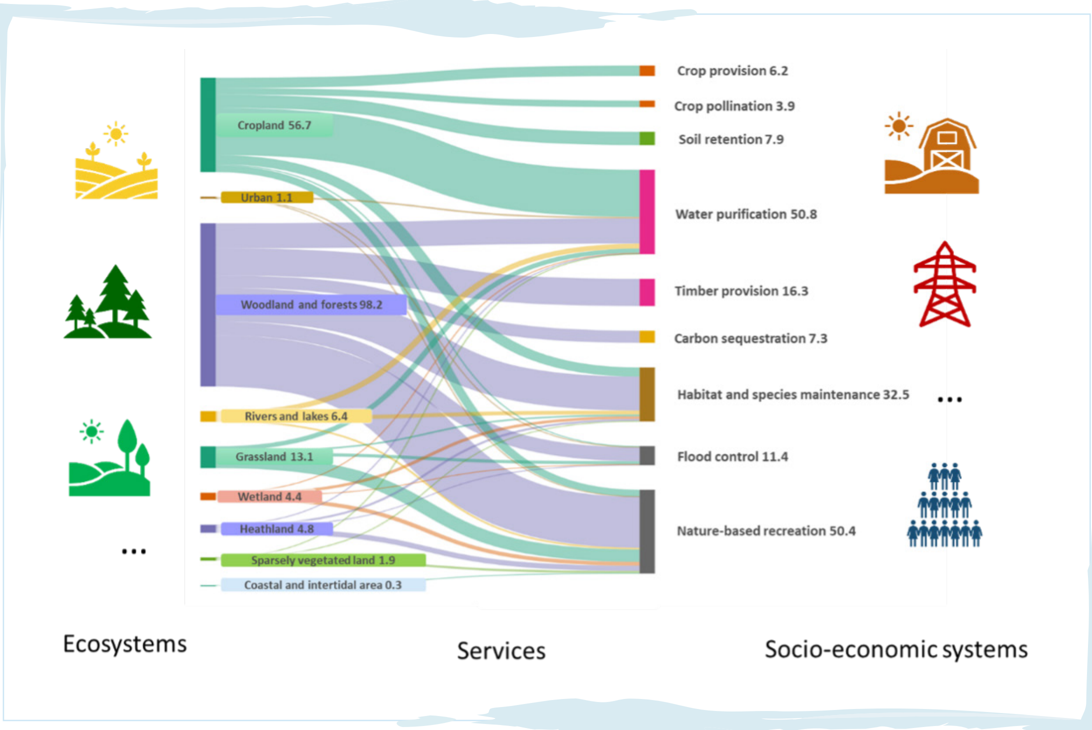
The European Commission has been proactive in testing and implementing the experimental version of the SEEA EA (UN et al., 2014; United Nations, 2019) through the Integrated system for Natural Capital Accounting (INCA) project based on the partnership among Eurostat, the Joint Research Centre, the European Environment Agency, DG Environment and DG Research and Innovation (European Commission, 2021).

With a focus on ES accounting, the many lessons learned (La Notte et al., 2022a) have provided an important contribution to the expert discussion underpinning the SEEA EA Handbook at international level (UN et. al., 2014; UN 2019), and the drafting of Regulation (EU) 2024/3024 of the European Parliament and of the Council of 27 November 2024 amending Regulation (EU) No 691/2011 as regards introducing new environmental economic account modules, that in Annex IX explicitly include ecosystem accounting (European Commission, 2022).

The ES accounts that are part of INCA are slowly starting to play an active role in a variety of policy contexts ranging from ECB/ESRB macro-prudential framework (European Systemic Risk Board, 2023) to the European Economic Forecasts - Spring 2024 as a case study (European Commission, 2024) to the calculation of the Gross Ecosystem Product (Rokicki et al., 2024).

The structure of such accounts can greatly facilitate to establish a link with the economy. Ecosystems as a whole are too complex to be able to generate one indicator that is able to quantify their support to economy and society. On the other hand, the concept of ES can simplify such complexity and identify one-by-one the flow that are used by human activities (Figure 102).

Figure 102. **Selected ecosystem services in the EU-27 (billion euros, 2018), based on INCA accounts.**



Source: adapted from ESRB (2023).

For example, Figure 102 shows that once ES are assessed in physical terms, eventually translated into monetary terms and aggregated, the ecosystem "woodland and forests" can provide not only the wood provision service that supports forestry, but also carbon sequestration that supports international agreements on climate change; flood control that protects human settlements, agricultural fields, infrastructure, industrial and commercial sites; soil retention that supports cultivation; water purification that removes pollutants discharged directly and indirectly into freshwater ecosystems; and nature-based recreational services that support both the tourism sector and households that enjoy daily recreation. "Woodland and forests" is the ecosystem type providing the 53% of the total (of the 9) services. Wood provision is the 17% of the services generated by woodland and forests. The implementation of ES accounting allows for the assessment of the potential impact of sustainable woodland and forest management practices on the quantity and diversity of ecosystem services. Conversely, ES accounting also enables the evaluation of the risks associated with the transformation of these ecosystems, including the loss of the ES that they provide and that support human activities.

7.3.2 Potential uses beyond the national accounts

Once ES accounts are available, it is important to ascertain how they can be utilised, particularly in conventional economic instruments. Indeed, the principal advantage of SEEA is its coherence with the SNA, which ultimately permits the incorporation of ecological information into economic tools and models. This is the objective of an initiative, LISBETH (LInking ecosystem Service and Benefits to Economic models THrough bridging), that is directly related to INCA. As a result of LISBETH Part I, it was possible to test several applications of INCA outcomes to construct composite indicators, to populate multiregional input-output models and to shock variables into economic general equilibrium models (La Notte et al., 2020).

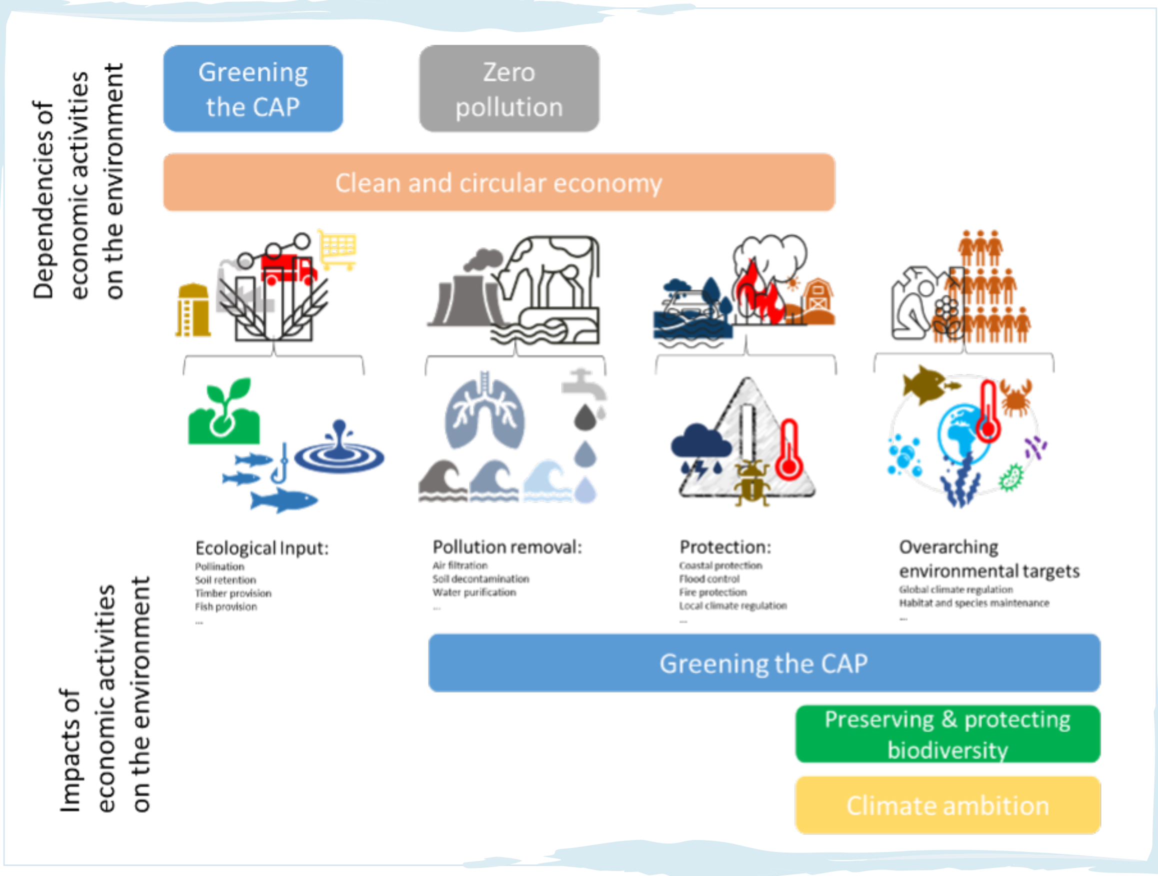
Depending on the ES assessment approach, it is possible to assess not only the ES flow that is provided to economic sectors and households, but also the ES that is required but not provided due to the absence of ecosystems or their degradation. This mismatch between the availability of ES and the demand for ES gives rise to an ES vulnerability that can expose the economic sectors that depend on these ES to risk. Thanks to LISBETH part II, it was possible to attempt to construct indicators of ES vulnerability indicators, to estimate the flow of the ES lost due to the mismatch and to integrate the monetary estimates of ES by adding indirect use and non use values to direct use value in a consistent manner (La Notte et al., 2022b).

While the ES accounts have been compiled in accordance with the accounting structure of the national accounts, their utility extends well beyond the conventional applications of SNA users. As evidenced by certain studies (Ingram et al., 2024, Fatica et al., 2024, Grunewald et al. 2024, D'Amato et al. 2024), they could also serve as a valuable source of information for private companies situated in regions where they require data on ecosystems and the services they provide. Additionally, they could prove beneficial for those overseeing areas of exceptional ecological significance, such as nature parks (Faccioli et al., 2023).

The systematic availability of ES accounts can facilitate the process of greening finance by providing detailed and science-based estimates of nature-related risks. Furthermore, they can support the process of financing green by providing monetary estimates of the use and non use values of the ES delivered, as well as monetary estimates of the ES that are needed but not delivered (La Notte et al., 2022).

