European Environment Agency

Enhancing Europe's land carbon sink: status and prospects

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Key messages

- The land use, land use change and forestry (LULUCF) sector is the only sector that removes carbon on a large scale, and it has become a key component of EU and Member State policymaking in the transition to a climate neutral economy by 2050.

- A wide variety of options is available to protect carbon stocks and to enhance removals in all land categories. Applied at scale, these options can jointly have a significant climate change mitigation potential and offer many co-benefits to society. In view of the increasing effects from climate change on terrestrial ecosystems, increasing their resilience is a prerequisite for effective mitigation action in the sector.

- Between 2014-2023, the EU's average net annual carbon sink was 30% smaller compared to the decade before, largely due to dynamics in forest land. In 2023, the EU LULUCF sector provided a net carbon sink of 198 MtCO_2e, relative to around 6% of EU gross emissions from other sectors.

- Member State projections from 2024 suggest the EU LULUCF removals target for 2030 is at considerable risk of not being met. Several Member States also face a challenge meeting their national removal target for 2030.

- To ensure adequate progress to target, an increased focus on implementing already agreed-upon policy instruments is needed, with a focus on leveraging financial investment and improving monitoring, reporting and verification (MRV) systems to enable Member States and land practitioners to take adequate action. Leveraging the evolving technological and data landscape can increase the effectiveness and cost-efficiency of LULUCF mitigation action by public and private actors.

Executive summary

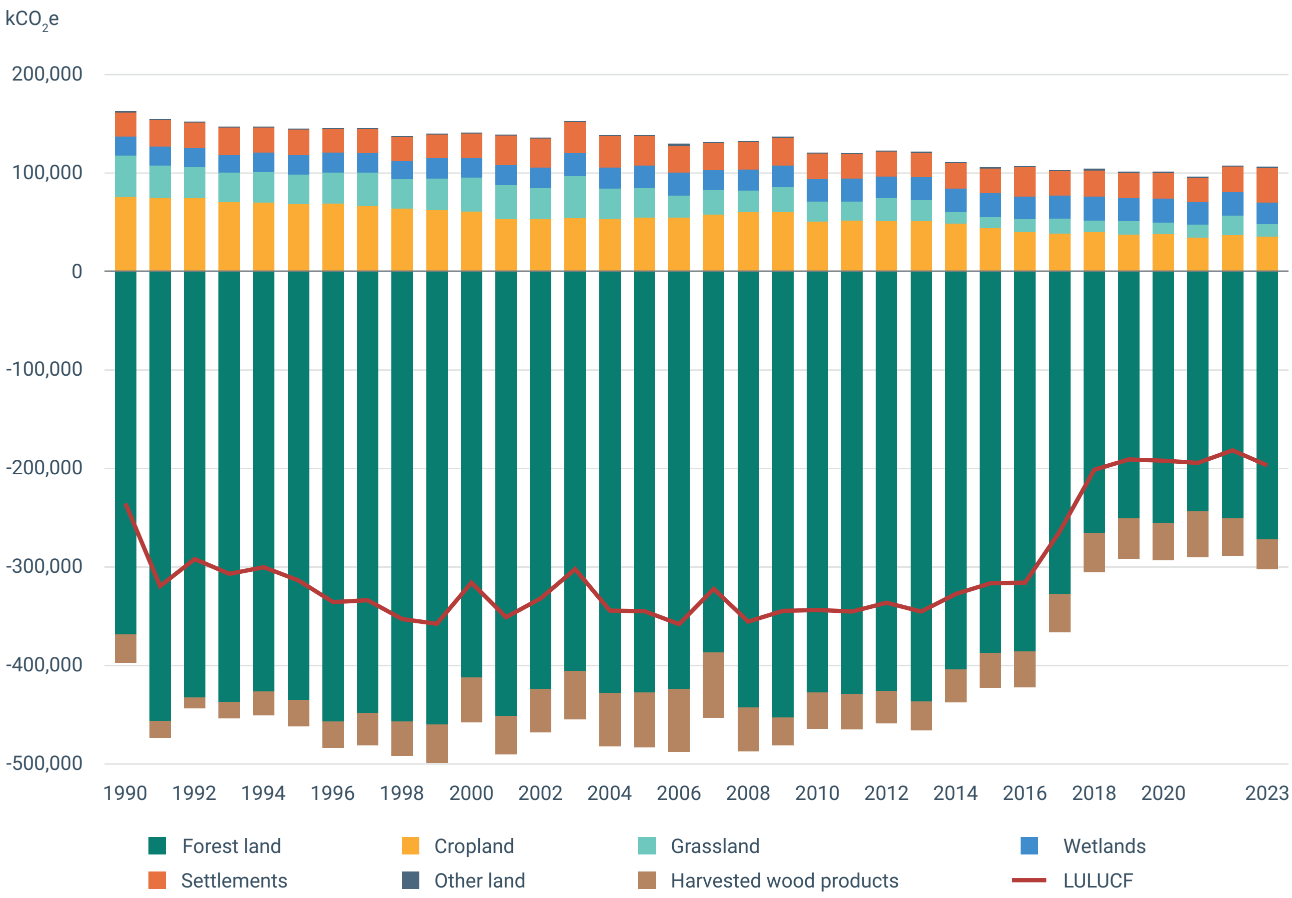
This report provides a description of the land use, land use change, and forestry (LULUCF) sector, as a relatively new sector in EU climate governance. It assesses the sector in terms of reported GHG emissions and removals, based on information provided in the latest EU greenhouse gas inventories as well as latest available projections data (reporting years 2023-2024). The report provides insights on ways to mitigate GHG emissions and enhance removals in the LULUCF sector, and what enabling conditions are most relevant to upscale options.

The LULUCF sink has declined significantly in the last decade and is becoming less predictable

The LULUCF carbon sink is now influenced by anthropogenic activities more than ever before. These are notably linked to land use, land use change and the management of land and forests, and – increasingly – by negative impacts from human-induced climate change. Natural disturbances are also playing a growing role in influencing carbon stocks and fluxes.

In 2023, the LULUCF sector provided a net carbon sink of 198 $MtCO_2e$, counterbalancing around 6% of the EU's GHG emissions from other sectors. The LULUCF sink has been on a declining trend for about a decade. The sector provided an average carbon sink of 335 $MtCO_2e$ in the period 1991-2013. Between 2014-2023, the average annual LULUCF sink shrunk by 30% compared to the previous decade (Figure ES.1). This also means that the relative role of LULUCF, in terms of counterbalancing gross GHG emissions from other sectors, has declined. This goes against relevant climate change mitigation scenarios' projections.

Figure ES.1 **LULUCF net emissions (+) and removals (-) for the EU-27 (1990-2023) in kilotonnes of carbon dioxide equivalent ($ktCO_2e$)**



Source: EEA, 2025.

The decline in LULUCF is mainly caused by dynamics in forest land. Since 1990, the net carbon sink showed initially an increasing trend, driven by an expansion of forest area and a higher increase in net forest carbon sequestration.

However, over the past decade, this trend reversed to a declining carbon sink. This decline has been driven by a combination of interrelated factors:

i. Forest stands have matured, resulting in higher forest carbon stocks. While they still sequester carbon, they do so at a lower rate.

ii. Forest harvests have increased due to economic and policy drivers, and salvage logging.

iii. Climate change has accelerated the decay process of carbon stored in soils and dead organic matter. Natural disturbances, including forest fires, droughts and pests have affected standing trees.

iv. The annual rate of afforestation has decreased compared to 50-70 years ago, contributing to factor (i) here above.

Cropland and settlements are the major net sources of GHG emissions due to the management of organic soils, as well as the conversion of high carbon stock land to settlements. Grasslands and wetlands show mixed trends depending on management practices and effects on carbon fluxes.

Natural disturbances have become more frequent and severe, and they can negatively affect the LULUCF sink with potentially long legacy effects. This is the main driver of interannual variability in LULUCF and affects the predictability of the sector in terms of GHG emissions and removals.

Improved GHG reporting is essential for improving policy effectiveness

The quality of inventories is crucial for an assessment of trends and drivers, for assessing progress to climate targets, and for both designing policies and measures and evaluating their effectiveness. Generally, the higher the quality of the inventory, the better it will be able to perform in view of these functions.

Reporting in LULUCF is complex and therefore characterised by one of the highest levels of uncertainty among sectors included in the GHG inventories. This complexity is inherent in the LULUCF sector due to the biological and environmental variability of natural processes such as those related to site conditions, weather patterns, climate variability and natural disturbances. It can also be complex to measure or monitor changes in carbon stocks in the different carbon pools accurately and with enough detail.

The accuracy of reporting varies widely while Member States rely on different estimation methods (or tiers). In some land categories and due to the use of lower-tier reporting, inventories are currently not equipped to properly capture the effects of management practices, thus failing to reflect related policies and measures or the finance allocated.

EU Member States have agreed to invest in collective efforts to improve reporting in the LULUCF sector in terms of TACCC ([1]) and results of their efforts are already visible. Areas for attention are, among others, timely data provision, the use of higher tier methods and improved modelling approaches, more complete reporting in terms of carbon pools, and the use of geographically explicit data.

While forest inventories (which inform GHG inventories for LULUCF) are sometimes updated only in a 5- or 10-year frequency, new data and associated recalculations can lead to unexpected changes regarding the reported sink. A better use of remote sensing data will be necessary to provide more up-to-date information to policymakers.

The EU is not on track to achieving its collective LULUCF target for 2030

The European Climate Law fully integrates the concept of removals, i.e. to counterbalance unavoidable and residual GHG emissions by 2050 and to contribute to achieving negative emissions thereafter. The revision of the LULUCF Regulation in 2023 established a collective EU removals target of 310 million tonnes of carbon dioxide equivalent ($MtCO_2e$) by 2030, and targets for Member States that result in an additional removal of 42 $MtCO_2e$ compared to the 2016-2018 average. Projections reported to the EEA in 2024 foresee the EU is not on track to meet its target for

([1]) Transparency, accuracy, comparability, completeness and consistency.

2030 and suggest a reduction in removals compared with the 2016-2018 average. A recently published Commission assessment of final National Energy and Climate Plans (NECPs) showed Member States have stepped up efforts in the land sector, but that there is still a gap of about 45-60 $MtCO_2e$, equivalent to about 100% to 140% of the target of additional removals in LULUCF (EC, 2025b). The status in LULUCF in terms of trends and projections poses an urgent challenge to reverse the declining trend, to allow the sector to contribute effectively to climate change mitigation in the coming decades.

Multiple mitigation options offer vast potential for climate change mitigation with significant environmental and societal co-benefits

A wide variety of mitigation options in the LULUCF sector is available to reduce emissions, such as to protect carbon stocks in soils and biomass, and to enhance removals in forest land, cropland, grassland, wetlands and settlements. Sustainable forest management combined with an increase of biomass use in long-lasting products – such as construction materials – could also increase carbon storage in harvested wood products. Many of these options are considered to be in a 'mature' development phase and are at relative low-cost compared to mitigation costs in other sectors or via industrial removal options.

Activities in the forest sector and agroforestry have significant potential EU-wide but are characterised by a time lag between implementation and mitigation results. Investing in these options now is important to ensure LULUCF effectively contributes to climate change mitigation in the medium- to long-term, i.e. towards achieving climate neutrality by 2050 and negative emissions beyond. Nonetheless, other mitigation options can provide mitigation in the short-term, including forest protection, reduce forest harvest levels, crop- and grassland management, rewetting of drained peatlands, mitigation options for wetlands and the prevention of conversion of land to settlements. Relative sequestration rates vary between different types of mitigation options and are generally higher for those involving carbon sequestration in above-ground biomass (Table ES.1).

Most of the options assessed offer significant co-benefits, in terms of increased ecosystem resilience, restoration of degraded ecosystems and enhanced ecosystem services, including for biodiversity, water, soil and air quality, climate adaptation, cultural services and income diversification (see Table 1). Importantly, increasing the resilience of ecosystems can both help prevent unintended reversals of carbon stored in soils and vegetation and safeguard sustainable biomass provision and related value chains. In some cases, however, trade-offs can occur, including increased water- or fertiliser use, displacement of land-use and carbon leakage, reduced biomass supply and related impacts on people's income or wealth.

Table ES.1 Summary of mitigation options in LULUCF and co-benefits and risks

Range of average sequestration potential in tCO2e/ha per year over entire implementation period

	Forest protection	Afforestation/ reforestation	Improved forest management	Agroforestry	Improved cropland/ grassland management*	Wetlad/ peatland restoration*	NBS in settlements*
Above-ground biomass		2-35	1-14	0.4-26.7			
Soil organic carbon		3.5-7	0.1-6	0.4-8.5	0-3		
Time lag mitigation							
Biodiversity							
Water, air and soils							
Local climate effects							
Land use, biomass supply**							
Resource use***							
Socio-cultural							
Socio-economic							

Generally providing opportunities

Generally providing risks

Combination of positive and negative effects can apply at the same time or in different time periods following implementation

Not applicable or negligible

Uncertain or mixed effects

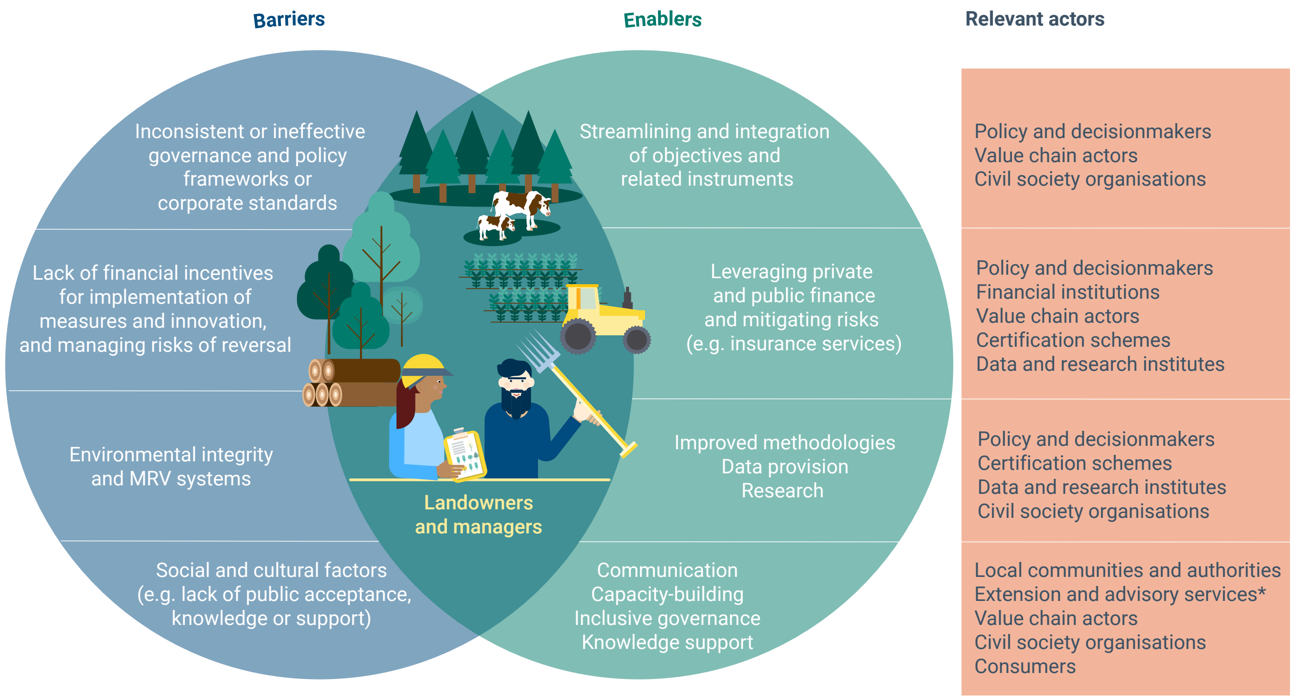
Highly dependent on implementation/method and/or local circustances

Notes: (*) Individual options for cropland, grasslands, wetlands/peatlands and settlements have been aggregated in this table; (**) And related effects on income or land prices (foregone income); (***) More details regarding the type of resource use per option are available in Chapter 3.

Source: Author's own compilation based on expert judgement.

From a macro-economic perspective, mitigation options in LULUCF are considered 'mature' and relatively low-cost compared to industrial removal options. However, landowners and managers are confronted with several barriers that can affect their willingness to adopt a change of management practices. These include inconsistent governance or policy frameworks or corporate standards, a lack of financial incentives and associated risks, lack of affordable or effective MRV systems, and social and cultural factors (Figure ES.2).

Figure ES.2 **Overview of mitigation options in LULUCF and co-benefits and risks**



Note: *Extension and advisory services (EAS) are institutions and activities to assist farmers in accessing knowledge, information, capacities and technologies. These services aim to develop technical, organisational, and management skills and practices, as well as enhance their interactions with markets, research, and education. EAS also include functional elements such as communication, facilitation, and empowerment.

Source: Author's compilation based on expert judgement.

Engagement of a wide variety of stakeholders is needed to realise enabling conditions, including streamlining objectives and instruments, leveraging public and private finance, mitigating financial risks, improved MRV methodologies and data provision, and knowledge support, capacity-building and inclusive governance. Various policy initiatives have been adopted recently in support of developing these enabling conditions (Box ES.1).

Box ES.1

Enabling policy and governance framework for LULUCF mitigation

New EU policies have been adopted aiming to encourage and enable Member States to take adequate policy action, and to allow landowners and managers to engage in 'scaling up' of a change in land management practices. The revised LULUCF Regulation and Governance Regulation provide frameworks for encouraging and governing national action. The Carbon Removal and Carbon Farming (CRCF) Regulation provides a novel and voluntary instrument to leverage public and private finance to such practices via the certification of the abatement effects, in terms of carbon removals and emissions reductions. EU State aid rules and the Common Agricultural Policy (CAP) further provide important frameworks for leveraging public support to carbon farming activities.

Member States are in a relatively early phase of implementing additional policies and measures relevant to the sector. Their ongoing commitment is needed to ensure the effective contribution of the LULUCF sector to short- and medium-term climate goals. Foreseeable negative effects from climate change and natural disturbances on value chains in the bioeconomy serve as an important incentive to invest in increasing the resilience of agricultural and forest ecosystems. Integrated policy planning can help ensure coherency between policy goals, such as relating to biomass use- and supply and enhancing the LULUCF sink.

An emerging role for geospatial data

The new policy and governance framework relevant for LULUCF mitigation results in data needs corresponding to subsequent phases of the ambition cycle: reporting, review, planning and implementation (Table ES.2).

Table ES.2 Phases of the ambition cycle and drivers for data needs

Phase	Drivers for data needs
Reporting	Timely information, robust GHG inventory data and site-based GHG emissions- and removal tracking methods (for carbon certification).
Review	Review of progress to targets, assessment of trends and drivers, evaluation of the effectiveness of policies.
Planning	Establishment of targets, design of policies and policy scenarios (and information for assessment models).
Implementation	Quantification of baselines and mitigation effects from an implemented activity; Better targeting interventions; Assessing environmental- and climate conditions for addressing risks or targeting co-benefits.

Source: Author's compilation based on expert judgement.

Quality and timely data provision, such as to inform activity data and emission factors, will be the backbone for effective and efficient monitoring of public and private action in LULUCF. The required characteristics, e.g. level of detail, geographical and temporal scales, and type of parameters, depend on the specific use case. Successful LULUCF strategies and policies will depend on how they capitalise on the potential of an evolving technological and data landscape. Integrating GHG inventories with other land-related reporting databases and geographic information systems (GIS) presents a valuable opportunity to enhance data interoperability, enabling more efficient data sharing, minimizing redundancy, and streamlining reporting across multiple policy areas.

1 Introduction

Key messages

- The EU has a net target of reaching carbon neutrality by 2050, which will require rapid and substantial emission reductions in all sectors. By that year, residual greenhouse gas (GHG) emissions will need to be balanced by carbon being removed from the atmosphere. The largest potential removals in the short- to medium term are expected to come from the land use, land use change and forestry sector (LULUCF). LULUCF currently provides a net carbon sink, counterbalancing around 6% of the EU's GHG emissions from other sectors.

- In line with the EU Climate Law, the EU has set its first net LULUCF removals target, to be met by 2030. Yet the LULUCF carbon sink has been declining in the last decade and this target is at risk of not being met. Member States must urgently act to reverse this trend, both by reducing GHG emissions and increasing removals.

- GHG fluxes in the LULUCF sector are impacted by human activities, mostly associated with land use, land management and land use change, as well as by natural processes such as changing weather patterns, climate variability and natural disturbances.

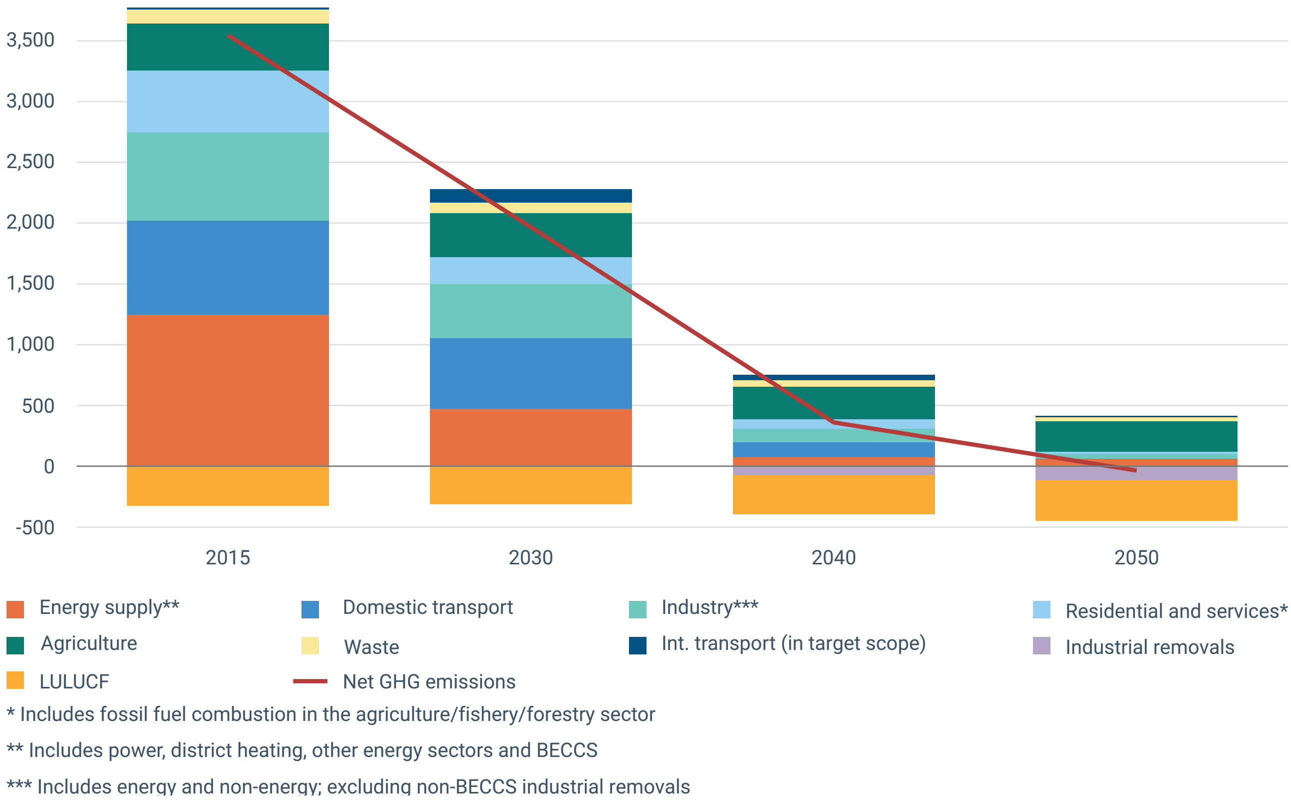
- Europe is the continent with the most managed land. While land management is crucial for biomass provision and people's livelihoods, it also puts pressure on biodiversity and other ecosystem services that land and forests provide. At the same time, terrestrial ecosystems are increasingly vulnerable to climate change and natural disturbances, undermining their role for providing ecosystem services, including carbon sequestration.

- Climate change and biodiversity loss are mutually reinforcing and share common drivers. Resolving either requires consideration of the other. Restoring ecosystems can support both climate change mitigation and increase their resilience, which means that pursuing synergistic policies and measures in LULUCF is beneficial on multiple levels.

1.1 The role of carbon removals in reaching climate change mitigation goals

Since the European Green Deal (EGD) came into force in the early 2020s, European climate strategies have been premised on the idea that all economic sectors must play a part in mitigating GHG emissions and – where possible – enhancing carbon dioxide removals (hereafter: removals) from the atmosphere. The EU Climate Law (2021) provides targets to reduce GHG emissions by 55% by 2030 and achieving climate neutrality by 2050. These are net targets; this means they take into account both GHG emissions and removals. In the coming decades, removals are expected to play an important and increasing role in achieving these targets by compensating for residual and unavoidable emissions and helping the EU reach net-negative emissions beyond 2050 (Figure 1.1). An assessment of over 1000 scenarios by the European Scientific Advisory Board on Climate Change (ESABCC) shows reaching climate neutrality by 2050 is not possible without rapid and substantial reductions in GHG emissions in all sectors, but also that removals will be needed to counterbalance a certain level of residual emissions by 2050 (ESABCC, 2023).

Figure 1.1 Historical and projected sectoral GHG emissions in the EU-27 in the period 2015-2050 in $MtCO_2e$



Notes: In this figure, industrial removals refer to processes whereby carbon is captured partly through industrial processes. These removals relate predominantly to Bioenergy with Carbon Capture and Storage (BECCS) and Direct Air Capture and Storage (DACCS).

Source: EC, 2024a.

1.1.1 What are carbon removals?

The recently adopted EU Carbon Removals and Carbon Farming Regulation (CRCF Regulation) defines carbon removals as 'the anthropogenic removal of carbon from the atmosphere and its durable storage in geological, terrestrial or ocean reservoirs, or in long-lasting products'. Removal methods can be categorised according to different characteristics, including the process of sequestration; the pool in which carbon is stored; their technological 'readiness'; or the expected duration of storage. The CRCF Regulation sorts activities into the following categories: permanent carbon removals, carbon farming activities and carbon storage in products.

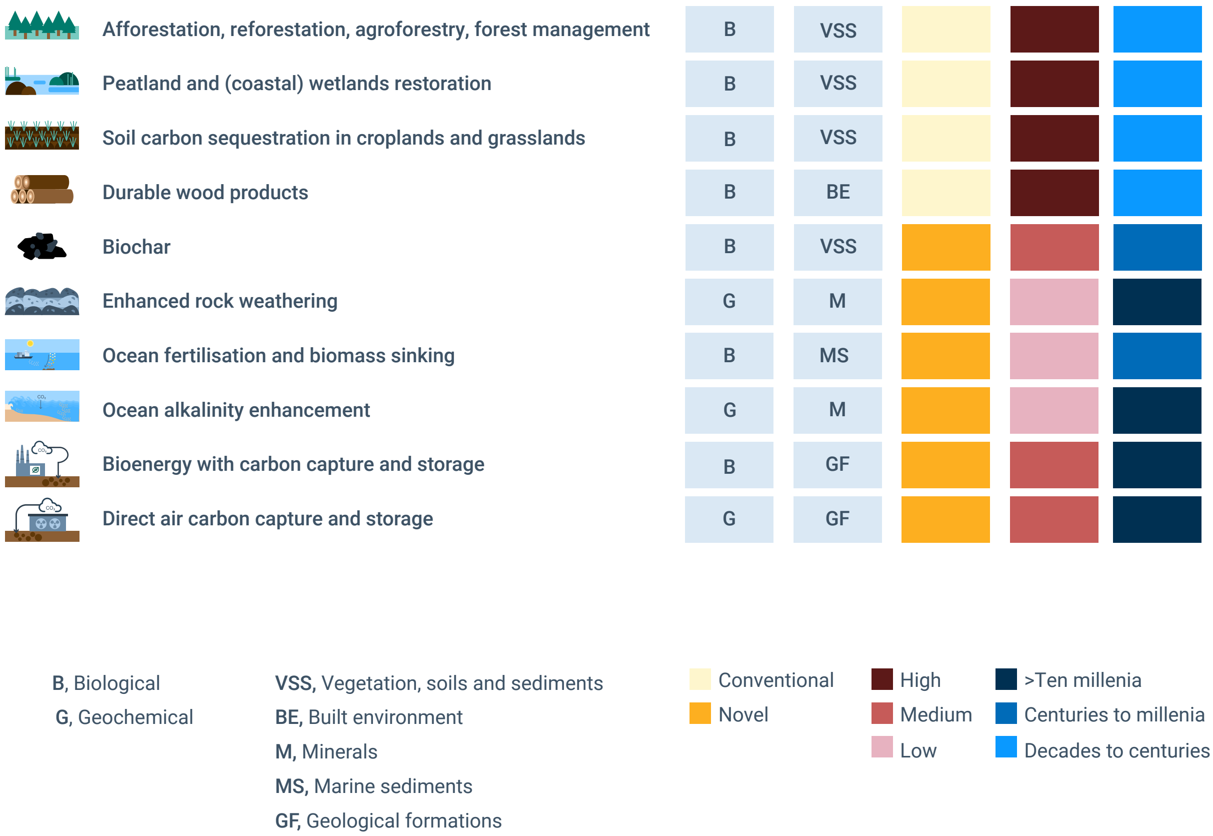
Figure 1.2 provides an overview of a selection of proposed removal methods, distinguishing between conventional and novel options based on Smith et al., 2024. Conventional methods are generally well-established and deployed at scale. They include methods used in the LULUCF sector whereby carbon is sequestered via biological processes and then stored in vegetation, soils, or durable wood products and other biomaterials.

Proposed novel methods include options that sequester carbon from the atmosphere via biological and geochemical processes, and store the captured carbon in soils, geological formations, products or minerals. These are commonly characterised by a lower technological or commercial readiness for deployment compared to conventional methods. Some of the novel methods have not been tried or demonstrated yet and may never become viable or effective options ([2]). Equally, they could lead to significant negative impacts on the environment. The options vary in terms of their cost-effectiveness, cumulative mitigation potential and the timescale for carbon storage (Fuss et al., 2018).

This report focuses on terrestrial removal methods and other mitigation activities in LULUCF (i.e. those important for reducing emissions in the sector). The LULUCF sector includes GHG emissions and removals resulting from human-induced land use and land use change activities in six land-use categories: forest land, cropland, grassland, wetlands, settlements and other land (further explained in Chapter 2). The LULUCF sector is distinct from other sectors, as it can both function as a source and sink of carbon. Section 1.3. further outlines anthropogenic drivers of GHG emissions and removals in LULUCF. According to the Intergovernmental Panel on Climate Change (IPCC), the LULUCF sector includes coastal ecosystems. To date, however, these marine ecosystems have not played an important role in the EU GHG inventory (GHGI). In this report, we further distinguish between industrial and LULUCF removals. Industrial removals in this report refer to BECCS and DACCS.

([2]) The actual deployment of BECCS and DACCS depend on several factors, including costs, technological uncertainty and competition for biomass sources, infrastructure and public acceptance.

Figure 1.2 Summary of proposed carbon-dioxide removal methods



Notes: (i) The methods in this figure align with those in a recent assessment report by the ESABCC (ESABCC, 2025). However, geoengineering approaches in the marine environment fall under an international de facto moratorium on geoengineering techniques, which has also been reiterated in the Joint Communication on climate and security (EC, 2023a)([3]); (ii) peatland restoration only refers to those activities that result in net sequestration. However, methods to reduce emissions from drained or forested peatlands offer high mitigation potential in Europe, as further discussed in the following chapters.

Source: Author's compilation based on Smith et al., 2024.

1.1.2 What role do carbon removals play in climate change mitigation scenarios?

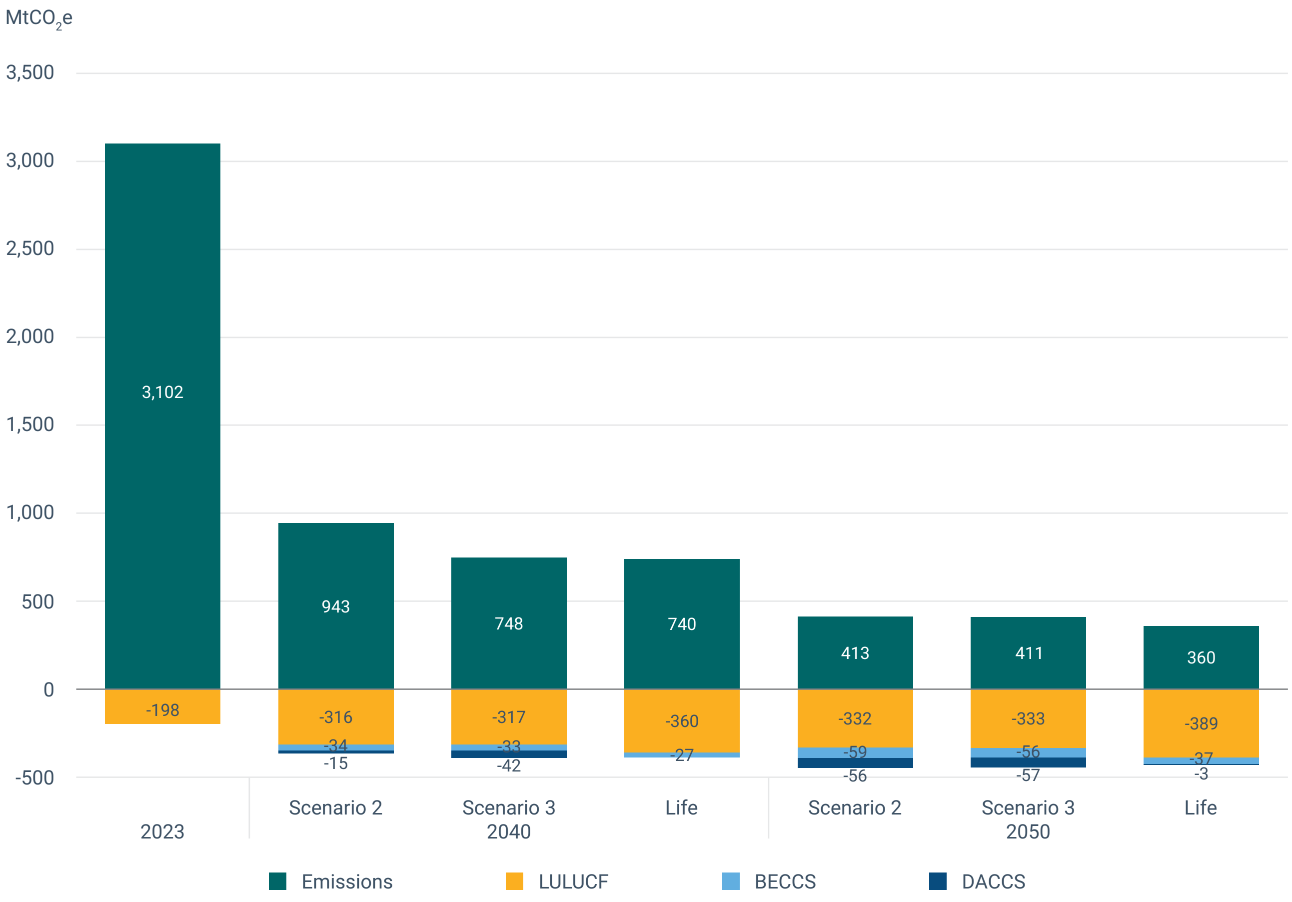
The European Commission's (EC's) Impact Assessment (IA) informing an EU climate target for 2040 indicated that a minimum of 365 million tonnes of carbon dioxide equivalent ($MtCO_2e$) removals is needed to reduce net GHG emissions by 90% by 2040. By 2050, approximately between 430 and 450 $MtCO_2e$ removals would be needed according to the assessment. The LULUCF sector is expected to play a particularly significant role in achieving these 2040 and 2050 targets: by 2040, LULUCF is projected to contribute between 316 and 360 $MtCO_2e$ of removals and between 332 and 389 $MtCO_2e$ of removals by 2050 (Figure 1.3) (EC, 2024a) ([4]). This is a significant increase compared to the current (2023) level of the net LULUCF carbon sink. Industrial removals are projected to contribute between 27 and 75 $MtCO_2e$ by 2040 (EC, 2024a) and to further expand towards 2050. These figures

([3]) The United Nations (UN) Conference of the Parties (COP) to the Convention on Biological Diversity (2024) decided on a de facto moratorium on geoengineering techniques, notably ocean based.

([4]) Scenario 1 was disregarded in this range, while it was considered less policy relevant in view of recommended climate action according to the ESABCC (ESABCC, 2023).

broadly correspond with the results from the analysis by the European Scientific Advisory Board on Climate Change (ESABCC) of climate-neutral scenarios, the majority of which suggest a range for LULUCF contributions of removals between 300 and 400 $MtCO_2e$ and for industrial removals of between 46 and 214 $MtCO_2e$ for 2040 (ESABCC, 2023).

Figure 1.3 Anticipated role of carbon removals relative to GHG emissions in different climate change mitigation scenarios for 2040 and 2050 for the EU-27 in $MtCO_2e$



Notes: Scenario 1 was disregarded in this figure, since it was considered less policy relevant.

Source: EC, 2024a.

Contributions from LULUCF in these scenarios depend on a wide range of assumptions, including estimated GHG reductions from other sectors, deployment of and reliance on industrial removals and both anthropogenic and natural drivers affecting the emissions and removals in LULUCF. The differences between the S2, S3 and LIFE scenarios are partially driven by bioenergy needs in the energy systems. Meanwhile, LIFE is characterised by different food system and consumption patterns, resulting in land made available for carbon farming.

Other climate change mitigation scenarios include a wide range of contributions from LULUCF (i.e. between 244 $MtCO_2e$ and 288 $MtCO_2e$ of removals for a Business as Usual (BAU) scenario and between 300 $MtCO_2e$ and 787 $MtCO_2e$, depending on different assumptions about changes in land use and land management), as well as future impacts from climate change (Böttcher et al., 2021; Meyer-Ohlendorf et al., 2023). Pilli et al. (2022) took into account projected impacts from climate change in their scenario and suggest a potential contribution from LULUCF removals of between 100 and 400 $MtCO_2e$ of removals by 2050 ([5]).

Importantly, as acknowledged by both the EC (EC, 2024a) and the European Scientific Advisory Board on Climate Change (ESABCC, 2023), there is a certain competition within scenarios between avoiding emissions from fossil fuel use with bioenergy (i.e. substitution) and increasing BECCS on the one hand and enhancing the LULUCF carbon sink on the other. This is largely due to trade-offs in biomass utilisation pathways and forest sink capacity related to harvest levels. It should be noted however that the negative impacts from biomass-reliant energy pathways are not immediately apparent in the climate change mitigation effects of the energy sector but are reflected in the LULUCF sector, where they are reported and accounted for. To develop and assess the various scenarios, it is also important to consider opportunity costs, e.g. from displacement of production and/or GHG emissions and counterfactuals (i.e. what would the land/biomass use or energy source have been in the absence of bioenergy/BECCS?).

1.1.3 EU LULUCF climate change mitigation ambition

In Europe, carbon removals generated in the LULUCF sector are expected to deliver the largest share of removals in policy-relevant scenarios in the short to medium term (ESABCC, 2023; EC, 2024a). In this context, the EU has set a LULUCF target of 310 $MtCO_2e$ of net removals in the sector by 2030; meanwhile, no policy targets have been adopted for industrial removal options in this governance period.

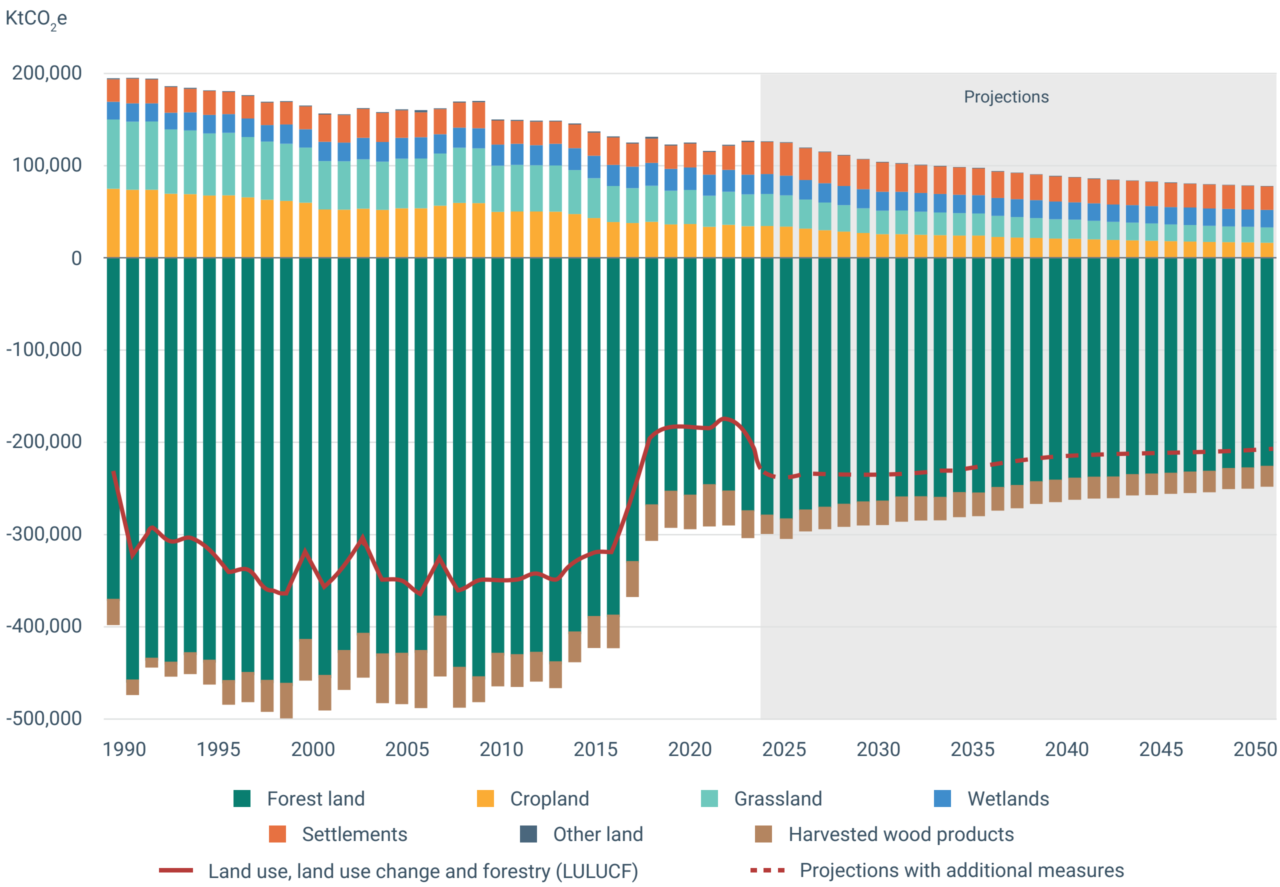
Enhancing the capacity of the LULUCF sector to increase its net removals of CO_2 from the atmosphere depends on how effective strategies, policies and measures are both in terms of reducing GHG emissions from land use and land use change and increasing removals.