Ecosystem accounting is related to EDG in different ways because of the different roles that ES can play in supporting human activities: namely by (a) providing ecological input, (b) removing negative externalities, (c) protecting against physical and biological threats, (d) achieving overarching environmental targets (such as climate change mitigation and halting biodiversity loss). In illustrating the connection between ES accounting and the EGD, Figure 103 introduces two key concepts: dependency and impacts.

Figure 103. Contribution of the ES accounting to the EGD.



Source: JRC own elaboration.

Primary sector activities rely heavily on the ecological inputs that nature provides to activate the production process, from insect pollination to the natural growth of biomass. Polluting activities rely on the capacity of ecosystems to remove the negative externalities they emit into the air, soil and water. The use and transformation of resources throughout their life cycle have many elements of interaction with the physical environment in which they take place. The impact of policies related to the greening of the CAP, zero pollution and circular economy can also be measured by accounting for those ES that provide ecological inputs, pollution removal and protection so that economic activities can take place.

On the other hand, the way in which economic activities are carried out can affect the potential of ecosystems to provide ES that affect the whole planet in the medium and long term, which is relevant for policies that aim to preserve and protect biodiversity and have a climate ambition. Furthermore, the greening of the CAP in this case does not refer to the dependence of the agricultural sector on ecosystems for the provision of ecological inputs, but to the impact that different agricultural practices have on the degradation (or not) of ecosystems and thus their capacity to filter and absorb pollutants, to act as a barrier against physical and biological hazards, to sequester carbon and to maintain habitats and species.

7.3.3 Conclusions

The systematic accounting and reporting of ES has the potential to be a powerful measurement tool for a number of reasons, including:

- ES flows operate as transactions between ecosystems and socio-economic systems, thereby facilitating the link to economic models and tools that use accounting frameworks by default;
- the conceptual framework underpinning ES does not overlook the complexity of ecological processes, as the multifaceted roles of ES in relation to human activities are recognised, both in terms of dependencies and of impacts;
- ES can be assessed in physical terms and eventually translated into monetary terms, which opens up the possibility of using this metric in a variety of different ways, for example to reward primary producers' income (payments for ES) or to calculate of biodiversity credits.

Most importantly, the concept of ES allows for a shift from a single resource metric (crops, timber, fisheries) to a multi-perspective positive contribution to nature by relevant bio-based sectors.

7.4 Societal shifts: Food waste reduction

Valeria De Laurentiis & Laura Garcia Herrero

7.4.1 Addressing a complex challenge: food waste at consumer level

The amount of food wasted during its production and consumption is staggering. While around 20% of food produced in the EU is lost or wasted, some 33 million people cannot afford a quality meal every second day. In 2021 the EU generated 58.4 Mt (million tonnes) of food waste (including both edible and inedible parts), which correspond to around 131 kg of food wasted per inhabitant per year[36].

Food waste has a significant environmental and climate impact, and puts an unnecessary burden on limited natural resources, such as land and water. The generation of food waste is associated to 252 MtCO_2–eq (million tonnes of carbon dioxide equivalent). meaning that if EU food waste were a Member State, it would be the EU's 5th largest emitter (Sala et al., 2023). 54% of the total amount of food waste was generated at household level, equivalent to 70 kg per inhabitant[37]. As the environmental impacts of food accumulate across the supply chain, the generation of food waste at consumer level (i.e. including in addition to households also food services) is responsible for more than 70% of the overall environmental impacts of food waste. It is therefore crucial to focus on prevention efforts at this stage of the food supply chain.

Food waste reduction is thus key for the establishment of sustainable food systems and the deployment of a circular bioeconomy, in which biological resources are used sustainably. Moreover, the recovery of surplus food for redistribution to those in need has an important ethical and social dimension and ensures that more food is made available for human consumption.

7.4.2 How can we achieve a societal shift to reduce food waste?

Consumer food waste is essentially a behavioural issue. Reducing food waste is crucial to achieving the Sustainable Development Goal Target 12.3 of halving the amount of food waste per capita by 2030. To tackle consumer food waste, the Joint Research Centre, in collaboration with the Directorate-General for Health and Food Safety (DG SANTE), has set up the European Consumer Food Waste Forum (ECFWF). Researchers and practitioners worked together to find solutions and develop effective tools.

The Motivation-Opportunities-Abilities (MOA) framework was adopted in this work to classify drivers, levers, and interventions related to consumer food waste. Motivation encompasses attitudes,

[36] *https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Food_waste_and_food_waste_prevention_-_estimates*

[37] *https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Food_waste_and_food_waste_prevention_-_estimates*

intentions and norms. Opportunity refers to the accessibility of materials and resources needed to change behaviour. Abilities refer to the knowledge, skills and individual capacities to solve the problems encountered when changing behaviour, including breaking well-formed habits and routines or countering the peers' arguments (Vittuari et al., 2023). Based on the latter review, behavioural factors, drivers, and levers were classified as indicated in Table 20.

Table 20. **Behavioural factor associated with divers and levers from each MOA feature.**

MOA framework	Behavioural factors	Drivers	Levers
MOTIVATION	Social norms (Schanes et al., 2018a; Elhoushy, 2020)	Environmental concern; injunctive social norms; descriptive social norms.	Host community events to promote good practices in reducing food waste and conduct awareness campaigns.
	Awareness (van Geffen et al., 2020a; Parizeau et al., 2015)	Awareness/perception of consequences of food waste.	Emphasise food waste-related issues for instance raise awareness.
OPORTUNITY	Time, schedule, and lifestyle (Silvennoinen et al., 2012; Stancu et al., 2016; Vittuari et al., 2021; Hebrok and Boks, 2017)	Availability of time; time pressure; purchase planning.	Promote efficient food planning or storage methods, especially with busy schedules.
	Availability of tools and/or technologies (van Geffen et al., 2020b)	Availability of tools and technologies, resources.	Provide affordable technology and tools (e.g., smart kitchen tools) to improve food management.
ABILITY	Capabilities and skills (van Geffen et al., 2020a; Bravi et al., 2020).	Food management skills; food literacy.	Promote and introduce food planning or storage methods, cooking skills, and food reduction tips.
	Knowledge of techniques for purchase, manage food efficiently; knowledge of the amount of food waste produced (Vittuari et al., 2021; Neff et al., 2019).		Promote self-learning methods to increase the food waste related knowledge.

Source: Vittuari et al. (2023).

Addressing these motivations, opportunities, and developing these abilities by implementing evidence-based recommendations and tools identified under the ECFWF work could be of effective support in fighting food waste at consumer level.

There is evidence that interventions targeting specific consumer profiles are more effective. Another key aspect emerging from this work was thus the need to provide more guidance on how to segment consumers and tailor interventions.

7.4.3 How is the EU addressing food waste at consumer level?

7.4.3.1 By setting legally binding targets

The Farm to Fork Strategy puts forward a series of actions to enable the EU's transition to a sustainable food system. The European Commission is proposing to set legally binding food waste reduction targets to be achieved by EU Member States by 2030, as part of the revision of the Waste Framework Directive, Proposal adopted on 5 July 2023. The results of the first EU-wide monitoring of food waste levels carried out in 2020 will serve as a baseline to assess progress towards the targets. More specifically, Member States are required to take the necessary measures to reduce food waste by the end of 2030:

- by 10% in processing and manufacturing,
- by 30% (per capita), jointly at restaurants, food services and households.

The legislative proposal is currently being discussed by the European Parliament and Council.

7.4.3.2 By fostering collaborations and knowledge sharing

Within the above-mentioned project ECFWF, several tools, best practices, and recommendations have been developed[38]. These include a food waste prevention calculator, an interactive online tool based on Life cycle thinking to understand the impacts of our waste (or avoided waste) from food production to consumption; and the Food waste action planner, an interactive online tool classifying more than 70 food waste prevention actions to inspire replicability to get impactful results. The use and scalability of these tools, best practices and recommendations can help in reducing food waste.

Key is also the collaboration between actors and knowledge sharing, as knowledge and experiences exchange stimulate action in food waste reduction. Practitioners, including public authorities, often lack access to evidence-based resources like tools and best practices. National programs can facilitate resource sharing and screen best practices, while expert hubs and networks enhance international collaboration. Some key platforms stimulating and sharing knowledge are the EU Platform on Food Losses and Food Waste EU [39] or the EU Food Loss and Waste Prevention Hub[40].

7.4.3.3 By allocating funds for research

There are several research programs assessing behavioural change while reducing food waste. A key one is the Horizon Europe Programme (HE). The HE addresses food waste by funding research and innovation projects that focus on sustainable food systems and consumer behaviour change steered by the Food2030 R&I Inititative. Initiatives under HE aim to develop technologies, policies, and strategies to reduce food waste throughout the supply chain. The programme supports collaborative efforts across Europe to implement effective interventions, such as innovative packaging solutions, smart food storage technologies, and behavioural insights to promote responsible consumption practices. By fostering cross-sectoral collaborations and knowledge-sharing, this funding programme aims to achieve significant reductions in food waste while promoting sustainable consumption behaviors among European consumers and beyond.

7.4.4 Environmental and economic benefits

Decreasing food waste offers both environmental and economic benefits, as it reduces resource consumption, environmental impacts, and allows monetary savings. Food waste reduction preserves natural resources by decreasing the need for production, processing, and other steps along the food supply chain needed to produce food that will not be finally consumed. Additionally, generating less food waste saves the emissions caused by waste treatment (e.g., landfilling, anaerobic digestion). In economic terms, food waste reduction may translate into savings for households, while at business level can help in optimising processes and costs

[38] *https://knowledge4policy.ec.europa.eu/bioeconomy/reduce-food-waste_en*

[39] *https://food.ec.europa.eu/food-safety/food-waste/eu-actions-against-food-waste/eu-platform-food-losses-and-food-waste_en*

[40] *https://ec.europa.eu/food/safety/food_waste/eu-food-loss-waste-prevention-hub/*

avoiding overproduction or extra-purchasing. It could also reduce costs associated with food waste management or related taxes.

7.4.5 Trade-offs

Increased efficiency in resource usage might also have unintended consequences known as rebound effects, tracing back to the so-called Jevons paradox. In the context of food waste reduction, it can occur when efforts to decrease waste could lead to unforeseen outcomes, such as increased consumption due to lower prices or overproduction. It can happen that economic savings due to purchasing less food – that comes with reducing food waste – might lead to an increased consumption of other goods. Therefore, in case those goods have a greater environmental impact than the food waste prevented (Albizzati et al., 2022; Hegwood et al., 2023), this could lead to increased overall impacts. Furthermore, food waste reduction could lead to potential economic loss due to lower consumption, affecting primary production and the associated economic sectors (De Jong et al., 2024).

7.4.6 The true cost of food

The application of the "true food cost" concept is also relevant to address food waste and change behavioural aspects. This emphasises the comprehensive economic and environmental impacts of food across the supply chain. By calculating the true cost of food, including its environmental footprint and societal costs, consumers and other relevant actors can make more informed decisions that prioritise sustainable production, resource efficiency and waste reduction. Understanding the true cost of food can foster an increase in the societal awareness of the issue and thus encourage behaviours that minimise waste throughout the food system life cycle, thereby contributing to more sustainable food practices (Hendriks et al., 2021). A project already investigating this aspect is the Horizon Europe project FOODCoST[41].

7.4.7 Key messages

- Food waste reduction is key for the transition to sustainable food systems and the deployment of a circular bioeconomy, in which biological resources are used sustainably;
- Food waste mainly occurs at consumer level. Effective prevention strategies require a multi-stakeholder approach across the whole food chain;
- Urgent action is needed. Ongoing policies and projects are achieving positive results in addressing food waste, yet more work is required to fully tackle the issue.

7.5 Dietary shifts

Beyhan de Jong, Patricia Gurria

7.5.1 The importance of dietary choices

According to the widely accepted EAT-Lancet report, a shift to healthy diets from sustainable food systems can make an important contribution to meet UN goals (e.g., climate action, responsible consumption and production) and the Paris Agreement. In that report, a healthy diet is defined as consisting of balanced plant-based foods, low amounts of animal products, and low levels of highly processed foods, unsaturated fats, refined grains and added sugar. To achieve a healthy diet, significant changes will be required, including a 50% reduction in consumption of unhealthy foods[42] and a 100% increase in intake of healthy foods such as fruits, vegetables, and nuts. The nature of these changes would differ greatly from one region to another (Willett et al. 2019). If the EAT-Lancet planetary health diet is adopted globally, it could lead to a 17% reduction in current annual dietary emissions by 2050, which is largely due to a significant shift away from red meat and towards legumes and nuts as primary protein sources (Li et al., 2024), and could lead to a reduction in agricultural land use, greenhouse gas emissions (GHG) and pasture land by 8%, 9% and

[41] Consortium - FOODCoST PROJECT *https://www.foodcost-project.eu/consortium/*

[42] As defined in the quoted EAT-Lancet report.

21%, respectively, while increasing global blue water and cropland requirement by 5% (Philippidis et al., 2021). There is a body of research that corroborates these findings, demonstrating similar positive impacts of reducing the consumption of animal-based foods and transitioning to plant-based diets on reducing GHG emissions (e.g., Frank et al., 2019, Springmann et al., 2016, Springmann et al., 2018a, Springmann et al., 2018b), mitigating eutrophication, and optimising land use (e.g., Gibbs and Cappuccio, 2022).

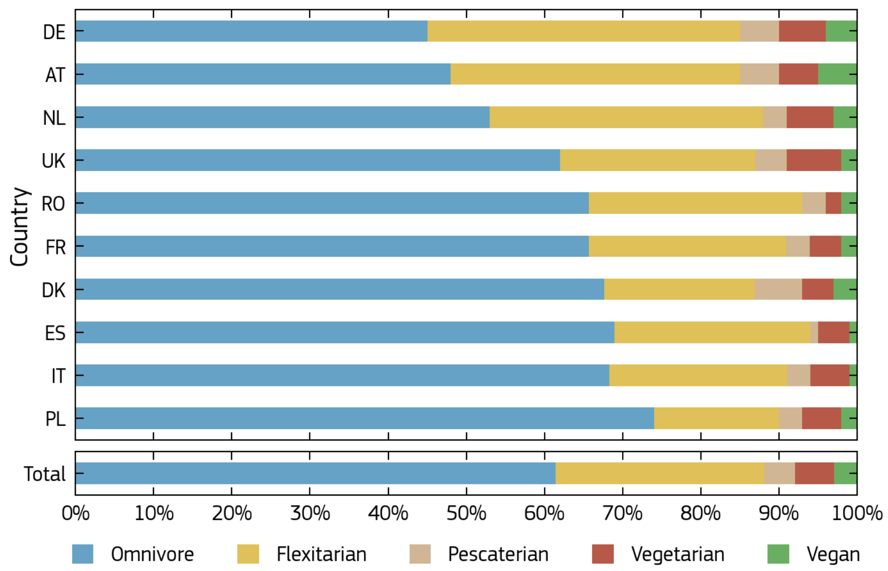
However, it is crucial to take a nuanced approach when assessing the impacts of animal production, recognising that the livestock sector holds significant economic and social value (Dumont et al. 2019, Guyomard et al. 2021). In addition, animal production can also offer environmental benefits, particularly when raised in mixed and extensive systems, which can utilise crop residues, by-products, and grass from marginal lands that are not suitable for crop production (Mottet et al. 2015, Herrero et al. 2013), which contributes to human food supply in the end (van Zanten et al. 2018, 2019). The benefits provided by livestock farming systems must be carefully balanced against their environmental drawbacks and compared to alternative land uses that offer distinct advantages, including reforestation, rewilding, and renewable energy generation (European Commission, 2024). Furthermore, the complexity of the challenges associated with livestock production at a global scale should not be ignored. A nuanced debate is needed, one that acknowledges the significant human health, environmental, and socioeconomic costs of industrial livestock production in high-income countries (Bryant et al. 2024).

Adopting a plant-based diet can significantly improve health by boosting fibre and essential vitamin and mineral intake, while reducing saturated fat consumption (Landry et al, 2024) and increase the number of avoided deaths (Springmann et al., 2016). A wealth of evidence from population studies and clinical trials confirms that adopting plant-based diets can play a crucial role in preventing obesity and obesity-related diseases, bodyweight control, and in promoting cardiovascular health and playing a key role in the prevention and management of diabetes (e.g., Gibbs and Cappuccio, 2022, Viroli et al., 2023). However, it is also important to recognise that, while animal product consumption can impact health outcomes, obesity, diet-related diseases, non-communicable diseases (NCDs), and cancers are influenced by a variety of dietary and lifestyle factors beyond just animal product intake. Several studies have highlighted the significant role of other dietary components and patterns in the development of these conditions (Gaesser 2020, Lane et al. 2024, Różańska et al. 2023).

7.5.2 Current EU dietary preferences

In recent years, the EU has witnessed a shift in dietary trends, driven by growing concerns over environmental sustainability, health, and animal welfare. As consumers become increasingly aware of the impact of their food choices, there has been a growing interest in diets which are more plant-based, with a rising number of flexitarians - individuals who primarily eat vegetarian but occasionally consume meat. According to the Smart Protein Project's consumer survey, and as shown in Figure 104, a significant share of respondents (27%) identifies as flexitarian, with Germany and the Netherlands leading the way at 40% and 35%, respectively. A notable 7% of the total consumers sampled report that health benefits are the primary reason for reducing meat intake, while environmental concerns coming in second (Smart Protein, 2023). Another survey from EIT Food, in which consumers from 17 EU MS participated, reveal similar results with almost 60% of respondents believing the consumption of animal-based products should decrease in their country. The most frequently cited reasons for reducing animal products were health-related concerns, followed closely by animal welfare (EIT Food, 2022). These trends suggest a growing shift towards reduced animal-based and more plant-based eating habits among European consumers.

Figure 104. Dietary lifestyle choices of EU consumers in selected MS, 2023.



Note: In this survey, “Omnivore” is defined as frequently eating meat (such as beef, pork, chicken, turkey, fish and/or shellfish), “Flexitarian” is defined as sometimes eating meat, but trying to reduce meat consumption and often choosing plant-based foods instead, “Pescatarian” is defined as eating fish and/or shellfish, but no other types of meat, “Vegetarian” is defined as not eating meat or fish of any kind, but eating eggs and/or dairy products, and “Vegan” is defined as not eating meat, fish, eggs, dairy products, or any other animal-based ingredients.

Source: JRC based on Smart Protein Project.

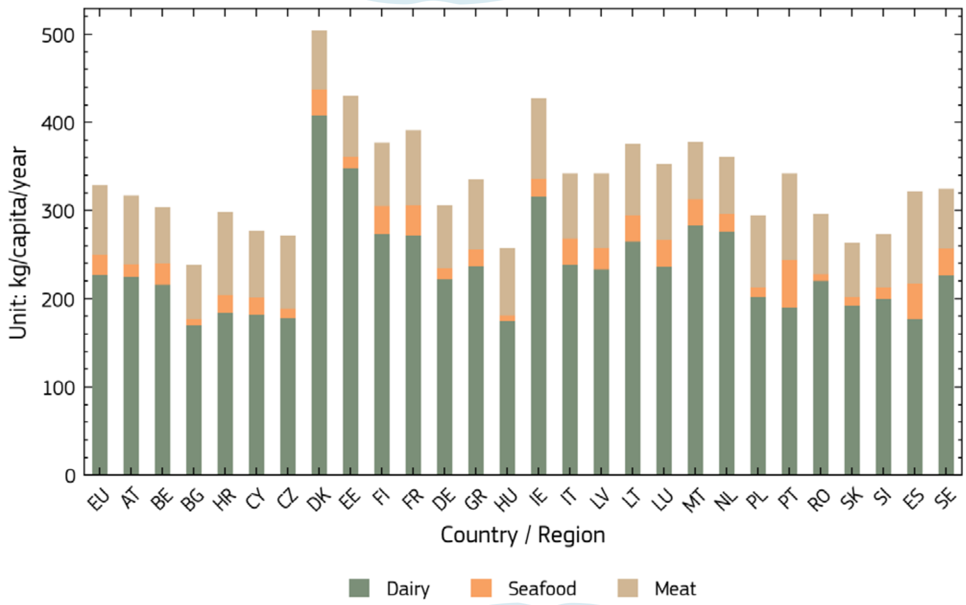
7.5.3 Trends in animal and plant-based protein consumption

In the EU, animal products are currently the primary source of protein in human diets (European Commission, 2024), and while their consumption has remained stable over the last decade, the sales of plant-based alternatives have increased their market share.