While the EU has committed to enhancing carbon removals in the LULUCF sector, in the last decade there has been a declining trend in the extent to which Europe's terrestrial ecosystems are able to sequester carbon from the atmosphere. The LULUCF sector has provided an average carbon sink of 335 $MtCO_2e$ in the period 1991-2013. Between 2014-2023, however, the average annual sink was 30 percent smaller compared to the decade before, amounting to net removals of 198 $MtCO_2e$ in 2023. Reasons for this decline are further outlined in Chapter 2.

([5]) For forest land in the EU-27+UK.

Furthermore, projections submitted to the EEA by Member States in 2023 and 2024 indicate that the EU is currently not on track to achieving its collective LULUCF target for 2030. According to these projections, the EU-27 will jointly reach 224 and 240 $MtCO_2e$ of removals from LULUCF in 2030, with existing measures (WEM) and with additional measures (WAM) scenarios respectively (Figure 1.4 and Figure 4.4) ([6]). In 2040, this range is projected to further decrease to 195 and 220 $MtCO_2e$ of removals, respectively. A recently published Commission assessment of final NECPs shows Member States have stepped up efforts in the land sector, but that there is still a significant gap to the target of additional removals in LULUCF (EC, 2025b).

Figure 1.4 GHG emissions (+) and removals (-) from the LULUCF sector, showing historical trends (1990-2023) and projections (2023-2050) for the EU-27 in $MtCO_2e$



Notes: Projections may alter depending on Member States' updates in their final national energy and climate plans (NECPs), as submitted from June 2024 (EC, 2024a).

Sources: EEA, 2025b; EEA, 2024b.

([6]) The WEM scenario reflects existing policies and measures, whereas the WAM scenario considers the additional effects of planned measures reported by Member States. Projections are based on data submitted to the EEA under Article 18 of the Governance Regulation in 2023 and 2024.

As such, the trend must be reversed, and the implementation of measures to enhance removals and reduce emissions in LULUCF must be accelerated in the coming years. The good news is that various measures are readily available to reduce emissions or increase removals. These involve land-based activities, many of which have significant co-benefits. Possible measures include improved forest management and reduction of forest harvest levels, afforestation, prevention of deforestation, fallowing of soils, as well as improved crop and grassland management. Rewetting of organic soils and the restoration of carbon-rich ecosystems as peatlands can also significantly decrease emissions in the LULUCF sector. However, the measures vary significantly in terms of their cost-effectiveness and efficiency across different timescales and might involve difficult trade-offs. Their relevance for different policy targets over time further varies across measures and Member States (Korosuo et al., 2023).

1.2 Where and how is carbon sequestered, stored and released in the LULUCF sector?

Governance of climate action in the LULUCF sector, as well as the design and implementation of policies and measures, requires careful consideration of both natural and anthropogenic factors that affect emissions and removals from terrestrial ecosystems.

This section discusses key concepts relating to carbon fluxes and reservoirs on land. Carbon dioxide (CO_2) is essential for life on Earth, as carbon atoms form the primary basis for living organisms. Carbon reservoirs in photosynthetic organisms are consumed by other life forms (e.g. animals and fungi) and are released into the atmosphere as CO_2 from respiration and mineralisation processes. Carbon can also be stored for longer periods of time in reservoirs or carbon pools such as forest biomass or soils. The circular process by which carbon enters the atmosphere and is then absorbed into organisms and minerals before being released into the atmosphere again is generally known as the global carbon cycle.

Box 1.1

Definitions of concepts

Pool/reservoir: A component of the climate system, other than the atmosphere, that has the capacity to store, accumulate or release a substance of concern (e.g. carbon).

Carbon sink: Any natural or technological process, activity or mechanism that removes a GHG, an aerosol or a precursor to a GHG from the atmosphere, via natural and technological solutions. It includes industrial carbon removals and certain nature-based processes that remove CO_2 from the atmosphere. Carbon sinks store carbon in pools.

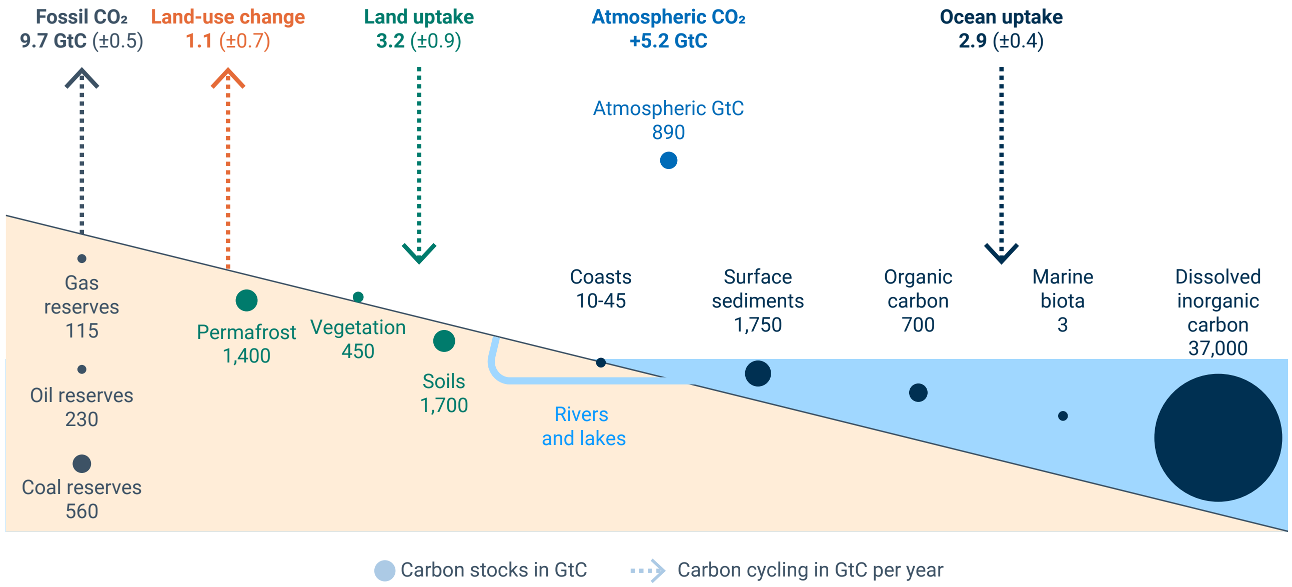
Carbon flux: The transfer of carbon from one carbon pool to another measured in mass per unit area and time.

Carbon stock: The absolute quantity of substances of concern (e.g. carbon) held within a reservoir.

Source: IPCC, 2018.

In the global carbon cycle, soils and vegetation represent the largest carbon reservoirs after the oceans (including the seabed); they contain much more carbon compared to the atmosphere and fossil reserves (Figure 1.5) ([7]). At the same time, the extent of vegetation growth is the main factor affecting CO_2 sequestration from the atmosphere in the land sector. Carbon storage in soils and vegetation is not permanent: there are constant transfers of carbon between vegetation, other living organisms, soils and the atmosphere and vice versa. However, in the last 200 — and particularly the last 50 — years, the amount of anthropogenic CO_2 emissions, primarily driven by fossil fuel combustion and deforestation, has led to an increase in the concentration of CO_2 in the atmosphere to 424 parts per million (ppm) ([8]). Scientists consider 350ppm to be the safe limit. Biogenic carbon cycles, centred on absorption by plants, and fossil carbon cycles differ a lot. For example, carbon is accumulated in biological and geological systems at differing rates. Compared to the relatively fast circulation of biogenic systems, carbon accumulates in fossil reservoirs at a very low rate, which is why losses from these reservoirs (i.e. extraction) can be regarded as a one-way flow. Essentially, climate change mitigation through biogenic systems can only be effective when it is paired with sharp and rapid phasing out of GHG emissions from fossil fuel use.

Figure 1.5 **The global carbon cycle and the role of land and oceans**



Notes: Land uptake refers to net uptake of CO_2 by vegetation and soils. The high figure for permafrost reflects fast thawing and the consequent release of GHG, in particular methane, to the atmosphere (Moving Still Productions, Inc., 2020). GtC refers to Gigatonnes of Carbon.

Source: Author's compilation based on Friedlingstein et al., 2025.

([7]) Increased removals of CO_2 by oceans can lead to ocean acidification.
([8]) https://www.co2.earth; when considering other GHG emissions than CO_2, agriculture is also a major driver.

Through biological processes, vegetation and soils can both sequester and store CO_2 from the atmosphere and emit CO_2 back into the atmosphere. Living plants absorb CO_2 from the atmosphere through photosynthesis, and this CO_2 is transferred to other land carbon pools (Table 1.1). The process involves plants converting CO_2 into organic carbon compounds, which are used to build plant biomass, such as leaves, stems, branches and roots. When plants shed leaves or die some of the organic matter accumulates on the ground as litter and deadwood. Soil microorganisms decompose this organic matter, which releases nutrients that allow plants to grow. During this process of decomposition some organic carbon is stored in soils, and some is released back into the atmosphere as CO_2. This process is known as soil respiration, and in comparison with respiration from roots, leaves and stems, it accounts for the largest share of land ecosystem respiration.

Table 1.1 Descriptions of carbon pools in the LULUCF sector

Carbon pool	Description
Living biomass: above-ground biomass (AGB) and below-ground biomass (BGB)	Differentiated according to whether the biomass is above ground (i.e. stems, branches and leaves) or below ground (i.e. roots)
Litter	A specific pool of dead organic matter in forests
Deadwood	Non-living woody biomass, including standing dead trees, stumps and fallen logs
Dead organic matter (DOM)	Dead plant material transferred to the pools dead wood and litter; the pool is reported as a pool if dead wood and litter cannot be separated, e.g. for cropland, grassland and wetlands
Soil organic carbon (SOC)	Organic matter in mineral and organic soils
Harvested wood products (HWPs)	Paper, wood used for construction or furniture and others

Note: Through anthropogenic processes, carbon is also stored in a sixth 'carbon pool' of HWPs, further discussed in Chapters 2 and 3.

Sources: EEA, 2024d; IPCC, 2006.

While carbon stored in vegetation and soils as organic matter is not permanent, it can persist for long periods, from decades to centuries (Schmidt et al., 2011). The rate at which terrestrial ecosystems sequester and store carbon and the amount of time carbon remains stored in soils and vegetation are both influenced by natural and anthropogenic factors that interact in complex ways. Factors that can affect carbon storage include the type and characteristics of the vegetation or soil, climate, natural disturbances and land management practices (further details are given in Sections 1.3 and 1.4).

In addition, an increase in atmospheric CO_2 levels driven by human behaviour can increase plant growth, a process known as 'CO_2 fertilisation'. Ecosystems' full potential to sequester carbon also depends on the possible saturation of carbon in soils and vegetation (e.g. forests). In other words, carbon storage in a pool is finite. Over time, the pool reaches saturation point, at which point the balance between the carbon inflow and outflow of the system is in equilibrium (Guillaume et al., 2022). Chapter 3 further elaborates on the potential of different carbon removal options, for forests, agricultural areas, wetlands and settlements.

1.3 Anthropogenic impacts on terrestrial carbon cycles

Human activities can affect carbon storage and sinks in the land sector directly and indirectly, and both negatively and positively. For example, human activities can affect the capacity of one or more pools to sequester carbon or reduce or enhance the emissions of existing pools (e.g. in wetlands). Land use change alongside land and forest management practices are the most direct anthropogenic drivers affecting carbon stocks and fluxes in land (Box 1.2). Management decisions can have long legacy effects on how effectively an area of land can deliver ecosystem services, including carbon sequestration and storage.

Box 1.2

Land use and land use change

Land use is a socio-economic term relating to an area's functional usage (e.g. for residential, industrial or commercial purposes, for farming or forestry, for recreational or conservation purposes, etc.).

Land use change, like deforestation or land take for settlements, and the consequent removal of vegetation cover and soil disturbances can result in GHG emissions and reduce carbon sequestration due to a permanent reduction in biomass. Conversely, afforestation or reforestation or the conversion of cropland to grassland can stimulate the sequestration of carbon from the atmosphere in vegetation and soils, respectively.

Beyond the effects from changing land use, specific land or forest management regimes can influence carbon storage and fluxes associated with different carbon pools. For example, changing when harvesting takes place (i.e. the forest rotation period) can affect the carbon stored in managed forests as well as in HWPs, while simultaneously impacting the carbon sink for several decades. Management practices relating to agricultural soils, for example more or less intensive tillage, can affect the storage and release of SOC. Rewetting of peatlands can result in more carbon being retained in the soil, since it can prevent peat from oxidating, or possibly even lead to increased carbon sequestration due to the formation of new peat.

In Europe, terrestrial ecosystems have been subject to human interventions for centuries, if not millennia. In the past century, urbanisation, deforestation, reforestation, and changes in cropland and grassland are estimated to have contributed to a gross land use area change of around 56% in Europe from 1900-2010 (Fuchs et al., 2015). This has been driven by demographic and socio-economic trends and technological, political and policy developments (Fuchs et al., 2015; Korosuo et al., 2023). These land use changes have sometimes had long legacy effects, with consequences for the LULUCF sink today. For example, the 'afforestation wave' after the Second World War has resulted in some forests in Europe now reaching a certain maturity level, affecting their annual forest growth and related level of carbon sequestration (Section 2.3.1).

Today, most land and forests in Europe are subject to management. Forests cover around 40%of the EU land area, and in Europe, on average, 85% of the forest area is considered available for wood supply, taking into account environmental, social or economic restrictions (Avitabile, 2020). Overall 0.8% of total EU territory or less than 4% of EU forests is covered by primary and old-growth forests (Barredo et al., 2021). In 2020, 157 million hectares (Mha) of land (38% of total EU land area) were used for agricultural production by EU farms, of which almost 80% included either a specialist crop farm or a mixed farming system (EEA, 2023). Climate change mitigation pathways are predicted to have a varied effect on future land use dynamics in Europe in terms of area used for forest land, cropland and grassland (EC, 2024a).

1.3.1 Increase in biomass supply and demand

One of the key drivers of land use and land management in Europe is biomass consumption: the lion's share of biomass supply is produced domestically, and only 3-4% of biomass supply comes from net imports (Avitabile et al., 2023). Of total biomass supply, almost 70% derives from the agricultural sector and 27% from forestry.

Reported roundwood production in the EU increased by 25.6% from 2000 to 2021 (Eurostat, 2022). In general, crop production in the EU has become more stable in recent decades, discounting years in which yields were heavily affected by droughts. This overall stability does not hold true for some energy crops, such as rapeseed, however (EEA, 2023).

An important driver for biomass demand is bioenergy, which represented around 23% of all biomass uses in 2017 (JRC 2025a) and accounted for 60% of the EU's gross final renewable energy consumption in 2022 (IEA Bioenergy, 2024). Almost 70% of the current bioenergy supply is produced with wood (IEA Bioenergy, 2024) and almost half of all woody biomass is directly or indirectly used for energy purposes (JRC 2025a; Camia et al., 2020). Various studies project that there will be a growing gap between biomass demand and supply between now and 2050, in part because of an increase in the demand for biomass as a substitute for fossil fuels and carbon-intensive materials (EEA, 2023; Material Economics, 2021; Andersen et al., 2021). This may lead to increased land use change and other pressures affecting terrestrial ecosystems and the services they provide (EEA, 2023).

1.3.2 Substitution of material and energy products by biomass

Avoiding emissions from using fossil fuels and related materials can be achieved by substituting them with biomass. The net GHG impact from biomass substitution can result in a carbon debt ([9]), climate neutrality or a carbon gain (Strengers et al., 2024). The 'payback' time for the carbon debt (Agostini et al., 2014) and the net GHG impact vary depending on a number of factors including GHG emissions from biomass production and use, possible displacement effects, counterfactual scenarios (e.g. the carbon intensity of the fuel replaced and the use to which the land and biomass would be put in the absence of the biomass substitution) and timeframes considered (EEA, 2023; Strengers et al., 2024).

Increased biomass demand for substitution, such as for bioenergy, can negatively affect the LULUCF sink and HWP pool. When producing biomass for energy leads to a sustained decline in agricultural and/or forest carbon stocks, this results in a net transfer of CO_2 to the atmosphere. Conversely, increasing the LULUCF sink, such as by reducing harvest rates, can reduce the availability of biomass as a substitute for fossil fuels and carbon-intensive materials.

A combination of LULUCF mitigation and increasing biomass demands could also lead to more land use, forest harvests and deforestation in third countries, in effect displacing or externalising certain GHG emissions from the EU (an effect also described as carbon leakage). An increase in the use of wood-based products in one region can significantly impact harvests, production and consumption both locally and in other regions through international trade (Jonsson and Rinaldi, 2017; Jonsson et al., 2018).

These possible trade-offs have been explored in detail in the EEA report *The European biomass puzzle* (EEA, 2023). As such, they are discussed more superficially in this report in Chapters 3 and 4 in relation to the scale up of mitigation options in LULUCF and an enabling policy framework. Nonetheless, the impact of the EU's biomass demand on domestic and third-country supply merits careful consideration. This is especially true in national policy and governance frameworks for LULUCF and other sectors, which must consider biomass provision- and use, and associated effects on carbon sequestration (e.g. Leclère et al., 2020).

1.3.3 Environmental pressures from agriculture and forestry

Most of the pressures affecting both species and habitats stem from agricultural and forestry activities (EEA, 2020), which are leading to the loss, fragmentation and degradation of natural and semi-natural ecosystems. Over-exploitation, invasive alien species, pollution and climate change place additional pressures on biodiversity (IPBES, 2018; EEA, 2020). At the same time, destruction or coverage of agricultural soils because of expansion of settlements or infrastructure is one of the main causes of soil degradation. Poor land management, climate change, unsustainable agricultural or forestry practices, pollution, hedge removal and deforestation can also contribute to soil degradation; this includes soil erosion and loss of organic matter, affecting the soil structure (Allen et al., 2018). Biodiversity loss reduces the resilience of ecosystems and their capacity to adapt to climate change, which poses a risk for ecosystem services they provide, and the value chains reliant on them.

([9]) 'Carbon debt' refers to the cumulative net emissions of biogenic CO_2 into the atmosphere that occur in certain circumstances when forest management is changed in certain ways to increase the supply of forest biomass (Strengers et al., 2024).

Action is needed to address biodiversity loss and ecosystem conservation and restoration with integrated strategies (Leclère et al., 2020), including sustainable land management approaches and food-system transformation. Such approaches can provide a multitude of benefits, including for LULUCF mitigation. For example, increasing vegetation cover and sustainable agricultural land management practices can enhance carbon sequestration while improving soil structure, and reducing erosion and degradation (Trenčiansky et al., 2021). Paludiculture, agroforestry, extensive crop and grassland management, and improved forest management can provide similar environmental benefits while ensuring their role in local and regional economies. In forestry and grasslands, there is also a clear relationship between tree-species diversity and ecosystem multifunctionality (van der Plas et al., 2016; Peura et al., 2018). Many practices to maintain and restore ecosystems can thus enhance their productivity, their role in climate change mitigation and their resilience to a changing climate (IPBES, 2018; Liang et al., 2016). Chapters 3 and 4 further discuss synergies between climate change mitigation, climate adaptation and ecosystem restoration, and how such synergies are currently encouraged by EU policies.

1.4 Terrestrial ecosystems' vulnerability to climate change and natural disturbances

Europe's terrestrial ecosystems are becoming increasingly vulnerable to climate change and related weather events and natural disturbances, like extreme droughts, wildfires, storms and pest outbreaks (Patacca et al., 2023). Changing climate impact drivers, including temperature, precipitation, extreme weather events and the concentration of CO_2 in the atmosphere, as well as related natural disturbances, significantly impact the functioning of terrestrial ecosystems and their capacity to store and sequester carbon (EEA, 2024c). Natural disturbances can turn ecosystems from carbon sinks into carbon sources, while a combination of effects can also result in negative feedback loops, such as for forests. For example, single tree mortality can increase the vulnerability of forest ecosystems (L. Rossi et al., 2023).

This is concerning considering the current temperature and precipitation trends. The mean annual temperature across European land areas over the last decade was estimated to be more than 2°C higher than during the pre-industrial period (EEA, 2024c; IPCC, 2022). The highest level of warming is projected across north-eastern Europe, northern Scandinavia and inland areas of Mediterranean countries (EEA, 2024c).

There is great variability in precipitation trends and droughts across Europe, both in terms of regional differences and seasonal effects. Data over longer time series indicate that northern Europe is becoming wetter and southern Europe is becoming drier (Copernicus; Caloiero et al., 2018). However, trends depend on which seasons are considered, and changes can be analysed in terms of rain distribution over the year (longer dry periods) and increased intensity of rainfall (e.g. in the northern part of Europe). Impact drivers differ across Europe, with warm and dry conditions in the south and altered rain seasons and frost periods in the north. The key climate impact drivers, impact indicators and associated risks and GHG effects are summarised in Annex 1.

Over the past decades, ecosystem functioning and related carbon sequestration in Europe has revealed a regional pattern of increase and decline due to the climatic effects discussed above but also non-climatic drivers (like nitrogen deposition, land use change and land management practices) (Carozzi et al., 2022). Up to 2010, the growing season lengthened in many parts of Europe due to increasing temperatures; since then, this trend has slowed down or even reversed since less moisture is now available during the summer (Rahmati et al., 2023; Menzel et al., 2020) ([10]). Warmer temperatures and changing humidity levels also favour the spread of pests and diseases that further reduce agricultural productivity (Deutsch et al., 2018; Singh et al., 2023a).

For forests, while rising temperatures and longer growing seasons can increase their productivity (Vaughan et al., 2024; Luyssaert et al., 2010), reduced precipitation and more frequent droughts have partly offset the gains (Montibeller et al., 2022). Droughts lead to lower tree vitality and eventually direct tree mortality, especially when combined with heat extremes (Hartmann et al., 2022; Hammond et al., 2022; Bednar-Friedl et al., 2022). In addition, poorer vitality makes trees more susceptible to insect outbreaks and fire, indirectly impacting carbon sequestration (Senf and Seidl, 2018; Seidl et al., 2017). The resilience of forests to climate change and disturbances varies across regions and depending on the dominant disturbance forces. For example, in regions affected by increasing fire and drought, forests might turn from carbon sinks into carbon sources earlier than in regions dominated by other forces (Thom, 2023).

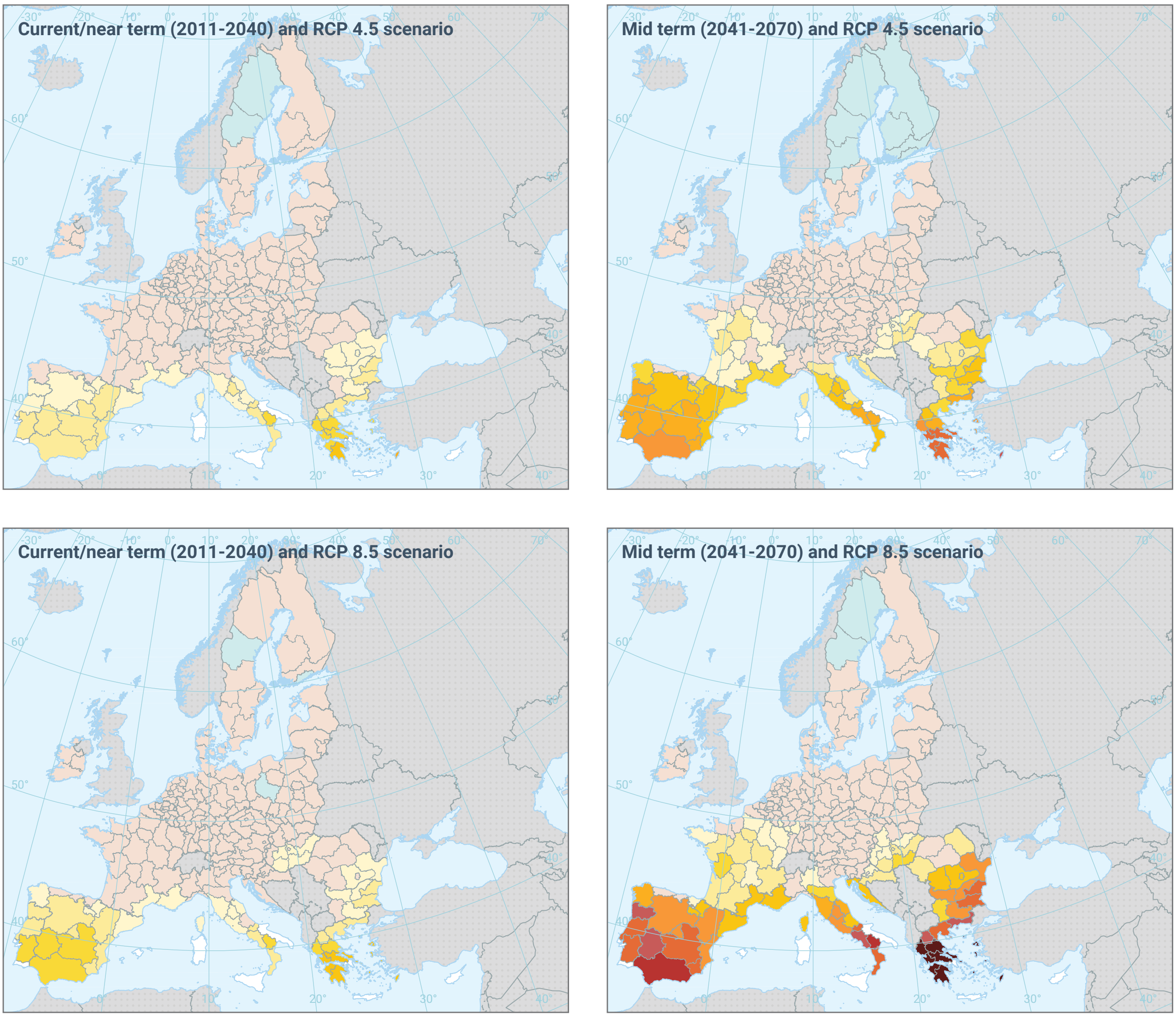
SOC in agricultural soils is estimated to have decreased in recent years (De Rosa et al., 2024). A higher soil temperature and lower precipitation/soil moisture can increase soil respiration and decomposition, releasing carbon from terrestrial ecosystems into the atmosphere (Zhang et al., 2023; Gallego-Sala et al., 2018). Floods, droughts, high winds and heavy rains can exacerbate soil erosion and the depletion of nutrients (Panagos et al., 2021). These effects can increase the risk of wildfires, also resulting in more CO_2 emissions (Turetsky et al., 2015).

Moreover, the longer dry spells resulting from climate change during summer months are increasing the risk of wildfire in many parts of Europe, especially when the more severe droughts are combined with sufficient biomass/fuel (Stoof et al., 2024). The data available at the EU level indicate that there was an increase in the area of forest land that burned and the number of fire events in 2022 and 2023 (San-Miguel-Ayanz et al., 2024). The Fire Weather Index, which estimates fire danger based on temperature, relative humidity, wind speed and precipitation, indicates that there is a moderate to very high danger of forest fires in a significant part of Europe as well as an increasing risk. In a moderate emissions scenario, many parts of Europe could experience a longer fire season (Map 1.2). Southern Europe is particularly at risk, where the probability of catastrophic fires is estimated to increase tenfold (El Garroussi et al., 2024).

High temperatures and low humidity (atmospheric humidity and soil moisture) are only two of the atmospheric and meteorological factors to be considered when assessing fire risks, however (EFFIS, 2025). Other important elements are biophysical factors (e.g. species composition, fuel accumulation, topography) and the role people play in causing and mitigating fires (Chuvieco et al., 2023). Today, most wildfires are still ignited by humans (El Garroussi et al., 2024). Human activities which exacerbate wildfire risk include recreational activities causing intended or unintended ignition; land abandonment creating more fuel; and the creation of large-scale tree plantations with flammable species such as pines and eucalyptus.

([10]) Increased productivity is not exclusively influenced by changes in temperature, daylight, precipitation and resulting changes in the growing season. It is also affected by other factors including atmospheric CO_2 levels (fertilisation effects) and increased nitrogen deposition.

Map 1.1 **Weather-driven forest fire danger during the near-term period (2011-2040) and mid-term (2041-2070) under two emission scenarios**



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

Weather-driven forest fire danger in the current/near term (2011-2040) (left) and mid term (2041-2070) (right), and projected changes under moderate emissions scenario (RCP 4.5) (top) and high emissions scenario (RCP 8.5) (bottom)

Risk of fire days

<0, 0-4, 4-7, 7-11, 11-15, 15-19, 19-22, 22-26, 26-30, 30-34, 34-37, >37

No data

Outside coverage

0 500 1,000 1,500 km

Source: EEA High Fire Danger Days index.

The effects of climate change and natural disturbances on terrestrial ecosystems can have significant implications for their role in climate change mitigation. Annex 1 summarises various climate-induced risks and associated effects on carbon stocks and fluxes in land. This overview indicates that while some drivers can increase removals, most involve a potential negative impact in terms of GHG emissions. As an example, a sensitivity analysis to the GHG balance of living trees in forests in Germany demonstrated that the forest sink capacity can range between approximately 10 and >40 $MtCO_2e$ of removals depending on the extent of natural disturbances (Hennenberg et al., 2024). This underscores the fact that avoiding natural disturbances and their effects on terrestrial ecosystems are among the most important mitigation measures available in the LULUCF sector.

1.4.1 Adapting to impacts from climate change and natural disturbances

In the land sector, climate change mitigation measures are closely connected to climate adaptation (i.e. limiting the impacts of climate change) and in some cases, there are important win-win situations. For example, forest restoration, conservation agriculture, peatland restoration and agroforestry can result in both more carbon sequestration (or reduced emissions) and more climate-resilient ecosystems. Weakened and ageing forests can be susceptible to pests and diseases (Forzieri et al., 2021), while changes in forest management, involving for example a greater range in the types of trees species and ages of trees, can help to stimulate natural processes and increase the resilience of forests to climate change and natural disturbances, thereby protecting carbon sinks and biodiversity (Pilli et al., 2022; Vacek et al., 2023; EEA, 2024c).

Generally, key risk mitigation measures can relate to governance, economy- and finance, technology (e.g., early warning systems), nature-based solutions, and knowledge and behavioural change (Leitner, 2020). Nature-based solutions for terrestrial ecosystems include the creation of new, or the improvement of existing, green infrastructure and natural or semi-natural land-use management. Examples of relevant nature-based solutions are provided in Table 1.2.

The implementation of adaptation actions often require engagement from various stakeholders, including policymakers and (sub-)national public authorities, monitoring agencies and forest and land managers. Increased monitoring and understanding of the impacts of climate change on ecosystems are particularly important to inform policies and measures, as well as preventive and responsive action both locally and regionally. The development of management systems under the Copernicus Emergency Management Service (e.g., the European Drought Observatory, the European Forest Fire Information System, and the European Flood Alert System) is important in this context.

Interactions between risk drivers are complex and can lead to trade-offs in land and forest management, such as between disturbance prevention, carbon sequestration and other ecosystem services (Anderegg et al., 2020). Adaptation actions may not always provide immediate co-benefits for climate change mitigation and certain mitigation activities in LULUCF — such as monoculture planting of short rotation coppices — are not beneficial for adaptation. In addition to these biophysical elements, it is also important to take into consideration socio-economic factors within the system (Keesstra et al., 2018; Visser et al., 2019).

This presents both land managers and policymakers with the challenge of designing strategies and approaches, which aim for synergies over time, between carbon sequestration, increasing land- and forest resilience to climate change, enhancing biodiversity, and supporting economies.

Table 1.2 Examples of nature-based solutions for adaptation

Type	Examples
Planning	Climate change adaptation management plans, ground-water management plans, drought and fire management plans, land use planning (e.g., green infrastructure, green corridors, buffer zones), improved connectivity of ecological networks.
Restoration	Forest restoration after climate-related disasters, re-wilding, restoration of the landscape water balance, peatland restoration, rewetting, hydrological restoration, soil microbial restoration, establishment and restoration of riparian buffers.
Management	Agriculture: agroforestry, conservation agriculture, climate smart urban agriculture, precision agriculture, adapted crops and varieties, grazing management, improved water retention, water sensitive management, soil erosion control and stabilisation, re-forestation/afforestation. Forestry: prioritising fire-resistant vegetation, closer-to-nature forest management; climate resilient forest management, dead biomass management, prevention of climate-related damages to forests, water sensitive forest management.

Source: Climate-Adapt.

1.5 Scope, objectives and structure of the report

This introduction has pointed to the need for action in the LULUCF sector to ensure that the EU reaches its carbon removal target by 2030 and that the sector effectively contributes to climate change mitigation in the coming decades. Various options to enhance removals and reduce emissions in the LULUCF sector are ready to be upscaled to reverse the trend of decreasing carbon removals. These have significant potential to deliver co-benefits for biodiversity and increase the resilience of ecosystems to climate change. Action and buy-in from public and private actors are however needed, both to change management practices on the ground and provide financial support to spur the changes.

To this end, new EU governance strategies and policy tools have emerged to enhance climate action in LULUCF. Policy instruments focus on encouraging and enabling Member States to adopt effective policies and measures towards this policy aim.

However, while the LULUCF Regulation focuses on the need for countries to implement policies and measures to encourage land managers and farmers to change their land management practices, such changes will also rely on support from public authorities, private financial institutions and actors in biomass value chains (e.g. biomass producers, food processors, bioenergy companies). To engage these actors, new financial, governance and legal frameworks have been established to encourage engagement and investment from public and private actors, notably via the CRCF Regulation in combination with a new common agricultural policy (CAP) and State aid rules.

The success of these instruments for climate action in LULUCF will also depend to a significant degree on whether capabilities for monitoring, reporting and verification (MRV) of GHG emissions and removals in the sector are enhanced. Robust monitoring and reporting are not only important for assessing national performance towards climate goals, they also allow for the assessment of different sequestration practices, helping identify which methods are most effective in specific contexts. This, in turn, leads to better-informed decisions and a more efficient use of resources. Robust MRV systems are also key for evaluating policies and measures over time, ensuring that they achieve the desired outcomes and for certifying (and financing) carbon removal activities. Various frameworks requiring the delivery of environmental co-benefits from mitigation activities result in additional monitoring needs for biodiversity and other ecosystem services.

Improving the quality and detail of GHG inventory data will be crucial for identifying and evaluating the effects of policies and measures to increase carbon removals in land and the effects of ecosystem restoration measures on carbon sequestration and alternative land use systems. For this purpose, various remote sensing methods, geospatial datasets and products are being developed to contribute to more detailed and frequent mapping of land use patterns, land management practices, natural disturbances and effects from climate change. Yet (pan-European) geospatial data are limited in respect of their use and certain data gaps remain.

In the context of the need for swift action to slow and reverse the current trend indicating a declining LULUCF sink, this report provides a detailed assessment of this sector, with a specific focus on enhanced monitoring and reporting capabilities. Subsequent chapters of this report will cover:

- Chapter 2: the status and historical trends of carbon removals in the LULUCF sector, including an assessment of reporting practices, outlining shortcomings and areas for improvement;

- Chapter 3: an overview of abatement options to increase land-based carbon removals and reduce GHG emissions in LULUCF, providing insights on abatement potential and reflections on co-benefits, barriers and enabling factors;

- Chapter 4: a description of the current EU policy and governance frameworks relevant for LULUCF, outlining relevant interaction between LULUCF and other policy domains and resulting data needs and data provision;

- Chapter 5: a description and assessment of the capabilities of Pan-European geospatial datasets to support monitoring of land-based carbon removals and related emissions in the land sector; and

- Chapter 6: conclusions and outlook.

2 Status of reported emissions and removals in the LULUCF sector

Key messages

- In 2023, the LULUCF sector provided a net carbon sink at the EU level of 198 $MtCO_2e$, counterbalancing around 6% of EU emissions from other sectors. However, there is strong variability between Member States: some report LULUCF as a net sink, others as a net source of GHG emissions. Such variability arises from differences in land characteristics, management intensity and climate conditions, and the impacts of natural disturbances.

- The LULUCF sink has been declining for about a decade. The LULUCF sector provided an average annual carbon sink of 335 $MtCO_2e$ in the period 1991-2013. Yet between 2014 and 2023, the average annual sink was 30% smaller compared to the decade before.

- This decline largely has to do with a reduction in Europe's forest sink, driven by a combination of interrelated factors, including the ageing of forests and increase of harvests. Cropland and settlements are the major sources of net emissions. The management of organic soils results in high GHG emissions in cropland, while the conversion of land with high carbon stock is a primary driver of emissions in settlements. Natural disturbances have become more frequent and severe, and can suddenly 'shock' the LULUCF sector, potentially leading to long legacy effects. This is the main driver of interannual variability and can affect the predictability of the sector in terms of GHG emissions and removals.

- Currently, the accuracy of LULUCF reporting varies widely due to the use of different estimation methods (or tiers), and overall, the status of emissions and removals in the LULUCF sector has higher uncertainty compared to other sectors. In some land categories, inventories are not equipped to properly capture the effects of management practices, thus failing to reflect related policies and measures, and as such the effects of finance allocated. In this context, EU Member States and the Commission have committed to enhance reporting in the LULUCF sector.

- Ongoing improvements of GHG reporting are essential for enhancing policy effectiveness over time, such as facilitating assessments of trends and drivers, progress to target analyses and for the evaluation and design of policies and measures. This can be achieved by timely data provision, the use of higher-tier methods and improved modelling approaches, more complete reporting in terms of carbon pools, and the use of geographically explicit data for land use conversions.

2.1 Introduction

The LULUCF sector is the only sector reported on in national GHG inventories that shows both emissions and removals of CO_2. At the EU level, the sector acts as a net sink of CO_2. In 2023, it counterbalanced ~6% of the EU's GHG emissions from other sectors. According to policy-relevant climate change mitigation scenarios, this level should increase in the coming decades ([11]).

The EU LULUCF sink has, however, shown a declining trend in the past decade. Climate change and natural disturbances effects also mean that the LULUCF sink is at risk of becoming less predictable and stable. In view of both short- and long-term climate change mitigation commitments, Europe and individual countries are confronted with an urgent challenge to reverse this LULUCF trend at the same time as increasing the resilience of ecosystems in the face of climate change.

Tracking GHG emissions and removals over time is key to helping the EU and its Member States meet this challenge. Specifically, reporting at the EU level and under the United Nations Framework Convention on Climate Change (UNFCCC) aims to ensure that anthropogenic GHG emissions and carbon removals are tracked and documented over time. Resulting GHG inventories provide the basis for assessing compliance with relevant policy targets. Improving how the LULUCF sector is monitored is the basis for the current EU LULUCF Regulation framework (see Chapter 4), but it also raises several challenges given the complexity of the sector.

This chapter will provide a high-level assessment of trends in the EU LULUCF sector (Section 2.2), and with a focus on each land use category (Section 2.3). The chapter will also provide information on current reporting practices and share lessons learned on reporting practices for the LULUCF sector (Section 2.4). The analysis of this Chapter was conducted based on the EU GHGI 2024. Only the information on the general trend in LULUCF and on recalculations in the sector include information from the EU GHGI 2025.

2.2 Current state of GHG emissions and removals in the LULUCF sector

In order to report on GHG emissions and carbon removals in the LULUCF sector, national territories are classified according to six land use categories (see Table 2.1). In addition, changes in carbon stocks in the five carbon pools, brought about by land use change or land management practices, are monitored (see Table 1.1). Emissions or removals resulting from land use changes are reported under the land use category corresponding to the new land use. For instance, conversion of cropland to forest land is reported under forest land and conversion of wetlands to cropland is reported under cropland.

Another reporting category under LULUCF is Harvested wood products (HWP). This refers to wood materials derived from forests that are used in various products and for which the wood carbon content remains stored in wood form (excluding those products used for energy purposes). Despite the predominant focus on CO_2 in the LULUCF sector, nitrous oxide (N_2O) and methane (CH_4) are also reported under LULUCF in some cases, for example when they result from burning biomass and soil management (EEA, 2024d).

([11]) Possible abatement effects from the substitution of fossil fuel use or carbon-intensive materials with biomass are not considered in this chapter; they are also excluded from the scope of reporting and accounting under LULUCF.

Table 2.1 Reporting land use categories

Forest land	This refers to all land with woody vegetation consistent with thresholds used to define forest land in the national GHG inventories ([12]). It also includes systems with a vegetation structure that currently fall below these thresholds but that could, *in situ*, potentially reach the threshold values used by a country to define the forest land category.
Cropland	This is cropped land, including rice fields and agroforestry systems where the vegetation structure falls below the thresholds used for the forest land category.
Grassland	This term includes rangeland and pastureland that is not considered cropland. It also includes systems with woody vegetation and other non-grass vegetation such as herbs and bushes that fall below the threshold values used in the forest land category. The category also includes all grassland from wild lands to recreational areas as well as agricultural and silvopastoral systems, consistent with national definitions.
Wetlands	These are areas of peat extraction and land that are covered or saturated by water for all or part of the year (e.g. pristine peatlands) and that do not fall into the forest land, cropland, grassland or settlements categories. They include reservoirs as a managed sub-division and natural rivers and lakes as unmanaged sub-divisions. They do not include drained peatlands converted to other land uses.
Settlements	This category includes all developed land, including transportation infrastructure and human settlements of any size, unless they are already included under other categories. This should be consistent with national definitions.
Other land	This category includes bare soil, rock, ice and all land areas that do not fall into any of the other five categories. It allows the total of identified land areas to match the national area, where data are available.