7.5.3.1. Animal protein

Dairy is the most available and consumed animal product across all EU countries, with levels generally ranging between 170-400 kg per capita among MS (Figure 105). Denmark and Ireland report higher levels of availability, whereas countries like Bulgaria and Czechia report lower levels. Meat supply quantity in the EU also varies across EU countries, with levels ranging from 60-100 kg per capita. Seafood availability and consumption is lower than dairy and meat consumption, with an average of 23 kg per capita in the EU. Countries with coastal access, such as Portugal and Spain, have higher seafood consumption rates.

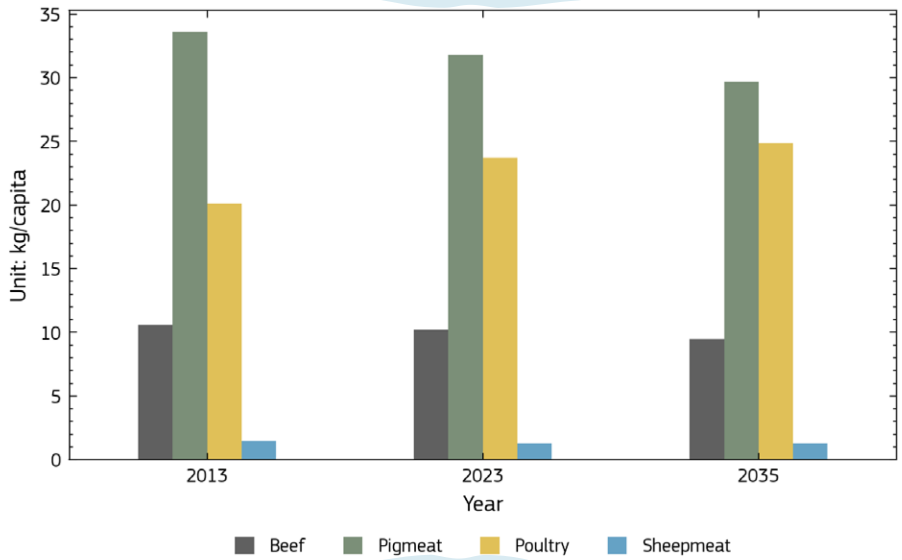
Figure 105. **Per capita supply quantities of meat, fish and dairy in EU MS, 2022.**



Source: JRC elaboration of FAOSTAT, 2024 data.

The overall trend for meat consumption indicates stability from 2013 to 2023, and is projected to remain stable until 2035 (Figure 106). However, there are differences across categories. While beef consumption has been relatively steady over the last decade, a decrease of around 7% is expected up to 2035. Pigmeat consumption shows a downward trend from 2013 to the projected period of 2035. The decline in beef and pigmeat consumption can be attributed to several factors, including high prices, shifting consumer preferences, growing health awareness, and increasing concerns about sustainability and animal welfare. Sheepmeat consumption has remained stable in the last decade and expected to remain stable going forward as well. Notably, poultry is the only meat category that has experienced growth over the last 10 years, with an expected increase of around 5% per capita (European Commission, 2023). Poultry's growth is primarily fuelled by its healthier image and competitive pricing, along with its versatility, strong retail demand, and relative environmental advantages.

Figure 106. **EU per capita consumption rates of meat by category.**



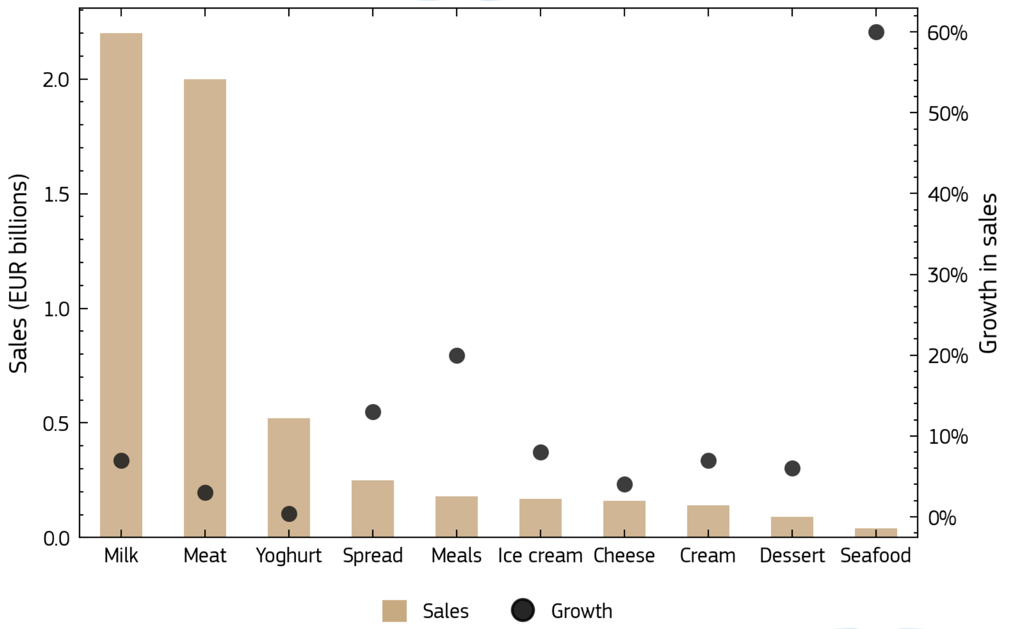
Source: JRC elaboration based on European Commission, 2023.

7.5.3.1.2 Plant-based alternatives

In recent years, a shift in dietary preferences and growing consumer interest in plant-based alternatives to meat, dairy and seafood have driven a significant surge in sales in these categories, with consumption increasing by a factor of five since 2011 in the EU (European Commission, 2023). The demand for plant-based alternatives extends beyond vegetarians and vegans, with meat-eaters (Neuhofer and Lusk, 2022) and flexitarians (Euromonitor, 2022) driving the growth.

Recent data reveals that in 13 European countries searched, plant-based food sales experienced a remarkable 21% growth between 2020 and 2022, reaching a market size of €5.8 billion. As illustrated with Figure 107, within the plant-based alternatives category, plant-based drinks is the most established segment, holding the largest market share, followed by plant-based meat alternatives. Conversely, plant-based seafood alternatives currently represent the smallest share, yet are experiencing the most rapid growth. Furthermore, demand for plant-based alternatives varies significantly across European countries. While Germany leads in terms of total plant-based food sales value, the Netherlands boasts the highest average spend per capita on plant-based food among the countries studied (GFI, 2023).

Figure 107. European plant-based food sales: 2022 market size and growth trends (2020-2022) by category.



Note: Countries included in analysis are Austria, Belgium, Denmark, France, Germany, Italy, Netherlands, Poland, Portugal, Romania, Spain, Sweden, and the UK. Some category names in this chart are retained from the original source data, such as “milk” being used instead of the term “plant-based drinks”, to maintain consistency and accuracy.

Source: JRC elaboration based on GFI 2023.

In addition, emerging alternatives such as cell-based meat and insects might be a complementary source of food, although they are not yet widely commercially available. Further evaluation is needed to assess their sustainability, production costs, food safety, contribution to healthy diets and consumer acceptance (Parodi 2018, Post et al. 2020, Rubio et al. 2020, Lähteenmäki-Uutela et al. 2021).

7.5.4 Conclusion

There is a growing awareness among EU consumers about the environmental and animal welfare impacts of food production. Some consumers are also becoming more health-conscious about the food they eat. These factors have led to a willingness in reducing meat consumption and increasing the consumption of plant-based foods. While this trend has been unfolding, over the last decade a wide range of plant-based meat alternatives have entered the market, with sales showing double-digit growth. These products have not only appealed to vegetarians and vegans but have also captured the attention of flexitarians and meat-eaters seeking versatility. Although surveys (e.g., EIT Food, 2022, Smart Protein, 2023) suggest that EU consumers are decreasing their meat consumption, actual meat consumption over the last decade has remained relatively stable, with only a slight decline expected in certain types of animal protein (European Commission, 2023), indicating a simultaneous growth in plant-based alternatives and certain animal protein categories is possible.

While consumers make decisions about food based on health, sustainability, or animal welfare concerns, the price of food products also plays a significant role in these choices. Moreover, considering the current food inflation, price is likely to become an even more important factor in consumers' purchasing decisions going forward, potentially influencing demand for both animal-based and plant-based foods.

7.5.4.1 Key messages

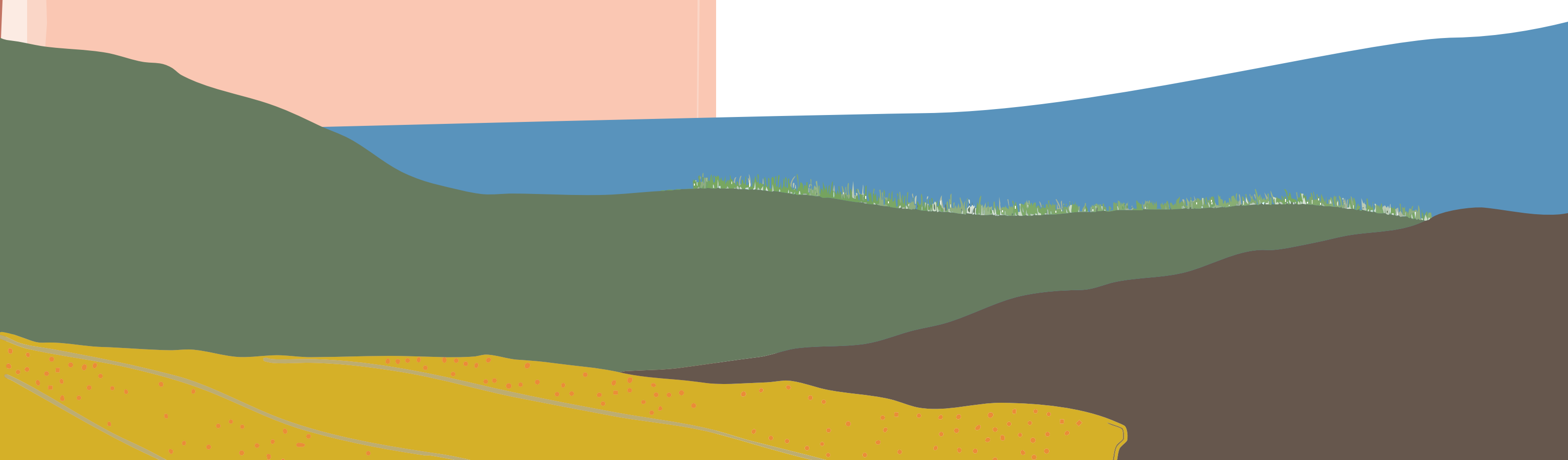
- EU consumers are increasingly aware of the environmental, health, and animal welfare impacts of food choices, leading to a willingness to reduce meat consumption and increase plant-based foods and alternative protein sources;

- While plant-based food sales have surged, overall meat consumption has remained stable, suggesting that plant-and animal-based protein markets can coexist simultaneously;

- Reducing animal consumption and adopting plant-based diets can increase sustainability, lower emissions, and improve health. However, policy decisions must consider the role of livestock, while also addressing diet-related health issues through a holistic approach.