Source: IPCC, 2006.

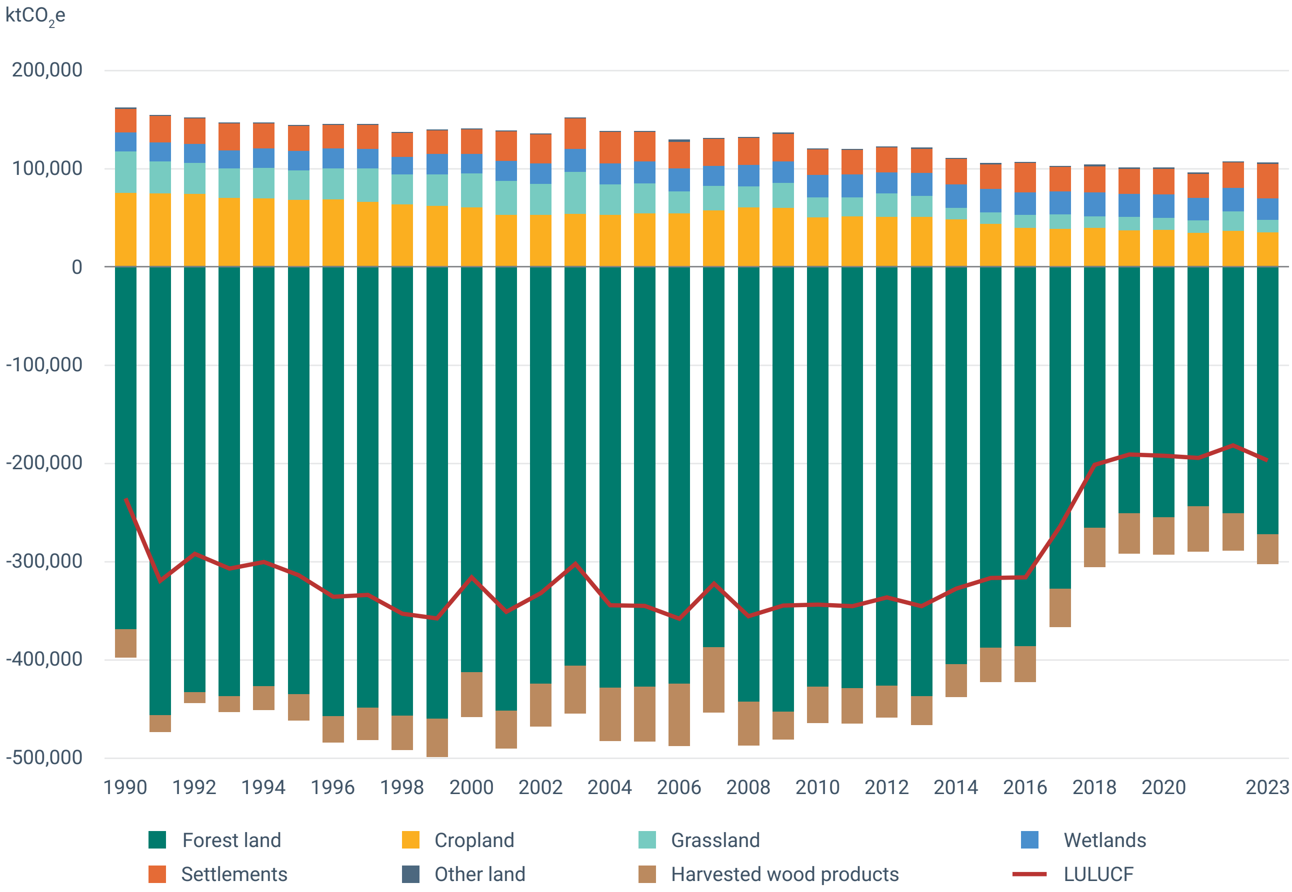
At the EU level, the carbon sink is driven by the forestry sector, with net removals reported under forest land and HWPs. Meanwhile, other land use categories represent a net source of emissions (Figure 2.1). The two land use categories responsible for most emissions are cropland and settlements. Yet in some Member States or regions, forests can represent a carbon source, and cropland can represent a sink.

Since 1990, the first reported year covered in the time-series of the inventories, the EU LULUCF sector has removed more CO_2 annually than it has emitted to the atmosphere, making this sector a net CO_2 sink. This is in spite of the fact that for specific countries and years, the LULUCF sector has occasionally been reported as a net source of emissions due to the impact of natural disturbances (e.g. Czechia in 2020, Portugal in 2017) or increased forest harvests rates (e.g. Latvia in 2020-2022 and Finland in 2021-2022).

([12]) Quantitative thresholds used by Member States to define forest land can also be found in Annex II of the EU LULUCF Regulation (EU, 2018a).

Over the last decade or so, the EU net sink has been decreasing (Figure 2.1), largely due to changes in the net value of carbon emissions and removals estimated for the forest land category (Section 2.3.1).

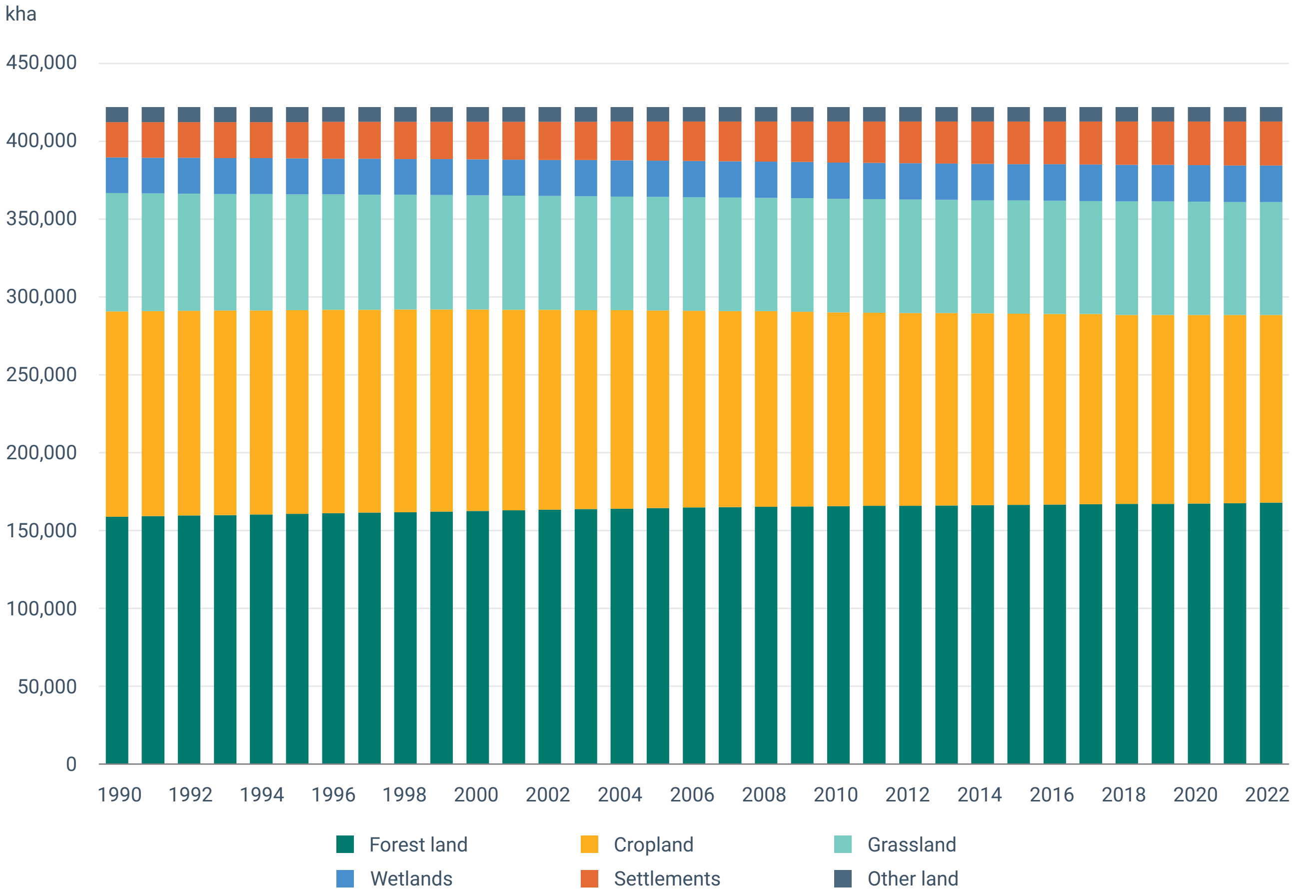
Figure 2.1 **LULUCF net emissions (+) and removals (-) for the EU-27 (1990-2023) in kilotonnes of carbon dioxide equivalent (ktCO$_2$e)**



Source: EEA, 2025b.

In many instances, land use changes are a relevant driver of the reported emissions and removals under the LULUCF sector. While, at the same time, as shown in Figure 2.2, the overall area covered by different land use categories is relatively stable at the EU level. An increase in the area is reported for forest land and settlements since 1990. Additionally, the wetlands reporting category (see definition in Table 2.1) increased in area a small amount, although the change is almost negligible. In contrast, the cropland and grassland categories have decreased in size by a small but steady amount since 1990.

Figure 2.2 **Total area of each of the LULUCF land use categories (1990-2022) in the EU-27 in kilo hectares (kha)**

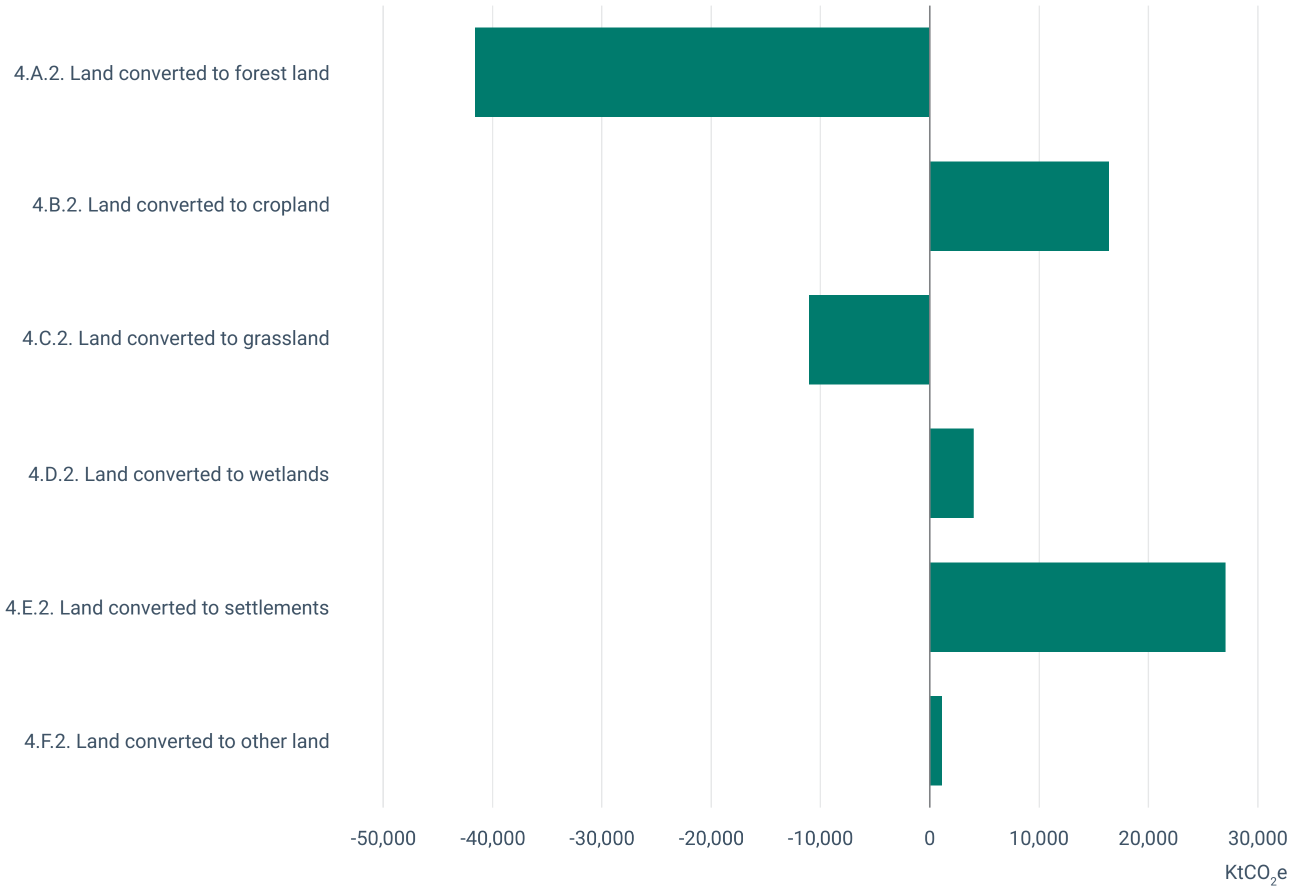


Source: EEA, 2024a.

It is important to recognise, however, that the figure above does not explicitly show the gross extent of land use changes but rather the resulting net coverage for each category over time. Why land use changes take place and what area is affected can often be relevant factors for emissions and removals reported under the different LULUCF categories. These changes can also have a significant impact at the national and sub-national levels. This underscores the importance of carefully monitoring and reporting land use changes that have occurred. Data on their location, scale, drivers and trends over time are important both for the purpose of maintaining accurate GHG inventories and for preparing and evaluating the effectiveness of policy.

Currently, increased removals from afforestation and conversion of lands to grassland offset GHG emissions from other land use changes. The conversion of land to settlements represents the largest source of emissions, followed by the conversion of land to cropland.

Figure 2.3 **Net emissions (+) and removals (-) for the EU-27 from land conversion categories reported in 2024 for 2022 in $ktCO_2e$**

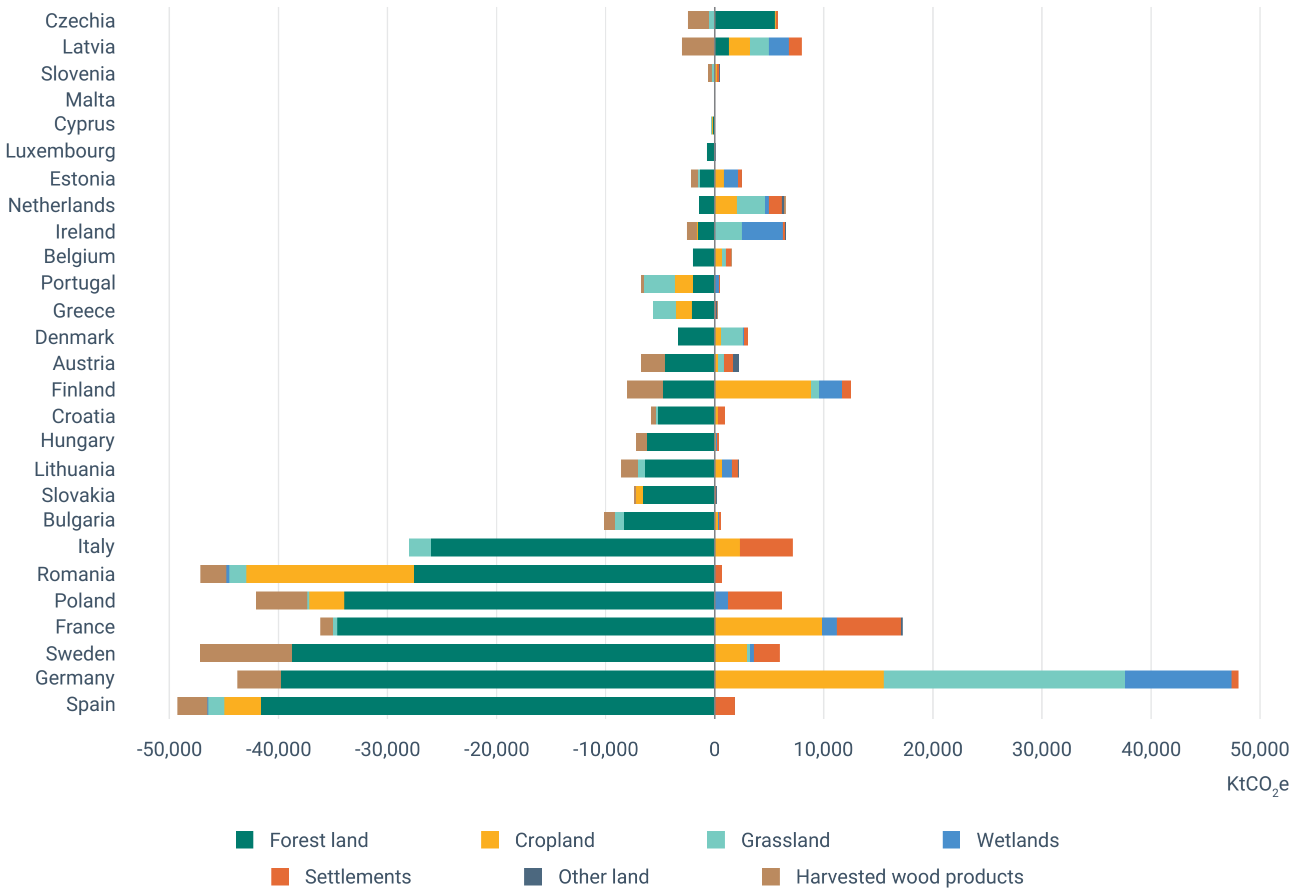


Source: EEA, 2024a.

2.2.1 Variability across countries

While the EU GHG inventory, which reflects the direct sum of national inventories, reports the LULUCF sector as a net carbon sink, there is high variability across Member States. Some report the sector as a net sink and others report the sector as a net source of emissions.

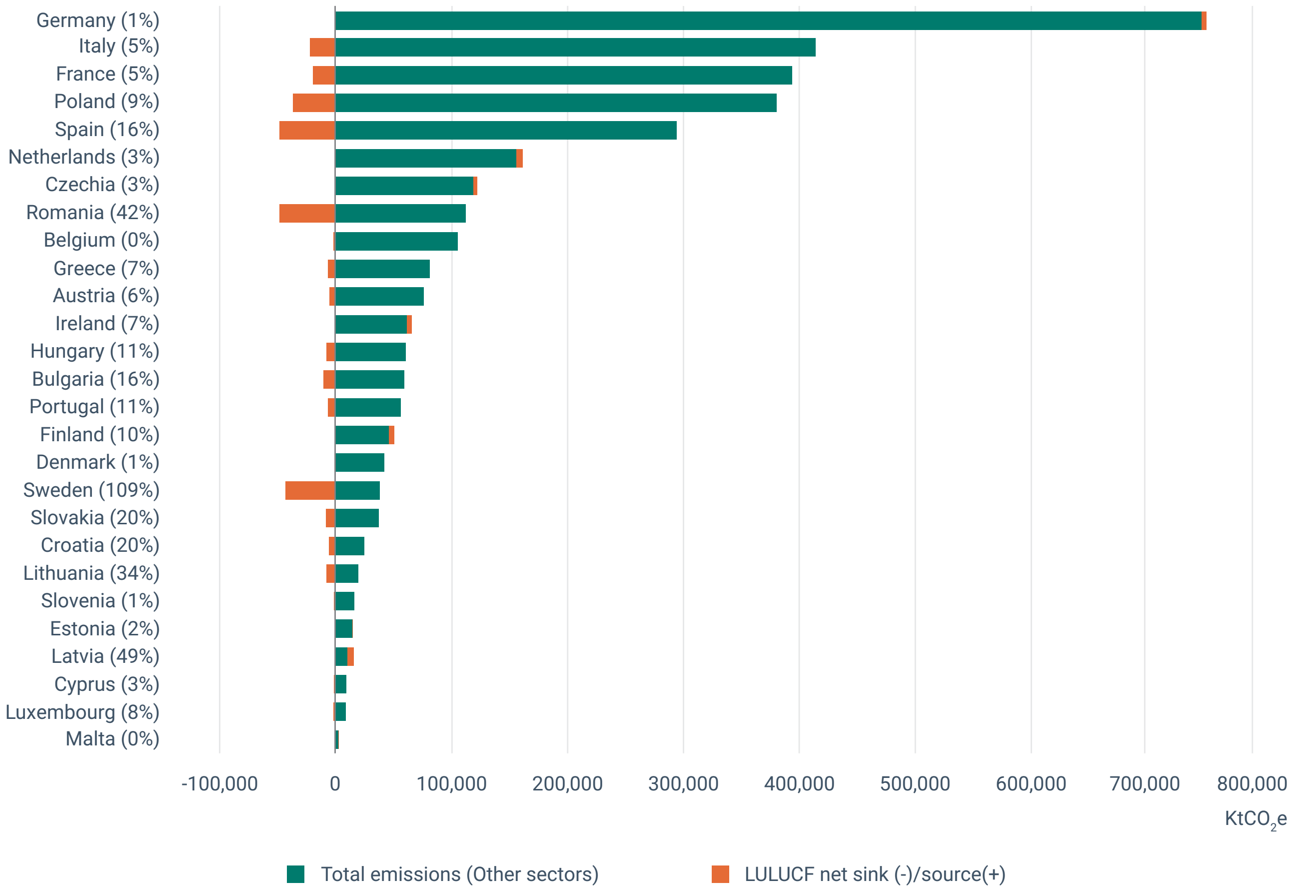
Figure 2.4 **Emissions (+) and removals (-) per land use category and EU Member State in 2022 in $ktCO_2e$**



Source: EEA, 2024a.

Country reports also show large variations in trends since 1990, from a substantial reduction in the sink to a significant increase. The reasons behind this are manifold, ranging from different land characteristics (e.g. the presence of cropland on organic soils) to different shares of land use categories. Historic land use and management intensity also play a role, both of which can differ significantly depending on economic dependencies. In addition, climatic conditions, climate change and natural disturbances lead to differences between the Member States. The LULUCF sector and the forest land category in individual countries are of different importance when comparing how much they contribute to total national emissions compared to other sectors (Figure 2.5).

Figure 2.5 **LULUCF net emissions (+) or removals (-) compared to GHG emissions from other sectors in 2022 per EU Member State in percentages and in $ktCO_2e$**

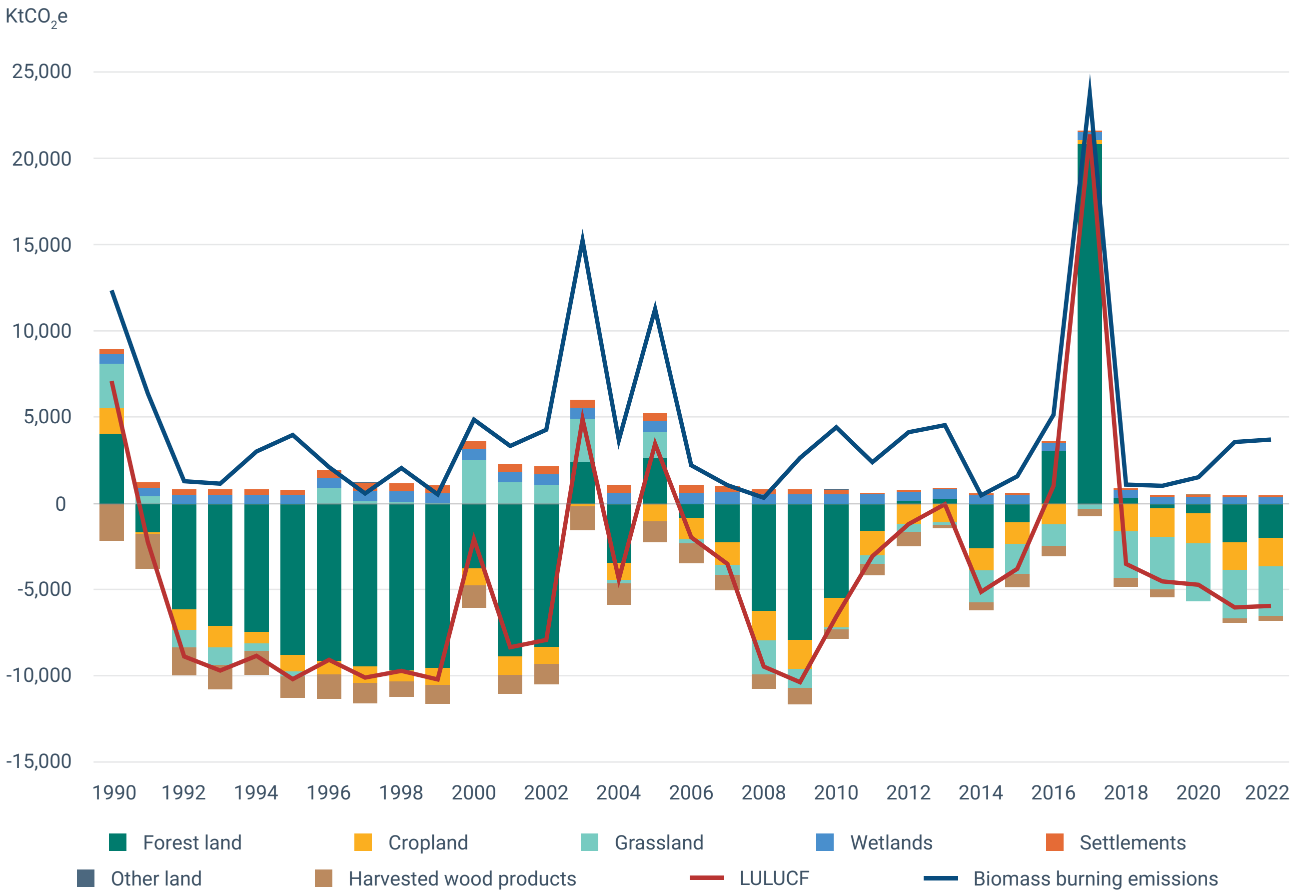


Source: EEA, 2024a.

2.2.2 Natural disturbances and interannual variability

Natural disturbances in the EU are increasing in frequency and in terms of the magnitude of their effects (Section 1.4), including forest fires, pests, wind throws, droughts and water stress. The occurrence of natural disturbances can affect the rate of net carbon emissions or removals from year to year, causing inter-annual variations. Disturbances can accelerate tree mortality or reduce tree growth, thereby slowing carbon sequestration, driving carbon emissions and reducing forest carbon storage in stable pools. The effects can vary in terms of the speed of impacts (e.g. wildfires have more immediate emission effects than droughts) and the pace of recovery, which can take years after a seasonal event (e.g. a wildfire). In some countries, including Czechia and Portugal, natural disturbances such as wildfires and insect outbreaks have had a devastating effect on forest sink capacity. Figure 2.6 illustrates the effects of wildfires in Portugal in 2023, in terms of data reported for the LULUCF sector. It clearly demonstrates the high impact of wildfire emissions on the overall balance of the LULUCF sector.

Figure 2.6 **Trend in LULUCF emissions and removals per land category, reported by Portugal for the period 1990-2022 in ktCO$_2$e**



Source: Portuguese Environment Agency, 2024.

2.3 Trends and assessment according to land category

This section discusses the trends in reported data according to each land use category in terms of area changes and GHG emissions and removals.

2.3.1 Forest land

The overall area of forest land in the EU has increased by 6% since 1990, and it currently represents about 40% of EU territory. All but two EU countries reported growth in forest area since 1990. Finland, a country with much higher forest cover than the EU average, is more prone to deforestation. Nonetheless, it reported only a negligible decrease of 1% since 1990. Malta instead reported a decrease by 5%.

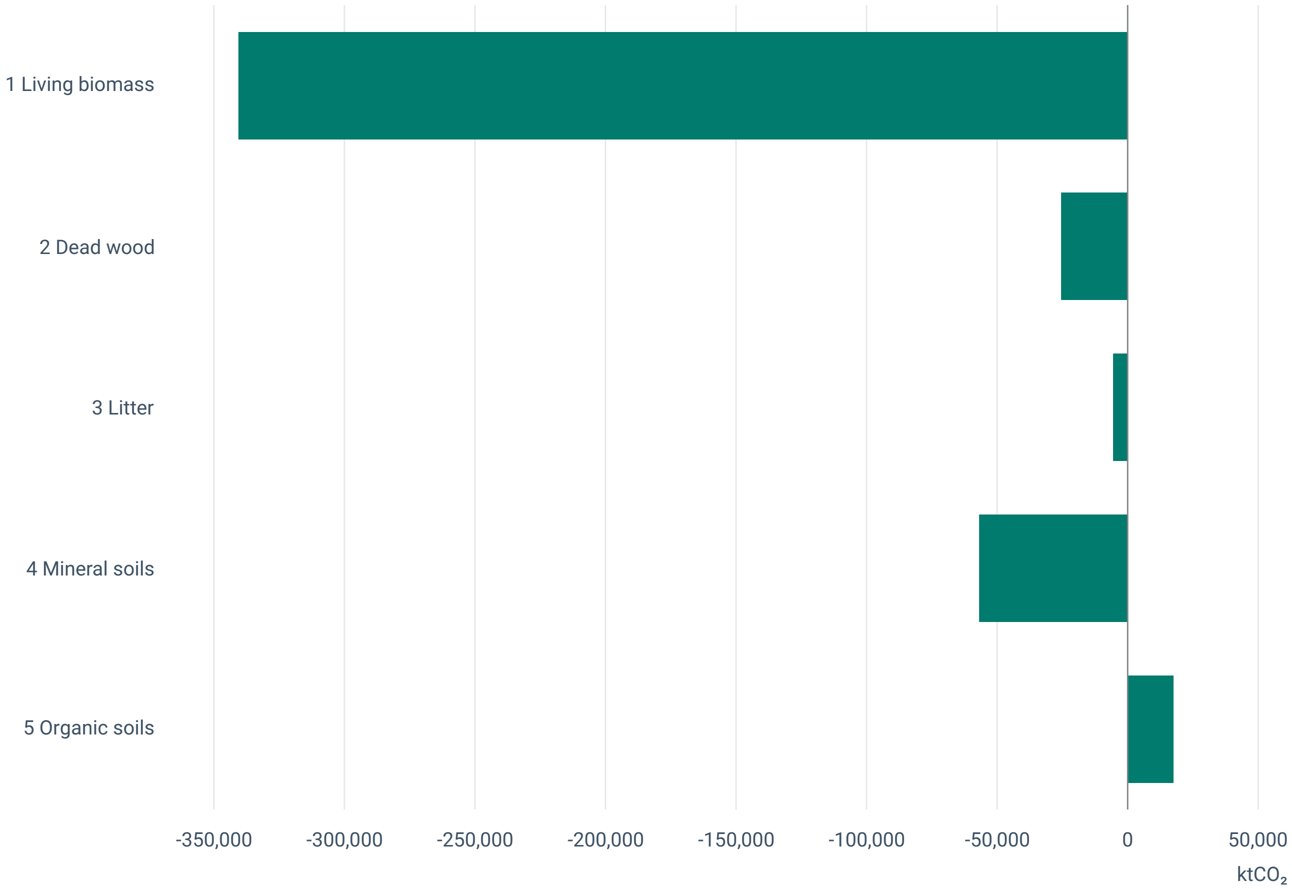
Forests play a critical role in reaching LULUCF and climate goals; cumulatively they removed, on average, the equivalent of about 9% of total GHG emissions from the other sectors in the EU between 1990 and 2022. In most EU countries, the capacity of forests to sequester atmospheric carbon is the key factor in the overall LULUCF sink, underscoring the importance of this land use category.

In forests, most of the carbon sink reported in LULUCF is attributed to living biomass (i.e. the trunk, branches, leaves and roots). At the EU level, living biomass constitutes on average about 85% of the absolute removals from forests. Dead wood, litter and mineral soils are also contributors to the forest sink, although their carbon removals are often less significant than those from living biomass, representing on average 22% of the total forest sink in the latest submission. In contrast, forest management practices relating to organic soils release CO_2 emissions equivalent to 4.5% of the net EU forest sink.

Generally, the capacity of forests to sequester carbon is influenced by a variety of factors and the interplay between them, including tree species and their diversity, age structure, harvesting intensities, rotation periods, climatic dynamics and the occurrence of natural disturbances. The annual net gain in living biomass is determined by estimating the growth in biomass minus the loss due to harvest, natural mortality and disturbances (e.g. fires).

In the EU, harvest rates have generally been below net forest increment ([13]). Thus, forest growth has led to an increase in carbon sequestration from the atmosphere. Yet the capacity of forests to sequester carbon has been decreasing in the last decade.

Figure 2.7 **Annual average GHG emissions (+) and removals (-) per carbon pool in forest land from 1990-2022 for the EU-27 in $ktCO_2$**



Source: EEA, 2024a.

([13]) Net annual increment refers to the annual increase in all trees minus natural losses.

The decline in the LULUCF carbon sink is mainly caused by dynamics in forest land. Since 1990, the net carbon sink initially showed an increasing trend, driven by an expansion of forest area and a higher increase in net forest carbon sequestration.

Since around a decade however, this trend reversed to a declining carbon sink. This decline has been driven by a combination of interrelated factors (EEA, 2025a; Korosuo, 2023):

1. Forest stands have matured, resulting in higher forest carbon stocks. While they still sequester carbon, they do so at a lower rate.

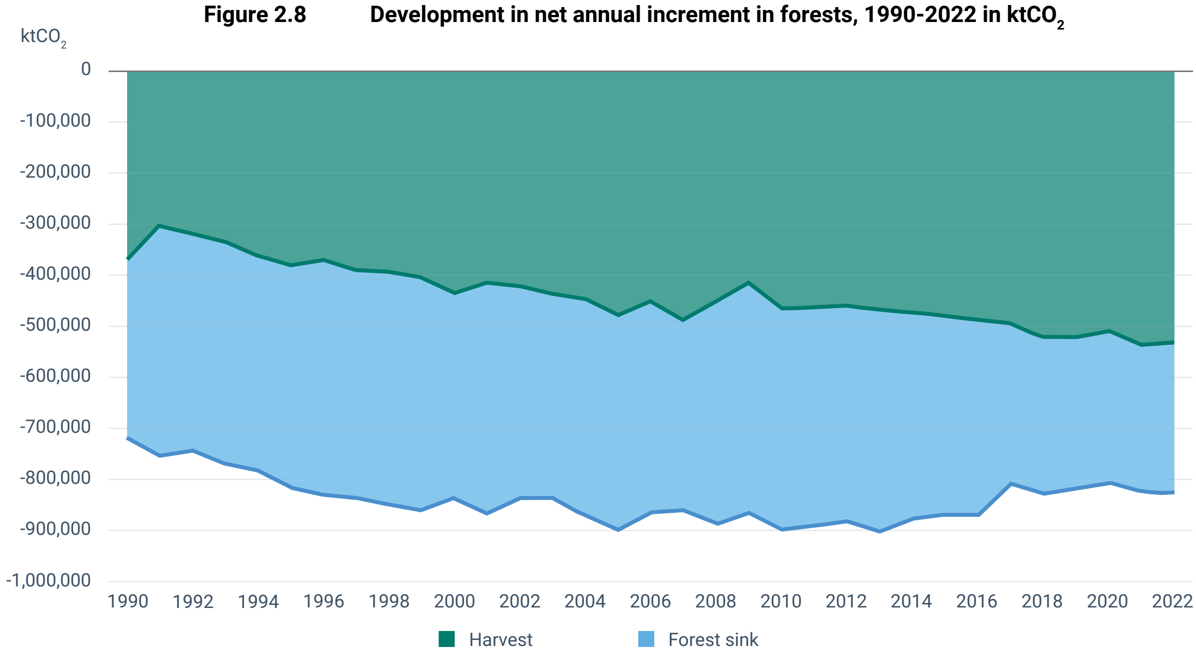
2. Forest harvests have increased due to economic and policy drivers, and salvage logging.

3. Climate change has accelerated the decay process of carbon stored in soils and dead organic matter. Natural disturbances, including forest fires, droughts and pests have affected standing trees.

4. The annual rate of afforestation has decreased compared to 50-70 years ago, contributing to factor (1) here above.

Since 1990, wood harvests increased while the forest sink remained relatively stable until about 2013, suggesting a growing net annual forest increment. However, while harvests further increased since, the net forest sink started to decline faster than the increase in harvest, suggesting a reduction in net annual forest increment that goes beyond the harvesting rates (Figure 2.8). A reduction in net forest increment can have several causes, including saturation of forests and climatic effects such as drought. The figure should however be read with caution as harvests are generally underreported and emissions from forest fires are not included.

Figure 2.8 Development in net annual increment in forests, 1990-2022 in ktCO$_2$



Notes: This figure combines and compares two independent datasets, 1) biomass harvest (FAOstat, 2024), converted from m³ roundwood to CO_2; and 2) Forest carbon sinks as reported in EU's GHG inventory (EEA, 2024a) under LULUCF/forest land.

2.3.2 Cropland

Cropland covers about 29% of EU territory, and the definitions of cropland currently used are similar across Member States. They usually represent areas occupied by annual and permanent crops, as well as set-aside lands. The main difference between inventories is whether trees outside forests and small fast-growth tree plantations (e.g. poplars or Christmas tree nurseries) are reported under cropland, forest land or grassland.

At the EU level, cropland area has steadily decreased since 1990 by about 8%. The cropland category represents the largest source of emissions reported under the LULUCF sector. Therefore, it has a high potential to reduce emissions or increase removals (see Chapter 3.3). However, the mitigation potential varies significantly between European countries.

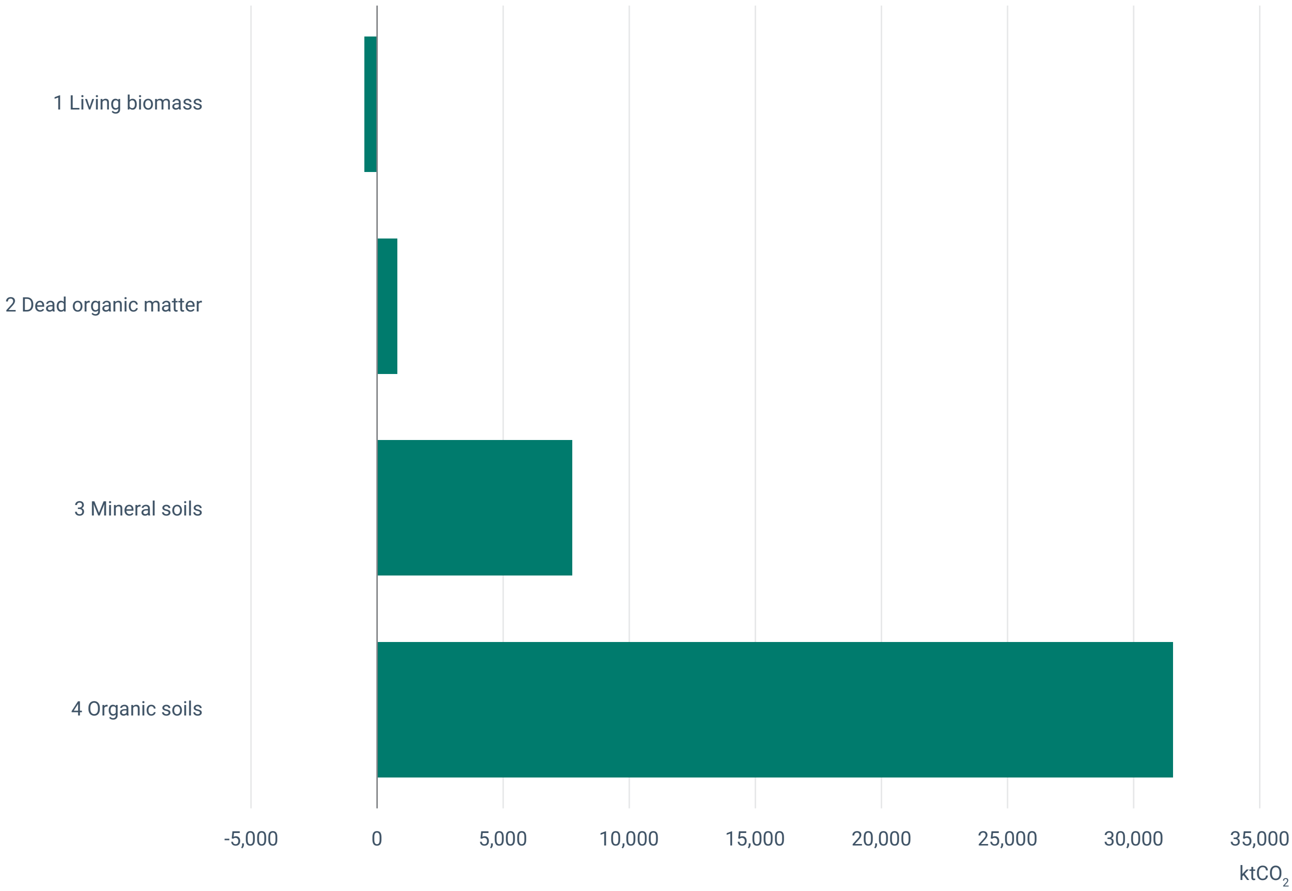
Cropland emissions reported in the EU LULUCF inventory account on average 43,603 ktCO_2e (emissions of 44,312 ktCO_2e vs a net sink of 278,433 ktCO_2e) of all emissions from the sector. A significant share of cropland emissions is due to agricultural activities on organic soils, which are considered a hotspot due to their high carbon content. When organic soils are subject to agricultural activities that enhance carbon oxidation, these soils release significant amounts of GHGs that are reflected in the GHG inventories. Nonetheless, at EU level, the area covered by cropland organic soils has decreased by 14% since 1990. This decrease is mainly driven by the overall decrease in the area of cropland but in some instances, it is also partly driven by soil drainage as a management practice to prepare land for agricultural production.

Cropland emissions have decreased about 67% since 1990. The reduction is partly driven by the decrease in overall cropland area but there has also been a noticeable positive effect from agricultural policies (e.g. the CAP) promoting the adoption of more climate-friendly management practices, such as setting aside areas from agricultural production, reduced burning of agricultural residues, and the maintenance of ground cover.

A comparison of reported cropland emissions from EU countries indicates large variations. As reflected by the EU GHGI, most of the countries report this category as a net carbon source of emissions — opening the door to exploring mitigation strategies for GHG emission reduction. Moreover, as shown in the next chapter, there is significant potential to increase removals in the cropland category. As for the forest land category, one challenge in analysing the data is that countries often report only net numbers so that carbon gains and losses are not visible.

Whenever cropland is reported as a net sink, the removals are often linked to either the net carbon sequestration occurring in living woody biomass, mainly in countries where woody crops represent a high share of the total category, or to a shift in soil management towards more carbon-friendly practices.

Figure 2.9 Annual average GHG emissions (+) and removals (-) per carbon pool in cropland from 1990-2022 for the EU-27 in ktCO$_2$



Source: EEA, 2024a.

At EU level, emissions from cropland organic soils are about 60% higher than the sum of removals reported from living biomass and mineral soils, although there is variation across countries and years. The prominence of the effects of organic soils is related to their increased area under anthropogenic management and the role that all other pools play within the cropland category with significant variations across Member States; thus, the resulting sink fluctuates from country to country (Section 2.3).

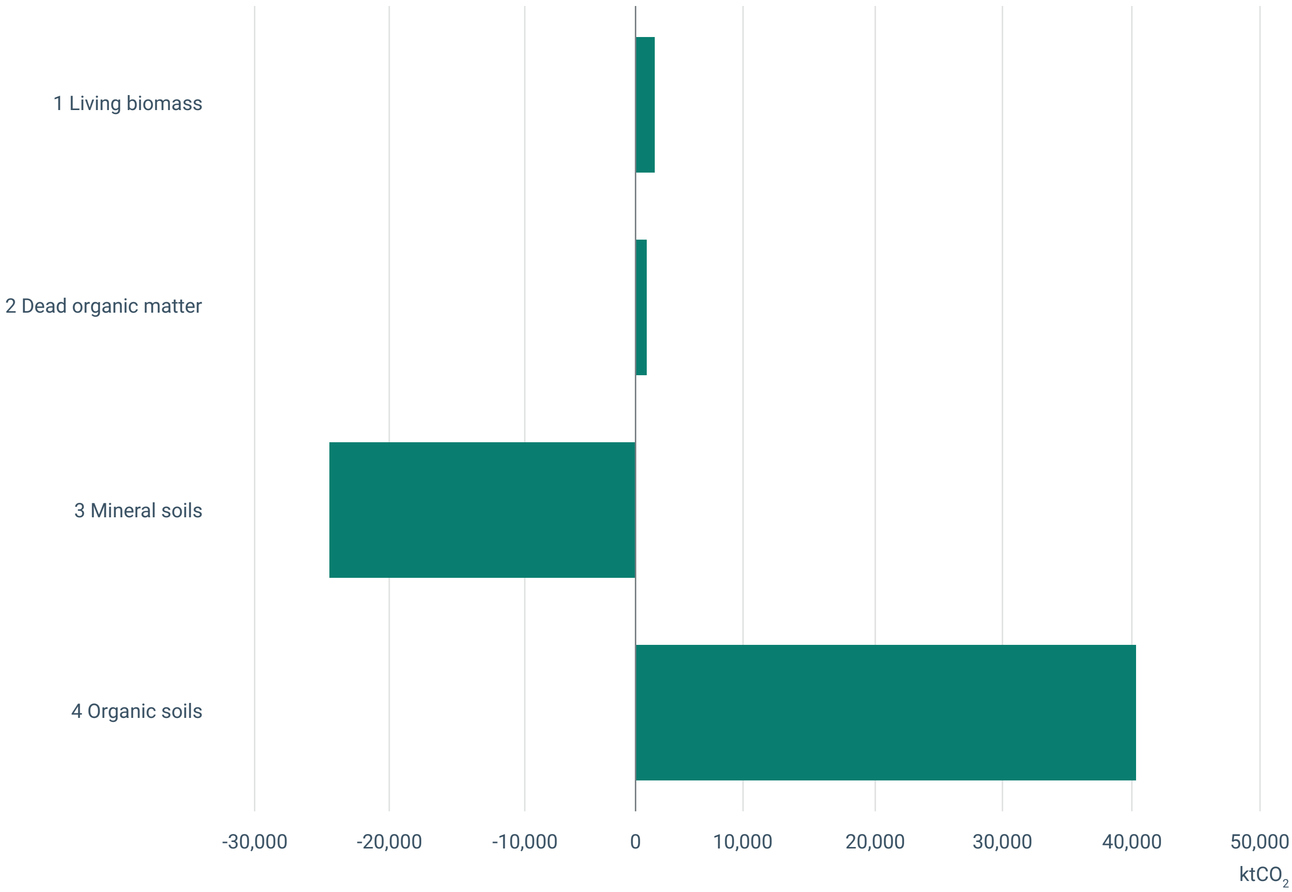
2.3.3 Grassland

Grasslands cover 17% of all EU territory, this area has decreased since 1990 due to the expansion of forest land and urban areas.

In the LULUCF inventories, grasslands are reported either as net carbon sinks or net carbon sources. These ecosystems vary significantly in terms of how much woody biomass they contain, and this influences their role in sequestering carbon (see definition in Table 2.1). Additionally, their management, grazing practices, the presence of grassland on organic soils (e.g. peatland) and the percentage of unmanaged grassland areas in a particular country can determine whether the category is reported as a net source of carbon or a net carbon sink. In some countries, unmanaged grasslands account for up to 36% of the total grassland area and no GHG emissions and removals are monitored in these areas.

Wildfires can also have a significant impact on emissions from grassland. In certain regions, like the Mediterranean basin, wildfires occur often, preventing the normal evolution of the vegetation towards natural tree stands. Within the LULUCF reporting framework, the emissions resulting from these fires can counterbalance the sink from grassland for several years, resulting in the category being reported as a net source of emissions.

Figure 2.10 Annual average GHG emissions (+) and removals (-) per carbon pool in grassland from 1990-2022 for the EU-27 in $ktCO_2$



Source: EEA, 2024a.

At EU level, the 2024 EU GHGI for LULUCF indicates that all carbon pools reported under the grassland category, except for grassland on mineral soils, act as a net source of CO_2 emissions.

The largest emissions reported under this category are associated with carbon oxidation due to management practices taking place on organic soils, followed by the living biomass that is lost during the conversion of forest land to grassland.

In contrast, the largest removals are linked to mineral soils, relating mainly to the conversion of cropland into grassland. As such, removals from mineral soils are almost of the same order of magnitude as emissions from organic soils.

In terms of emissions and removals, living biomass and dead organic matter are mainly reported by countries as net sinks due to carbon accumulation in woody biomass. Organic carbon in soils is reported either as a net source or as a net sink, depending on whether management practices and land use changes enhance the oxidation or accumulation of carbon in SOC.

2.3.4 Wetlands

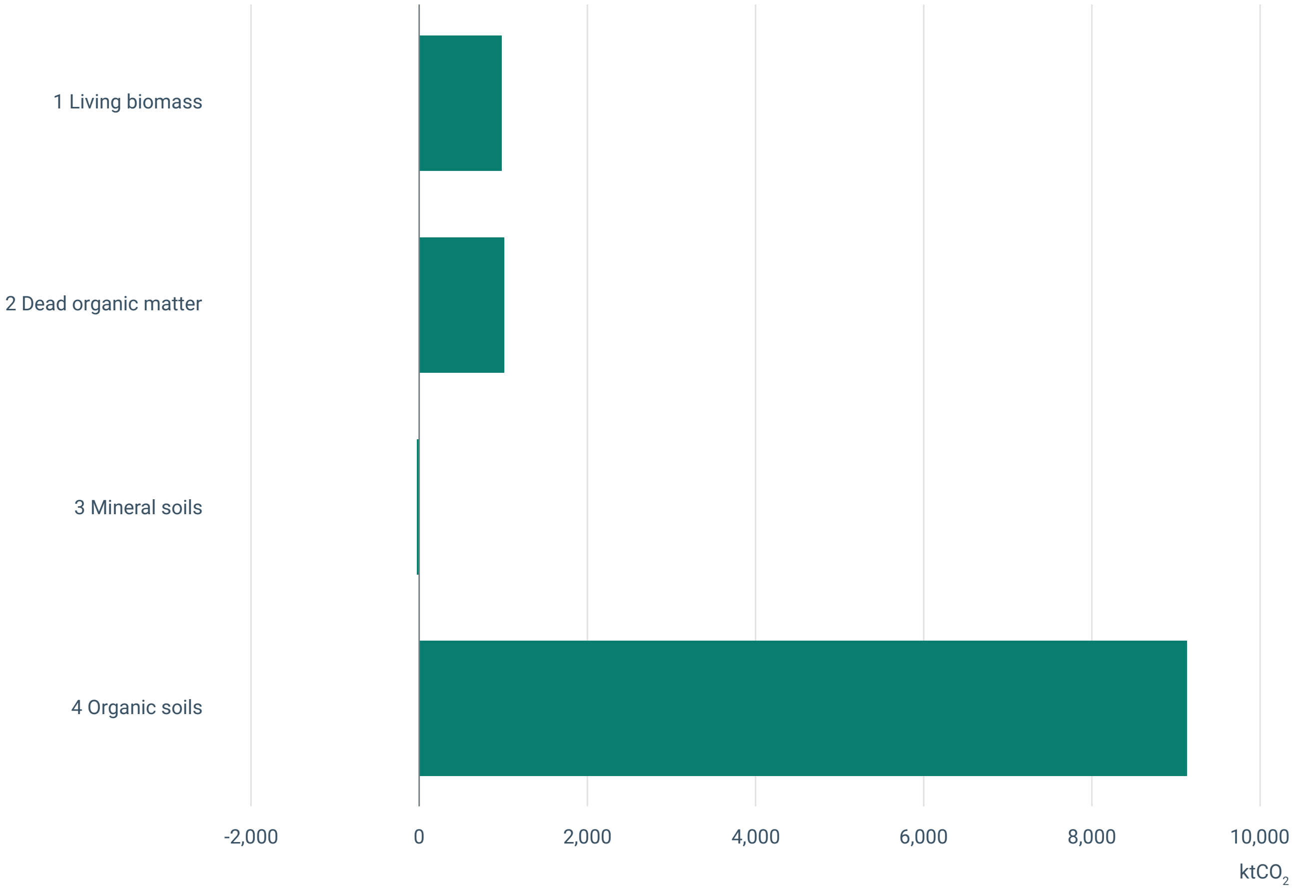
Wetlands in the LULUCF sector are usually defined as areas saturated by water for all or part of the year (lakes, rivers and peatland); the definition excludes areas that fall into other land use categories such as forest land, cropland, grassland or settlements (see definition in Table 2.1). Wetlands cover 5.5% of all EU land; 95% of them are classified as inland wetlands and 5% as coastal wetlands.

In this context, however, it must be noted that GHG inventories cover only land subject to management, and two-thirds of wetland areas in Europe are considered unmanaged. Member States do not provide information on carbon fluxes in these unmanaged areas. Given this, wetlands coverage in the GHG inventory may differ from the definition of wetlands in use for national nature conservation purposes.

Wetlands have increased by less than 1% since 1990, with most individual inventories reporting increases in the area of wetlands. For instance, Portugal and Romania have reported an increase of around 30%. In contrast, four northern countries, Finland, Ireland, and Sweden, have reported a decrease in the area of wetlands ranging from 1-10% compared with 1990.

Wetlands are reported at EU level as a net source of CO_2 emissions, and the latest EU GHGI shows an emissions increase by 23% compared to 1990. The same data source indicates that in recent years wetlands have accounted for a similar amount of CO_2 emissions as areas reported under the cropland and grassland categories (where emissions mostly derive from organic soils). This is significant given that the total area covered by wetlands is notably smaller than that covered by cropland and grassland.

Figure 2.11 **Annual average GHG emissions (+) and removals (-) per carbon pool in wetlands from 1990-2022 for the EU-27 in $ktCO_2$**



Source: EEA, 2024a.

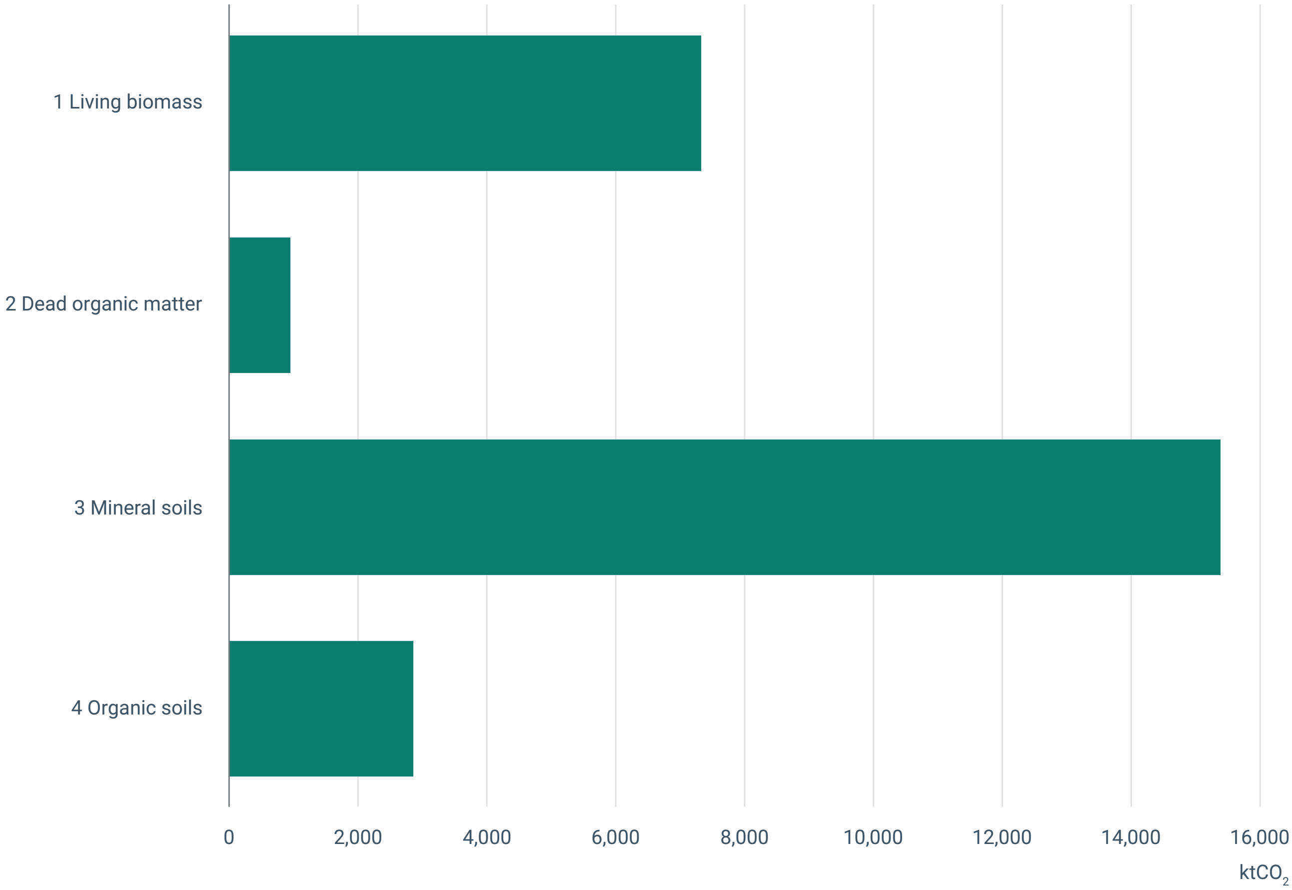
2.3.5 Settlements

Settlements cover 7% of total EU territory. The area reported for this category in the latest GHGI is 25% larger than in 1990. Generally, under this category, countries report urban areas, infrastructure, parks and gardens, as well as commercial or industrial parcels.

At EU level, all individual inventories have reported increasing area of Settlements since 1990. The growth rates are different, however, ranging from 3% reported by Czechia to around 90% as reported by Slovakia and Spain.

In terms of emissions and removals, all individual countries report that the category is a net source of emissions (Figure 2.12). Emissions are driven by the carbon loss that occurs during land use conversions into settlements.

Figure 2.12 Annual average GHG emissions (+) and removals (-) per carbon pool in settlements from 1990-2022 for the EU-27 in ktCO$_2$



Source: EEA, 2024a.

2.3.6 Other land

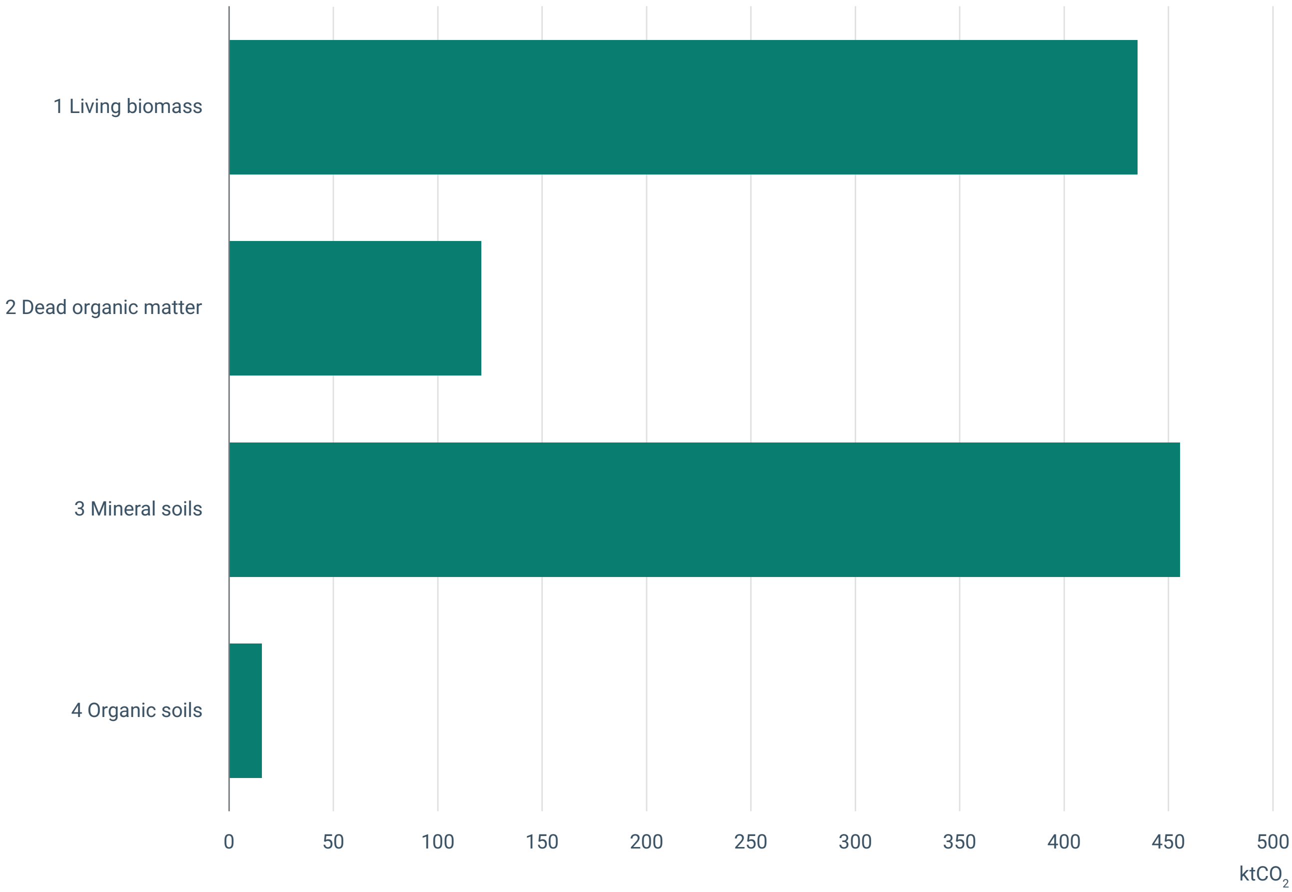
This category includes bare soils, rock, ice and ultimately all those areas that do not fall under any other land use category (see Table 2.1). In many countries this remaining land represents rather an artificial category which is used for balancing statistics and ensuring the sum of land use categories is constant across reported years. The category covers only 2% (9,299 kha) of EU territory.

In principle, areas assigned the other land category are zones without significant carbon stocks. This explains why the IPCC 2006 guidelines do not provide reporting methods or default factors for estimating carbon stock change in this category. However, countries must still report on carbon fluxes whenever a piece of land is converted to or from the other land category.

In the latest GHGI submission about half of the countries reported land use conversions to the other land category and their associated carbon fluxes, indicating that other land represents a small net source of CO_2 emissions at the EU and Member State levels. Sweden and Romania were exceptions to this, reporting negligible carbon sinks from carbon accumulation in living biomass following from the conversion of settlements into other land and in soils from the conversion of grassland.

The other land category has decreased in area by 5% since 1990 at the EU level. The main driver of this is the need to expand settlements as well as natural colonisation of grassland and forests.

Figure 2.13 **Annual average GHG emissions (+) and removals (-) per carbon pool in other land from 1990-2022 for the EU-27 in ktCO$_2$**



Source: EEA, 2024a.

2.3.7 Harvested wood products

Within the LULUCF sector, the HWP category is not literally considered a sink, as it does not actively remove carbon from the atmosphere. Nonetheless, HWPs represent a temporary carbon pool in the inventory. HWPs store carbon that was previously absorbed by trees during their growth. When wood is harvested it is considered a source of emissions as the carbon stored in the wood leaves the forest land category. After harvest, harvested carbon enters the HWP pool and remains stored in wood products during their lifetime in use (inflow), during which the carbon is gradually released due to decay or disposal (outflow). HWPs include wood-based products originating from domestic forests, such as sawn wood, wood-based panels, as well as paper and paperboard.

At the EU level, HWPs account for an average yearly value of 10% (36,928 ktCO$_2$) of the net CO$_2$e sink within the LULUCF sector. This means that the product inflow is higher than the product outflow.

According to the 2006 IPCC guidelines, 'HWP includes all wood material (including bark) that leaves harvest sites, where this removal is initially counted as a loss of carbon from living biomass'. In practice, countries report carbon stock changes in HWPs as the net difference between the product-inflow and product-outflow. The reporting is undertaken in an aggregated manner, whereby HWPs belong to some of three predefined categories: sawn wood, wood-based panels, and paper and paperboard; these are considered to have different lifetimes and decay rates. The HWPs in solid waste disposal sites and produced for energy purposes are accounted for as being directly emitted into the atmosphere after harvesting (instantaneous oxidation).

The IPCC default approach assumes that HWPs are discarded from use at a constant rate. This constant rate of decay is associated with a half-life in years until half of the amount is lost as emissions.

2.4 Reporting status, challenges and lessons learned

The EU, as a party to the UNFCCC, publishes a GHGI annually for the years between 1990 and the reporting calendar year (t) minus two (t-2), for anthropogenic GHG emissions and carbon removals within the area covered by its Member States (i.e. emissions taking place within its territory). The EU's GHGI reports the direct sum of Member States' GHG inventories. These inventories are fundamental tools which enable an understanding of the levels and trends of GHG emissions and removals from all sectors; they build mutual trust among countries in view of the shared mitigation responsibility agreed under the Paris Agreement. Higher quality reporting data could further enhance effective and efficient policies and measures in the sector. For example, such data could help to identify hotspots for action and support evaluation of the effectiveness of mitigation actions. GHG emissions data are made publicly available to inform national and international stakeholders in a transparent manner.

The reporting of GHG inventories must follow certain requirements agreed under the UNFCCC and the Paris Agreement and the IPCC 2006 Guidelines (see Box 2.1). At the EU level, Member States need to follow specific additional requirements for the compilation of the inventory and comply with the overall UNFCCC and IPCC reporting frameworks (EU, 2018c).

Box 2.1

General reporting methods according to IPCC guidelines (IPCC, 2006)

Estimates for emissions and removals in the GHGI are commonly derived by multiplying information on activity data with an EF. Information on activity data represents 'the magnitude of a human activity resulting in emissions or removals taking place during a given period of time'. Emissions factors are used to 'quantify the emissions or removals of a gas per unit of activity'.

In the LULUCF sector:

- Activity data mainly refer to land use areas and changes in land use areas.
- Emissions factors predominantly refer to the change in carbon stock that takes place per hectare under certain conditions and the land use category.

In many cases, this simple approach can be modified to include other relevant parameters or to better estimate the emissions using complex modelling approaches. In preparing their inventories, countries are required to follow LULUCF reporting guidelines developed by the IPCC (2006), though there is some flexibility in terms of the reporting methodologies to accommodate national monitoring capacities and resources. Due to difficulties in disentangling the human- versus natural-induced effects, in the GHG inventories, anthropogenic fluxes in the LULUCF are considered to be all those occurring on 'managed lands', defined as 'lands where human interventions and practices have been applied to perform production, ecological or social functions'. Countries can apply their own definition of managed and unmanaged land within the broad IPCC definition. The guidelines provide both approaches for acquiring information on activity data and tier methods for acquiring information on emissions, as well as default EFs that allow countries to prepare their inventories where no country-specific information is available. The tiers express the complexity of the estimates according to the following factors (IPCC, 2006, Vol. 4, Box):

- Tier 1 is based on using default methodologies and EFs that are provided at the level of climate zones, global ecological zones and soil types. In some cases, it is assumed there is no net change in the carbon stock (i.e. the pool is in equilibrium).
- Tier 2 is based on default methodologies but with country-specific EFs and parameters. The quality of Tier 2 depends on the temporal and spatial scale of the monitoring data used.
- Tier 3 uses more accurate country-specific methods, including models and inventory measurement systems tailored to address national circumstances, repeated over time, driven by high-resolution activity data and disaggregated at sub-national level.

Even when national circumstances are similar, this reporting flexibility can lead to differences in reported data on carbon pools. Since GHG emissions and removals are accounted for based on these reports, cross-country comparisons may highlight not only potential inconsistencies in reporting but also challenges in achieving transparent, shared responsibility for effective climate action.

The IPCC guidelines aim to ensure that GHG inventories are reported in a transparent, accurate, complete, consistent and comparable (TACCC) manner across countries (see Table 2.2). Following these reporting principles should ensure the credibility and accountability of global climate action and ultimately enable the timely compilation of verifiable data and information. It is also important to ensure that interoperability is possible between LULUCF estimations and the different datasets under the land-related policy frameworks, such as the CAP or the Nature Restoration Regulation (NRR) (see Chapters 4 and 5). This is crucial for incorporating all the relevant information needed to estimate emissions and removals. For this reason, EU regulation encourages Member States to facilitate interoperability between land monitoring systems for LULUCF inventories and other pertinent spatial databases. Interoperability is for example relevant for areas with significant carbon stocks, subject to protection or restoration or facing high climate risks, all of which are governed by various European or national regulations.

Table 2.2 TACCC principles and other elements relevant for LULUCF reporting

Transparency	There is sufficient and clear documentation that individuals or groups other than the inventory compilers can understand how the inventory was compiled, replicate the calculation and assure themselves it meets the good practice requirements for national GHG emission inventories.
Accuracy	The national GHG inventory contains neither over- nor under-estimates so far as can be judged. This means all steps should be taken to remove bias from the inventory estimate and move from lower to higher tiers (Tier 3), as well as through an accurate representation of land areas and their changes across time.
Completeness	Estimates are reported for all relevant categories of gases, pools and areas to provide a full picture of the implications of land use on GHG emissions and removals. Where elements are missing, their absence should be clearly documented together with a justification for exclusion.
Consistency	Estimates for different inventory years, gases and categories are made in such a way that differences in the results between years and categories reflect real differences in emissions. Consistency between historic estimates and most recent inventory information is particularly important for accounting against historic references. Inventory annual trends, as far as possible, should be calculated using the same method and data sources in all years and should aim to reflect the real annual fluctuations in emissions or removals and not be subject to changes resulting from methodological differences.
Comparability	The national GHG inventory is reported in a way that allows it to be compared with national GHG inventories for other countries. This comparability should be reflected in the appropriate choice of key categories.

Table 2.2 TACCC principles and other elements relevant for LULUCF reporting (cont.)

Other elements	
Timeliness	The data need to be up to date to provide timely estimates of changes in trends of emissions and removals. While countries are required to provide annual GHG inventories back to 1990, the information used for this purpose is often based on periodical measurements and auxiliary datasets that do not always reflect timely data (see e.g. Section 2.3.1).
Interannual variability	Interannual variability of GHG emissions and removals needs to be reflected, including the effect of natural disturbances and underlying longer-term trends. On the other hand, the inclusion of interannual variability driven by natural factors can hide the effect of the policies and make such effects less visible in the inventories.
Interoperability	The reported estimates of GHG emissions and removals can inform other policy processes. This can result in a need for a certain level of interoperability that involves ensuring that land-related data and information can be easily shared and understood across policies, borders and administrative levels.

Source: Own compilation based on IPCC, 2006.

The extent to which inventories can capture the effects of specific policies and measures is fundamental for driving policy effort and financial investments. However, there are still areas where estimations of emissions and removals remain highly uncertain in the current inventories, especially for certain sectors. Reporting in the LULUCF sector is complex and affected by one of the highest levels of uncertainty of all the sectors included in the GHG inventories (57% of estimates are uncertain against 2.7% for the energy sector within the EU inventory) (EEA, 2024a).

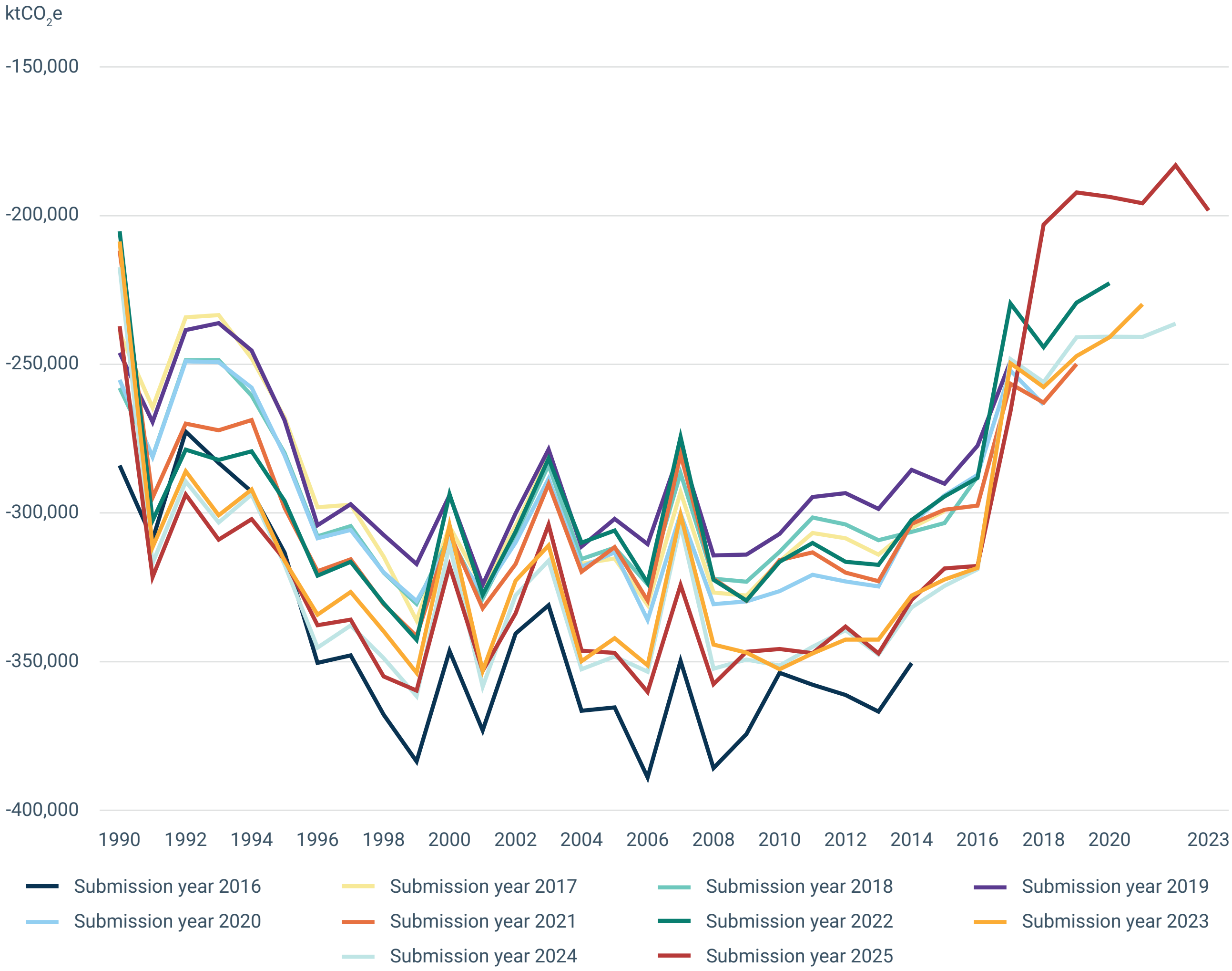
This complexity is inherent in the LULUCF sector due to the biological and environmental variability of natural processes such as those related to site conditions, weather patterns, climate variability and natural disturbances. It can also be complex to measure or monitor changes in carbon stocks in the different carbon pools accurately and with enough detail. In the LULUCF sector, GHG emissions and carbon removals occur across large areas of land rather than at point sources. They also occur across different land use categories varying somewhat across biogeographical regions. Monitoring GHG emissions and removals in the LULUCF sector therefore requires data and monitoring capabilities at temporal and geographical scales that are specific for LULUCF reporting but challenging to put in place.

Embracing the importance of improving the inventories over time and moving from statistical to geographically explicit data, the EU has also agreed on specific monitoring and reporting obligations (Box 4.1.), including the use of geographically explicit land use conversion data (EU, 2018c, Annex V, Part 3). Specifically for LULUCF, countries will have to upgrade their reporting of GHG emissions and carbon removals with the use of higher-tier methods from 2028 (see Section 4.4 for more detail). The objective is to promote a positive feedback loop between better policies and better inventories, requiring Member States to better estimate the impact of many practices (in particular those related to carbon farming) that are currently not reflected in a GHG inventory.

Over the last decade, EU Member States have significantly improved their reporting of GHG emissions and removals in the LULUCF sector, resulting in recalculations over the reporting time series (Figure 2.14). These improvements have been encouraged by enhanced UNFCCC reviews; efforts by the Joint Research Centre ([14]); the EEA and national quality assurance and quality controls; and new EU reporting requirements.

Recalculations can also be caused by updated national forest inventory (NFI) data, which can affect the reporting in the years between the two forest inventories.

Figure 2.14 LULUCF recalculations for GHG emissions (+) and removals (-) in the EU GHG inventories from 2016-2025 for EU-27 in ktCO$_2$e



Source: EU GHG inventories 2016-2025.

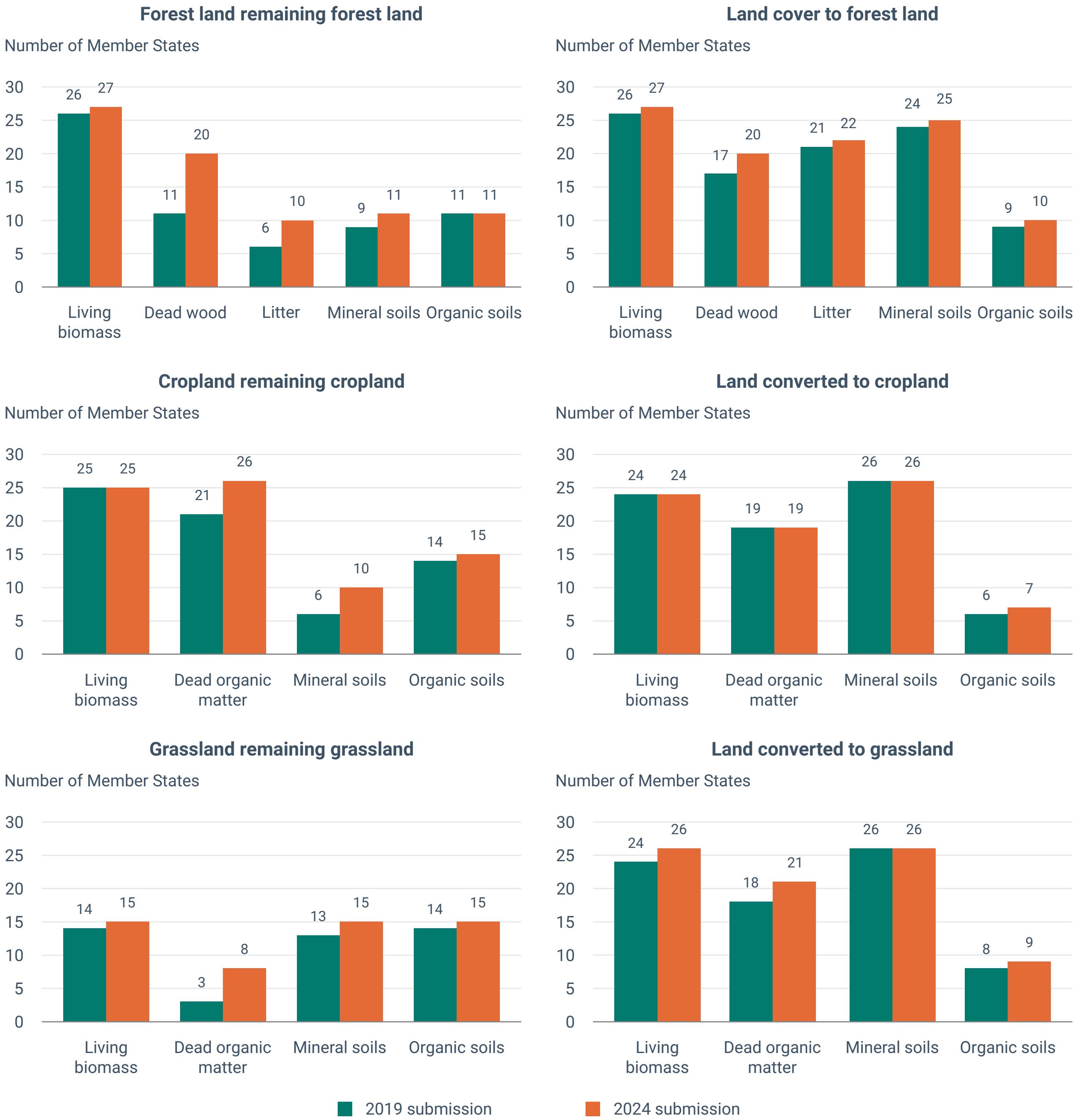
([14]) The Joint Research Centre has organised technical workshops in the last 20 years, dedicated to enhancing GHGI reporting in LULUCF and sharing experiences amongst Member States.

The methods Member States can or should follow in LULUCF reporting are guided by international and EU legal frameworks and informed by financial costs, institutional needs and human resources left to the discretion of each country. This section does not identify which methods are best or most effective but rather reflects on the current reporting practices and main challenges around them. Certain improvements could result in better and more timely insights into GHG emissions and removals in the LULUCF sector. The accuracy of the inventory could be improved with higher-tier reporting which could also reduce uncertainty, but this generally would also increase the complexity of reporting and the resources required. Thus, in many cases, countries will be confronted with the challenge of balancing costs and improving reporting quality. At the same time, better reporting will capture the benefits resulting from policies (e.g. CRCF, CAP).

2.4.1 Reporting practices and challenges

While the LULUCF sector at the EU level is constantly improving over time, there are significant challenges around compiling the GHG inventory. This is particularly due to the fact that the availability of data and methods that allow for higher accuracy across pools, land categories and Member States is highly variable (Figure 2.15).

Figure 2.15 **Number of Member States reporting GHG emissions (+) or removals (-) in different carbon pools per land use category**



Source: Author's compilation based on EU Member States GHG inventories (EEA, 2024a).

2.4.2 Forest land

In the forest land category, there is significant variation in the completeness and accuracy of reporting across countries and carbon pools. Living biomass, which has traditionally received the most attention, is reported by all Member States and generally at a higher level of detail (Tier 2-3) ([15]). Nonetheless, several EU countries still rely on IPCC default EFs, resulting in higher uncertainties.

Many countries use the IPCC 'stock-difference method' for estimating changes in carbon stock in living biomass; it is based on calculating the difference in stocks measured at two points in times. In the forest sector, this method makes use of data from the National Forest Inventories (NFIs) which often collect information periodically (e.g. every 5-10 years). Although fully in line with the IPCC guidelines, the stock-difference method can, in some circumstances, affect the transparency of the inventories as it gives details of net changes of carbon but does not provide information on biomass gains or losses from harvests or other disturbances. Furthermore, GHG annual data dependent on periodical inventories can be outdated, which is a barrier to tracking trends and interannual variability in a timely and accurate manner. The periodic updates can then potentially require significant recalculations (see Figure 2.14). The recently published German NFI is an example of how new data made available in 2024 will lead to significant recalculations of net removals for the period 2017-2022 and result in the sector no longer being recorded as a net sink but as a net source (Reidel, 2024).

For dead wood, litter and SOC in mineral soils, current reporting practices indicate widespread reliance on Tier 1 methods. Only 20 Member States provide quantitative estimates corresponding to Tier 2 or 3 of carbon stock changes for dead wood under 'remaining forest land', 10 Member States for litter and 11 Member States for SOC in mineral soils. The Tier 1 method assumes that the carbon stocks of these pools are in equilibrium. For the 'remaining forest land' category, 11 Member States out of the EU-27, all located in northern or central-eastern Europe, report a net source of emissions from forest management practices on organic soils, which contain high SOC levels. Most of these countries use higher-tier methods for estimating these emissions. In principle, this increases the accuracy of the estimates; however, further disaggregated information is still needed to identify key 'hotspots' for mitigation measures and to assess more accurately the effect of management practices and climatic conditions on carbon fluxes.

2.4.3 Cropland

In the cropland category, emissions from organic soils are approximately 60% higher than the sum of removals from living biomass, dead organic matter and mineral soils, though this varies across countries and years. However, the contributions from the living biomass, dead organic matter and mineral soil sinks are not fully reflected as their estimation is largely based on IPCC default factors and Tier 1 methodologies. The use of IPCC default factors is based on country aggregated estimates. In some cases, these only take into account climate, soil or global ecological zones, ignoring further variables that might alter how carbon fluxes occur in cropland.

([15]) For example, Czechia uses the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3, ver. 1.2, here denoted as CBM (Kurz et al., 2009; Pilli et al., 2018)).

For example, the carbon stock changes in dead wood are often assumed to be in balance, which can hide actual emissions or removals in this pool. Only five EU countries report dead wood data using country-specific information.