8 Conclusions

This report comes in the early stages at the start of the new European Commission mandate, where several initiatives concerning natural resource management are planned. For this, the JRC Biomass Mandate remains highly relevant, and its continued evolution is vital for addressing the EU's biomass-related challenges while ensuring policy coherence.



We describe, in chapters 1 and 2, that the European Commission's policies surrounding biomass and bioeconomy converges around a single justification narrative, meaning that the overall goals to pursue are in common: Acknowledged in all of these is a need to address the multiple crises we are facing today (climate change, biodiversity loss, social inequality, excessive consumption and waste etc.), and furthermore, to do this in the spirit of policy coherence by acknowledging multiple facets at once in each policy. Hence the the story told about these issues is coherent throughout our polcy recitals, albeit each policy has its own area of emphasis. We also report however that the proposed actions in these policies may not necessarily be in line or are sometimes underdeveloped in the policies.

With the intent to contribute to policy coherence through a common evidence base, the JRC Biomass Mandate has contributed to the scientific evidence used in the process of policy and decision-making. This contribution to what we describe as the explanation narratives, refer to the mechanisms and causal relationships underlying biomass, especially biomass flows, demonstrating how supply chains, environmental constraints, and governance structures interact. Chapters 3 and 4 contain this evidence and are at the heart of the Mandate as we know it historically. In these chapters we quantify the biomass availability and trends.

On the premis that "The more evidence one gathers, the more single models of complex systems fail" (Rocha, 2001), we emphasise that assessments of ecosystem condition are relevant to report alongside quantifying biomass. Biomass is primarily sourced from ecosystems and the reporting of ecosystem condition, and the contextualisation of provisional services alongside regulatory and cultural services, helps puts into the perspective that biomass is limited and the provision of it relies on the ability of the ecosystem to continue to produce it. More importantly, ecosystem condition is necessary to sustain the fabric of life on Earth. It would be irresponsible to report on biomass production without an assessment of ecosystem condition as though biomass were an unlimited resource whose extraction bears no consequences. Furthermore, the EU is dependent on imports and importation implies production in regions that do not fall under EU juristiction. Any assessment of EU biomass supply and use must include the dependencies on third countries and the social, economic and environmental implications of trade on those countries must be considered. In this way, this reporting scheme of the JRC Biomass Mandate has evolved to an improved cross-sectoral coordination and better integration of ecological and spillover considerations into policy decisions.

Chapters 5 to 7 present our normative narratives. Here we consider possible strategic actions, addressing the option space of policy and governance responses with an aim toward bettering the alignment of biomass uses with societal wants. The selection of these actions is highly influenced by the actions described in European policies. Returning to the discussion in Chapter 2 on the assessment of policies, we concluded that the justification for the policies is aligned. But we also highlight that the actions proposed in the policies is varied and sometimes not complimentary, and in some cases, are incomplete in their description and definition. This inspired the chapters on the normative narratives, where we explore different actions in more depth, highlighting their pros and cons where possible.

Tying these three main components together (justification, explanatory and normative narratives), we gather the insights from the previous sections in these conclusions and attempt to integrate the content into a coherent and integrated structure.

For agriculture, we see that for the past two decades, the biomass available from agriculture has increased thanks to, depending on the crop and country, changes in the cultivated areas or improvements in agro-management practices which impacted crop yields. However, approximately 24% of the agroecosystems (pastureland and cropland together) are in good condition, while roughly 53% are in moderate condition, meaning that it is below the threshold for good condition, but can be restored with limited efforts. The remaining 23% are in bad condition, raising the question whether the increase in biomass availability from agriculture is sustainable. To address this, we dedicate a detailed section on agroecology, intent on describing the concept in its full, also because we conclude in Chapter 2, that this solution is mentioned in the 2018 EU

Bioeconomy Strategy as an important action but is underdeveloped as a concept. We therefore dedicate space to defining its two parts: the application of ecological principles to food and farming systems and as a social and political process, in order to frame food systems as both technical and social to be able to set the groundwork for a discussion about the full potential to transform food systems through agroecology. The management of pastureland is also relevant to the topic of agroecological condition (agroecological areas include both cropland and pastureland). We discuss how different management strategies can lead to different goals, and we show that there are trade offs between climate, biodiversity and the productivity goals of the European Green Deal.

In 2021, 76% of the total agricultural biomass supply was used as food and feed and approximately 80% of that is used as animal feed or to produce animal-based food, while the rest is directly consumed as plant-based food or is food wasted before consumption. We explore actions to hypothetically reduce the biomass needed for animal-based food both through direct ations such as dietary shifts, reduction in food waste, and novel foods; and indirect actions such as seaweed farming. We conclude that dietary shifts are indeed already occurring in Europe, with more people identifying themselves as "flexitarian" (people who primarily eat vegetarian but occasionally consume meat), and that multiple triggers are behind this shift from dominantly omnivore habits. We report on different novel foods, describing their chracteristics, and through a life cycle analysis lens, describe also how some novel foods may not necessarily be beneficial from an environmental perspective. Food waste reduction efforts are also described here in the report as well, cautioning however that there may be a trade-off in food waste reduction if food prices drop and extra income is used to purchase more goods with high environmental footprint.

Looking to forests, we report that 50% of the Habitats Directive's Annex I forest habitats is in good condition, 21%, in not–good condition, and in 29% the condition is unknown. Forestry practices are the dominant pressure on these forest habitats and the second largest pressure on species, with the roundwood removal hovering around the 500 Mm^3 u.b. these past years. We report on the expected increasing impact of climate change and natural disturbances, not only on forest biomass but also on net annual increment and what this means for the EU's forest sink (currently and into the future). We are approaching the limits of harvest levels that are compatible with the land sink targets embedded in the EU climate legislation. We present the evidence that the EU forest sinks are not within the targets, nor will they be in the future if harvest rates follow current trends. Under possible actions we discuss forest management strategies, and the pros and cons of sharing or sparing forest land, and dive deep into detail on forest-based carbon farming strategies within the broader discussion on nature-based solutions and the less obvious implications of these.

Throughout our reporting on forest-based biomass and other woody biomass, we emphasise the uncertainty on data reported by official statistics, above all for wood used for energy and strongly encourage to develop a near-real-time monitoring system of the overall flow of wood material through the forest supply chain, from the harvest to final use of wood products, such as what is proposed through the Forest Monitoring Law, arguing that we cannot discuss cascade and circular use of wood for the future until we have a clear picture of how this is implemented today. We also conclude that any assessment of the future biomass availability in forests should take climate change into consideration. We are certain that the estimates for net annual increment in EU forests are not fully taking climate change into consideration, which is in part the reason for a declining EU forest sink.

Closing the discussion on approaches to land-based natural resource management, we would like to highlight the chapter on Earth-Centered land stewardship not only for its content, but for how it was shaped and written. To produce this section, we reached out to indigenous and traditional land practitioners so that they may share their wisdom and experiences. In this section, we explore the concept of going back to a basic set of principles to guide decision-making for natural resource management. This approach requires discipline yet in its simplicity, also ensures more just decisions are made to ensure intergenerational fairness (also known as sustainability).

Regarding the marine ecosystems, we report that the situation is improving, approaching a threshold of sustainable fishing although there is still room for improvement. Throughout the report several sections describe possible actions to improve marine ecosystems, both biological solutions such as algae farming, and financial mechanisms related to aquaculture. In these sections we describe pros and cons of the actions, relating these actions also to the productivity and therefore to the socio-economic aspects of their implementation.

In closing, we maintain that while scientific evidence alone is not enough to identify a specific course of action regarding natural resource management, it is a necessary input for policy coherence. With this in mind, this report quantifies biomass supply and uses derived from the agriculture, forest, marine and freshwater ecosystems, as well as from waste streams. As we know, the basis of scientific evidence are mostly numbers, yet timely and high-quality data with good geographical coverage is a challenge in every sector. Efforts to improve this situation should be made. We cannot discuss important issues such as a biomass gap or the implications of applying a cascading principle to the different biomass categories if the supporting data is not reliable and available.

Assessments of ecosystem condition are relevant to report alongside quantifying biomass that is sourced from ecosystems because this helps puts into the perspective that biomass is limited and the provision of it relies on the ability of the ecosystem to continue to produce it, but more importantly, ecosystem condition is necessary to sustain the fabric of life on Earth and it would be irresponsible to report on biomass production without linking it to ecosystem condition. Likewise, in the spirit of looking into the whole bio-based system, we must acknowledge and quantify the EU dependencies on imports and the social, economic and environmental implications of trade.

Throughout these years, the JRC's findings have been updated in quantitative terms, and the overall findings are constant: there is a steady increase in use of biomass. Indeed, what motivated the initial inception of the JRC Biomass Mandate is unfortunately that there is little doubt that our current global overall use of biomass is in its sum unsustainable. We make this statement in the context of a highly uncertain research topic, a context where decisions are urgent and where various solutions of the past have failed to deliver on desirable outcomes. Achieving sustainable biomass governance requires not just technical solutions but also deep structural and functional transformations in the way biomass is conceptualised, managed, and integrated in our institutions and governance frameworks.

8.1 Future work

The JRC Biomass Mandate is highly relevant today. Biomass is central to many EU policies (see Chapter 2) and the JRC Biomass Mandate has had an impact on policies under different portfolios, due to the overarching nature of the Mandate.