At the same time, emissions from cultivated organic soils are recorded as being significant, but this is in a context where many countries rely on the IPCC default approach, which assumes a constant carbon-oxidation rate yet entails a high level of uncertainty (up to 90%). The recent incorporation of the IPCC Wetland Supplement goes some way towards addressing this issue but local circumstances are still not reflected adequately.

The IPCC method for estimating carbon stock changes in mineral soils relies primarily on measurements from the top 30 cm of the soil. But this fails to capture changes in tillage practices and the impacts of no-till management that affect the distribution of the carbon at greater depths, of up to one metre (Xiao et al., 2020).

To address these challenges, models (e.g. RothC (Coleman and Jenkinson, 1996) and Century (Parton et al., 1996; Parton et al., 1987)) may offer more accurate estimates by incorporating variables such as climate, species and management practices, although they require considerable initial data resources to calibrate and verify the models. However, their use could reduce long-term costs associated with large-scale field measurements.

Furthermore, the classification of cropland involved in short-rotation cycles is complex due to the need for timely data, typically gathered through remote sensing or expensive annual reporting systems. Some countries address this by implementing a temporal window of five years before reclassifying land from cropland to grassland or vice versa to avoid yearly reclassification of cropland which is temporarily covered by grass. The use of geographically explicit data allows for more accurate and timely classification, replacing these interim solutions. The integration of data from sources from the CAP such as the Integrated Administration and Control System (IACS) and the Land Parcel Identification System (LPIS) can also provide valuable information for tracking the main management systems at plot level (see Chapter 5).

2.4.4 Grassland

In the case of grassland, Tier 1 methods are commonly used by a significant number of countries to estimate emissions and removals while assuming long-term carbon equilibrium for certain pools. Although some improvements have been made in this area in recent years, further efforts are still required to ensure that the large variations in these ecosystems are properly taken into account in terms of their relevance for carbon sequestration.

Within this context, actions to improve reporting must also include consistently and accurately distinguishing between grassland and certain wetlands types. Often land classification systems encounter difficulties in terms of how to classify these lands consistently across time and space according to national definitions. For example, currently around half of individual inventories assume that there is no woody vegetation on grassland, that dead organic matter is in long-term carbon equilibrium and that there are no anthropogenic GHG fluxes in soils where they are not subject to management practices or changes in such practices. As a result, the extent to which grassland information can currently inform the preparation of mitigation policies and measurements in these ecosystems is very limited.

2.4.5 Wetlands

Reporting GHG emissions and removals in wetlands within the EU presents several challenges due to the complex and variable nature of wetland ecosystems. There is incomplete reporting for CH_4 and N_2O emissions from wetland drainage and rewetting, primarily due to limited guidance in the IPCC 2006 guidelines on how to estimate these gases. However, reporting is gradually improving as countries adopt additional guidance from the IPCC Wetlands Supplement 2013 (IPCC, 2014) and the 2019 Refinement (IPCC, 2019a).

Notably, around half of EU countries now report on carbon stock changes in long-lasting wetlands (a 'Wetlands remaining Wetlands' category), though emissions are more frequently reported in the context of land conversion to Wetlands. This incomplete reporting is partly due to the fact that most emissions in the Wetlands category stem from peat extraction activities, for which the 2006 guidelines offer specific guidance. However, there is no similar guidance for other Wetlands subcategories, such as flooded lands and other wetlands; as such, some countries only report carbon fluxes associated with land use changes.

Additionally, two-thirds of Europe's wetland area is reported as unmanaged; since only managed land is included in LULUCF reporting, carbon fluxes from these unmanaged areas are often not reported. While the IPCC Wetlands Supplement and 2019 Refinement offer guidance on expanding reporting of emissions from wetlands in expanding reporting beyond peat extraction, it is not currently mandatory for countries to expand their reporting. In this context, while countries are fulfilling their international obligations, there is a significant knowledge gap in understanding the emissions from wetlands across different regions, management practices and wetland types. It is essential to close this gap to fully realise the mitigation potential of European wetlands. Progress in this area will require further science-based developments, such as dedicated research projects on carbon oxidation rates under various climates and management regimes.

2.4.6 Settlements

The settlements category is mostly lacking in terms of country-specific data for estimating carbon stock changes, leading to a lack of reliable data on the role of urban areas in carbon fluxes. Settlement areas are being extended over time, but they also have a potential role to play in contributing to mitigation action (e.g. through NBS). As such, ideally, any improvements in reporting for settlements should recognise the importance of categorising and further disaggregating the different types of areas within this category and how they behave in terms of carbon released or accumulated. One example of this is apparent for most of the areas classified as 'settlements remaining settlements'; currently, these are commonly reported based on an assumption of long-term equilibrium of the carbon stocks, with no associated emissions or removals.

Dedicated studies or projects are needed to collect the necessary information to allow carbon fluxes in settlements to be monitored, for example where tree planting takes place, to move beyond the assumption of 'equilibrium'.

2.4.7 Harvested wood products (HWP)

The HWP estimations are based on the so-called 'Production approach', whereby the country accounts for the HWPs that are produced domestically, regardless of whether they are consumed at country level or exported; this avoids double counting with the importing countries. However, the way this method is implemented means that some products are not reported. Specifically, raw wood traded between countries (e.g. logs or pulp wood) is reported as a loss of carbon, i.e. an emission, from forest living biomass but is not included in the calculation for carbon removals in the HWP category, since only semi-processed wood (e.g. sawn wood, paper, panels) is considered.

Furthermore, all Member States use the same default values (so called half-life values) for estimating how long it takes for carbon from HWPs to be released back into the atmosphere. Since more detailed values are not available the inventories are limited in their capacity to reflect policies that could promote the cascading wood utilisation and recycling policies that can prolong the life time of products (EEA, 2023; Bozzolan et al., 2024).

2.4.8 Lessons learned

Despite significant efforts to improve the TACCC of European national LULUCF inventories and to follow IPCC guidelines, as discussed above, there is still significant uncertainty in terms of the accuracy of LULUCF reporting compared to most other sectors in the national GHG inventories. The uncertainties represent a barrier to a comprehensive understanding of the GHG emissions and removals in the sector and to assessing progress towards targets and the effectiveness or potentials of policies over time.

Improved inventory approaches promoted by EU regulations, such as striving for Tier 3 levels of reporting and improving land representation, will improve the accuracy of LULUCF inventories.

This chapter has highlighted various challenges which must be addressed to improve LULUCF national GHG inventories. They are summarised below:

- For various carbon pools (mostly SOC and dead organic matter) and categories (beyond forest land), countries still rely on Tier 1 reporting methods. The use of IPCC default factors and/or generic equations, which this approach entails, commonly result in estimates that do not accurately represent GHG emissions and removals based on country-specific circumstances. The acquisition of country-specific data and/or methods, including advanced modelling are necessary to address this challenge. To this end, there may be an important role for knowledge-sharing platforms among countries.

- The different methods used for reporting certain pools do not allow GHG inventories across different Member States to be assessed for comparability. One reason for this is that some countries may assume carbon stock equilibrium, under the Tier 1 assumption of long-term carbon equilibrium, while neighbouring countries report carbon stock changes for the same pool and category. Thus, the reported figures may not be comparable, while pointing out that there may be over- or underestimations in some cases. More harmonised approaches to making reporting comparable could be achieved through cooperation and exchanges between countries with similar conditions. Better comparability allows for more effective joint climate change mitigation strategies which are easier to prepare.

- A further challenge is that LULUCF information is often rather coarse in terms of how data are aggregated (e.g. a single figure may be reported for removals from forest land without further separation for forest types, species etc.). This issue hampers transparency and means that the reported figures do not offer a complete understanding. More effective disaggregation and avoiding the use of unique carbon stock factors for a whole land use category would allow trends and progress to be assessed on a more granular level. IPCC decision trees are available, which could support countries in selecting the best reporting tier method based on their national circumstances. In addition, geospatial datasets which are currently available could also support improved land stratification (see Chapter 5).

- Generally, it is presumed that the use of country-specific information supports higher-tier reporting methods. While this is often true from an IPCC classification perspective, it is important to note that the simple use of higher-tier methods may not necessarily reduce uncertainties. For example, this can be the case when LULUCF estimates for certain pools are calculated using only a single country-specific factor and not enough temporal and spatial resolution to capture the characteristics of land uses. In line with IPCC good practices, LULUCF inventories would benefit from improvement plans based on an uncertainty analysis and an assessment of key categories. These two tools should support efforts to improve reporting for those carbon pools that contribute the most to the GHG budget and which have the potential to accommodate enhanced estimation methods.

As further outlined in Chapter 4, from 2028 onwards, the EU requires Member States to use at least Tier 2 reporting methods for all carbon pools. Additionally, Member States are already required to use geographically explicit land use conversion data (see Chapter 5). The new governance framework for LULUCF, which includes national targets and annual budgets for 2026-2030, further requires information to be reported in a timelier manner to reflect the most accurate state of emissions and removals. In this context, there will be an increasing need to use high-resolution data on emissions and removals (temporal and spatial) to inform models and other inventory methods. Geographically explicit information able to represent the impact that anthropogenic and natural drivers have on the performance of the difference ecosystems in the carbon cycle will also be necessary to inform policy going forward.

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3 Measures to enhance carbon removals and preserve carbon stocks in the land sector

Key messages

- There are many ways to protect carbon stocks and sinks, and to enhance removals in the forest land, cropland, grassland, wetlands and settlements categories. These include land use change for carbon enhancement, sustainable land management practices and ecosystem protection. Effective land-based mitigation requires tailored, sustainable actions while addressing site-specific conditions, trade-offs, and implementation challenges. The use of wood in long-lasting products, such as construction materials, can also increase the storage of carbon in Harvest Wood Products (HWPs). Various options have a high level of 'technological readiness' and are relatively low cost compared to 'industrial carbon removals'.

- While mitigation options in forest land and agroforestry provide the largest potential in both relative and absolute terms, many of these are confronted with a time lag between implementation and mitigation result (i.e. trees take time to grow). Upscaling these options now is important for LULUCF to deliver effectively in the medium- to long term, i.e. towards achieving climate neutrality by 2050 and negative emissions thereafter. Nonetheless, other options can provide mitigation in the short-term, including forest protection, reduced forest harvest rates, improved crop- and grassland management, rewetting of drained peatlands, mitigation options for wetlands and the prevention of conversion of land to settlements.

- Potentials over time vary significantly between and within countries in consideration of several factors, including extent of ecosystem types and current land use, regional climatic and site characteristics, and the vulnerability of ecosystems in a changing climate and towards natural disturbances. Preventing intended and unintended reversals of carbon removed and carbon leakage (e.g. from the displacement of production) will help ensure optimal results.

- Most of the options assessed offer significant co-benefits, in terms of enhancing various ecosystem services, including for restoring/protecting biodiversity, water, soil and air quality, climate adaptation, cultural services and income diversification. Options can also help increase the resilience of ecosystems to climate change and natural disturbances, and in this sense prevent unintended reversals caused by forest fires, droughts, pests and diseases, thus increasing the duration of carbon storage. In some cases, trade-offs can occur, including increased water- or fertiliser use, displacement of land-use, or reduced biomass supply and foregone income from reduced yields. Scaling up activities can also affect GHG mitigation potential in other sectors, or in LULUCF over time. Robust governance, context-specificity, and the design and implementation of measures can maximise co-benefits and reduce the risk of potential trade-offs.

- Landowners and managers are confronted with several types of barriers that can affect their willingness to adopt a change of management practices. These include inconsistent governance- or policy frameworks or corporate standards, a lack of financial incentives and financial risks (such as related to reduced land value or risk of reversals), affordable and effective monitoring, reporting and verification (MRV) systems, and social and cultural factors. Engagement of a wide variety of stakeholders is needed to support enabling conditions, including streamlining objectives and instruments, leveraging public- and private finance and financial risk mitigation, improved MRV methodologies and data provision, knowledge support, capacity-building and inclusive governance.

3.1 Introduction

Land management directly impacts many GHG emissions, including CO_2. Different management options affect carbon stocks and fluxes from different carbon pools (i.e. AGB, BGB, soil, litter and dead wood) in various ways. Land mitigation measures must be adopted in the LULUCF sector to achieve the agreed targets for 2030, to support the EU decarbonisation pathway up to 2050 and to help achieve 'negative emissions' in the second half of this century.

This chapter discusses both land-related emission reduction activities, resulting in measurable reductions in GHGs released into the atmosphere, and carbon removal activities, referring to the removal of CO_2 from the atmosphere and its storage in different carbon pools. In order to implement different options successfully, it is necessary to make informed choices about the selected measures as well as their scale and timing; such considerations must also address the sustainability (including economic aspects) of various measures and the feasibility challenges. It should also be noted that carbon removals and emission reductions can occur simultaneously for some of the measures presented. Additionally, to determine how each measure impact emissions and removals under specific conditions, the initial carbon status on the site and its most likely evolution in the future (i.e. baseline) must be analysed and then compared with the results achieved with the implementation of such measure.

Specifically, this chapter analyses three main categories of mitigation measures in the land sector:

- Land use change for carbon enhancement: actions in this category focus on land use changes to increase carbon stocks, such as cropland to forest land or cropland to grassland.

- Sustainable land-management practices: this category includes the management of certain land use to increase the sink or reduce sources of emissions. Examples include cropland soil management and improved forest management, which aim to optimise carbon sequestration under the ongoing land uses.

- Ecosystem protection and restoration: actions under this category target the restoration and protection of ecosystems that naturally store high quantities of carbon (e.g. peatlands). These practices can involve land use changes or changes in management within land use categories (e.g. rewetting organic soils in cropland either by changing cropland into wetlands or continuation of agricultural activities through paludiculture).

Various actions can enhance carbon removals and/or reduce emissions on land, but a complex landscape of co-benefits, trade-offs and barriers must be navigated in order to implement them successfully. This chapter discusses the most relevant measures for different land use categories (e.g. forest land, cropland, grassland, wetlands, peatlands and settlements) and assesses co-benefits and risks according to a set of parameters included in Annex 2. The final section will provide insights on actors, barriers and enabling factors relevant for the uptake of various mitigation measures.

3.2 Forest land

3.2.1 Description of measures

In Europe, forest land is the largest land use category and has the greatest potential for carbon sequestration. This underpins the importance of adopting measures to reverse the decreasing trend in the forest carbon sink observed over the last decade (Forzieri et al., 2021). Sustainable measures in forestry can help carbon accumulate both in living biomass and soils but also contribute to reducing and avoiding emissions. These measures (Table 3.1) include the protection of primary and old-growth forests, the prevention of deforestation and forest degradation, forest restoration, improved forest management, and afforestation and reforestation (IPCC, 2019a; IPCC, 2019b). Other processes like natural succession of plant communities can contribute to climate change mitigation but do not require direct anthropogenic intervention; these are not analysed in this chapter.

Table 3.1 Definitions of measures and types of climate change mitigation

Measure	Definition	Type of mitigation
Forest protection	Implementation of policies, strategies and practices aimed at conserving existing forests, and preventing further deforestation and forest degradation ([a])	Protection of carbon stocks and their removal capacity
Afforestation/reforestation (*)	The direct, human-induced transformation of land from another land use into forest ([b])	Carbon removal
Forest restoration	The process of regaining ecological integrity and enhancing the productivity of degraded, deforested or disturbed forest landscapes ([c])	Carbon removal/emission reduction
Improved forest management	All the activities which result in increased carbon stocks within forests and/or reduce GHG emissions from forestry activities when compared to business-as-usual forestry practices ([d])	Carbon removal/emission reduction

Note: (*) These terms are defined according to the land's historical use: afforestation occurs on land that has not been forested for at least 50 years, whereas reforestation takes place on land that was forested more recently but has not been forested since 31 December 1989 (IPCC, 2006).

Sources: ([a]) Dudley, 2020; ([b]) IPCC, 2006; ([c]) Gilmour and Lamb, 2003; ([d]) Forest Europe, 2003.

3.2.2 Mitigation potential

The extent to which forest measures can mitigate climate change differs significantly per measure in terms of the effects each has on the respective forest carbon pools over time (Table 3.2).

Forest protection

The target of forest protection is to avoid deforestation and conversion to a different land use category with a view to limiting emissions (e.g. establishment of forest reserves). Increasing the area of land covered by protected forests (e.g. up to 7%) could provide a substantial contribution to the 2050 EU climate target (Nabuurs et al., 2017). The specific mitigation potential of forest protection cannot be quantified easily since it depends on the actual ratio of deforestation or degradation that can be prevented (i.e. reducing emissions). Additionally, it depends on the actual characteristics of the forest or if protection measures will result in additional carbon removals. Approximated values have been proposed in previous studies for the EU (Table 3.2).

Afforestation and reforestation

Afforestation and reforestation activities can lead to larger areas of forest across the EU. The effects of this mitigation measure depend, among other factors, on the type of land cover being replaced by the afforested/reforested area (e.g. annual crop, grassland, shrubland), how much land is afforested/reforested and the growth rate of the tree species. A 6% increase in the EU forest area up to 2050 (10 Mha) could result in mitigation totalling 77 $MtCO_2$/yr (2.2 tCO_2/ha per year) (Böttcher et al., 2021). EEA/ETC CA estimations of tree planting on 5% (or 4.1 Mha) of agricultural areas resulted in an average annual removal of about -45 $MtCO_2$ per year (at an average of 11 tCO_2/ha per year for the living biomass) (see par. 3.2.4), while the Advisory Board reports removals ranging from 17 to 75 $MtCO_2$/yr by 2050 (ESABCC, 2025).

The extent to which afforestation measures can be implemented is limited by land availability (see Section 3.6) and can provide a net mitigation effect only if the measure results in a net increase in carbon stock in comparison with the previous/existing land cover and soil condition etc. (e.g. avoiding a scenario whereby tree planting results in carbon losses from organic soils). The potential of afforestation to deliver climate benefits in the short term is limited since the sequestration rates of forests are relatively low in young stands with higher sequestration rates occurring after a certain period depending on which species of tree are growing.

Improved forest management

Improved forest management implies a change in silvicultural practices within existing forests, with the aim of enhancing carbon removal and increasing climate resilience, including through biodiversity restoration. Some examples of practices include continuous cover forestry (as opposed to clear cutting), species selection and lengthening the forest rotation period (thus reducing the harvesting frequency), among others (Chiti et al., 2024). In general, it is estimated that forest management activities within the EU will offer a mitigation potential ranging from 90-180 $MtCO_2$ annually by 2040 (Nabuurs et al., 2017). More recent studies suggest even larger potential from changes in forest management by 2050 (EC, 2021b). Improved forest management can either contribute to increasing carbon removals or reducing emissions from existing carbon stocks (i.e. reverting carbon losses due to degradation).

Table 3.2 presents the estimates for mitigation potential obtained from scientific studies and referring to the whole EU. The mitigation potential is expressed as total value for the whole EU area (i.e. $MtCO_2$/yr) or as an average value per area unit ($MtCO_2$/ha per year).

Table 3.2 Ranges of annual carbon emissions (-) /removal (+) rates for forestry practices and related influencing factors in Europe

Measure	$MtCO_2$/ yr (*)	Factors affecting carbon removals
Forest protection	AGB: 58 ([a]) to 64 ([b]) SOC: No data	Forest age and growth stage, natural disturbances like pests and wildfires; the actual mitigation potential would also depend on the ratio of deforestation-degradation considered in the baseline scenario.
Measure	**tCO_2/ha per year (*)**	**Factors affecting carbon removals**
Afforestation/reforestation	AGB: ~2 ([c]) to 35 ([d]) SOC: -3.5 ([e]) to ~7 ([f])	Prior land use, local climate, tree species, stand age and management regime
Improved forest management	AGB: ~1 ([g]) to 14 ([h]) SOC 0.1 ([d]) to 6 ([i])	Forest age and growth stage, duration of lengthening rotation period, thinning intensity, species selection

Notes: (*) The removals rates consider only the impact of the measure on AGB and SOC, without taking into account the emissions related to management activities. Numbers for ([a]) are for EU-27 and depend on the actual ratio of deforestation or degradation that can be prevented (i.e. reducing emissions).

Sources: ([a]) Verkerk et al., 2022; ([b]) Nabuurs et al., 2017; ([c]) Ťupek et al., 2021; ([d]) Chiti et al., 2024; ([e]) Rytter and Rytter, 2020; ([f]) García-Campos et al., 2022; ([g]) Akujärvi et al., 2019; ([h]) Moreno-Fernández et al., 2015; ([i]) Bravo-Oviedo et al., 2015.

The potential for different forest management measures to mitigate climate change effectively depends on several factors. For example, how managed forests grow, and their carbon stock are determined by a number of manageable (e.g. harvesting cycle, tree species) and non-manageable (e.g. pedoclimatic conditions) factors. These include the extent to which climate change affects the biophysical conditions of forests in the medium and long term.

In conjunction with the biophysical conditions at each site, specific management practices (e.g. increasing rotation length; decreasing harvest intensity) determine the forest carbon removal potential. How long a measure is implemented for (e.g. forest protection), along with the stand age, structure of the forest and type of tree species planted as well as the management regime can further affect how long removals take place for and possible saturation effects in the long term.

As an example, preserving and enhancing carbon stocks in forests has immediate climate benefits. However, the sink can saturate and is potentially vulnerable to future climate change, suggesting the importance of defining the right management regime (Seidl et al., 2017), balancing harvesting and regrowth. It is worth noting that different forest management activities take different amounts of time to deliver carbon benefits, from at least 10-30 years and up to a century (Barredo et al., 2021).

The different measures considered (except for forest protection and reduced harvesting) help mitigate climate change only in the medium to long term and thus will only contribute to the 2050 target and beyond. To ensure that these forest measures are as effective as possible, they should be adopted and implemented quickly. The current trend and status of the sink of forest land, and the declining trend in terms of mitigation potential (see Chapter 2) must be taken into account when projecting the performance of this sector into the future and when considering the reasons for potential reductions in its contribution to climate change mitigation.

Measures in forest land have to be designed and implemented to reduce or mitigate the effects of natural disturbances (e.g. pests and diseases, fires) that could negatively impact carbon stocks; they must also avoid competition in terms of land availability in the case of afforestation measures and the shift in wood harvesting to other areas or third countries (e.g. leakage). The lack of expertise/machinery to implement certain forest measures could also be a limiting factor (see Section 3.6 for more details).

The possible risk of carbon saturation in Europe's managed forests (in old forests) justifies the need to evaluate the climate change mitigation potential of forest management in connection with the use of HWPs (Nabuurs et al., 2017), particularly in view of the substitution effects of other high GHG-emitting materials such as steel or concrete. Nevertheless, increments in wood harvest must be carefully managed to prevent overexploitation, reduced forest mitigation potential and the degradation of forest ecosystems.

Improved forest management and afforestation activities, in combination with a shift towards durable wood products (instead of using the wood for energy production) can help increase the amount of carbon stored in the HWP pool and at the same time contribute to rejuvenating and increasing the resilience of EU forests. While this remains an important notion for Europe, where a large share of forests is considered 'managed', the specific approach to forest management and its role for climate change mitigation and substitution though the use of HWPs varies across countries and regions and trade-offs need to be carefully considered to avoid an overall increase in carbon emissions due to HWP production (Jonsson et al., 2021).

3.2.3 Trade-offs and co-benefits

Forests offer many ecosystem services beyond carbon removal and biomass provision. They regulate and support ecosystem functions as well as offering provisional and socio-cultural services (Jenkins and Schaap, 2018). Regulating services include effects on local temperatures and hydrological systems; provisional services include the production of both wood and non-wood products; and supporting services include providing habitats for different species.

In terms of societal and economic benefits, afforestation projects can stimulate local economies by creating job opportunities in tree planting, forest management and systems for reporting and verifying carbon removals as well as offering new revenue streams for communities where traditional agriculture may not be economically viable. This may lead to increases in land value and attract investments and tourism. Forests may be managed by prioritising one or other ecosystem functions and services; in this context, synergies and trade-offs may occur between them.

Table 3.3 provides an overview of the co-benefits provided by forests in relation to implemented measures which are relevant for the LULUCF forest land category. Evidently, all measures have the potential to provide a wide range of co-benefits for biodiversity, water, soil, air quality, climate adaptation and also for local economies and livelihoods.

However, in some cases, measures can also involve risks and trade-offs if they are implemented in such a way that they only consider the carbon removal perspective. In some cases, implementing specific forest measures (e.g. extending monocultures of tree species not adapted to the changing climatic conditions) could lead to increased risk of natural disturbances such as forest fires and pathogen attacks, which could affect the permanence of the removed carbon. Large-scale afforestation projects can impact land availability, restricting access to land for agriculture, reducing biodiversity in grassland ecosystems and affecting local economies and food security. Finally, the risk of carbon leakage or increased imports from third countries due to a reduced harvest intensity can lead to unintended displacement of activities (e.g. wood harvest or agricultural activities) that result in GHG emissions elsewhere, offsetting the carbon removal benefits of a project. Hence, it is of great importance to synchronise measures to increase the services provided and policies, with a focus on the demand side.

Table 3.3 Co-benefits and risks from measures in forest land

Effects	Afforestation/reforestation	Forest protection	Improved Forest Management
Biodiversity	Generally providing opportunities ***	Generally providing opportunities	Generally providing opportunities
Water management	Generally providing opportunities	Generally providing opportunities	Generally providing opportunities
Air quality	Generally providing opportunities	Generally providing opportunities	Generally providing opportunities
Soil conservation	Generally providing opportunities ***	Generally providing opportunities	Generally providing opportunities
Resilience ecosystems	Generally providing opportunities ***	Generally providing opportunities	Generally providing opportunities
Local climate effects	Generally providing opportunities ***	Generally providing opportunities	Generally providing opportunities
Land use and biomass supply	Combination of positive and negative effects ***	Not applicable or negligible	Combination of positive and negative effects ***
Resource use: water	Generally providing risks	Not applicable or negligible	Not applicable or negligible
Socio-cultural	Generally providing opportunities	Generally providing opportunities	Generally providing opportunities
Socio-economic	Not applicable or negligible	Not applicable or negligible	Not applicable or negligible
Income diversification; support local economies	Generally providing opportunities	Generally providing opportunities	Generally providing opportunities
Foregone income	Combination of positive and negative effects	Combination of positive and negative effects	Generally providing risks

Not applicable or negligible

Uncertain, or mixed effects

Generally providing opportunities

Generally providing risks

Combination of positive and negative effects can apply at the same time or in different time periods following implementation

*** = Highly dependent on implementation/method and/or local circumstances

Note: Annex 2 provides the list of specific co-benefits and risks considered for each effect.

Source: EEA compilation based on expert judgement.

3.2.4 Afforestation/reforestation (ETC-CA scenario assessment)

The range of climate change mitigation potential that afforestation in Europe has, is strongly dependent on several factors, from prior land use- and cover, to local climate and tree species, stand age and management regime. The EEA has been supported by the European Topic Centre on Climate change Adaptation and LULUCF (ETC CA) in developing scenarios for afforestation at the EU level taking into account several factors (Box 3.1). It has been estimated that afforestation of 5% (or 4.1 Mha) of agricultural areas (annual crops area) in 2025 would lead to removals of about 449 $MtCO_2$ and 1,208 $MtCO_2$ during the periods 2025-2035 and 2025-2050, respectively. These cumulative values would result in average annual removals of about 45 $MtCO_2$ per year (at an average of 11 tCO_2/ha per year) but the mitigation potential increases the longer the measures are in place (2025-2050) due to emissions expected during the initial phases.

To provide the right context for this projection, the areas to be afforested and estimates for CO_2 removal should also be compared with existing data on afforested areas and actual carbon removal in European forests. In the GHG inventories, Member States reported net increments of forest land of about 90 Mha during the period 1990-2021 (or an increment of roughly 3 Mha/yr at EU level). The information reported by Member States indicated that the 2.1 Mha of cropland converted to forest land in the EU resulted in a sink of 12.7 $MtCO_2$ per year (or a net sink of 6.0 tCO_2/ha per year) (EEA, 2024a).

The variables that most significantly impact projections are land availability (e.g. cropland or pasture) and the growing rates of the different tree species suitable for each climatic area. In this regard, central, eastern and western Europe show the largest potential for living biomass sequestration, followed by northern Europe and south-western Europe. South-eastern Europe has a very low potential for carbon sequestration through afforestation because of the limited area of cropland available in comparison with the other European areas. Overall, there is significantly higher potential from cropland than pasture because there is more cropland available for afforestation/reforestation (as only areas without woody vegetation were considered for the estimation). However, pasture in central-western Europe has significant potential for afforestation.

These projections suggest afforestation/reforestation measures at EU level are very promising. They have the potential to contribute to reducing the gap that previous analyses identified between the trends and projections for the LULUCF sector and the climatic targets set by the EU (EU, 2018a). Box 3.1 presents further details of the variables and assumptions used for the projections connected to afforestation/reforestation activities. It should be noted that several risks and trade-offs discussed in the previous sections were not considered in the analyses presented nor did they take into account any limitations to the adoption of measures which are further discussed in this chapter.

Box 3.1

Quantitative assessment of afforestation/reforestation (Source EEA, ETC CA 2024)

The approach used is a Tier 2 methodology based on a combination of increment values for the living biomass (above and below ground biomass) of tree species and the identification of areas suitable for afforestation based on the CORINE land cover (CLC) 2018 dataset. The projections took into account increment values for living biomass from NFIs, partly included in the publication by Pilli et al. (2024), and IPCC factors to convert the increments into annual carbon removal.

EU countries were grouped into five main broad ecological zones, following the FOREST EUROPE 2020 approach (Köhl et al., 2020). The predictions also considered the foreseeable evolution of climatic conditions and their impact on land/forest productivity by analysing the suitability of planting a specific tree or group of tree species in a certain area given current and future climate conditions; the inputs were based on the EU-Trees4F dataset (Mauri et al., 2022). Several criteria were applied to determine land potentially suitable for planting trees; the factors considered related to biodiversity and trade-offs (e.g. impact on soil carbon).

Only cropland or pasture not covered by woody biomass, according to CLC 2018, was considered as having the potential for afforestation. Protected areas were excluded to reduce the potential impact on other conservation objectives. The area considered suitable for afforestation was estimated to be 82 Mha.

Projections were finalised based on the assumption that 5% of EU agricultural areas could be considered for afforestation. A discount factor for living biomass of 4.7 tonnes of carbon per hectare (tC/ha) and 5.0 tC/ha was also applied to account for emissions from planting activities (IPCC, 2006).

Projections are available for the following spatial levels: (1) Regional level (NUTS-3)); (2) country level (NUTS-0) and (3) EU27 (based on 22 out of the 27 EU countries).

3.3 Cropland and grassland

Cropland and grassland represent the second- and third-largest areas of managed land as reported by Member States in their national GHG inventories (EEA, 2024a). According to the EEA GHG inventory at EU level (2024a), cropland and grassland remain net emitters of carbon. A wider adoption of sustainable management practices could help to support these land use categories to fulfil their mitigation potential.

This section presents the mitigation potential, trade-offs and benefits of three selected measures that encompass a variety of practices: agroforestry, improved soil management in cropland, and grassland management. A systematic overview and analysis of the impacts of mitigation practices in the agricultural sector, including cropland and grassland, is also being produced and maintained by the JRC and is available online (JRC, 2025c).

3.3.1 Agroforestry

Description of measures

Agroforestry can be defined as 'land-use systems and technologies where woody perennials (e.g. trees, shrubs, etc.) are deliberately used on the same land management units as agricultural crops and/or animals, in some form of spatial arrangement or temporal sequence' (Food and Agriculture Organization of the United Nations, 1999). Another definition is 'land use systems in which trees are grown in combination with agriculture on the same land, without the intention to establish a remaining forest stand' (EU, 2013a). This practice is characterised by diverse arrangements between trees, crops and livestock. Examples include sheep grazing under cork oaks in the montados and dehesas ([16]) of Portugal and Spain, and tall fruit trees under which crops are grown, or livestock are grazed, as seen in the Streuobst systems of central Europe. Livestock agroforestry systems are the most prevalent type of agroforestry land use in Europe, encompassing 15.1 Mha, which accounts for 3.5% of the European land area (den Herder et al., 2017). Table 3.4 provides definitions of the different agroforestry systems.

Carbon removals in agroforestry systems are associated with the presence of trees and increasing soil fertility (i.e. cropland-grassland productivity). Decreasing emissions are usually associated with a shift away from existing agricultural practices, such as the use of inputs (e.g. fertilisers) or with emissions due to soil disturbances. Whether agroforestry is considered an emission reduction activity (e.g. through a reduced use of fertiliser) or a carbon removal activity (e.g. though planting trees) depends on the specific practices implemented and the primary mechanisms through which they impact GHGs (Table 3.4).

Table 3.4 Definitions of measures and types of climate change mitigation provided

Measure	Definition	Type of mitigation
Silvopastoral agroforestry	A mild successional system of grasslands for the purpose of grazing or fodder production, interspersed with trees and shrubs ([a])	Emission reduction/carbon removal
Silvoarable agroforestry	A system where woody perennials, such as trees or hedges and agricultural, usually annual, crops are grown on the same cropland in a specific spatial and/or temporal fashion ([b])	Emission reduction/carbon removal

Sources: ([a]) Jose and Dollinger, 2019; ([b]) Borelli et al., 2019.

([16]) Montados, dehesas and streuobst systems are local names for different agroforestry systems across Europe.

Mitigation potential

The mitigation potential of agroforestry systems depends on the composition, density and age of the tree species, geographic location, environmental conditions and management practices (Nerlich et al., 2013). Additionally, soil type and the historical management of the land play significant roles. Agroforestry also has important potential for indirect climate change mitigation as it can help decrease pressures on forests (e.g. by providing woody biomass thus potentially reducing forest harvesting). A study by Kay et al. (2019) indicated that implementing agroforestry systems on 8.9% of EU agricultural land could potentially store 1.4-43.4% of all EU agricultural GHG emissions (7.78-234.85 MtCO_2e per year).

In general, both silvoarable and silvopastoral systems can preserve or enhance not only the carbon in the living biomass but also SOC stocks (Bambrick et al., 2010; Wotherspoon et al., 2014). Most studies focus only on the topsoil (i.e. 0-30 cm), although trees in agroforestry systems can develop very deep root systems (Cardinael et al., 2015), influencing carbon storage in deeper soil layers. A study in the Mediterranean region revealed that an 18-year-old silvoarable system (e.g. hybrid walnuts intercropped with durum wheat) increased SOC stocks by 0.25 tC/ha per year in the topsoil and by 0.35 tC/ha per year when measured down to 100 cm, compared to a nearby agricultural plot (Cardinael et al., 2015).

The potential of silvoarable and silvopastoral agroforestry systems for carbon removal in AGB and soil is presented in Table 3.5. However, the effectiveness of agroforestry in removing carbon over the long term depends on maintaining the stability and permanence of the carbon stocks. As for measures associated with other land uses, there is the risk of reversing carbon removal if the practice is not implemented in the long term (e.g. if land becomes purely agricultural again due to lack of economic interest).

Table 3.5 **Ranges of annual carbon emissions (-) /removal (+) rates for agroforestry practices and related factors in Europe**

Measure	tCO_2/ha per year (*)	Factors affecting carbon removal
Silvopastoral agroforestry	AGB: 0.6 ([a]) to 23.2 ([a]) SOC: -1.5 ([b]) to 8.5 ([b])	Tree density, tree species, previous land use (i.e. cropland or grassland)
Silvoarable agroforestry (including hedgerow)	AGB: 0.4 ([a]) to 26.7 ([a]) SOC: 0.4 ([c]) to 1.7 ([c])	Tree density, tree species

Note: (*) The removal rates are based only on the impact of the measure on AGB and SOC; they do not take into account emissions related to management activities.

Sources: ([a]) Kay et al., 2019; ([b]) Cardinael et al., 2018; ([c]) Cardinael et al., 2017.

Considering that soil carbon dynamics are slower than the ABG dynamics, a consistent contribution to EU targets from the two possible agroforestry systems can only be expected in the medium to long term (20-30 years).

When agroforestry is implemented in croplands, there is a high mitigation potential in terms of soil carbon removal, but it has no or limited impact when implemented on grasslands (De Stefano et al., 2018).

In addition, the contribution of these practices to climate change mitigation can be affected if agroforestry practices are adopted in a limited way or if existing agroforestry systems are converted into conventional cropland or grassland. The initial costs of investments, low economic revenue in the absence of economic support (Giannitsopoulos et al., 2020) and a lack of expertise for implementing the specific measures can also limit their potential.

Trade-offs and co-benefits

When considering agroforestry as a sustainable agricultural practice, it is essential to recognise and address the potential risks and trade-offs connected to its implementation. In agroforestry systems, trees and crops share the same land, which means they might also compete for vital resources like water, nutrients and sunlight. This can complicate regular agricultural management practices. It is crucial to plan effectively and select species carefully to minimise competition and avoid reduced crop yields which could pose a risk to food production, economic viability and efficient carbon removal. Furthermore, the integration of trees and shrubs into agricultural landscapes leads to new dynamics in terms of pest and disease management. While some agroforestry systems have the potential to reduce pest pressures naturally, others might introduce new pests or diseases into the system (Houndjo Kpoviwanou et al., 2024). This necessitates a more vigilant approach to management.

On the other hand, agroforestry systems come with a series of co-benefits. They play a crucial role in enhancing biodiversity by creating diverse habitats that support a wide range of species both above and below ground. These systems significantly improve soil health by contributing to better soil structure, increased organic matter and enhanced nutrient cycling. The root systems of trees and shrubs also help prevent soil erosion and boost soil fertility. Agroforestry also benefits water management, with practices that enhance the infiltration and retention of water, reducing runoff and improving groundwater recharge, thereby mitigating the impacts of droughts and extreme rainfall events.

These co-benefits highlight the importance of strategic planning and proactive management in agroforestry systems to ensure that the benefits outweigh the potential drawbacks.

3.3.2 Improved soil management in cropland

Description of measures

Cropland covers about 30% of the EU (EEA, 2024a). However, the overall area in this category is steadily decreasing; it has shrunk by 8% compared to 1990.

Agriculture contributes significantly to global and European GHG emissions, either directly or indirectly (Fuentes-Ponce et al., 2022; EEA, 2024a). Direct contributions from agriculture include emissions of GHG from livestock (including manure management), cropland and grassland. Cropland emissions include direct emissions from the soil or crop during production, whereas additional contributions come from the connected industry, transportation and agricultural operations (e.g. fertilisers, pesticides, fuel, electricity and machinery) (Cillis et al., 2018). Considering the urgent need to reverse the current global warming trend, sustainable practices for agricultural management must be adopted to enhance SOC stock and reduce GHG emissions.

Improved soil management in cropland refers to a number of management practices such as the use of cover crops or the use of crop residues, both of which help enhance carbon removal. The specific measures analysed in this section can lead to reductions in emissions (e.g. reduced tillage) or carbon removal (e.g. cover cropping and crop rotation). Table 3.6 summarises the specific practices and the types of mitigation provided. The measures analysed in this section focus on on-site practices. Practices which have a direct effect on SOC and other practices based on external sources (e.g. use of biochar or organic fertilisers) are excluded.

Table 3.6 Definitions of measures and types of climate change mitigation provided

Measure	Definition	Type of mitigation
Cover crops	Plants sown on arable land specifically to reduce the loss of soil, nutrients and plant protection products (e.g. herbicides, pesticides) during the winter or other periods when the land would otherwise be bare and susceptible to losses ([a]).	Carbon removal/emission reduction
Crop residue management	Agricultural practice that involves fewer and/or less intensive tillage operations and preserves more residue from the previous crop ([b]).	Carbon removal/emission reduction
Minimum/zero tillage	Practices utilising a reduced number of tillage operations, avoiding soil inversion and leaving at least 30% residues on the soil surface, which increases water infiltration and reduces erosion. It can be roughly divided into no-tillage (NT), mulch tillage (MT), strip tillage (ST), ridge tillage (RT) and reduced/minimum tillage (RMT) ([c]).	Carbon removal/emission reduction
Crop rotation	The practice of alternating crops grown on a specific field in a planned pattern or sequence in successive crop years so that crops of the same species are not grown without interruption on the same field. In a rotation the crops are normally changed annually but they could also be changed multi-annually ([d]).	Carbon removal/emission reduction

Sources: ([a]) EU, 2009a; ([b]) Reicosky and Wilts, 2005; ([c]) Eurostat, 2024b, ([d]) Eurostat, 2024a.

Mitigation potential

Cover crops offer an average SOC removal rate of 1.43 tCO_2e/ha per year (Schön et al., 2024). Based on the same study, SOC removal is 2.3 times higher for grass cover crops than legume cover crops. As an example, planting cover crops before maize in the EU-27 is estimated to potentially offer a removal of 49.8 $MtCO_2e$ per year, resulting in average values of 0.7-6.1 tCO_2e/ha per year. This would represent a total mitigation potential equivalent to 13.0% of all EU-27 agricultural GHG emissions (Schön et al., 2024).

Research and information about carbon removal rates related to crop residue management in the EU are not exhaustive; however, there is evidence that retaining residue totalling at least 1 tCO_2 per year (ECCP, 2006), generally results in greater SOC accumulation or reduced SOC loss compared to completely removing residue from crop fields. The potential soil carbon removal rates of the different agricultural practices are reported in Table 3.7.

Analysis by Freibauer et al. (2004) suggests that the carbon removal capacity for EU-15 ([17]) could reach 59-70 $MtCO_2$ annually. A key strategy in their analysis is the enhancement of cropland management, including boosting organic matter and reducing tillage. Studies estimate that reduced or no tillage could reduce carbon emissions by 0.37-0.92 tCO_2/ha per year (Aertsens et al., 2013; Vleeshouwers and Verhagen, 2002). De Cara and Jayet (2006) have indicated that conservation tillage in the EU-15 could reduce carbon emissions by 8 $MtCO_2$ annually while the Piccmat project (2008) assessed the mitigation potential of reduced or minimum tillage in the EU-27 to be approximately 10 or 20 $MtCO_2$ per year, respectively.

Meanwhile, a meta-analysis on long-term experiments indicated that enhancing the complexity of crop rotation could contribute with a removal rate of 0.73 tCO_2/ha per year (West and Post, 2002). A simulation across European arable land indicated that integrating ley (i.e. two consecutive years of alfalfa) within the crop rotation led to constant carbon accumulation with median annual SOC removal rates of 0.40 tCO_2 per ha per year by 2050. A scenario with cover crops (grass mix or rye grass) in the crop rotation resulted in similar removal potential as the integration of ley but with much higher variability related to climate change (Lugato et al., 2014).

Table 3.7 **Ranges of annual carbon emissions (-) /removal (+) rates for cropland management practices and related factors in Europe**

Measure	tCO^2 per ha per year (*)	Factors affecting carbon removal
Cover crops	SOC: 1 ([a]) to 3 ([a])	Type of species selected, pedoclimatic conditions
Crop residue management	SOC: 1 ([a]) to 3 ([a,b])	Amount and decomposition rate of the residues, pedoclimatic conditions
Minimum/zero tillage	SOC: 0 ([a]) to 3 ([a])	Frequency of tillage, pedoclimatic conditions, crop residues left or removed from the soil surface, soil compaction

Note: (*) The removal rates are based only on the impact of the measure on SOC; they do not take into account emissions related to management activities.

Sources: ([a]) ECCP, 2006; ([b]) Smith et al., 2000.

Measures in the agricultural sector contribute to mitigation mainly through the soil carbon pool. The risks of saturation and reversibility depend on the soil characteristics and how long the mitigation measure is implemented for. Carbon storage in soils can also be reversed as a result of a change in farming practices (e.g. ploughing) or the climate (e.g. prolonged droughts).

([17]) EU-15: Composition of the European Union from 1995 to 2004: Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, the Netherlands, Portugal, Spain, Sweden, and the UK.

In agriculture, the adoption of sustainable practices involves a change in management. The positive effects occur over the long term due to the slow ratio of accumulation of carbon in soil compared to that in vegetation. The rates of carbon removal attributed to the different practices presented in Table 3.7 represent a mean value over a maximum period of 15-20 years. After that period, the soil system should find a new equilibrium as a result of the adopted management practice. Limitations that could reduce the contribution to the EU climate targets are the investments required to apply specific techniques due to a change in management (e.g. acquisition of specific machinery) and by the lack of expertise for those farmers implementing the specific measure for the first time.

Trade-offs and co-benefits

Cover crops offer several co-benefits; they enhance soil health by improving its structure, increase the amount of organic matter present in the soil and promote microbial activity. They help manage nutrients by capturing and storing them, with legumes even fixing atmospheric nitrogen. Additionally, cover crops suppress weeds, control erosion and improve water management by retaining moisture and reducing runoff. They also promote biodiversity by providing a habitat for beneficial insects and wildlife (facilitating biological pest control) and their deep roots help reduce soil degradation due to compaction (Yousefi et al., 2024). These benefits are particularly important to enhance resilience of agricultural systems to climate change effects (e.g. drought, extreme wheather events etc.).

However, they can also present challenges such as inducing N_2O emissions (Lugato et al., 2018), acting as hosts for pests and competing with main crops for water and nutrients. Their use can be further complicated if they decompose inconsistently or their presence requires additional pest management.

Moreover, increasing the volume of crop residues incorporated into cropland could lead to carbon leakage (i.e. increasing demand for animal feed from other areas) and thus intensify agricultural activity beyond the EU. Straw from small grains and other crops is a profitable and valuable source of animal feed in several areas in Europe and its economic value could limit the adoption of this practice.

Reduced and zero tillage practices offer significant co-benefits but also involve trade-offs. On the positive side, they enhance soil health by improving soil structure, increasing organic matter and promoting water retention, which supports carbon removal and reduces erosion. Additionally, they reduce fuel consumption and labour costs, contributing to more sustainable farming. However, they can lead to soil compaction, slower decomposition of residues and increased weed or pest pressure, which may necessitate the use of herbicides. While long-term carbon removal improves as a result of these practices, the benefits may take years to materialise, requiring careful management to balance the pros and cons.

In all the cases, trade-offs need to be evaluated in the context of the pedoclimatic conditions of specific areas, since their impact varies depending mainly on the soil features and climate.

Table 3.8 Co-benefits and risks from measures in cropland

Effects	Afforestation	Cover crops	Crop residue management	Reduced tillage
Biodiversity	***	***	***	***
Water management				
Air quality				
Soil conservation				
Resilience ecosystems	***	***		
Local climate effects	***			
Land use and biomass supply				
Resource use: water pesticides, fertiliser*				
Socio-cultural				
Socio-economic				
Income diversification; support local economies				
Foregone income				

- Not applicable or negligible
- Uncertain, or mixed effects
- Generally providing opportunities
- Generally providing risks
- Combination of positive and negative effects can apply at the same time or in different time periods following implementation

*** = Highly dependent on implementation/method and/or local circumstances

Notes: Annex 2 provides the list of specific co-benefits and risks considered for each effect; *Agroforestry could lead to an increase in the use of water, fertiliser and pesticides; Cover crops could lead to an increase in the use of water; Crop residue management and reduced tillage can reduce fertiliser use.

Source: Authors' own compilation based on expert judgment.

3.3.3 Improved grassland management

Description of measures

Grassland covers 17% of the total territory of the EU (EEA, 2024a). However, as for cropland, the EU area covered by grassland has been steadily decreasing since 1990 (i.e. by 8%). The main cause is conversion to agricultural activities (EEA, 2024a).

Permanent grasslands provide a diverse range of essential ecosystem services, such as biodiversity, soil erosion prevention, water quantity and quality regulation and cultural services, to mention some (Bengtsson et al., 2019). Since most EU grasslands are maintained through human intervention (e.g. pastoralism and feed production), they are considered semi-natural, even though their plant communities are naturally occurring (Gorris et al., 2025).

In the framework of carbon mitigation, improved grassland management refers to a range of practices to enhance its ecological and economic performance (i.e. reducing management costs or increasing outcomes). Grassland management practices can lead to emission reductions (e.g. from fertilisation) or carbon removals (e.g. enhanced growth after reseeding). Table 3.9 summarises the specific practices and the type of mitigation provided. The measures which are included do not take into account the emissions from livestock usually associated with agronomic exploitation of grassland but only refer to emission reduction and carbon removal from activities which directly impact the soil.

Grassland offers a relative advantage over cropland in terms of carbon storage, both in terms of the soil and living biomass. In the context of the existing trend of land use change (see Chapter 2), it is important to maintain permanent grasslands to maximize their potential benefits in terms of carbon removal.

Table 3.9 Definitions of measures and type of climate change mitigation provided

Measure	Definition	Type of mitigation
Rotational grazing	A practice whereby grazing areas (e.g. pastures) are divided into smaller sections and animals are rotated between them on a set schedule. This approach allows one section of the pasture to be grazed while others are resting and recovering, which helps maintain healthy vegetation, improve soil health and prevent overgrazing ([a]).	Emission reduction/carbon removal
Fertilisation	Judicious use of organic or inorganic fertilisers to promote healthy plant growth without causing nutrient runoff or soil degradation.	Emission reduction/carbon removal
Reseeding and overseeding	Reseeding involves scratching the surface of the soil with a series of tines and spreading seed on the scratched surface. It is often used as a way of rejuvenating pastures. Overseeding is the planting of grass seed directly into existing turf, without tearing up the turf, or the soil. It is used to fill in bare spots, improve the density of turf and establish improved grass varieties.	Emission reduction/carbon removal

Source: ([a]) Teague et al., 2011.

Mitigation potential

Rotational grazing can increase soil carbon when root biomass, ungrazed plant residues and animal faeces contribute to the soil carbon, or when manure compensates for any reduction in plant residue inputs. However, excessive grazing can reduce plant biomass and lower carbon inputs to the soil (Bardgett and Wardle 2010).

Grassland fertilisation can mitigate climate change primarily by enhancing grass growth; in turn, this increases living biomass and its input to the soil with roots and decomposed leaves and grasses. By applying fertilisers, particularly nitrogen-based ones, grass growth increases (Da Silva et al., 2022; Sainju et al., 2020). Finally, fertilisation can lead to improved soil structure if managed correctly, allowing for increased infiltration of water and reduced erosion, both of which help maintain the carbon stored in the soil. However, fertilisation must be managed carefully to avoid negative impacts, as described in the sub-section about trade-offs and co-benefits.

Reseeding and overseeding, and increased forage production, often result in increased belowground production (Crawford et al., 1996). This leads to increased inputs of carbon in the soil and can result in soil carbon sequestration.

Meta-analyses indicate that improved grazing practices, such as optimising grazing intensity, implementing fire management, sowing legumes or grasses and fertilising pasture, generally result in soil carbon removal, at an average rate of 1.8 tCO_2/ha per year, excluding other potential GHG associated with the practices (Conant et al., 2001, 2017).

In general, carbon removal in grassland varies quite a lot, according to the composition and yield of pasture but also depending on local pedoclimatic conditions. Existing information and studies about removal rates related to improved grassland management in the EU are not exhaustive but the information collected about the removal potential of some practices adopted in improved grassland management is reported in Table 3.10.

Table 3.10 Ranges of annual carbon emissions (-) /removal (+) rates for grassland management practices and related factors in Europe

Measure	tCO_2/ha per year (*)	Factors affecting carbon sequestration
Rotational grazing	1.2 ([b]) to 1.8 ([c])	Grazing intensity and timing, plant species diversity, pedoclimatic conditions
Fertilisation (e.g. increase of fertiliser on nutrient-poor permanent grassland)	0.7 ([a]) to 1.1 ([b])	Plant species composition, acidification and nutrient imbalances, pedoclimatic conditions
Reseeding and overseeding (e.g. increase in the duration of grass leys)	0.4 ([a]) to 1.8 ([a])	Root biomass and depth, grazing management, pedoclimatic conditions
Change from short duration to permanent grasslands	1.1 ([a]) to1.5 ([a])	Types of grass, grazing intensity, pedoclimatic conditions

Note: (*) The sequestration rates are based only on the impact of the SOC measure; they do not take into account emissions related to other management activities.

Sources: ([a]) Arrouays et al., 2002; ([b]) Conant et al., 2001; ([c]) Conant et al., 2017.

The different possible measures in grassland might have an impact mainly on SOC, despite accumulation of BGB and the fact that many grassland areas include perennial vegetation. In general, SOC in grassland is high compared with other land uses (e.g. cropland) implying that it offers long-term mitigation potential. Degraded grassland and grassland in arid conditions have higher potential to accumulate SOC due to their relatively low SOC levels (Chiti et al. 2018). The rates for the different practices reported in Table 3.9 represent the estimated mean over a 10-15-year period; after that, the soil system should reach an equilibrium phase (i.e. saturation).

Trade-offs and co-benefits

Trade-offs and co-benefits characterise the implementation of different management practices in grasslands. During the transition to improved management practices, it is possible that forage production will decrease over the short term as the ecosystem adjusts; this can temporarily affect livestock productivity and income. Additionally, the enhanced soil fertility and increased biomass production associated with the practices can create challenges in terms of nutrient management, with the risk of nutrient leaching or runoff, especially if fertilisers are not carefully managed. Fertilisation can also impact grassland biodiversity because it leads to increased competition for light and can mean that smaller species are shaded out by taller plants (Hautier et al., 2009). Moreover, nitrogen fertilisers may lead to increased emissions of N_2O, a powerful GHG gas, potentially offsetting some of the carbon sequestration benefits (Jones et al., 2005).

In terms of co-benefits, improved grassland management enhances biodiversity by increasing the diversity of plant species; in turn, this provides habitats for a wider range of animal species. Practices such as rotational grazing and organic fertilisation improve soil health by enhancing soil structure, water infiltration and organic matter content, leading to more productive soils over time. The improvement in soil health and biodiversity also makes grassland systems more resilient to environmental stresses like droughts and floods, thereby boosting long-term productivity and sustainability. Additionally, improved grassland management enhances water regulation and quality by increasing the water retention of soil and filtering out pollutants, thereby benefitting both local ecosystems and communities (Boch et al., 2021). An overview of potential risks and co-benefits from measures in grassland is provided in Table 3.11.

Table 3.11 Co-benefits and risks from measures in grassland

Effects	Rotational grazing	Fertilisation	Re-/overseeding
Biodiversity	Generally providing opportunities ***	Uncertain, or mixed effects ***	Uncertain, or mixed effects ***
Water management	Generally providing opportunities	Uncertain, or mixed effects ***	Generally providing opportunities
Air quality			
Soil conservation	Generally providing opportunities	Generally providing opportunities ***	Generally providing opportunities
Resilience ecosystems	Generally providing opportunities	Uncertain, or mixed effects ***	Generally providing opportunities
Local climate effects			
Land use and biomass supply			
Resource use: water and fertiliser		Generally providing risks	Generally providing risks
Socio-cultural			
Socio-economic			
Income diversification; support local economies	Generally providing opportunities	Generally providing opportunities	Generally providing opportunities
Foregone income	Combination of positive and negative effects		

Not applicable or negligible

Uncertain, or mixed effects

Generally providing opportunities

Generally providing risks

Combination of positive and negative effects can apply at the same time or in different time periods following implementation

*** = Highly dependent on implementation/method and/or local circumstances

Notes: Annex 2 provides the list of specific co-benefits and risks considered for each effect; positive effects of fertilization on water and soil can apply when organic fertiliser is used.

Source: Authors' own compilation based on expert judgment.

3.4 Wetlands and peatlands

Wetlands can be either managed or unmanaged. Managed wetlands are wetlands where the water table is artificially changed (e.g. drained or raised for peat extraction) or those created through human activity (e.g. flooding for reservoirs). Emissions from unmanaged wetlands are not estimated in GHG reporting. It only includes managed wetlands that are covered or saturated by water for all or part of the year and that do not fall under the category of forest land, cropland, grassland or settlements (IPCC, 2006). Wetlands and peatlands offer important opportunities to reduce GHG emissions or even increase CO_2 removals from the atmosphere.

An important distinction needs to be made between wetlands occurring on mineral soils and those on organic soils. Wetlands on mineral soils do not accumulate peat and their carbon stocks are not very large but some of them (particularly mangroves or coastal wetlands) have a large capacity for CO_2 removals. If degraded, these capacities need to be restored by implementing appropriate measures that maintain the ecologic conditions that enable their pristine functioning.

The added value of wetlands on organic soils (called mires or peatlands) is that their existing pools are protected from mineralisation, provided that drainage does not occur. Those wetlands also remove CO_2 from the atmosphere by slowly accumulating peat from dead plant material (e.g. Sphagnum moss) over decades or centuries. At the same time, however, the anaerobic decomposition of plant material causes CH_4 emissions which need to be taken into consideration in the assessment of the mitigation potential of various measures.

In Europe, nearly 50% of peatlands have been drained and degraded during recent decades for economic purposes, such as energy production, agriculture or forestry (Laine et al., 2024); they currently remain a net source of emissions. It is essential to protect intact peatlands to preserve their carbon stocks and prevent CO_2 emissions in the LULUCF sector. Active measures, as described in this section, can also contribute to reducing existing emissions.

3.4.1 Description of measures

Wetland restoration focuses on returning degraded wetlands to a pristine functioning state, often by restoring the physical and biological characteristics that define a wetland, namely the water table depth, water quality and the presence of native, aquatic species. Restoration has a significant impact in reducing emissions from drained or degraded peatlands. It can also increase carbon removal capacity in coastal wetlands (Otero et al., 2024).

Wetland protection refers to conservation measures taken to safeguard wetland ecosystems and their associated species from degradation or destruction. Protection of functional wetlands (i.e. the maintenance of their hydrological functioning in its pristine state) has different possible effects. On peatlands, it prevents degradation of their huge organic matter and carbon stocks. Existing estimates indicate that peatlands store one third of the total global organic carbon all over the world (Global Peatlands Initiative, 2022). For wetlands on mineral soils, protection involves maintaining their often significantly high CO_2 removal capacity.

Restoring coastal wetlands

Coastal wetlands in Europe encompass salt marshes and seagrass meadows. Salt marshes can remove carbon from the atmosphere efficiently while emitting less methane compared to peatlands (Morant et al., 2020). Since the early 20th century, land reclamation, pollution and altered water flow due to dams and dykes have caused extensive damage to these ecosystems. Converting coastal wetlands for aquaculture, infrastructure like harbours or agriculture can significantly increase CH_4 and N_2O emissions, transforming these ecosystems from carbon sinks to sources. The protection and restoration of coastal wetlands in Europe has been proposed as a cost-effective climate change mitigation strategy in line with the European Climate Law (Otero et al., 2024).

Strategies for restoring coastal wetlands include:

- restoring geo-morphological structures (such as salt marshes and mudflats) by adding sediment to elevate the ground level, allowing for the natural colonisation of wetland plants and preventing erosion;
- diverting waterways, dredging sediments and maintaining natural canals to ensure water flows through them in a beneficial manner;
- rewetting former coastal wetlands that were drained for agricultural or urban development by bringing them back into their natural state;
- managing realignment and depolderisation by shifting the line of flood defences inland and raising the ground level to create new intertidal habitats between old and new defences, serving as a buffer against storm surges; depolderisation specifically refers to returning drained land to the sea, while managed realignment might involve breaching or removing coastal defences entirely;
- implementing small-scale measures to reduce human impact on wetlands by clearing trees, modifying agricultural and grazing practices to improve habitat quality and implementing changes in land use that enhance natural landscapes;
- replanting seagrass species in their naturally occurring habitat; and
- preventing fertiliser inflows and other harmful chemical inflows into the sea (e.g. plastic).

Drained peatlands

There is limited public awareness of the importance of peatland habitats and historically a low socio-cultural value has been placed on them. As a result, they have been rapidly converted for peat extraction and dryland agriculture and forestry, significantly altering their functioning. The largest peatland areas are found in Finland, Ireland, Latvia, Estonia, Germany and Sweden. In 2022, drainage and cultivation of peatland led to emissions of 124 $MtCO_2e$ as reported by the EU-27. Some studies evaluating these emissions assert that this is an underestimation, offering the following alternative figures: 153 $MtCO_2e$ per year in 2018 (Martin and Couwenberg, 2021) and 184 $MtCO_2e/yr$ per year (Greifswald Mire Centre et al., 2020; Tanneberger et al., 2021a).

Both restoration and protection of peatlands can mitigate climate change. In cropland or grassland, restoring the water table to pre-drainage levels through rewetting reduces peatland degradation and related emissions significantly and immediately (Evans et al., 2021; Laine et al., 2019; Zou et al., 2022). Changing the type of crop or the land use from cropland to grassland without changing the water table levels does not significantly reduce the emissions (Angileri et al., 2024). In addition, keeping remaining peatlands in a wetland state (i.e. avoidance of drainage) protects their carbon stocks.

One solution which allows for a certain level of agricultural production on rewetted peatlands but still mitigates drained peatland emissions is paludiculture, i.e. the cultivation of plants adapted to wet conditions for which a market can be developed in the construction, energy and horticulture sectors, among others (Tanneberger et al., 2024). More than 300 species of plants as well as water buffalo grazing have been identified as possible productions (Abel et al., 2013) but developing new value chains for them remains challenging. Where complete rewetting is not possible, water management and agricultural practices need to reduce the intensity of drainage and avoid disturbing the soil to minimise emissions as far as possible.

A special and debated case is that of forest-drained peatlands where drainage results from artificial measures or simply from water uptake by the trees; these induce the water table to recede and hence contribute to peat degradation and GHG emissions. One difficulty in managing this type of land is that the carbon absorption by tree photosynthesis compensates at least partly for the peat emissions and removing the existing carbon stock accumulated by the trees would induce additional GHG emissions. More knowledge is required to provide guidance in this area because the overall GHG balance depends on many different factors including the type and age of the trees, average water table depth or possible uses for the wood.

Some typical cases can however be listed here:

- In the case of mature trees and a deep average water table depth, the emissions due to peat degradation are not compensated for by tree growth. In this scenario, there are two possible options: to harvest the wood, particularly if it can generate long-lived products that store carbon, or to leave the trees. In both cases, the land should be rewetted at least partially to reduce emissions and replacing the trees with new ones, such as alders or willows that are adapted to wetland conditions, should also be considered. Recent investigations in Finland have also shown that continuous cover forest management practices are a significantly better option than clear-cutting in terms of carbon emissions (Lehtonen et al., 2023).

- In the case of a high average water table depth, tree planting should be avoided to protect the peat carbon stock, unless species such as alders or willows are being considered.

- In the case of a recent plantation characterised by dynamic tree growth, rewetting compatible with tree development should be considered.

3.4.2 Mitigation potential

The role of wetlands and peatlands in climate change mitigation at the EU level is not fully known. The mitigation potential of this kind of land depends on local conditions and the information which is currently available is scarce and incomplete. For example, only managed wetlands are included in the GHG inventory and coastal wetlands are only partly included (e.g. for France and Malta) despite their significant capacity for carbon sequestration.

Within coastal wetland habitats, salt marshes can contain up to 400 tC/ha in the top metre of soil, with an average annual sequestration rate between 1.7 tC/ha and 2.8 tC/ha when healthy (Abdul Malak et al., 2021). Research suggests that restoring degraded coastal wetlands through measures like removing tidal barriers is more effective for emission reductions than creating new ones. Restoring natural salinity conditions in salt marshes helps keep CH_4 emissions low and supports a healthy ecosystem (Kroeger et al., 2017)

Peatland protection and restoration (including rewetting) are proposed as a key strategy for climate change mitigation (Humpenöder et al., 2020; Leifeld and Menichetti, 2018). Like intact peatlands, rewetted peatlands remove CO_2 from the atmosphere but emit more CH_4, particularly in the years following rewetting (Abdalla et al., 2016). The radiative effects and atmospheric lifetimes of these gases differ, with CO_2 being a weak but persistent GHG and CH_4 a strong but short-lived GHG. Therefore, the emission reductions from rewetted peatlands vary over time and across different climatic regions, making it hard to quantify them (EC, 2024a).

According to a global sensitivity analysis, prompt rewetting of drained peatlands reduces climate warming despite the increased CH_4 emissions (Günther et al., 2020). In addition, the results of a global modelling study suggest that the land system would turn into a net carbon sink by 2100 if about 60% of present-day degraded peatlands were to be rewetted in the coming decades, combined with the protection of intact peatlands (Humpenöder et al., 2020). The estimated net effect would be a reduction in emissions despite the increase in CH_4 emissions due to rewetting, in line with Günther et al. (2020).

Tier 1 EFs for CO_2, CH_4 and N_2O for drained and rewetted peatlands provided by the IPCC indicate that the average mitigation effect of peatland rewetting in temperate regions is an emission reduction of 75% for both cropland and grassland. Specific emissions from paludiculture crops remain poorly documented and could decrease these benefits, particularly in the case of nitrogen fertilisation.

The above figures do not address the case of forested peatlands. As mentioned above, these areas are very complex because carbon removals and storage in biomass partly compensate the emissions. To predict the effects of different measures, a variety of situations would need to be considered that take account of the types and ages of the trees, the climate and the water table levels. More research is still needed to provide a clear view of the possible mitigation options in that case.

Considering the variability of the mitigation potential of wetlands and the number of effects to be considered when assessing the total effect, the key to achieving climate change mitigation targets seems to lie in selecting restoration sites and implementing measures that match the specific site conditions, including fertility, water table levels, vegetation type and nutrient status (Tanneberger et al., 2021b, 2021c). This potential exists only if the hydrological conditions still provide sufficient water to rewet — even partially — the drained peatland. In each case, this would need to be verified precisely since climate change is already impacting the hydrological regime in many regions.

3.4.3 Trade-offs and co-benefits

While wetland restoration offers significant benefits in terms of preserving ecosystems, enhancing biodiversity and sequestering carbon, there are also challenges related to costs, land use changes, potential environmental hazards and the complexities of managing dynamic ecosystems.

Restoring coastal wetlands contributes to habitat creation, which is crucial for preserving biodiversity. Peatland rewetting can also offer economic opportunities in areas where water management can be monetised. Rewetting projects can support tourism and high-quality water sources essential for industries such as beverage production. These habitats also serve as nurseries, spawning sites or feeding grounds for commercially valuable species. Wetlands act as natural filters, trapping nutrients and contaminants that could otherwise pollute nearby water bodies.

Implementing restoration projects in coastal wetlands may require significant changes in land use and governance structures, leading to potential relocation costs and disruptions to human activities in affected areas. Restoring wetlands can result in the loss of land used for recreation and agriculture. The creation of soft, waterlogged soils could pose a flooding hazard to nearby houses and infrastructure and create ground instability if neighbouring locations are not also managed carefully. Restoration projects may need real-time monitoring due to the dynamic nature of these ecosystems, which could be challenging and costly. The cost of larger restoration projects could also be prohibitive, especially for smaller regions or communities.

Rewetted peatlands not only emit far fewer GHGs: they also help improve water quality, provide habitats for rare and threatened species, have a cooling effect and help restore typical mire biodiversity (Tanneberger et al., 2024). In terms of hydrology, like other wetlands they have the potential to mitigate extreme events due to their buffer role (i.e. their ability to store water during humid periods and release it slowly during droughts). Equally, restoration and protection measures could support the economic role of paludiculture, which is an important factor for local communities.

A possible trade-off from rewetting peatlands is the emission of CH_4 and the consequent reduction in mitigation potential (Zou et al., 2022). In the case of forestry, as mentioned above, a possible trade-off relates to the carbon stock that the forest has accumulated: removing this stock to avoid the drainage effect of trees would partly offset the expected reduction in emissions due to rewetting in the short term. On the other hand, long-term carbon losses from forests planted on drained peatland could, in certain conditions, exceed the amount of carbon stored in the forest biomass (Dunn and Freeman, 2011; Makrickas et al., 2023).

An overview of potential risks and co-benefits from measures in wetland areas is provided in Table 3.12.

Table 3.12 Co-benefits and risks from measures in wetland areas

Effects	Protection of wetlands	Restoration of coastal wetlands	Restoration of wetlands/ peatlands
Biodiversity			
Water management			
Air quality	***	***	***
Soil conservation			
Resilience ecosystems			
Local climate effects			
Land use and biomass supply			
Resource use: water			
Socio-cultural			
Socio-economic		***	***
Income diversification; support local economies			
Foregone income			

Not applicable or negligible

Uncertain, or mixed effects

Generally providing opportunities

Generally providing risks

Combination of positive and negative effects can apply at the same time or in different time periods following implementation

*** = Highly dependent on implementation/method and/or local circumstances

Notes: Annex 2 provides the list of specific co-benefits and risks considered for each effect.

Source: Authors' compilation based on expert judgment.

3.4.4 Drained peatland restoration (ETC-CA scenario assessment)

The mitigation potential from wetlands-peatlands restoration in Europe depends heavily on several factors, including prior land use, climatic conditions and the management regime. More than 50% of peatlands in Europe are degraded by drainage and used for agriculture, forestry and peat extraction (Joosten et al., 2017). Peatlands converted to agriculture after drainage represent an area of 5.5 Mha or 3% of all agricultural land in the EU. In total, they emit around 149 $MtCO_2e$ per year, i.e. one third of the agricultural emissions reported by Member States (EEA, 2024a). Restoration of peatland is one of the main objectives of the NRR which sets a series of incremental targets over time, aimed at the achievement of 50% of rewetted peatland currently in agricultural use (cropland and pastures). According to a simulation performed by the EEA and the ETC CA, the fulfilment of the NRR peatland rewetting targets could lead to an emission reduction ranging between 10.2 and 22.6 $MtCO_2e$ per year when only cropland area is rewetted. If focusing on grassland only, reductions range between 6.2 and 13.8 $MtCO_2e$ per year (Table 3.13). These values represent relatively low fractions of the total emissions from peatlands drained for agriculture (see Box 3.2 on details of the calculation), nevertheless they would provide a relevant contribution to EU LULUCF policy.

Table 3.13 Rewetting targets analysed, resulting areas and mitigation potential in $MtCO_2e$ and percentage of the total drained peatland emissions for each land use category

Rewetted area (%)	Rewetted area (kha)	Cropland scenario		Grassland scenario	
		GHG reduction $MtCO_2e$	% reduction of emissions	GHG reduction $MtCO_2e$	% reduction of emissions
7.5%	415	10.2	6.9%	6.2	4.2%
13.3%	738	18.1	12.1%	11.1	7.4%
16.6%	923	22.6	15.1%	13.8	9.2%

Source: Authors' compilation based on calculations described in Box 3.2.

Box 3.2

Quantitative assessment of peatland rewetting

The EEA has been supported by the ETC CA in developing scenarios for rewetting drained peatlands at EU level, based on existing information about emissions and the extension of peatlands and policy targets under the NRR.

Using the IPCC Wetlands Supplement (2013) guidelines as a reference, the steps below were followed:

- assessing and locating peatland areas drained and converted into grassland or cropland across all Member States;
- computing the emissions for all EU Member states using Tier 1 EF values provided by the IPCC (2013);
- defining scenarios for rewetting according to NRR targets;
- assessing the remaining emissions after rewetting; and
- comparing the emissions before and after rewetting to evaluate the reduction.

Peatland areas were identified based on the latest map of EU peatlands published by Tanneberger et al. (2024). The classes selected for the scenario described included: (1) peatland dominated areas and (2) 'peat in mosaic' areas.
Degraded peatlands were identified as those peatlands that have been converted into cropland or grassland, thus classified under these land uses in the CLC 2018. Targets defined in the proposed NRR were considered when analysing the potential of rewetted areas, i.e. 7.5%, 13.3% and 16.6% of drained peatlands under agricultural use to be rewetted by 2030, 2040 and 2050 respectively (EU, 2024a). These result in an estimated area of 415, 738 and 923 kha of drained peatland to be rewetted. The reduction in GHG was computed separately for: (1) a mixed scenario (i.e. rewetting peatlands in cropland and grassland, based on their proportions in each of the two land use categories); (2) a scenario focusing on cropland rewetting only; and (3) a scenario focusing on grassland rewetting only.

For the mixed scenario (Scenario 1), reductions in emissions of 8.5 $MtCO_2e$ per year, 15.1 $MtCO_2e$ per year and 18.9 $MtCO_2e$ per year (i.e. 5.7%, 10.1% and 12.6% of the total drained peatland emissions or 149 $MtCO_2e$ per year) could be achieved for the three target areas, respectively. For cropland only (Scenario 2), the emission reduction would be 20% higher. When applied to grassland only (Scenario 3), it would be 27% lower (see Table 3.13).

These scenarios have been downscaled to the NUTS-3 regions of the different Member States. The results provide orders of magnitude and locations for drained peatland emissions and point to a big potential for abatement through peatland rewetting across Europe. The highest potential is found in northern Europe, particularly in Finland, Germany, Lithuania, and Poland. However, such scenarios should be considered as a first approximation that shall be further refined to take account of regional differences and applying higher Tier methods than those used in this analysis.

Source: EEA, ETC CA 2024.

3.5 Settlements

3.5.1 Description of measures

Settlements, despite being predominantly characterised by sealed surfaces, still have the potential to enhance carbon storage by incorporating green areas within their infrastructure. Furthermore, avoiding soil sealing and minimising land take for new settlements can preserve existing green spaces. Table 3.14 provides definitions for the types of measures which can potentially be applied in settlements. This section will describe these measures' potential for climate change mitigation alongside the resulting potential trade-offs and co-benefits, and the enabling factors required to implement them.

Table 3.14 Definitions of measures for settlements

Measure	Definition	Type of mitigation
Increasing green areas and green infrastructure	Green spaces or infrastructure within urban or rural environments are a strategically planned network of natural and seminatural areas, such as parks, rooftop gardens, green corridors and natural reserves ([a]).	Emission reduction/carbon removal
Avoiding soil sealing	Soil sealing refers to the permanent covering of land surfaces with impervious materials, such as concrete or asphalt or buildings which prevent water infiltration and natural vegetation growth ([b]).	Emission reduction
Minimising land take	Land take refers to the area of land that is 'taken' by infrastructure itself and other facilities that necessarily go along with the infrastructure, such as filling stations on roads and railway stations ([c]).	Emission reduction

Sources: ([a]) EC, 2019 ; ([b]) Gardi et al., 2015; ([c]) EC, 1999.

3.5.2 Mitigation potential

Green roofs and walls, urban parks and green infrastructure form vegetation elements that increase carbon uptake in soils and living biomass (Castleton et al., 2010). Both the rate and duration of the resulting carbon sequestration depends on a variety of factors, including the climatic region and the type of tree species or vegetation planted (Seyedabadi et al., 2021). Avoiding soil sealing and land take ensures that areas can be preserved and either maintain their existing level of carbon storage and sequestration or increase it via measures such as developing green areas. While the multiple benefits of these measures are evident (e.g. human health and wellbeing and cooling effect), there is a lack of data on their potential to mitigate climate change, mainly due to their high rate of variability. At the same time, not all these measures are reflected in the reporting methodologies for the purpose of the GHGI (Chapter 2); hence, they don't necessarily contribute to achieving climate change targets.

3.5.3 Trade-offs and co-benefits

Irrespective of the absence of clear EFs or a lack of clarity about their contribution towards targets, many of these measures offer significant and important co-benefits for people and nature (Table 3.15). Increased vegetation can help cities and their inhabitants adapt to climate change, reducing the heat island effect. Urban green areas and infrastructure offer habitats for biodiversity, reduce air pollution, support soil stability (Castleton et al., 2010; Paudel and States, 2023) and increase water infiltration.

Beyond helping to create cleaner air, green areas are important for recreational services and encourage healthier lifestyles, including green modes of transport. Both green roofs and walls, and their rehabilitation, can also help reduce emissions by increasing the energy efficiency of buildings and reducing emissions from new buildings, respectively. Some of these co-benefits for society could also involve a significant decrease in societal costs, e.g. reduced exposure to pollution could minimise related health issues (Paudel and States, 2023).

Effective land use planning in both urban and rural areas, coupled with early integration of green infrastructure, are essential strategies for mitigating environmental impacts and promoting sustainable development. Reduced impact urbanisation can be achieved by minimising soil sealing and increasing the height of buildings through extensions, preferably utilising wood as a construction material to further reduce the carbon footprint. These practices help preserve natural land surfaces which can absorb rainwater, reduce runoff and maintain natural carbon sequestration processes. These measures not only optimise space and resources but also contribute to reducing urban sprawl, thereby protecting the surrounding ecosystems and enhancing urban green spaces.

Table 3.15 Co-benefits and risks from measures in settlements

Effects	Green roofs and walls	Urban green infrastructure	Avoidance of soil sealing
Biodiversity	Generally providing opportunities	Generally providing opportunities	Generally providing opportunities
Water management	Generally providing opportunities	Generally providing opportunities	Generally providing opportunities
Air quality	Generally providing opportunities	Generally providing opportunities	Generally providing opportunities
Soil conservation	Not applicable or negligible	Generally providing opportunities	Generally providing opportunities
Resilience ecosystems	Not applicable or negligible	Generally providing opportunities	Generally providing opportunities
Local climate effects	Generally providing opportunities	Generally providing opportunities	Generally providing opportunities
Land use and biomass supply	Not applicable or negligible	Not applicable or negligible	Generally providing risks
Resource use: water and energy demand*	Combination of positive and negative effects	Combination of positive and negative effects	Generally providing opportunities
Socio-cultural	Generally providing opportunities	Generally providing opportunities	Generally providing opportunities
Socio-economic	Generally providing opportunities	Generally providing opportunities	Generally providing opportunities

- Not applicable or negligible
- Uncertain, or mixed effects
- Generally providing opportunities
- Generally providing risks
- Combination of positive and negative effects can apply at the same time or in different time periods following implementation

*** = Highly dependent on implementation/method and/or local circumstances

Notes: Annex 2 provides the list of specific co-benefits and risks considered for each effect; *green roofs and walls can increase water use, but decrease energy demand.

Source: Authors' compilation based on expert judgment.

3.6 Barriers and enabling factors

Farmers, foresters and landowners are the primary actors responsible for adopting mitigation practices on the ground. They are engaged in the management and protection of land and natural resources and are thus pivotal in ensuring that practices are implemented and adapted to local conditions and circumstances. The management decisions of farmers and foresters are influenced by a myriad of socio-economic, cultural and environmental factors, in addition to legislation and policy incentives. Decisions to implement climate change mitigation measures can be influenced by all these elements, as well as by a consideration of the financial cost of their implementation, community support and the perceived effects of sustainable land use and ecosystem services in the short and long term (Barillas, 2023).

The measures described earlier in this chapter offer great potential for climate change mitigation and may generate significant co-benefits. In addition, many of the management practices and measures described are cost-efficient and commonly known to land managers, i.e. they have a high level of technological readiness (ESABCC, 2025). However, there is a range of implementation barriers and limitations in the uptake and scaling of various measures. This section presents the key barriers and possible enabling factors, considering the roles of various actors involved.

From a macro-economic perspective, or even for local economies (job creation), the implementation of mitigation measures in the LULUCF sector can be cost-efficient while their costs can be lower than for industrial removals or abatement costs in other sectors (Table 3.16); however, financial costs for landowners or managers can be significant and pose an important barrier. Financial costs for implementing measures can include fixed establishment costs up-front, variable costs for a change in management practices (e.g. selective logging) and (opportunity) costs from foregone income from reduced biomass production levels (Kreibiehl et al., 2022).

For afforestation, for example, farmers incur costs relating the purchase of seedlings and fencing and from reduced agricultural crop production. Meanwhile, possible financial gains from forest harvesting will only occur decades after implementation. Similar financial barriers are observed in relation to measures for improved soil management, improved grassland management, agroforestry, the protection and restoration of wetlands and peatlands and also paludiculture (Kreibiehl et al., 2022).

For forest measures in particular, the long-term commitment (>20 years) is also considered a financial risk factor and this may become an increasingly important consideration given uncertainties around the effects of climate change and natural disturbances. These financial costs and risks can be significant, in particular for small holders (EC, 2022a).

Improved forest management and afforestation can provide relatively large mitigation potential for a relatively low price (EUR 20 per tCO_2e), while mitigation options for organic soils are realistic at a cost of EUR 50-100 per tCO_2e. In the area of agriculture, the costs are more diverse (ranging from EUR 5-150 per tCO_2e) (EC, 2024a).

Table 3.16 Potentials and costs of mitigation strategies

Method	Annual EU potential in 2050 ($MtCO_2/y$)	Costs (EUR/tCO_2)
Reduced deforestation/ forest protection	10	n/a
Improved forest management	53-70	0-50
Afforestation/reforestation	17-75*	20-100
Wetland and peatland restoration	50-100 (emission reduction)	10-100
Soil carbon sequestration	30-100 (economic/realistic potentials)	0-100
Agroforestry	10-250**	n/a

Notes: *Assuming 1-10% of agricultural land is being converted; **Limited studies, economic and realistic potentials likely to be lower; for reference, with a global perspective, Smith, 2024 provides slightly different cost estimates compared to ESABCC, with ranges for soil carbon sequestration of -45 to 100 USD/tCO_2, for afforestation/reforestation of 0 to 240 USD/tCO_2, for BECCS of 15-400 USD/tCO_2 and for DACCS of 200 to 1000 USD/tCO_2.

Source: ESABCC, 2025.

Essentially, this represents a market failure: while the negative effects from practices that cause environmental harm are not effectively priced-in, practices that result in GHG emission reductions or carbon removals are not rewarded effectively. In the context of European or international commodity markets, this means that there is little flexibility for farmers and foresters and few financial incentives to adapt their management practices. There is a need for a regulatory approach that ensures a level playing field.

Policies to date have approached this market failure by focusing on the role of public finance, such as in the form of State aid, conditionality for direct CAP support to farmers or payments for ecosystem services. For the latter, funds can currently be provided under the CAP's voluntary interventions (e.g. eco-schemes for organic farming, agroforestry, enhanced crop rotation, afforestation or sustainable forest management). However, they have had limited efficacy in the past, due to inadequate scope or finance and/or inconsistent financial incentives focused on promoting agricultural productivity (ESABCC, 2024).

For example, funds do not always adequately compensate for the loss in revenues resulting from a change in management practices.

There are also challenges related to 'conflicting' policies. The EU agricultural and energy policies and related financial incentives can increase demand for land and biomass resources (e.g. for food, feed, energy) and the cultivation of organic soils (ESABCC, 2024). For example, currently the CAP support is conditional to the protection of wetlands and peatlands, thus mostly focusing on limiting the conversion of wetland and peatlands, while disregarding the ongoing management of organic soils that remains a substantial source of emissions (Münch et al., 2023).

Recognising the need for adequate financial support and investment, targeting both public and private finance, the EU has recently focused on the roll out of 'result-based finance schemes', to encourage carbon farming. Results-based schemes are aimed at facilitating the allocation of finance directly to the abatement effect of carbon farming measures, such as with the use of certification.

For this purpose, a legal EU framework has been established for the certification of carbon removals and carbon farming (CRCF). As further discussed in Chapter 4, in combination with binding targets for the EU and Member States, a more climate-oriented CAP and revised State aid framework, the CRCF could enhance the role of public finance for carbon farming activities. The CRCF is further introduced in Chapter 4.

MRV methodologies for the certification of carbon farming activities aim to ensure the 'environmental integrity' of the quantified certified mitigation effect from specific measures. The robustness of quantification methodologies depends on the availability and cost-efficiency of quality monitoring data and technologies and this can pose a challenge in and of itself (EC, 2022a). Overcoming the barriers related to monitoring requires a coordinated effort in enhancing data infrastructure, building technical capacity, securing financial support, simplifying MRV processes and leveraging technology (Halsnæs et al., 2007) ([18]).

While certifying abatement via carbon farming is a potentially effective way to attract finance, farmers and foresters might still be reluctant to adopt a change in management practices or land use. One important reason for this may be the uncertainty related to the technical feasibility of implementing specific measures (e.g. effects from climate change on the feasibility of rewetting drained peatlands) or the fact that the measures to be implemented have a long lead time before they result in a climate benefit. There is also a risk of reversibility of the carbon removed in the case, for example, of forest fires (EC, 2022a). These circumstances mean that the forest or farm holding faces a financial risk and this might be a barrier to engaging in carbon crediting schemes.

This underscores the need to address financial risks. Several options such as liability and insurance mechanisms could lower the risk for the operator. Additionally, methodologies to better assess the baseline situation (e.g. hydrological conditions in drained peatlands) could help to minimise financial risks by taking into account possible effects from climatic change and the risk of disturbances.