We identify three main areas to focus upon through the next years:

1) Strengthened institutional (JRC) mandate to be more agile and policy relevant

The JRC Biomass Mandate was conceived to be overarching and agnostic to individual policy objectives yet aiming to be policy-relevant. Strengthened direction within the JRC is needed to cover more topics related to biomass, for example moving into the realm of health and zoonotic disease; participatory methods to engage more people; involvement of ecologists to go beyond ecosystem condition mapping; modelling teams for outlook studies, including at global scale; structural engineers for assessments on bio—based building materials; and many more. With a significant institutional directive to serve the best possible knowledge related to biomass in the Commission, and a certain degree of flexibility to do so, the Mandate becomes more policy relevant. Furthermore, related to the third ambition detailed below: with a strengthened institutional mandate, the JRC could move towards true system's level assessments as described in section 2.4.

2) Development of methods and tools to facilitate deliberation around questions surrounding natural resource management

We included a section on Earth-centred land stewardship (Section 5.1) specifically to illustrate the rich knowledge that lies beyond the normal European Commission circles of consultation. In the spirit of improving the robustness of policy support, we propose to broaden the solution space and to consult with unheard people whose livelihoods are impacted by European policies, not only so that they may explain the implications, but also so that they may share their wisdom and experiences.

In all of the mission letters to the Commissioners-designate, she mentions she wishes the College to work more closely together and take full ownership of what is agreed at that level, which implies a stronger cross-fertilisation of knowledge and a more system's level overview of each of the Commissioners. The JRC could facilitate this interaction and cross-fertilisation. This requires a different set of tools such as those proposed for example, in the Integrated Land Assessment project (see European Commission et al., 2025)

She encourages local and regional presence, namely a reinforced dialogue with citizens and stakeholders, with special emphasis on youth, announcing the intent towards a "lasting culture of participatory democracy". Here again, the JRC has experience in this and could facilitate this outreach through the development of tools and methods for outreach and inclusiveness.

Finally, data reporting by MS requires individual case-by-case attention, whereby the JRC can play a role in defining surveys, highlighting specific gaps, preparing conversion algorithms with experts etc.

3) Development of competence in system's level analyses.

Although there has always been a strong desire to harmonise the big picture with respect to the biomass production, supply and demand for all sectors, there has been little progress on approaching the mandate with a fully systemic analysis. The JRC Biomass Mandate is a coordinated effort between different scientific units of the JRC, each with its own set of competences, but additional efforts should be put into a whole system perspective. Thus, the work, although robust in its own sphere and for its own purposes, is not able to give a system's level assessment of the biomass demands and the biomass availability.

For future work, the JRC proposes to help renew focus on those urgent questions that are most relevant to broad, system-level assessment, and to work further toward cross-policy coherence through active facilitation of deliberation within the ISG Biomass. This point would mean adding a new set of skills to the mandate: from a predominantly silo approach to a means for understanding the full system behind biomass production and demand, as well as the implications of its extraction and processing as described in Section 2.4.

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Annexes

Annex 1. List of citations of JRC Biomass Mandate in policy documents.

2015	EU Bioeconomy Strategy and Action plan (COM(2012) 60	Mandating a knowledge base on biomass be built (i.e. birth of JRC Biomass Mandate)
2016	SWD(2016) 319 final Commission staff working document 'European Research and Innovation for Food and Nutrition Security'	Bioeconomy
2016	Contribution to the preparation of SWD(2016)418 - Impact Assessment on Sustainability of Bioenergy, accompanying the proposal for a Directive COM(2016)767	JRC Biomass Mandate used to frame IA
2016	Commission proposal of a Regulation on the Governance of the Energy Union	JRC Biomass Mandate contributed to drafting text of Annex VII
2017	Launch of KCB, Action "The setting up of a knowledge-base on biomass across sectors", in the 2012 EU Bioeconomy Strategy (COM(2012) 60	JRC Biomass Mandate a main data source
2018	Review of the 2012 European Bioeconomy Strategy	JRC Biomass Mandate mentioned
2018	EC guidance on cascading use of woody biomass, part of the Circular Economy Action Plan (COM/2015/0614 final)	JRC Biomass Mandate figures used, 2 Mandate cited
2018	Providing evidence for an infringement case regarding the habitats and birds directive	JRC Biomass Mandate only partially involved through forest biomass mapping
2018	2018 Bioeconomy Strategy COM(2018) 673 and SWD(2018) 431	JRC Biomass Mandate mentioned; Bioeconomy; STECF;
2019	ANNEX I to the Reflection paper Towards a sustainable Europe by 2030	Bioeconomy
2019	Corporate Modelling Inventory and Knowledge Management System (MIDAS) made available to the European Parliament	JRC Biomass Mandate only partially involved through preparation of metadata for relevant models
2020	Biodiversity strategy 2030 COM(2020) 380	JRC Biomass Mandate mentioned
2020	Biodiversity Strategy Action plan (under win-win solutions for energy generation)	JRC Biomass Mandate mentioned
2020	Leading the way to a global circular economy: state of play and outlook SWD (2020) 100	JRC Biomass Mandate mentioned

2021	Sustainable carbon cycles for a 2050 climate-neutral EU SWD(2021) 451 final	CCS technology, is this under CETO?
2022	Towards a Strong and Sustainable EU Algae Sector COM(2022) 592	JRC Biomass Mandate mentioned
2022	Implementation of the EU Bioeconomy Strategy action plan: enhanced knowledge on the bioeconomy through the Commission's Knowledge Centre for Bioeconomy	JRC Biomass Mandate publications and data
2022	Direct support to the European Parliament for RED II revision proposal	JRC Biomass Mandate
2022	EU Bioeconomy Progress report	JRC Biomass Mandate figures used
2022	EU Forest Strategy COM(2021) 572	JRC Biomass studies cited
2023	Forest Monitoring Framework Regulation COM(2023)728	JRC Biomass Mandate through harmonisation of forest attributes with National forest inventory
2023	Making available on the Union market and the export from the Union of certain commodities and products associated with deforestation and forest degradation Regulation (EU) No 995/2010	Contribution to Commission proposal, slightly part of JRC Biomass Mandate
2023	"Renewable Energy Directive III" Directive reviewing 2018/2001	JRC Biomass Mandate cited and some policy recommendations adopted (Art 29; Art 3)
2024	Towards EU climate neutrality – Assessment report 2024	JRC Biomass Mandate among many other studies in JRC

Annex 2. Narrative analysis categories

Category	**Definition**	**Guiding questions**	**Example: Biophysical Boundaries**
Problem framings	One of the central issues regarding the narratives is the description of the current state of affairs since this is the basis from which the story starts. Usually, this current state of affairs is presented as somehow challenging or problematic, hence calling for some sort of solution.	What is the problem that needs to be solved? What needs to change? What are the different elements of the problem-framing?	*Limits* “We live in a world of limited resources. Global challenges like climate change, land and ecosystem degradation, coupled with a growing population” (strategy) and *tipping points*, problem of “*overconsumption*” (progress report)
Knowledge claims	The knowledge claim category focuses on the “facts” that are used to support the problem framing.	What is the evidence (quantitative information, statistics, model, theoretical framing) that is used to substantiate the problem framing in a policy narrative?	Impending collapse “the declining health of global oceans and the collapse of biodiversity” (SWD)
Claims	Looking for claims means looking for statements about what will happen and what will be put in place by what time. Claims are usually more focused on practical actions or ‘inevitable developments’ (such as digitalisation, innovation, environmental collapse) and may include goals or targets.	What ’needs’ to happen? What will be put in place?	“need to respect limits “; “respect the ecological boundaries of our planet”” (strategy). Research to generate a better understanding of soil health, pollinators. Strategy will drive “the protection of the environment and will enhance biodiversity”
Promises	Promises articulate the future visions and the desirable states that the changes called for should achieve.	What is imagined to be achieved by when? How is success imagined? What is the expected societal change that will be achieved?	The European way: “doing it the European way: being economically viable with sustainability and circularity in the driver’s seat.” (strategy) “A sustainable bioeconomy has a pivotal role in reducing pressures on major ecosystems such as oceans, forests and soils to a level respecting all planetary boundaries, and support their pivotal role for balanced nutrient cycles and as carbon sinks” (Progress Report)

Theory of change	Narratives always describe the shift from one state of affairs to another (more desirable) one. This necessarily involves thinking about how this shift will come about. Sometimes such stories are very explicit and sometimes they remain more implicit. Often-used examples of such theories of change are the "techno-fix" narrative that focuses on emerging technological solutions that will make fundamental changes to how we organize ourselves as societies unnecessary. Especially when it comes to questions of sustainability, there is a continuum of positions ranging from minor reform and transitioning to deep change, system transformation or revolution (Hopwood, Mellor, and O'Brien 2005).	How is change imagined to happen? What drives change? Are current modes of operating sufficient to solve the problem or are fundamental changes necessary?	(1) "better understanding " drives change. "Enhancing the knowledge base and understanding of specific bioeconomy areas (Action 3.1) will be based on acquiring more data, generating better information and systemic analysis (e.g.,through AI) of data and information" (strategy). (2) Restore ecosystems "Timely action is needed to avoid ecosystem degradation, restore and enhance ecosystem functions, which can increase food and water security, and contribute substantially to the adaptation and mitigation of climate change through "negative emissions" and carbon sinks" (strategy)
Subject positions	Here we look at the actors that 'drive the change' and play a role in solving a problem. The notion of subject positions adds ideas about agencies to the narrative analysis. Subject positions can be the "innovative scientist", the "consumer", or the "disinterested public". These notions combine certain actors with implicit ideas about how they are (supposed to be) acting. We are interested both in identifying the actors listed and in how they are described.	Who is supposed to act in what capacity? How is responsibility distributed among actors?	Scientific knowledge (evidence as an agent)
Governance models	The range of proposed solutions, claims and promises also implies different models of governance: one can think for example about the distinction between top-down and bottom-up forms of governance (or democracy) or about the distinction between hierarchical, marked or network governance (Meuleman 2018)	What is the governance model implied in solutions proposed in a policy narrative?	Evidence-based policy
Reasoning (causality)	This category helps define the narrative, by linking problem framings, solutions, theory of change, subject positions and governance models. Under the label of reasoning, the analysis subsumes statements about cause-effect relationships. These are stories that justify why some course of action needs to be taken. These stories may also appear in the form of "if-then" statements.	What is the reasoning behind a proposed course of action? What is the relationship between the problem and the promises? How do the theory of change, subject position and governance model contribute to the (aspiration for) change?	Reasoning (causality)

Coherence of policy narratives	Coherence is a comparative category that allows for looking at potential conflicts between different policy narratives, such as e.g., between narratives that emphasize the biophysical limits (such as land use and biodiversity) of economic activity and others that emphasise the growth potential of bio-based economic activity.	How are other promises and reasonings affected by particular policy narratives? Are there potential conflicts?	Tension with growth, "Mitigation shows a negative trend due to the decline of the forest sink"" (progress report) ""a circular bioeconomy depends on an efficient and sustainable use of biological resources, against the backdrop of an increasing demand for biomass" (SWD)
Pedigree	Pedigree refers to the origins of particular ideas or concepts that are referenced in policy narratives. Once the origin of an idea is identified, the analysis can zoom in on how the meaning of a concept has shifted in the process of being incorporated into a policy narrative. In addition, also the history of policy development can be coded.	Where does a certain idea/concept come from and how is it applied in a policy narrative? What other policy documents are referenced? How is the relationship between the different policies/ documents described?	planetary boundaries: Steffen, Will, Katherine Richardson, Johan Rockström, Sarah E. Cornell, Ingo Fetzer, Elena M. Bennett, Reinette Biggs et al. "Planetary boundaries: Guiding human development on a changing planet." Science 347, no. 6223 (2015): 1259855.

Annex 3. Supplementary Material section 3.2.2 Forest biomass production

Figure 29a compares, for broadleaves and coniferous species, the evolution of the above ground Net Annual Increment (NAI) estimated by the JRC EU Forest Carbon Model (CBM) with the amount of fellings estimated by the same model and derived by removals reported by FAOSTAT (FAOSTAT 2024). All data are referred to the total aboveground biomass per unit of area. Because of the lack of data reporting of a harmonised assessment of NAI for different time steps, at EU level (see Avitabile et al. 2024), we derived this information from the CBM model, recently calibrated by the JRC, for the period 2010 - 2020, for all EU countries except Malta and Cyprus (Pilli et al. 2024). These data can be compared both (i) with the amount of fellings directly considered by the CBM model within the same calibration period, as assessed by the JRC according to other ancillary information reported by literature (i.e., to partially correct possible underestimation from official statistics), and (ii) even with the total fellings derived by FAOSTAT data, including 2021 and 2022. In this latest case, since statistics reported by FAOSTAT refer to under bark roundwood removals, original dataset was further corrected to include bark and total aboveground fellings residues, as estimated by CBM within the period 2010 - 2020[43].

Based on these data, we estimated, on Figure 29b, the fellings rate corresponding to the ratio between the amount of fellings (i) considered by CBM, within the period 2010 - 2020, and (ii) derived by FAOSTAT data series, until 2022, and the NAI as estimated by CBM for the entire period. In this case, NAI for 2021 and 2022 was assumed as constant and equal to the value reported for 2020.

[43] To include bark and logging residues, we applied to original FAOSTAT removals a correction factor, estimated on annual basis, equal to 1.2 and 1.2-1.3, for broadleaves and coniferous species, respectively.

Annex 4. Supplementary Material for section 3.4 European and Global macroalgae production and uses

Table A4.1. Quantity harvested of wild seaweed in tonnes wet weight worldwide per country. EU-27 countries highlighted in bold.

Country	2021	2022
Chile	394,860	464,024
China	202,850	193,920
Norway	160,432	171,142
Indonesia	89,357	90,111
France	**57,037**	**59,670**
Japan	61,780	56,600
India	33,345	52,107
Peru	49,491	50,896
Ireland	**28,000**	**28,000**
Iceland	16,407	18,300
Canada	12,542	12,097
Morocco	20,426	11,768
Russian Federation	7,464	8,041
Republic of Korea	7,435	7,435
South Africa	6,327	6,832
United States of America	7,449	5,864
Mexico	7,245	4,208
Spain	**2,603**	**3,316**
Australia	1,923	1,923
Portugal	**1,766**	**1,207**
Italy	**1,200**	**1,200**
Madagascar	800	800
Philippines	377	766
United Republic of Tanzania	600	600
New Zealand	666	566
Estonia	**181**	**381**
Taiwan Province of China	323	322
Fiji	135	135
Samoa	8	8

Table A4.2. **Quantity (tonnes wet weight) and value (thousands of EUR) of global seaweed produced by aquaculture in each country in 2021 and 2022. EU-27 countries highlighted in bold.**

Country/Year	2021			2022		
	Production (t.w.w)	Value (*000 EUR)	Price (EUR/ t.w.w)	Production (t.w.w)	Value (*000 EUR)	Price (EUR/ t.w.w)
China	21,500,705	10,491,043	488	22,404,167	11,400,243	509
Indonesia	8,957,291	1,872,997	209	9,219,982	2,592,156	281
Republic of Korea	1,846,404	597,535	324	1,725,598	525,608	305
Philippines	1,343,707	195,590	146	1,544,960	289,488	187
Dem. People's Rep. Korea	603,000	86,070	143	603,000	86,070	143
Japan	335,844	989,386	2,946	325,200	802,303	2,467
Malaysia	178,897	13,275	74	307,972	53,314	173
U.R. Tanzania (incl. Zanzibar)	144,846	1,716	12	167,378	2,029	12
Russian Federation	23,863	29,380	1,231	28,654	37,021	1,292
Madagascar	11,658	2,024	174	15,816	2,568	162
Chile	15,571	187,802	12,061	13,417	141,381	10,537
Solomon Islands	12,456	603	48	11,871	622	52
Viet Nam	14,054	3,776	269	10,515	2,836	270
India	5,300	371	70	5,300	349	66
Venezuela (Bolivarian Republic of)	4,005	1,522	380	4,205	1,598	380
South Africa	2,595	834	321	3,699	1,074	290
Brazil	1,130	398	352	1,100	405	368
Kenya	1,030	23	22	1,060	21	20
United States of America	430	295	685	740	501	677
Timor-Leste	700	67	95	700	67	95
Papua New Guinea	500	20	41	600	24	41
Ireland	214	842	3,933	493	395	800
Sri Lanka	218	63	287	271	53	194
Norway	246	688	2,793	221	418	1,892
Saint Lucia	204	3,455	16,921	201	2,063	10,246
Taiwan Province of China	290	62	214	193	23	118
France	**127**	**1,212**	**9,573**	**182**	**1,328**	**7,308**
Morocco	84	9	106	174	16	93
Faroe Islands	110	452	4,107	115	420	3,648
Cambodia	100	19	190	100	19	190
Ecuador	100	38	380	100	38	380
Tonga	100	21	210	100	20	204
Tunisia	30	6	204	79	17	214
Fiji	73	17	238	60	14	238
Grenada	22	52	2,375	25	59	2,375
Portugal	**17**	**35**	**2,043**	**17**	**31**	**1,818**

Senegal	-	-	-	16	244	15,230
Saint Vincent and the Grenadines	13	34	2,639	13	34	2,639
Antigua and Barbuda	10	46	4,574	10	46	4,574
Belize	9	32	3,563	10	37	3,658
Denmark	**9**	**26**	**2,795**	**8**	**19**	**2,484**
Spain	**5**	**1,798**	**359,552**	**5**	**3,700**	**792,284**
Samoa	2	4	1,857	4	7	1,767
Saint Kitts and Nevis	2	2	1,040	2	2	1,040
Dominica	1	5	10,203	1	10	10,203
Cook Islands	-	-	-	-	-	-
Italy	**-**	**-**	**-**	**-**	**-**	**-**
Kiribati	-	-	-	-	-	-
Marshall Islands	-	-	-	-	-	-
Mexico	-	-	-	-	-	-
Micronesia (Federated States of)	-	-	-	-	-	-
Mozambique	-	-	-	-	-	-

Table A4.3. Quantity of seaweed commodities (t w.w.) imported, exported and re-exported worldwide in 2021 and 2022. EU-27 are placed at the beginning of the table. Source: FAO 2024.

Reporting country (Name)	Export		Import		Re-export	
	2021	2022	2021	2022	2021	2022
Austria	107	108	1,161	1,372		
Belgium	506	495	1,447	1,561		
Bulgaria	64	85	91	93		
Croatia	1	1	120	89		
Cyprus	0	0	220	228		
Czechia	29	38	447	394		
Denmark	1,354	1,252	6,408	7,000		
Estonia	3	1	110	129		
Finland	5	25	277	236		
France	10,618	9,243	67,632	70,649		
Germany	1,565	1,501	4,247	3,421		
Greece	23	21	184	229		
Hungary	4	4	128	90		
Ireland	82,236	73,336	70,880	75,077		
Italy	1,781	1,619	6,280	6,594	-	2
Latvia	114	290	134	367		
Lithuania	412	331	635	241		
Luxembourg	4	2	30	28		
Malta	-	-	1	5		
The Netherlands	667	1,293	2,568	2,182		
Poland	278	92	1,949	2,532		
Portugal	1,229	405	575	742		
Romania	1	1	115	150		
Slovakia	55	20	93	60		
Slovenia	21	19	32	34		
Spain	4,962	4,230	14,208	15,703		
Sweden	47	34	559	541		
TOTAL EU-27	**108,106**	**96,470**	**182,552**	**191,770**	**2,021**	**2,024**
Afghanistan	-	-	-	-		
Albania	0	-	2	3		
Algeria	0	0	2	16		
Andorra			0	0		
Angola	0	0	5	6		
Antigua and Barbuda	2	-	8	6		
Argentina			739	710		
Armenia	0	0	17	25		
Aruba	-	-	26	21		
Ascension-Saint Helena and Tristan da Cunha			0	1		
Australia	579	797	12,450	15,863		