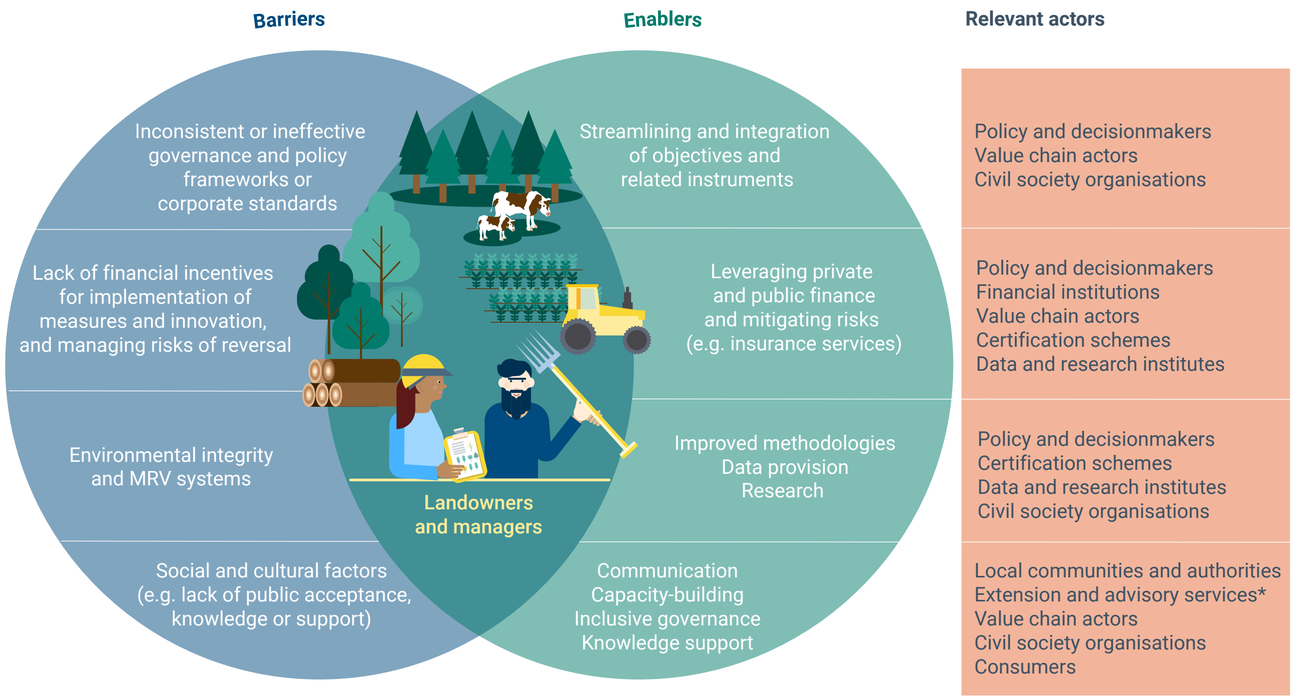
Finally, for all the measures, farmers and foresters need access to knowledge, training, technical support and human resources to implement and manage systems effectively. A lack of expertise can hinder the successful adoption and maintenance of such systems. Both public and non-governmental organisations can provide training on sustainable farming methods such as agroecology, regenerative agriculture and sustainable forestry. At the EU level, the EU Pact for Skills brings

([18]) The EU has established a technical support instrument to help Member States support the resilience of natural resources.

together public and private stakeholders to promote upskilling and reskilling in key sectors facing skills shortages, also to facilitate a green transition.

The relationship between farmers, barriers and enabling factors is shown in the schematic picture in Figure 3.1.

Figure 3.1 Overview of mitigation options in LULUCF and co-benefits and risks



Note: *Extension and advisory services (EAS) are institutions and activities to assist farmers in accessing knowledge, information, capacities and technologies. These services aim to develop technical, organisational, and management skills and practices, as well as enhance their interactions with markets, research, and education. EAS also include functional elements such as communication, facilitation, and empowerment. (The EC Knowledge Centre for Global Food and Nutrition Security, 2024)

Source: Author's compilation based on assessment by ETC/CA in this chapter.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4 Governance and policy frameworks impacting GHG emissions and carbon removals in the land sector

Key messages

- Following the adoption of the EU Climate Law, the EU adopted a first-ever LULUCF removals target for 2030, as well as supporting national targets, as part of the revision of the LULUCF Regulation in 2023. To a certain degree, evaluating the effectiveness of this revised Regulation and Member States' efforts in making progress towards these targets is hampered by the fact Member States are still in the early phases of implementing additional policies and measures. The results may take time to materialise. Moreover, GHG inventory data are currently only available until the year 2023.

- Projections submitted in recent years suggest a significant gap between the expected total LULUCF sink and the EU LULUCF removals target in 2030. While collective efforts are needed to reach this cumulative EU LULUCF target, various Member States must also take additional action to reach their individual targets.

- The EU has adopted a governance and policy framework aiming to encourage Member States, as well as landowners and managers, to design and engage in policies and measures aimed at changing management practices. The Carbon Removal and Carbon Farming Regulation provides a novel and voluntary instrument to leverage public and private finance to such practices via certifying the abatement effects, in terms of carbon removals and emissions reductions. The EU's State aid rules and Common Agricultural Policy provide important legal and financial frameworks for leveraging public support to carbon farming activities.

- Policies can also drive biomass supply and demand which may have a negative effect on the LULUCF sink. Streamlining policy objectives, and related legal and financial instruments, can help avoid negative cross-policy trade-offs. Streamlining is also important to ensure climate change mitigation in LULUCF also contributes to increasing the resilience of ecosystems (and supply chains), protecting biodiversity and ensuring a sustainable bioeconomy.

- The new governance and legislative framework relevant for LULUCF results in varying data needs, such as those related to carbon stocks, activity data, emission factors, biodiversity and the vulnerability of ecosystems. Specific data needs can vary in terms of type of parameters, geographical and temporal scales, depending on specific use cases. Various policies can also provide useful data, including from the Common Agricultural Policy and Carbon Removal and Carbon Farming Regulation, and in the future from the (expected) Soil Monitoring Law and the Forest Monitoring Law. This may give scope to increasing data interoperability and creating administrative synergies across different land-related policy frameworks.

4.1 Introduction

The potential of the LULUCF sector to help mitigate climate change by increasing the removal of carbon depends on complex interactions between natural and anthropogenic drivers. The complexity of these processes implies the need for timely information that accurately reflects the impact of practices in order to put in place effective mitigation measures. In addition, the extent to which mitigation options to enhance removals are taken up and scaled depends on financial, demographic, socio-economic and behavioural factors, which can be influenced by policies. In consequence, robust policy and governance mechanisms are needed to address anthropogenic drivers effectively and facilitate the uptake of mitigation options in a timely and holistic manner, while ensuring synergies with other policy objectives.

This chapter describes the various EU governance and policy frameworks and instruments relevant to enhancing carbon removals in the LULUCF sector and outlines how these instruments could meet new data needs or support data provision. The EU context for a new policy setting for LULUCF was the adoption of the EGD in 2019 (EC, 2019), following the adoption of the Paris Agreement climate goals and the 2030 agenda for sustainable development in 2015 (UNFCCC, 2015; UN, 2015).

The EGD presented novel political objectives to transform the EU into a resource-efficient and competitive economy that protects, conserves and enhances nature in the EU at the same time as attempting to safeguard the health and well-being of citizens from environment-related risks and impacts. Its objectives include reaching climate neutrality by 2050 while decoupling economic growth from resource use and ensuring a just transition. To reach these targets, the EGD proposes a roadmap for the development of policies and legislation, including the initiative for a first EU Climate Law, and a review of climate- and energy-related instruments.

Following the adoption of the EU Climate Law (EU, 2021a), the Fit for 55 package laid down a cross-sectoral approach to reaching the agreed EU-wide net target to reduce GHG emissions. The legislation adopted under this package covered all the economic sectors and for the first time, fully integrated the objectives and targets in the LULUCF sector within the climate policy framework.

The strategic and legal frameworks provided by the EGD and the Fit for 55 package are further supported by various instruments, including various action plans and policy strategies and the enabling framework provided by the Eighth Environment Action Programme (8th EAP) to 2030 (EU, 2022e). Similarly to the EGD, this programme underpins the potential of the land sector to support climate action via the enhancement of natural sinks. It further recognises the need to aim for synergies with relevant policy areas, including climate adaptation, ecosystem resilience, biodiversity protection and sustainable production and consumption.

4.2 Target-setting and integrated policy planning

4.2.1 Target-setting

The EU Climate Law (EU, 2021a) adopted in 2021 sets out a binding objective to reach climate neutrality in the EU by 2050 in pursuit of the long-term temperature goal set out in the Paris Agreement. This target means that residual and unavoidable GHG emissions need to be balanced by removals by 2050 at the latest. Further steps and reductions beyond 2050 are not prescribed but the legislation indicates the aim to achieve negative emissions after 2050.

The EU Climate Law also sets an intermediate target to reduce net GHG emissions by at least 55% by 2030 compared to 1990 levels; it establishes that the contribution of removals from the LULUCF sector to the intermediate net target will be limited to 225 $MtCO_2e$. The rationale behind this quantitative limit is to ensure that sufficient mitigation efforts are deployed by Member States in other sectors (i.e. to avoid mitigation deterrence).

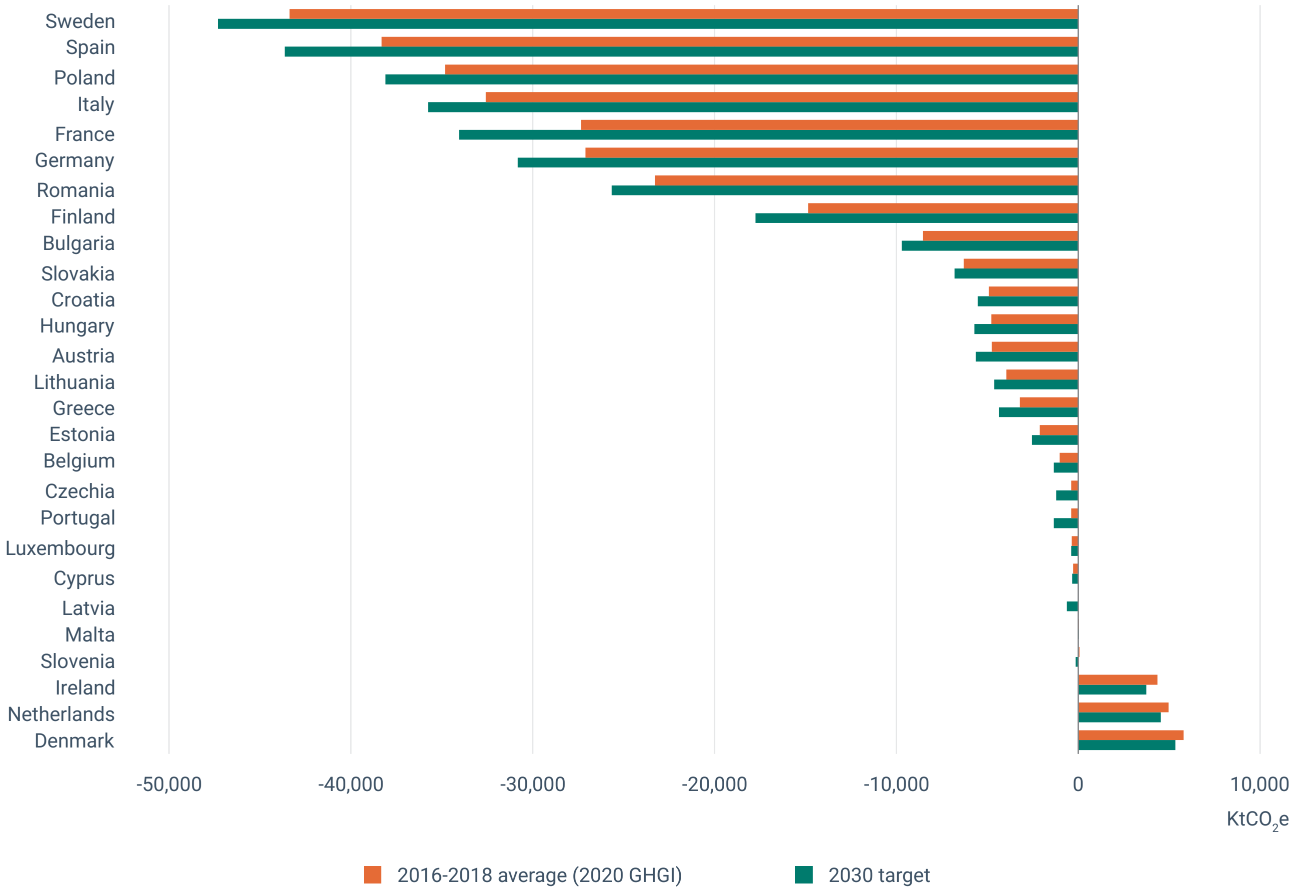
To reach these ambitious targets, all sectors must decarbonise to allow carbon removals to compensate for residual emissions from 'hard-to-abate' sectors, such as agriculture, cement, steel or aviation. At the same time, in view of the objective to reach climate neutrality by 2050, the EU Climate Law provides an EU-wide commitment to achieving a higher net sink in 2030. The targets in the Climate Law correspond to net emission reductions and do not specify the expected scale of emission reductions versus removals or the balance between them.

Corresponding to this ambition set out in the EU Climate Law, the revised LULUCF Regulation (EU, 2018a) provides the first EU-wide, separate land-based net carbon removals target of 310 $MtCO_2e$ by 2030, and binding targets for Member States that should deliver additional removals of 42 $MtCO_2e$ by 2030 compared to the reported average from 2016-2018. For the period 2021-2025, Member States must comply with the 'no debit commitment', ensuring that accounted emissions from land use are compensated for by at least an equivalent amount of accounted removals. At the same time, they must take into account flexibilities with the Effort Sharing Regulation (ESR) that covers road transport, buildings and agriculture ([19]). To a limited degree, Member States can use possible credits generated in LULUCF to comply with ESR targets. Vice versa, the flexibility to use of ESR credits to meet LULUCF targets is unlimited.

The effort to achieve this additional carbon sequestration is shared among Member States through individual targets (Figure 4.1), defined based on Member States' average net removals during the period 2016-2018 and based on each Member State's share of total EU managed land area. Not all Member States reported a net sink in their inventories for the base years for the period 2016-2018. However, the individual targets require each Member State to increase its climate ambition in terms of land policies. For countries with net emissions in the reference period this means reducing these emissions. The national target may change due to recalculations of the net removals or emissions for the years 2016-2018 if methodological changes and improvements are implemented (EEA, 2024d).

([19]) The Effort-Sharing Regulation(EU, 2018b) covers non-CO_2 emissions from agriculture; CO_2 emissions and removals are covered by the LULUCF Regulation.

Figure 4.1 **Average emissions for Member States for the period 2016-2018 and the 2030 targets under the LULUCF Regulation**



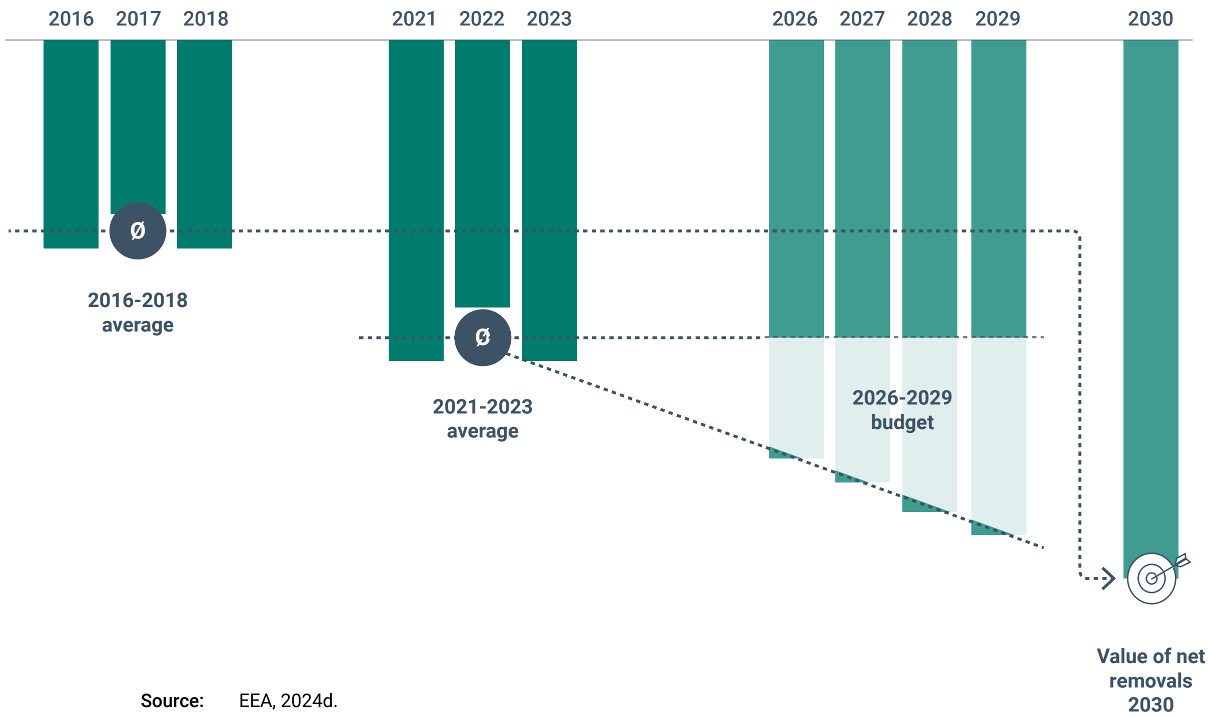
Source: Author's compilation based on (EU, 2018a)

Following the comprehensive review of the GHG inventories in 2025 (section 4.4.1.), national budgets and corresponding annual values will be determined for the period 2026-2029, aiming to ensure progressive action is taken towards reaching Member States' individual 2030 targets (Figure 4.2). This underscores the importance of robust GHG inventory data, but it is also aimed at facilitating the improvement of reporting methodologies.

Member States can incur financial liability if they do not comply with national budgets and targets. In principle, debits created in the LULUCF sector are transferred to the ESR but unless there is a surplus of credits in the ESR, Member States will need to purchase credits from another Member State. The EC will assess compliance with the no-debit commitment for 2025 in 2027 and with the 2030 target in 2032 ([20]).

([20]) Member States can also face EC legal action — an infringement procedure — in case they fail to meet the LULUCF target, which can result in financial sanctions.

Figure 4.2 Example of the target calculation for Member States for 2030



Source: EEA, 2024d.

While the Member States' LULUCF targets are legally-binding, the LULUCF Regulation and the ESR allow for certain, limited flexibilities to facilitate Member States to comply with their commitments, especially in the case of unforeseen circumstances (EEA, 2024d). The process for evaluating progress made by the EU and individual Member States towards reaching EU and national targets is further discussed in Section 4.4 below.

For the 2031-2040 period, the EC is expected to propose a 2040 climate target in 2025, consistent with the aim to reach climate neutrality by 2050 at the latest ([21]). The adopted target will then represent a starting point for further defining the role of the LULUCF sector and establishing a new climate and energy framework for this period.

4.2.2 Policy planning

The Governance Regulation (EU, 2018c) establishes a governance mechanism to facilitate integrated policy planning and track the progress of Member States' compliance with the EU's climate and energy targets, including for the LULUCF sector. Specifically, this Regulation aims to:

- contribute to implementing strategies and measures designed to meet the objectives and targets;
- stimulate cooperation between Member States;
- ensure the quality of reporting by the EU and its Member States to the UNFCCC and Paris Agreement secretariat; and
- contribute to greater regulatory and investor certainty.

([21]) As a Party to the Paris Agreement, in 2025, the EU also needs to submit a new Nationally Determined Contribution (NDC) with a timeframe for implementation up to 2035.

The governance mechanism is based on long-term strategies (LTSs) and integrated NECPs, which are both discussed in this section ([22]). The timelines for these are given in Table 4.1.

Table 4.1 Timelines for the drafting and final submission of LTSs and NECPs

Plan	Year
NECPs	
Draft NECPs 2021-2030	2018
Final NECPs 2021-2030 following EC assessment and recommendations	2019
Draft updated NECPs 2021-2030	2023
Final updated NECPs 2021-2030 following EC assessment and recommendations	2024
Draft NECPs 2031-2040	2028
Final NECPs 2031-2040 following EC assessment and recommendations	2029
Draft updated NECPs 2031-2040	2033
Final updated NECPs 2031-2040	2034
LTSs	
LTSs 2021-2050	2020
LTSs 2031-2060	2029

Source: Author's compilation based on (EU, 2018c).

Member States' plans for achieving long-term climate objectives are outlined in LTSs, taking a 30-year perspective. These strategies include projected emissions and removals by 2050, national targets for 2030 and indicative milestones for 2040 and 2050. They also provide sector-specific information, including an indication of total GHG emission reductions and enhancements of removals by sinks, as well as possible resulting effects on society and the environment ([23]).

Many Member States submitted their LTSs before or at around the time of the new and more ambitious climate targets which integrated removals via the European Climate Law and the LULUCF Regulation. Consequently, these strategies are not currently fully comprehensive or consistent with the current targets (Di Lallo et al., 2024). While most LTSs include a dedicated LULUCF section with qualitative information (Table 4.2), about 40% of the reports lack quantitative information on LULUCF mitigation, indicating that they could benefit from a more comprehensive and transparent assessment in terms of policies and measures (Di Lallo et al., 2024).

Member States are required to submit new LTSs by 2029. Since the LULUCF sector is characterised by long-term planning cycles, LTSs could prove a useful tool in the future for informing public policies and measures guided by longer-term transition plans for the sector and for avoiding trade-offs and inefficiency between short-term and long-term mitigation goals. This could be particularly relevant for forests and biomass use (Di Lallo et al., 2024; Soimakallio et al., 2021).

([22]) Corresponding progress reports and integrated monitoring arrangements provided by the EC which are further outlined in Section 4.4.
([23]) Article 15 of the Governance Regulation.

Table 4.2 Land-based policies and measures for climate change mitigation and adaptation in the LTSs

Land category	Policies and measures	Austria	Belgium	Croatia	Czechia	Denmark	Estonia	Finland	France	Germany	Greece	Hungary	Italy	Latvia	Litthuania	Malta	Netherlands	Portugal	Slovakia	Slovenia	Spain	Sweden	Total
Forests	Conservation and sustainable forest management	•	•	•	•		•		•	•		•		•	•			•	•	•	•	•	15
	Increase forest adaptation	•							•	•			•	•				•	•		•	•	9
	Afforestation			•	•	•		•	•	•		•	•	•	•	•	•	•	•		•		15
	Reforestation and forest restoration					•		•	•	•		•	•	•	•		•	•	•		•		12
	Restore important landscapes/forests		•	•									•	•			•			•			6
	Use more productive and better adapted varieties	•										•		•				•	•	•			6
Forests and agriculture	Increase soil carbon content	•	•	•	•							•	•		•		•		•	•	•		11
Agriculture	No tillage (or reduced)			•	•				•				•		•			•		•			7
	Use agroforestry systems		•	•					•										•		•		5
	Conserve or restore grasslands	•	•		•		•	•	•	•		•			•			•	•	•	•		13
	Longer crop rotation		•	•	•				•														4
All/other ecosystems	Biodiversity conservation		•	•		•	•		•			•			•	•		•		•	•	•	12
	Fire prevention			•	•				•			•	•		•			•	•	•	•		10
	Conserve wetlands						•		•	•					•				•	•	•	•	8
	Protect peatlands		•			•	•	•	•	•									•			•	8
	Restore degraded wetlands				•										•				•		•	•	5
Wood energy	Promote wood for energy	•	•	•			•	•	•	•	•	•	•	•	•		•	•	•	•	•	•	18
Demand management	Increase the share of HWP with long lifetimes		•		•			•	•						•				•	•		•	8
	Promote wood as substitute material	•	•	•			•	•	•	•		•	•	•	•				•	•		•	14
Other	Increase understanding and raise awareness						•		•				•		•					•	•	•	7
	Reduce land take	•					•		•	•			•										5
	Total	8	11	11	9	4	9	7	17	10	1	10	11	8	14	2	5	10	15	13	13	10	

Notes: Only policy and measures reported by a minimum of four countries are shown; Denmark and Greece provided little or no information on the role of LULUCF in reaching 2030 or 2050 targets; Finland presented three scenarios, of which the most ambitious one was selected here.

Source: Author's compilation based on Di Lallo et al., 2024.

NECPs are a governance tool to ensure that action is planned and coordinated across the five dimensions of the EU ([24]). For various policy objectives relevant to the Energy Union, including to LULUCF, Member States are required to present their national targets, provide analysis of the state of play and outline planned measures and policies, including an assessment of their effectiveness to reach the target. In this respect, the NECPs can play an important role in streamlining planning for different sectoral policies and measures; they can also allow for an integrated assessment of their combined effects.

Examples of areas which could benefit from streamlining policies and measures vis-a-vis the NECPs are the anticipated role of (forest) biomass for substitution and energy use, and related effects on the LULUCF sink. Another example is the role of the CAP in financing activities that can enhance removals and reduce GHG emissions in the LULUCF sector, alongside linkages of policy and financial incentives relevant for the LULUCF sector in the areas of biodiversity and climate adaptation.

The EC assesses draft and final LTSs and NECPs; in particular, the assessment looks at the interaction between and consistency of existing and planned policies and measures and also whether the contributions are sufficient in view of Energy Union objectives and collective objectives and targets under the EU's 2030 climate and energy framework. The EC can provide recommendations based on the draft documents and offer further guidance for completion of the final documents.

4.3 Ensuring a business model for farmers and foresters

As discussed in the previous sections, targets are important to encourage Member States to design effective policies and measures. At the same time, action is needed to ensure that land managers are adequately equipped to adapt their management practices to mitigate GHG emissions or enhance carbon removals. As outlined in Chapter 3, the management decisions of land managers are not influenced solely by legislation and policy incentives but also by a myriad of socio-economic, cultural and environmental factors (EC, 2022a). One of the key barriers is that farmers, foresters and landowners do not have sufficient financial incentive or capacity to engage in carbon farming activities.

Many new funding mechanisms and incentives are now available or being developed to encourage carbon removals and emission reductions in the LULUCF sector. For example, the previous EC (Von der Leyen I) introduced several initiatives in the context of its Carbon Farming Initiative to scale up mitigation activities in the land sector with the use of results-based schemes, whereby finance is directly coupled with the resulting abatement effect. This resulted in the EU CRCF Regulation (EU, 2024), which can unlock investments in land mitigation measures from both private and public finance, such as through the CAP and State aid.

([24]) (1) Decarbonisation, (2) energy efficiency, (3) energy security, (4) internal energy market and (5) research, innovation and competitiveness.

4.3.1 EU CRCF Regulation

Globally, the financing of carbon removals via voluntary and compliance markets as well as public financing schemes has been facilitated by standards that aim to enable certification of abatement results via credible MRV. However, it has been well documented that the quality of the methodologies and governance processes for those standards varies greatly, opening the door to unreliable and low-quality certificates, fraud, errors or double counting and thus greenwashing (Probst et al., 2024). These risks undermine the trust of stakeholders and financiers and create reputational risks. In recent years, many standards and protocols have been established to address the risks and improve the quality of standards ([25]).

In this context, the CRCF Regulation offers a harmonised EU certification framework to create a more level playing field across the EU and enhance the quality and comparability of permanent carbon removals (e.g. DACCS and BECCS), carbon farming activities and carbon storage in products. Such a framework should promote trust in the certification mechanisms and reduce administrative costs, for example by using standardised baselines. Existing or newly created certification schemes must apply to be recognised under the CRCF Regulation and confirmed by the EC based on a comprehensive assessment of governance, rules, procedures and methodologies ([26]).

In the CRCF Regulation, carbon farming activities include activities that both remove carbon and reduce GHG emissions, such as rewetting or restoring wetlands and peatlands, and improving the use of fertiliser. The regulation therefore sets out the requirements under which carbon removals and soil emission reductions are eligible for certification under the EU certification framework. These requirements address various factors, including accurate and robust quantification, additionality and broader sustainability (i.e. QU.A.L.ITY criteria) (see Table 4.3). The CRCF Regulation also establishes rules relating to third-party auditing by certification bodies to ensure the credibility and reliability of the certification process, as well as rules on the issuance and use of certified units (i.e. to avoid double counting or claiming). The CRCF Regulation builds on existing practices and examples of certification systems for carbon farming activities in various Member States (COWI et al., 2020).

([25]) GHG protocol Land Sector and Removals Guidance; ISO 14064-2:2019 GHG Part 2: specification with guidance at project level for the quantification, monitoring and reporting of GHG emission reductions or removal enhancement; Integrity Council for the Voluntary Carbon Market (ICVCM) the Core Carbon Principles.

([26]) For this purpose, the EC will establish certification methodologies for specific carbon farming activities in collaboration with an Expert Group; these will include methods to define standardised baselines, quantify removals or GHG reductions, broader sustainability and monitoring requirements and liability.

Table 4.3 QU.A.L.ITY criteria under the CRCF Regulation

Criterion	Principles
Quantification	• Estimates should be conservative, accurate, complete, consistent, transparent and comparable. • Quantification should be undertaken with a high level of accuracy to ensure the highest quality reporting and minimise uncertainties, where feasible based on Tier 3 methodologies. • Uncertainties need to be reported and accounted for in a conservative manner. • Emissions and removals should be monitored based on an appropriate combination of on-site measurements with remote sensing or modelling according to rules set out in the appropriate certification methodology. • Methods used should result in conservative emission or removal estimates so that emissions are not underestimated and removals are not overestimated. • Standardised baselines ([27]) should be used based on social, economic, environmental, technological and regulatory circumstances, taking into consideration the geographical context including local pedoclimatic and regulatory conditions.
Additionality	• Activities should go beyond any EU or domestic legal obligations. • The incentive effect of the certification is needed for the activity to become financially viable.
Long-term storage, monitoring and liability	• The operator should demonstrate that a carbon farming activity is aimed at storing carbon over the long-term. • Carbon removed and subsequently stored by a carbon removal activity shall be considered to have been released into the atmosphere at the end of the monitoring period.
Sustainability	• Measures undertaken should do no significant harm to the environment and should be able to result in a co-benefit in relation to sustainability objectives. • Carbon farming projects need to demonstrate co-benefits in terms of a substantial contribution for biodiversity.

Note: Various elements relating to standardised baselines, additionality, monitoring and liability will be further defined in methodologies for specific activities, to be enshrined in EC delegated acts.

Source: Author's compilation based on the CRCF Regulation.

([27]) Standardised baselines under the CRCF Regulation refer to the standard performance of comparable practices and processes in terms of CO^2 emissions or removals and will be key to demonstrating the additionality (QU.A.L.ITY criteria) of the actions.

The CRCF Regulation is a voluntary framework and does not prescribe how certified units should be financed. In this sense, a first role may be anticipated for public finance (CAP, State aid) and the voluntary carbon market (VCM), while potential future financing could result from mandates for high-emitting sectors, public procurement or carbon pricing (ESABCC, 2025).Through a voluntary carbon market, corporate or financial institutions willing to compensate their residual emissions or claiming a climate contribution can thus start financing carbon removals, allowing for farmers and foresters to be more effectively compensated for mitigation actions (e.g., a farmer who is looking for alternative income agrees to establish trees as agroforestry on a field and is compensated for additional costs or a loss of revenue).

Importantly, all carbon removals and soil emission reductions certified via schemes under the CRCF Regulation must contribute to achieving the EU's Nationally Determined Contribution (NDC) and its climate objectives ([28]). This means that mitigation results cannot contribute to the NDC of a third country or international compliance schemes (such as the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA)). At the national level, climate change mitigation effects resulting from activities should be reflected in national GHG inventories and contribute towards achieving the LULUCF target.

The CRCF Regulation and development of certification schemes will result in data needs to monitor each parcel of land under certification. Depending on the methodologies, this could involve on-site measurements as well as remote sensing and/or modelling data. There is a general challenge in trying to balance monitoring costs and acquiring reliable monitoring data for the quantification of carbon removals and emission reductions from practices at the parcel level (Mercer et al., 2024). In particular, for measures to increase SOC, the relative costs of MRV can be a significant share of the total costs. In this context, the CRCF Regulation suggests making the best use of data available in other systems, such as the Land Parcel Identification System (LPIS) relating the CAP as well as advanced technologies available under EU programmes, such as the Copernicus Land Monitoring Service (CLMS). Beyond quantification of GHG emissions and carbon removals, the CRCF Regulation will also result in data needs related to the requirements to Do No Significant Harm (DNSH) and to generate co-benefits for the protection and restoration of biodiversity and ecosystems.

4.3.2 CAP

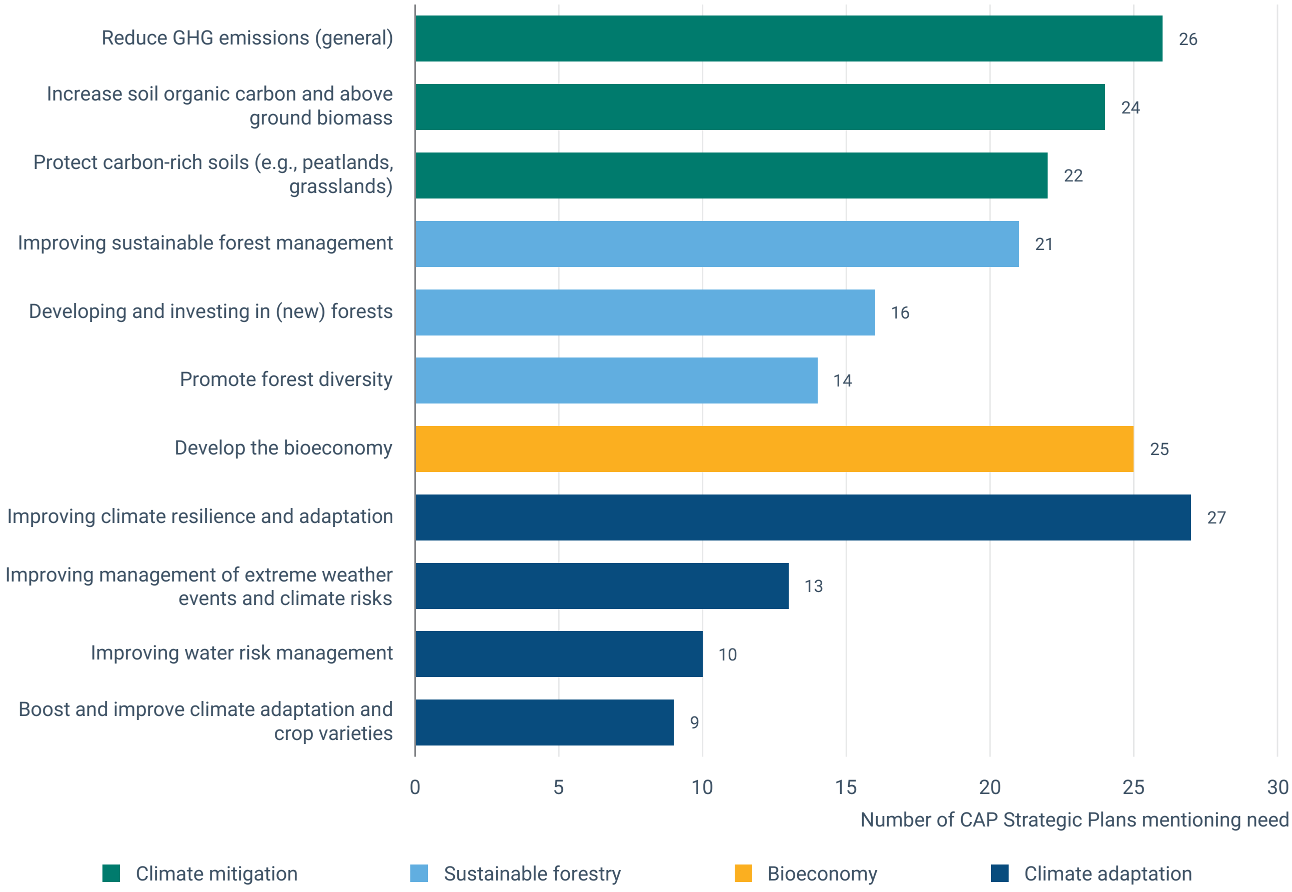
The EU's CAP integrates climate change mitigation and adaptation as a key objective for the 2023-2027 period. Under the Regulation in force (EU, 2021c), 40% of the CAP budget (EUR 386 billion in total) should be dedicated to climate change-related challenges.

Member States can provide financial support to farmers and land managers who commit to undertaking specific environmental and climate practices or investments via the CAP; this can include commitments for carbon farming practices. Relevant interventions can include payments granted directly to farmers and other land managers, investment, training and knowledge sharing or market measures. Beneficiaries must comply with specific management requirements (conditionality) to receive CAP payments.

([28]) During COP29 in Baku (2024) countries reached an agreement on international carbon markets, including new rules for transparency on bilateral carbon deals between Parties and a Paris Agreement Carbon Crediting Mechanism (PACM), including a standard for methodologies for carbon offsets (GHG reductions and carbon removals).

Member States implement the CAP by designing national CAP Strategic Plans (CSPs), which outline interventions tailored to their individual needs (Agrosynergy et al., 2023). In the CSPs, the needs to reduce GHG emissions and to increase removals, either in soils or AGB, were identified by the majority (26) of Member States (Figure 4.3). While some Member States (Greece, Hungary, Croatia, the Netherlands, Poland, Slovakia) intend to enhance removals in living biomass (e.g. through agroforestry and forest measures), others prioritise action related to soil carbon stocks (Belgium (Walloon region), Denmark, Germany, Ireland, Italy, Luxembourg, Malta, Romania and Sweden). Other Member States consider the two approaches to be equally important (Austria, Belgium (Flanders region), Bulgaria, Czechia, Estonia, Spain, Finland, France, Lithuania, Latvia, Portugal, Slovenia) (Agrosynergy et al., 2023). The CAP can also lever funds via carbon certification schemes, with countries such as Spain, France and Portugal proposing specific measures for their adoption.

Figure 4.3 **Needs identified in Member States' CAP Strategic Plans**



Note: Unit refers to number of countries mentioning need.

Source: Agrosynergy et al., 2023.

Only a limited number of CSPs provide a quantified estimate of the mitigation effect of their plans in the LULUCF sector (Agrosynergy et al., 2023). Additionally, the information produced under the CAP (e.g. indicators) refers mainly to practices or investments supported, rather than quantified estimates of mitigation in LULUCF. In this context, the EC has developed a methodology for estimating the climate change mitigation potential of CSPs and subsequently assessed the expected GHG effects from interventions included in the CSPs (Angileri et al., 2024).

The methodology applied is based on rough estimates of expected implementation levels alongside average emission and removal coefficients for farming practices. These coefficients are mainly derived from meta-reviews of scientific papers. Key results of the subsequent study 'Rough estimate of the climate change mitigation potential of the CPSs (EU-18) ([29]) over the 2023-2027 CAP programming period' (EC, 2024e) are given below:

- 32% of the total CAP funding is aimed at delivering benefits for the climate, water, soil, air, biodiversity and animal welfare and it is focused on encouraging practices beyond the mandatory conditionality.
- 19 CPSs indicate a potential positive contribution to GHG emission reductions and enhanced removals of 31 $MtCO_2e$ per year; 78% of this is expected to come from crop rotation or diversification, expansion of cover crops and conversion to organic farming.
- The analysis shows that 64% of the estimated potential mitigation benefit is associated with the cropland reporting category, which corresponds to storage of carbon in soils; The second-largest estimated mitigation potential relates to a reduction of non-CO_2 emissions from agricultural soils, and wetlands (CRF category 3.D and 4.D, accounting for 30% and 5% respectively).

The estimated mitigation from this study cannot be directly compared to the EU target to reach 42 $MtCO_2e$ of additional removals by 2030 compared to the base period 2016-2018, primarily because certain mitigation measures have already been captured by the GHG inventories. The expectation is that the interventions under the CAP which contribute to reducing the conversion of key land uses like wetlands or grassland or financing afforestation/reforestation are reflected in the existing inventories.

The 'rough estimate' study notes that these results provide a preliminary indication of the overall maximum potential contribution of the CSPs and should be interpreted with caution. The methodological study underpinning this quantification identified the need for further development and refinements to improve the accuracy of the estimates, such as the use of local coefficients and data on the actual uptake of the interventions (EC, 2024e).

From the perspective of carbon farming, the ongoing debate and foreseeable development of quantitative assessments indicates a substantial need for data and information beyond the national MRV processes and their use under other policy domains to evaluate, set targets and design policy scenarios and interventions. Unless more detailed data become available, the GHGI cannot reflect measures or changes in management practices financed and implemented at farm or parcel level. Improved monitoring and reporting, with a focus on spatially explicit data and

([29]) A final report for all 27 Member States will be published in the course of 2025.

changes measurable over time, will also contribute to the identification of areas or measures with higher mitigation potential to inform future CSPs. This will allow interventions to be better targeted.

4.3.3 State aid for agricultural and forestry practices

Under EU law, in view of a well-functioning internal market, Member States are generally prohibited from providing State aid to undertakings (EU, 2012), unless there is an exceptional justification. Under specific circumstances and complying with certain conditions, aid can be allowed. One example of this is in the case of addressing certain market failures in relation to the EU objective of environmental protection. Public funding by Member States in the area of agriculture and forestry outside of the CAP instruments is subject to EU State aid rules (ClientEarth, 2024).

Within the context of the EGD, the EC amended its State aid rules in 2022. The revised 'Guidelines for State aid in the agriculture and forestry sector and in rural areas' (EC, 2022b) are designed to guide the EC to assess whether a notification by a Member State to approve certain State aid is justified. Specifically, the revised guidelines allow for the possible allocation of State aid to agriculture and forestry practices that lead to a significant enhancement of the environment at larger scale or in a measurable way, via the use of collective schemes and result-based payment schemes, such as carbon farming schemes ([30]).

The Agricultural Block Exemption Regulation (ABER) (EU, 2022d) declares certain categories of aid to be compatible with the EU State aid rules and exempts them from prior notification to, and approval by, the EC. The ABER exempts aid from being obliged to notify the EC for a wide range of measures in agriculture and forestry relevant for emission reduction or enhancement of removals, up to a certain aid ceiling. Also covered by the ABER is aid aimed at preventing natural disturbances in forests or related restoration activities.