Azerbaijan			36	28		
Bahamas	5	2	3	30		
Bahrain	5	7	21	62	-	2
Bangladesh	15	42	41	112		
Barbados	-	-	36	23		
Belarus	100	12	1,227	1,118		
Belize	0	-	2	2		
Benin	1	-	3	3		
Bermuda			15	13		
Bhutan	-	-	0	0		
Bolivia (Plurinational State of)			5	6		
BosniaandHerzegovina			7	7		
Botswana	-	0	0	0		
Brazil	10,189	5,501	1,669	1,535		
Brunei Darussalam	14	10	189	131		
Burkina Faso	1	1	0	0		
Burundi			0	0		
CaboVerde			1	3		
Cambodia	0	-	60	48		
Cameroon	-	-	3	4		
Canada	7,084	5,698	3,620	3,806	238	122
Cayman Islands	-	-	5	4		
Central African Republic			-	2		
Chad	-	-	0	-		
Chile	67,897	70,336	5,429	4,979		
China	20,261	18,788	312,074	341,212		
China-HongKong SAR	281	287	1,252	1,166		
China-Macao SAR	-	-	45	46	-	0
Colombia	0	-	257	237		
Congo			6	0		
Cook Islands			1	1		
Costa Rica	-	-	128	154		
Côte d'Ivoire	-	0	2	3		
Cuba	-	-	2	3		
Curaçao	-	0	4	5		
Democratic People's Republic of Korea	1	6	-	-		
Democratic Republic of the Congo			1	10		
Djibouti			1	-		
Dominica	-	0	-	-		
Dominican Republic	2	3	28	39	-	0
Ecuador	28	32	63	81		
Egypt	-	-	76	155		
El Salvador	-	-	7	8		
Equatorial Guinea	-	-	0	0		

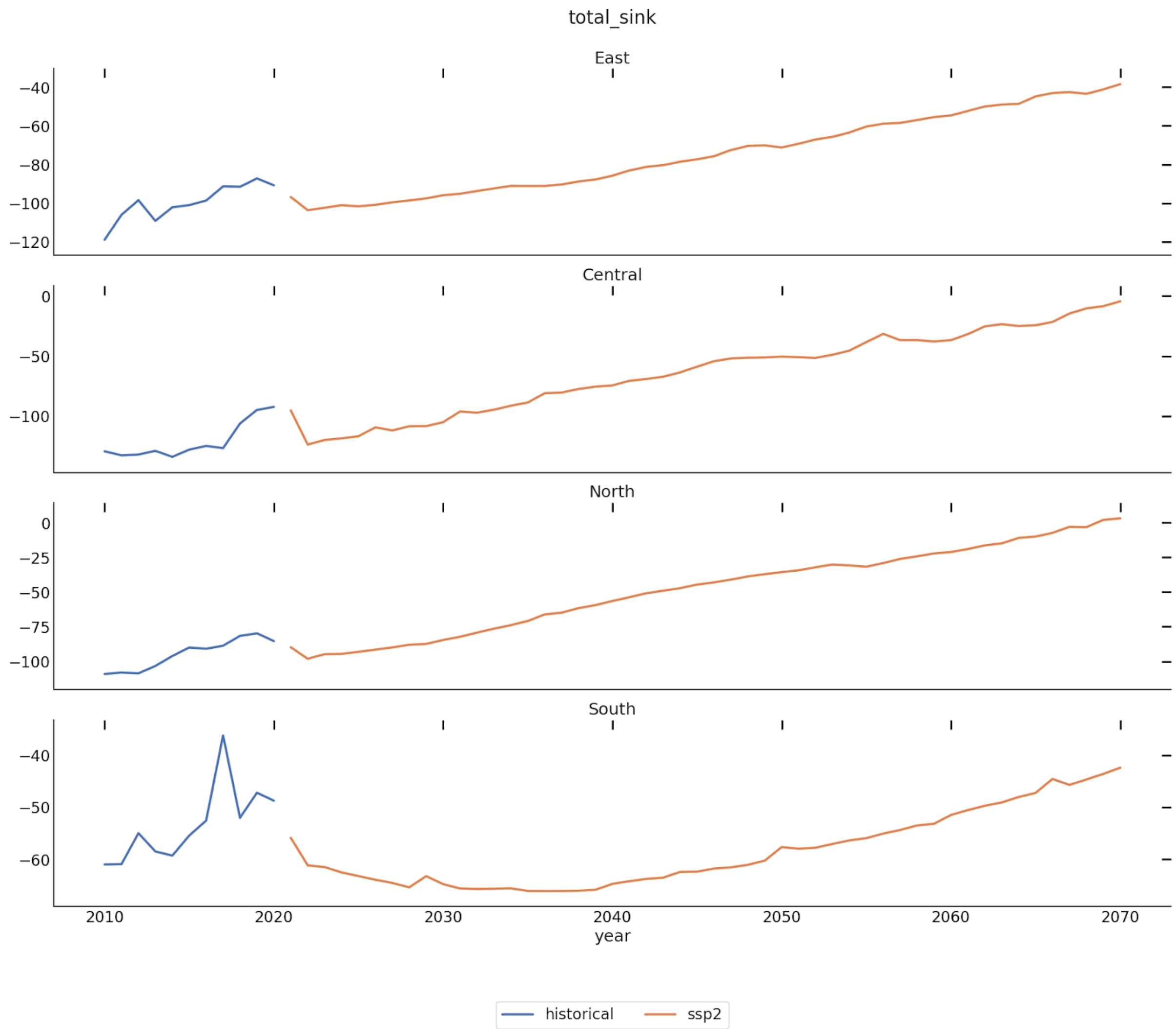
Eritrea			-	-		
Eswatini			0	0		
Ethiopia	1	-	3	3		
Falkland Islands (Malvinas)			-	-		
Faroe Islands	125	63	7	2		
Fiji	-	-	5	7	-	0
French Polynesia	0	1	19	19		
Gabon	97	-	27	0		
Gambia	-	2	1	-		
Georgia	0	0	12	8		
Ghana	0	0	1	3		
Greenland	2	0	4	3		
Grenada	2	3	1	1	-	-
Guatemala	-	0	37	10		
Guinea			121	-		
Guinea-Bissau			0	0		
Guyana			4	3		
Haiti	-	-	1	0		
Honduras	1	-	20	17		
Iceland	4,573	11,820	30	24		
India	286	270	681	1,434		
Indonesia	210,183	237,873	616	1,265		
Iran (Islamic Republic of)	126	35	133	360		
Iraq	-	-	6	18		
Israel	289	249	116	134		
Jamaica	5	2	109	36	0	0
Japan	1,569	1,708	40,679	39,274		
Jordan	1	-	98	601		
Kazakhstan	14	41	516	361		
Kenya	260	43	14	10	0	-
Kiribati			0	0		
Kuwait	-	-	105	116	-	-
Kyrgyzstan			32	32		
Lao People's Democratic Republic	0	0	9	68		
Lebanon	2	2	4	4		
Lesotho			0	0		
Liberia	-	-	0	0		
Libya			2	1		
Madagascar	2,709	3,172	3	2		
Malawi			1	1		
Malaysia	908	398	1,167	1,095		
Maldives			69	73		
Mali	-	-	4	1		
Marshall Islands			0	0		
Mauritius	0	0	33	32	-	0

Mexico	561	533	1,313	845		
Micronesia (Federated States of)			-	0		
Mongolia	-	-	327	332		
Montenegro			7	2		
Montserrat			-	0		
Morocco	2,570	2,851	252	213		
Mozambique	0	-	3	3		
Myanmar	312	129	43	43		
Namibia	0	0	3	3	-	0
Nepal			6	1		
New Caledonia	-	-	0	2		
New Zealand	87	13	621	699	-	-
Nicaragua	-	-	9	10		
Niger	-	35	1	1		
Nigeria	-	-	59	62		
North Macedonia	-	-	25	12		
Norway	2,891	1,378	4,494	4,206		
Oman	-	20	78	56	0	-
Pakistan	26	49	90	68		
Palau			5	2		
Palestine			1	2		
Panama	13	17	254	253		
Papua New Guinea			17	4		
Paraguay	2	-	18	7		
Peru	43,734	49,254	21	29		
Philippines	9,795	16,887	3,848	4,111		
Qatar			381	57		
Republic of Korea	25,107	26,018	10,397	12,483		
Republic of Moldova			20	20	0	2
Russian Federation	793	448	8,293	8,261		
Rwanda			0	2		
Saint Kitts and Nevis	-	-	0	-		
Saint Lucia	89	74	1	0		
Saint Pierre and Miquelon	-	-	5	8		
Saint Vincent and the Grenadines	2	4	0	-		
Samoa			0	0		
Sao Tomeand Principe			-	0		
Saudi Arabia	2	2	9,515	5,833	7	-
Senegal	-	0	1	1		
Serbia	19	19	122	143		
Seychelles			11	13		
Sierra Leone	-	1	-	0		
Singapore	145	186	998	981		
Solomon Islands	170	201	0	0		

Somalia			6	0		
South Africa	3,006	3,464	3,694	5,395		
South Sudan			0	0		
Sri Lanka	150	205	35	13	-	6
Sudan			-	1		
Suriname			0	2		
Switzerland	25	25	181	159		
Syrian Arab Republic	-	25	2	-		
Taiwan Province of China	610	606	14,724	13,487		
Tajikistan			1	3		
Thailand	374	351	5,152	5,579		
Timor-Leste	122	77	6	6		
Togo			-	-		
Tonga	114	44	0	0		
Trinidad and Tobago	14	6	66	56	4	0
Tunisia	77	84	398	479		
Türkiye	130	77	4,029	3,004		
Turkmenistan			4	3		
Turks and Caicos Islands	0	-	-	-		
Tuvalu			0	-		
Uganda	1	-	10	7		
Ukraine	38	21	1,056	921		
United Arab Emirates	56	32	317	223	56	53
United Kingdom	2,511	2,633	3,785	9,079	-	0
United Republic of Tanzania	9,373	10,861	0	0		
United States of America	2,130	1,762	28,090	30,534	219	248
Uruguay	0	-	168	40		
Uzbekistan	-	1	101	134		
Vanuatu			0	0		
Venezuela (Bolivarian Republic of)	582	945	0	25		
VietNam	5,320	4,800	1,661	1,678		
Yemen	-	-	1	2		
Zambia			5	38		
Zimbabwe			0	0		
Total rest of the world	**433,250**	**476,546**	**487,325**	**524,622**	**524**	**434**

Annex 5. Supplementary Material for section 4.2 Forest sink scenario analysis

The following figure reports the evolution of the total forest C sink, as estimated by EU-CBM-HAT, under the SSP2 scenario, further distinguished between the following geographical regions: East: Bulgaria, Croatia, Hungary, Poland, Romania, Slovenia; Central: Austria, Belgium, Czechia, Germany, France, Ireland, Luxemburg, Netherlands, Slovakia; North: Denmark, Estonia, Finland, Lithuania, Latvia, Sweden; South: Cyprus, Spain, Greece, Italy, Malta, Portugal. Please note that negative values represent a carbon sink, positive values a carbon source. All values reported in million tonnes of CO_2 equivalent.



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