An example of State aid in the area of LULUCF is the Ireland Forestry Programme 2023-2027 (Ireland Afforestation and Creation of Woodland). This programme aims to create up to 8,000ha of forest per year during the period 2023-2027 for the purpose of climate change mitigation, biodiversity and socio-economic benefits. The State aid will include grants and support for the establishment of afforested areas and annual premiums per ha over a maximum of 20 years. The programme recognises that different amounts of financial support are needed depending on the type of forest, in terms of the composition of species. Another example of State aid in this context is the French scheme (EUR 720 million) to support the forestry sector in the period 2023-2029 with a focus on increasing forest resilience and restoring damage to forests resulting from forest fires, natural disturbances, pests, diseases and climatic events.

4.4 Tracking the progress of mitigation action

MRV forms the basis of different types of governing frameworks relevant for undertaking activities or measures that aim to enhance carbon removals or reduce emissions from all sectors, including land use ([31]). MRV is carried out at the national level in countries that are parties to the UNFCCC; it follows specific guidelines and requirements (see Chapter 2).

([30]) Member States must still notify the EC of such schemes, which could facilitate testing innovative financing approaches, e.g. public procurement of carbon removal credits through reversed auctions.
([31]) Different notions and definitions of MRV exist, with the 'm' standing for either measurement or monitoring.

Under the UNFCCC, the verification process for GHG inventories is performed at two levels: international and domestic. At the international level, it takes place through the review processes under the UNFCCC and Paris Agreement to support transparency of the information provided. Domestically, it is part of the national GHG Quality Assurance/Quality Control and verification process, whereby data are checked using external methods and independent datasets.

In the private sector, MRV systems also apply to projects, companies or production chains, for different purposes. These include assessment in relation to corporate climate targets and that which informs corporate mitigation strategies, linking finance to mitigation activities and/or MRV in the context of regulatory requirements to do so (e.g. financial disclosure).

As such, MRV can serve various objectives, including data provision for policy decisions; ensuring good governance and accountability through increased transparency and credibility; engaging the private sector; and improved access to finance (Smith et al., 2024; Partnership on Transparency in the Paris Agreement, 2018). MRV can be applied to different climate-related areas, including total GHG emissions, mitigation actions (policies, projects) and financial support.

4.4.1 Reporting progress and the improvement of LULUCF inventories

Accurate reporting of GHG emissions and removals in the LULUCF sector is crucial to account for progress towards national targets and to assess Member States' compliance with targets and commitments under the LULUCF Regulation. Considering the new role of the LULUCF sector in the climate governance framework, EU regulation foresees a role for the EC in tracking the progress of Member States and at the EU level on an annual basis.

For the current LULUCF inventories, Member States are responsible for monitoring and reporting their GHG emissions and removals, compiling GHG emission estimates and reporting on methodologies applied to derive these estimates. Member States must also verify their data using independent national or international datasets, as part of their quality assurance (QA)/quality control (QC) and verification process. This type of comparison helps to identify major calculation errors or may highlight a subcategory in any sector that has been omitted or falsely allocated in the calculations.

The Governance Regulation (EU, 2018c) has established a subsequent process to allow the EC to check (QA/QC) the accuracy of the data reported by Member States on an annual basis via 'initial checks', in order to improve the inventory data and compile an aggregated EU inventory. In addition to the annual checks, the EC is due to conduct comprehensive reviews of national GHG inventories in 2025, 2027 and 2032; the primary purpose of these is to ensure robust data for compliance, in addition to informing target-setting, calculating possible technical corrections and analysing the effect of possible flexibility mechanisms applied.

The important role of inventory data means that it is essential for Member States and the EC to make efforts to improve the quality of inventory systems. More specifically, this involves improving reporting methods, increasing reporting transparency and promoting the use of datasets obtained via advanced land monitoring technologies (such as satellite images), and other, as elaborated in Section 2.4 and Chapter 5. The EU adopted new rules that require Member States to advance the tier levels they are using to report on specific areas and use geographically explicit land use conversion data (Box 4.1). The challenges involved are vast but there is scope for addressing them if data and best practice are exchanged and developed.

Box 4.1

Monitoring requirements as set out in Annex V, Part 3 of the Governance Regulation

The methodological requirements set out by the Governance Regulation to improve GHG inventories are given below:

- From 2021 the methodologies used for monitoring and reporting emissions under the LULUCF sector shall include the use of geographically explicit land use conversion data in accordance with the 2006 IPCC Guidelines for national GHG inventories.
- From 2021, the use of Tier-2 methods is required following the IPCC guidelines to estimate emissions and removals for carbon pools that account for at least 25% of emissions or removals in a source or sink category.
- From the 2028 GHG inventory submissions onwards, the Governance Regulation requires the application of at least Tier-2 methods for all managed land categories.
- Use of Tier-3 approaches is required from 2030 at the latest for all carbon pool emission and removal estimates falling in areas with high carbon stock, areas under protection or restoration and areas of land units under high future climate risk. The comprehensive list of area definitions is provided in Regulation 2018/1999 Annex V, Part 3 amended by Regulation 2023/839.

4.4.2 Projections for LULUCF

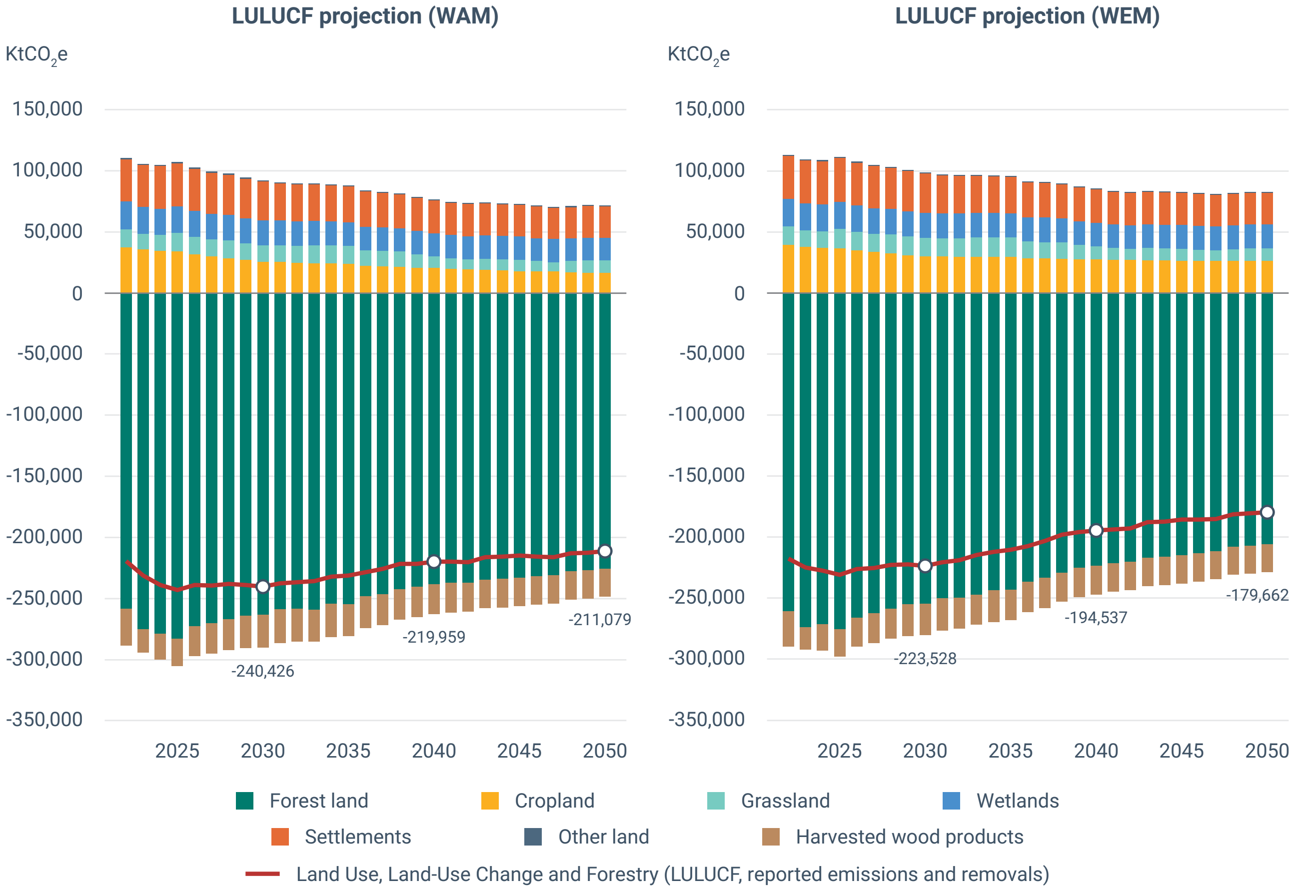
Projections provided to the EEA in 2023 and 2024 (Figure 4.4) by Member States indicate that the EU as a whole is not currently on track to meet its 2030 target for LULUCF and suggest a reduction in removals compared with the 2016-2018 average (EEA, 2024b).

Such projections suggest that net removals will decrease at EU level, from an average of 315 $MtCO_2e$ of removals per year in 1990-2021 to 206 $MtCO_2e$ in 2022-2050, with existing measures. Additional measures reported by Member States are expected to increase average net removals in 2022-2050, by 10% compared to the WEM scenario. All six of the Member States with the highest LULUCF net removals will see their capacity to remove emissions decrease considerably (Figure 4.5).

Figure 4.4 shows that the forest land sink is projected to further decline in the coming decades, while emissions from cropland and settlements are projected to decrease, with other categories remaining relatively stable.

Projections illustrate that additional Member States' policies and measures in LULUCF are needed to ensure that the EU target for 2030 is achieved, and to secure the effectiveness of the sector in contributing to climate change mitigation in the coming decades.

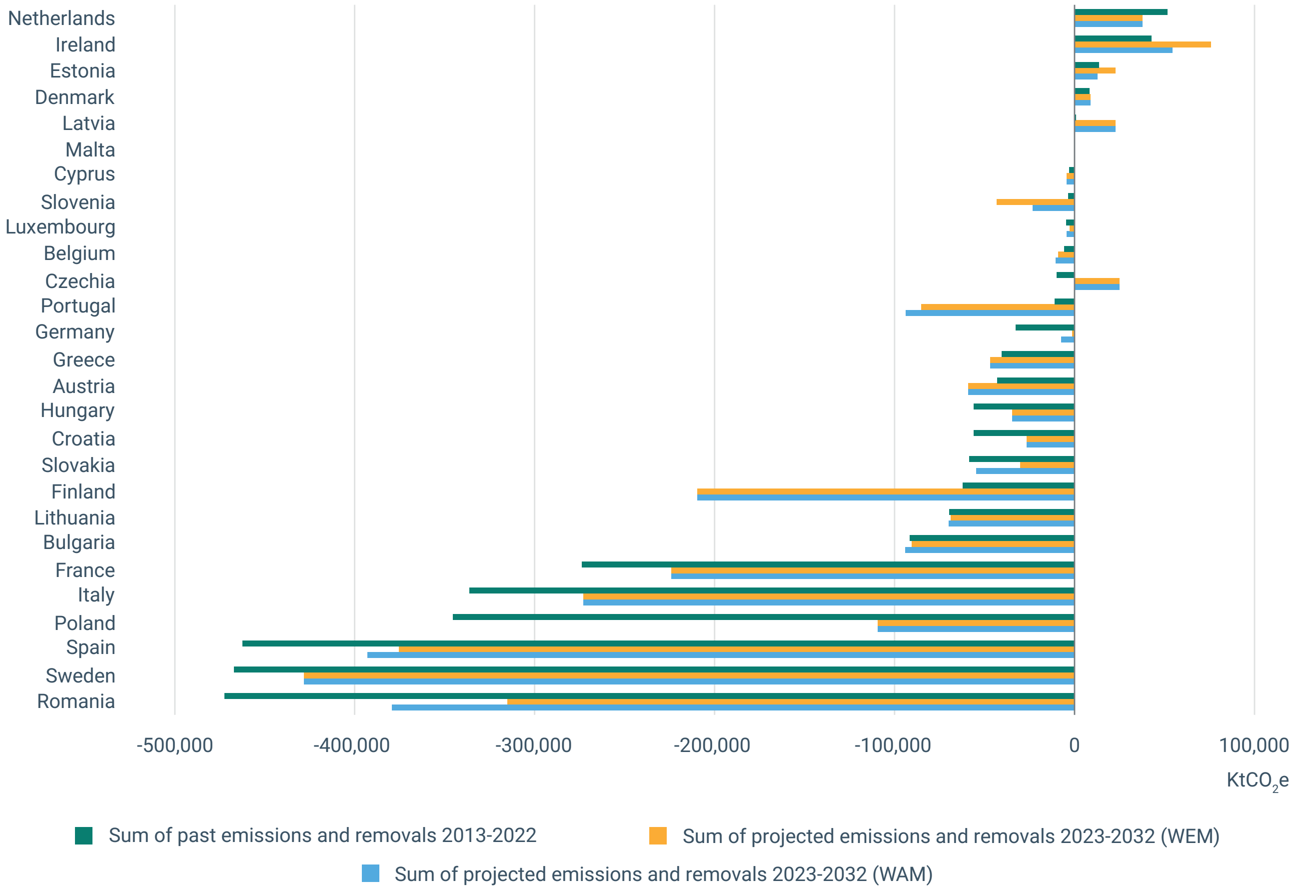
Figure 4.4 **WEM/WAM projections per LULUCF category for the period 2022-2050**



Source: EEA, 2024b.

A 2025 Commission assessment of the final NECPs shows that several Member States have stepped up efforts in the land sector compared to the draft plans and 9 Member States now project to reach their national LULUCF targets. However, the assessment also shows there is still a gap of about 45-60 $MtCO_2e$ compared to the LULUCF 2030 target, equivalent to about 100%-140% of the target of additional removals (EC, 2025b). The EEA is expected to publish an update of the projections submitted by EU Member States in the course of 2025.

Figure 4.5 **Comparison of cumulative historical (2013-2022) and projected (2023-2025) net LULUCF emissions or removals per EU Member State**



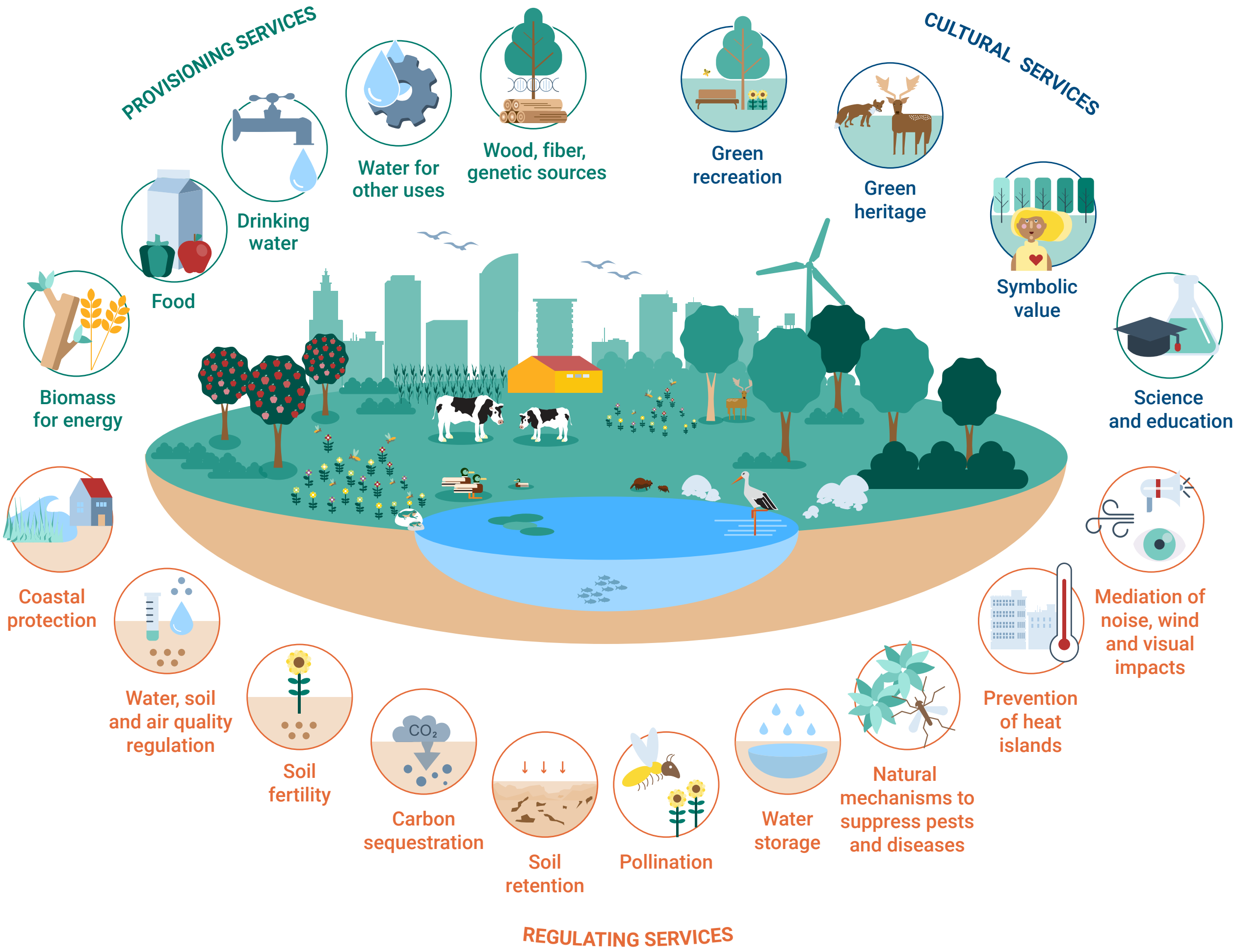
Source: EEA, 2024b.

4.5 Policy objectives relating to land and forests beyond climate change mitigation

In Europe, human activities have been driving biodiversity and ecosystem degradation. Land use change and overexploitation of natural resources have been the main drivers, together with pollution, climate change and the introduction of invasive alien species (IPBES, 2018; Maes et al., 2020). These are indirectly caused by economic, demographic, technological, institutional and cultural drivers, which interact in complex ways (IPBES, 2018; Maes et al., 2020; IPCC, 2019b). Most ecosystems in the EU are in an unfavourable condition, undermining ecosystem services, including to deliver biomass, protection against floods, crop pollination, biodiversity and nature-based recreation (Maes et al., 2020).

Terrestrial ecosystems offer a wide range of ecosystem services to societies, including provisioning, regulating and cultural services (Figure 4.6). In most cases, land or forests are being managed in such a way that they deliver multiple ecosystem services, following the principle of 'multifunctionality' (EC, 2021a). Yet, while this is relevant in certain areas, in other locations trade-offs can occur (as discussed in Chapters 1 and 3). In some instances immediate trade-offs occur but over longer time frames synergies between ecosystem services are still relevant (EEA, 2020). For example, measures that increase forest resilience to climate change and natural disturbances could reduce an area's role in climate change mitigation in the short term but preserve carbon stocks and sinks over a longer time span.

Figure 4.6 **Schematic overview of ecosystem services from terrestrial ecosystems**



Source: Author's compilation based on CICES classification of ecosystem services.

At the EU and national levels, various strategies, policies and measures have a direct or indirect effect on terrestrial ecosystems and can have a particular emphasis on one or more specific ecosystem services. Relevant EU policies and EU regulations are categorised in Figure 4.7 in relation to supporting objectives in the areas of: (1) climate and energy, (2) environment and ecosystems, (3) financial frameworks, and (4) monitoring and reporting. This shows the complexity of the regulatory landscape relating to terrestrial ecosystems, in terms of societal expectations and policy objectives as well as governance. In this section we focus on regulations relevant for biomass use, biodiversity and climate adaptation

Figure 4.7 **Schematic overview of EU policies and regulations relevant for land**

EU strategic and regulatory framework relevant for land

* EC proposal, awaiting adoption

** A new Bioeconomy Strategy will be published in 2025

EU strategic frameworks

- European Green Deal
- 8th Environmental Action Programme to 2030
- EU Biodiversity Strategy for 2030
- EU Forest Strategy for 2030
- EU Soil Strategy for 2030
- EU Climate Adaptation Strategy
- EU Zero Pollution Action Plan
- EU Bioeconomy Strategy **
- New Circular Economy Action Plan
- EU Farm to Fork Strategy
- Vision for Agriculture and Food
- Communication on Sustainable Carbon Cycles
- EU Industrial Carbon Management Strategy
- EU Industrial Strategy

Source: Author's compilation.

4.5.1 Balancing LULUCF and the bioeconomy

Since the mid-2000s the use of biomass, predominantly from domestic forestry, as a substitute for fossil fuel has increased significantly (EEA, 2023). As discussed earlier in this report, an increase in the use of biomass and its mobilisation from agricultural land and forests for substitution can have a negative effect on the ability of land and forests to sequester carbon from the atmosphere. The net GHG impact from biomass substitution can result in a carbon debt, climate neutrality or a carbon gain, depending on a variety of factors (Strengers et al., 2024).

For example, changes in forest management to supply forest biomass for energy purposes can result in both negative and positive climate impacts, depending on the factors and time frames considered. This means that focusing on the LULUCF sector in a silo and over the short term while ignoring substitution potentials can lead to negative mitigation outcomes. At the same time there is also a risk of substitution resulting in net GHG emissions if harvest levels are continuously increased (Aguilar et al., 2020; Birdsey et al., 2018).

While forest biomass can be considered a renewable resource over periods of multiple decades, it does remain limited, bounded by the availability of land and forest increment. Yet, in view of low-carbon transitions, various sectors are eyeing biomass resources as a way to decarbonise their value chains. This could result in levels of sustainable supply from within the EU and third countries being exceeded (Material Economics, 2021; EEA, 2023; ESABCC, 2023).

A sensitivity analysis produced as part of the EC assessment to inform the EU 2040 climate target indicated that increasing the demand for woody biomass by 20 million tonnes of oil equivalent (Mtoe) could result in a decrease of net LULUCF removals by around 100 $MtCO_2e$ (EC, 2024a). It is therefore necessary to be careful about determining the scale at which biomass can be supplied without risking the objective to enhance the EU's LULUCF sink. This also raises a question about the optimisation of biomass use within a developing bioeconomy, from the perspectives of mitigation pathways, energy transition and other socio-economic benefits in addition to other environmental objectives (EEA, 2023).

Policies at the EU and Member State levels have diverging effects on biomass production, biomass substitution and carbon sequestration (EEA, 2023). Since the early 2000s, the use of biomass as a substitute for fossils fuels and carbon intensive materials has been increasingly driven by policy ([32]). Most importantly, the Renewable Energy Directive (RED) (EU, 2009b) provides the basis for bioenergy to count towards the renewable energy targets of Member States and the EU as a whole. Additionally, bioenergy can be eligible for State aid and other regulatory incentives, such as energy taxation exemptions (EU, 2003a), zero-rating of biogenic emissions under the Emissions Trading System (EU, 2003b) and recognition under the taxonomy for sustainable finance (EU, 2020).

The RED provides criteria for the sustainable sourcing and cascading use of biomass, but the Advisory Board concluded these are not sufficiently stringent and operationalised (ESABCC, 2025). Regarding the Industrial Emissions Directive (IED), the Advisory Board flagged that it could undermine the land sink while it does not include specific requirements regarding efficiencies of the carbon capture process related to BECCS (ESABCC, 2025).

([32]) Starting with the Renewable Electricity Directive (2001) and biomass action plan (2005), predecessors of the Renewable Energy Directives (broader scope) and EU bioeconomy strategies.

Importantly, biogenic emissions from the combustion of biomass are not accounted (zero-rated) in the EU Emission Trading System (ETS). Consequently, the energy operator responsible for them does not incur any financial liability. Independent of possible avenues for State aid, an increasing carbon price may therefore encourage energy operators to substitute fossil fuels with biomass.

Instead, emissions from biomass combustion are reported and accounted in the LULUCF sector, i.e. 'at the point of harvest'; for these, the financial liability lies solely with Member States (and the taxpayer), as discussed earlier in this chapter. Different targets and financial liabilities and support mechanisms for the energy and LULUCF sectors could lead to optimisation of biomass use in the energy sector or broader bioeconomy without full consideration of the impact in the LULUCF sector, both in the EU and in third countries (Strengers et al., 2024; EEA, 2023). To reduce this risk, Member States should carefully assess the effect of the use of biomass on the LULUCF sink, both in their NECPs and climate progress reports (EU, 2018c).

Various policies aim to encourage removals, ensure progress in the LULUCF sector or create synergies with the bioeconomy. For example, the RED sustainability criteria recognise the need for compliance with LULUCF commitments and the newly established CRCF Regulation could lever finance for operators to support carbon farming and long-term storage in wood products. While the ESR (EU, 2018b) and the CAP could incentivise biomass substitution (e.g. in transport, buildings and agriculture), they could also encourage demand for carbon removal credits. This is because the ESR allows for flexibilities with the LULUCF sector and the CAP offers the possibility for Member States to financially incentivise carbon farming.

Importantly, the EU bioeconomy strategy (EC, 2018) and bioeconomy strategy progress report (EC, 2022c) recognise the importance of data for monitoring the bioeconomy in line with climate and sustainability objectives, including carbon sequestration, climate adaptation, and nature and biodiversity protection ([33]). Additionally, the EU Regulation on Deforestation-free Products (EUDR) (EU, 2023) has been proposed as one tool to address the bloc's responsibilities in relation to deforestation and forest degradation within the EU and in third countries, and consequently, GHG emissions embedded in imported products.

4.5.2 Creating synergies between LULUCF, nature restoration goals and climate adaptation

As indicated earlier in this report, biodiversity decline and climate change are closely interlinked; as such, the recommendation is that they should be addressed jointly (IPCC, 2019a; IPBES, 2021). Yet, there is scope at different levels of government for more integrated, multi-functional approaches to soils and forests, focusing on carbon sequestration, biodiversity, ecosystem resilience and sectoral transition pathways in a joint manner (see e.g., Beland Lindahl et al., 2023; Vrebos et al., 2017). The EU Forest Strategy also emphasised the need for improved forest management to increase carbon sequestration and other ecosystem services. In this context, an important objective of climate policies for land is therefore to create synergies between enhancing carbon sinks by NBS, nature restoration- and biodiversity objectives, and increasing resilience.

([33]) In 2025, the EC is expected to publish a new EU bioeconomy strategy.

The LULUCF Regulation specifically requires Member States to take into account biodiversity and adaptation to natural disturbances when developing their plans under the Governance Regulation. The CRCF Regulation includes a specific requirement for carbon farming to create co-benefits for biodiversity. Additionally and positively, the EU Taxonomy for sustainable finance recognises the need for activities to contribute to climate change adaptation and to the protection and restoration of biodiversity and ecosystems (EU, 2020).

The NRR (EC, 2024d) sets targets for Member States to implement restoration measures for an increasing share of terrestrial ecosystems in line with international commitments ([34]), and includes specific requirements for SOC in agricultural land, restoring forest ecosystems and contributing to the EU goal to plant at least 3 billion trees. Ecosystem restoration could deliver significant mitigation in LULUCF:

- Restoring 90% of terrestrial habitats that are either in 'not good' or 'unknown' condition to 'good' condition under Annex I of the Habitats Directive was estimated to have, over time, a theoretical sequestration potential of 286 MtCO_2e per year (Kopsieker et al., 2021).

- The restoration of peatland and wetlands could achieve additional net mitigation benefits of between 7.8 MtCO_2e per year and 22.8 MtCO_2e per year to 2030 and between 26.7 MtCO_2e per year and 62.9 MtCO_2e per year to 2050 (EC, 2021b).

- The restoration of arable land could result in removals of 20 to 200 MtCO_2e per year, with the lowest estimate relating to the implementation of measures which are considered economically feasible and the highest based on technical potentials (Smith, 2012).

As discussed in Chapter 1, the restoration agenda is closely linked with climate adaptation, and the EU Climate Adaptation Strategy (Climate-ADAPT) indicates: 'We need science-based, robust ecosystem restoration and management that helps minimise risks, improves resilience, and ensures the continued delivery of vital ecosystem services and features: food provision, air and water purification, flood protection, biodiversity, and climate mitigation.'

4.5.3 The importance of an enhanced monitoring framework for land

These objectives require a better understanding of the relations and interdependencies between land management practices, climate change, ecosystems and the services they provide, in particular in a context in which European terrestrial ecosystems and vegetation types are expected to undergo significant shifts in the coming decades (EC, 2021c; EEA, 2024c) ([35]). Understanding of the relations and interdependencies can only be achieved with adequate monitoring data, reporting and modelling capabilities.

According to the LULUCF Regulation, Member States are required to assess and report on the extent to which policies and measures result in synergies and trade-offs with climate adaptation and biodiversity (EU, 2018a). Equally, carbon farming certification methodologies developed under the CRCF Regulation will include monitoring and reporting obligations on synergies with environmental objectives.

([34]) Kunming-Montreal Global Biodiversity Framework.
([35]) See also the EC project: BIOCLIMA: Assessing Land use, Climate and Biodiversity impacts of land-based climate mitigation and biodiversity polices in the EU.

While the enhanced monitoring system for LULUCF described in Box 4.1. is primarily focused on areas of significance for climate change mitigation, the requirements for improved monitoring and reporting (e.g., Tier 3 methods) correspond to areas referred to in other regulations; areas with a high carbon stock, areas under protection or restoration and areas of land units under high future climate risk (see Table 4.4). As such, enhanced monitoring for LULUCF could potentially provide useful information for and contribute to an enhanced monitoring system for biodiversity and adaptation.

Table 4.4 Types of area covered under the Governance Regulation Annex V part 3 (see box 4.1) and how they relate to EU regulations

Regulation	High carbon stocks	Protection sites	Restoration sites	High climate risk zones	Soil carbon stocks
Renewable Energy Directive	X	X	X		
Birds and Habitats Directives		X	X		
Water Framework Directive		X	X		
EU Taxonomy on sustainable finance			X		
Regulation on Deforestation-free products		X	X		
Flood Directive				X	
National adaptation strategy				X	
Nature Restoration Regulation		X	X		
Forest Monitoring Law (*)		X	X		
Soil Monitoring and Resilience Law (*)					X

Note: (*) These are currently EC proposals, but they have not been (formally) adopted and implemented.

Source: Author's compilation based on the Governance Regulation.

The NRR provides the obligation for Member States to report every 6 years on various indicators, including on deadwood, share of forests with an uneven-aged structure, forest connectivity, SOC stock, and tree species diversity. Further implementation details are under development at the time of writing. In 2024, the EU also revised the Environmental Accounts Regulation, for compiling and harmonising national statistics, integrating modules on the condition of ecosystems, forests and environmental subsidies.

To contribute to monitoring in the land sector, the EC has published a proposal for a directive on soil monitoring and resilience (Soil Monitoring Law (SML)) (EC, 2023b) and a proposal for a regulation on a forest monitoring framework (Forest Monitoring Law (FML)) (EC, 2023c). These are under review by the Council of the EU and the European Parliament at the time of writing. These initiatives aim to close certain data gaps and contribute to improving soil health and resilient forest ecosystems in the EU by supporting a more comprehensive and harmonised knowledge base for the land sector for the entire geographical area of the EU (wall to wall).

Most Member States lack regular soil inventories. This hampers a good understanding of soil carbon dynamics (EEA, 2024c). The proposed SML could result in comparable standardised and harmonised data about soil properties (e.g. indicators on SOC) differentiated according to soil type, climatic conditions and land use. The proposed FML could provide information on a range of forest characteristics, such as carbon stock (living biomass, dead wood), biodiversity, disturbances, through a network of monitoring systems representative of a Member States' forest areas. While these sources of information may not result in an annual data flow directly informing GHG inventories, they might nonetheless provide useful information, such as for modelling. However, there is a need to ensure coherency and complementarity between the reporting obligations.

In view of various policy objectives for more 'win-win' strategies in the land sector, concerns regarding the practical feasibility and financial costs related to monitoring (see Chapters 2 and 3) call for the creation of reporting synergies and interoperability of data. For example, detailed, geographically explicit data from the IACS on cropland management at parcel level (e.g. cover crops, agroforestry or tillage intensity), could contribute to linking management practices and other biophysical characteristics, from soil type to environmental conditions. This could support the improvement of GHG estimates for cropland for the GHG inventories, but it could also help in identifying potential 'hot spots' for action in both the LULUCF sector and other policy areas. Additionally, certificates generated under the CRCF Regulation may in the future inform GHG inventories by providing geographically explicit data and information on the abatement effects from practices applied, such as emission factors to inform Tier 2 and Tier 3 methodologies. Section 5.2.6 further discusses the scope and challenges relating to data interoperability.

4.6 What data needs and data use cases result from EU policies?

The various legislative and financial frameworks described in this chapter point to varying data needs and the use of certain methodologies for different purposes and actors involved. Based on the new regulatory framework, Table 4.5 identifies six different categories of data use cases. These categories of data use cases represent varying data requirements in terms of: (1) geographical and temporal scales (e.g. the need for annual data); and (2) the extent of the information required from various parameters and indicators (e.g. in relation to land use, land management practices, data on carbon stocks and carbon flux; other environmental issues, such as water, biodiversity or other ecosystem services).

While different requirements were identified for the various use cases, the main characteristics of the requirements identified are summarised below:

- Geographical scale: geographically explicit data can contribute substantially to the needs identified. Geographically explicit data should be representative at the national and regional scales and compliant with the requirements to estimate changes at the desired scales. Equally, point data, referring to information at the level of projects and surveys, can provide important insights for some applications.

- Temporal resolution: independent of the time and frequency of data acquisition, annual information is required for most of the needs identified. Additional systems conceived to monitor the implementation of practices is also necessary at the level of projects and interventions. Certainty about the continuity of data acquisition is not a pre-requisite but can substantially facilitate the use of specific datasets.

- The extent of information required from various parameters and indicators includes activity data (e.g. extension of land uses or land use changes) and changes in carbon stock and fluxes. In addition and given the expected synergies under relevant legislation (from LULUCF to CRCF Regulation), information regarding other environmental issues (e.g. water, biodiversity or other ecosystem services) is necessary to assess co-benefits and negative impacts.

This table is merely a starting point, and further assessments are needed to identify in greater detail the specific information requirements to estimate a change in carbon stock or flux in addition to the data sources that might be able to accommodate such requirements.

Table 4.5 Overview of identified data use cases relating to mitigation measures in the LULUCF sector

Data use case	Primary actors	Legal/organisational frameworks	Objectives/applications	Main requirements for fit-for-purposes datasets
1. GHG inventory and improvements	EU and national authorities	Governance Regulation LULUCF Regulation UNFCCC Reporting IPCC Guidelines	Annual assessment of trends and drivers of trends Accounting for emissions and removals towards targets Better representation of the main characteristics of the different pools and potential changes Capturing mitigation effects from land policies (e.g. certified carbon farming activities and CAP measures)	Key areas for the LULUCF sector include changes in carbon stock or fluxes in the most relevant pools (i.e. SOC, living biomass) and land use changes. Temporal resolution should be sufficient to estimate annual values for the relevant variables (e.g. changes in carbon stock). The Governance Regulation sets out requirements in terms of required detail (tracking land use change and high accuracy reporting).
2. Verification of national GHG inventory data: initial checks, comprehensive review, corrections	EU authorities	Governance Regulation	Quality assurance based on independent datasets Checks and verifications of data and methods used in the inventories	This use case should ensure estimates of activity data and emissions independent from data used in the inventories. Temporal resolution should be sufficient to estimate annual values for the relevant variables. Spatial resolution could include geographically explicit data, surveys and point source data.

Table 4.5 Overview of identified data use cases relating to mitigation measures in the LULUCF sector (cont.)

Data use case	Primary actors	Legal/organisational frameworks	Objectives/applications	Main requirements for fit-for-purposes datasets
3. Target-setting, design of policy scenarios, policy design and evaluation of policies	EU and (sub-) national authorities	Governance Regulation (NECPs, LTSs) CAP Regulation EU Climate Law Supporting sectoral and Member States' targets Private/economic actors	Setting objectives and targets Identifying key areas, sectors and cost-effective measures Ex-ante evaluation of the impact of policies Monitoring the effect of policies	Beyond existing GHG inventories, comparable information and proxies would be necessary at more detailed scales (e.g. regions) and for sub-sectors for this use case. Data on biomass supply chains and their effect on forest/ land management and related carbon flows (Strengers et al., 2024) should be included for this use case. Synergies can be expected with the improvements in data availability described in Use Case 1 (GHG inventories).
4. Quantification of baselines and mitigation effects resulting from changes in practices at the level of implementation measures, for certification purposes; estimating mitigation effects from carbon insetting.	Private operators	CRCF Regulation CAP Regulation State aid rules Corporate Sustainability Reporting Directive (CSRD) ([36])	Definition of baselines in terms carbon removals or emissions associated with a business-as-usual scenario (ex-ante, ex-post) Quantification of mitigation effects Monitoring the implementation of individual projects under the certification framework	Detailed information on carbon stocks and fluxes is necessary at the parcel/plot level and more general estimates at regional scales, based on regular practices, to determine the baseline levels. Information at plot level should include evidence of changes in practices (e.g. soil data) and/or land uses (e.g. satellite data).

([36]) The Corporate Sustainability Reporting Directive (CSRD) (EU, 2022f) requires large companies and listed companies to publish regular reports on the social and environmental risks they face and on how their activities impact people and the environment.

Table 4.5 Overview of identified data use cases relating to mitigation measures in the LULUCF sector (cont.)

Data use case	Primary actors	Legal/organisational frameworks	Objectives/applications	Main requirements for fit-for-purposes datasets
5. Implementation of interventions	EU, national and sub-national authorities and private actors	CRCF Regulation CAP Regulation State aid rules CSRD	Improving the effectiveness and efficiency of policies and measures Allocating finance and resources, such as by better targeting interventions at specific geographic areas or LULUCF categories	Knowledge about the potential impact and other effects per practice, per sector and geographical areas is essential to better design interventions. Monitoring systems should be used to verify that the implementation of the interventions is also necessary as described in Use Case 4.
6. Assessing changes in environmental conditions (biodiversity, water and soil aspects et al.) and assessing trends and projections based on possible effects from climate change and natural disturbances.	EU, national authorities, and private actors	LULUCF Regulation Governance Regulation CRCF Regulation	Improving synergies, ensuring co-benefits and anticipating negative effects Anticipating effects from climate change and natural disturbances to help target and tailor actions in the LULUCF sector to specific circumstances	Reinforced monitoring systems should be used at the level of specific projects to evaluate co-benefits and potential negative effects, within the area of the intervention and affected-impacted areas. Temporal scales should be adapted to the effects monitored, from the short term (e.g. 1 year) to the medium term (5-10 years).

Source: Author's compilation based on expert review of the various regulations mentioned.

5 Europe-wide geospatial datasets for MRV of land carbon

Key messages

- Geospatial data play a fundamental role in tracking land use changes and their impact on land-based carbon removals. They can improve LULUCF carbon stock change assessments at national levels and support plot-level verification of certified removals (e.g. under schemes that are approved under the CRCF Regulation). These data, derived from earth observation (EO) and/or from sampling methods, support Member States in improving LULUCF reporting, filling possible gaps and enhancing comparability.

- A wide range of pan-European geospatial products are available, developed through collaborations between various EU institutions. Key products include land cover datasets provided by the Copernicus Land Monitoring Service (CLMS); forest fires' area and emissions from the European Forest Fire Information System; soil carbon data derived from Land Use/Cover Area frame Survey (LUCAS) and global systems like Global Soil Organic Carbon (GSOC); atmospheric data offered by Copernicus Atmospheric Monitoring Service (CAMS) for near-real-time greenhouse gas monitoring; and agricultural data from Common Agriculture Policy datasets like IACS and LPIS.

- For LULUCF inventory compilation, EO data offer multiple uses, such as identifying land cover changes, supporting emission and removal estimates, and verifying data accuracy. Challenges in their use include harmonising data definitions and semantics, improving spatial and temporal resolution, integrating old and new datasets, and filling data gaps in support of inventory compilers.

- To enhance the use of EO in the area of carbon removals in the land sector, data providers must better tailor EO products towards specific needs (such as reporting in GHG inventories), and ensure a timely delivery of data, including local and on-site observation data collected from the ground. There should be better collaboration between EO communities, policymakers, inventory reporting institutions and certification bodies.

- In this context, there is scope for aligning GHG inventories with other databases and GIS systems to improve data sharing, reduce redundancy, and enhance reporting efficiency across policy areas, using standards like metadata and semantic mapping for coherence and comparability.

5.1 Introduction

The success of climate policies in the land sector relies on improving the monitoring and reporting of GHG emissions and carbon removals, enabling accurate assessment of progress, effective sequestration practices and informed decision-making. Robust MRV systems are not only needed at the national level but also at the farm or forest parcel level.

As indicated in Chapters 1 and 2, preparing a GHG inventory for LULUCF requires data from various sources to be integrated to estimate CO_2 and non-CO_2 emissions and removals associated with human activities. These data include information on land cover and land use, land management and the related changes in biomass, dead organic matter and soil carbon stock pools.

Recent technological advancements have significantly improved the availability and quality of geospatial information, providing valuable insights into land use changes and their impact on carbon sinks and fluxes. By leveraging these advancements and fostering collaboration, the EU and Member States can strengthen their efforts to improve the quality of their reporting, ensuring interoperability between monitoring data and systems under land-related policy frameworks.

At the EU level, an increased focus on the integrated use of geospatial information is required under various policy frameworks, including the LULUCF Regulation, NRR, forthcoming Soil Monitoring and Forest Monitoring Regulations; this is supported by the INSPIRE Directive (EU, 2007) and Open Data Directive ((EU) 2023/138) (EU, 2022c). These policies call for enhanced data collection, sharing, standardisation and interoperability at various levels to improve the effectiveness of land-based carbon monitoring and reporting.

A wide range of pan-European geospatial products are available and can support a comprehensive understanding of carbon removals and storage in terms of quantifying and tracking the changes. These products, developed through collaborations between EU institutions, research organisations and private companies, provide high-resolution geospatial data and analytical tools. The integration of existing pan-European geospatial data can help fill gaps and improve the overall quality and comparability of LULUCF reporting in different land use categories and pools.

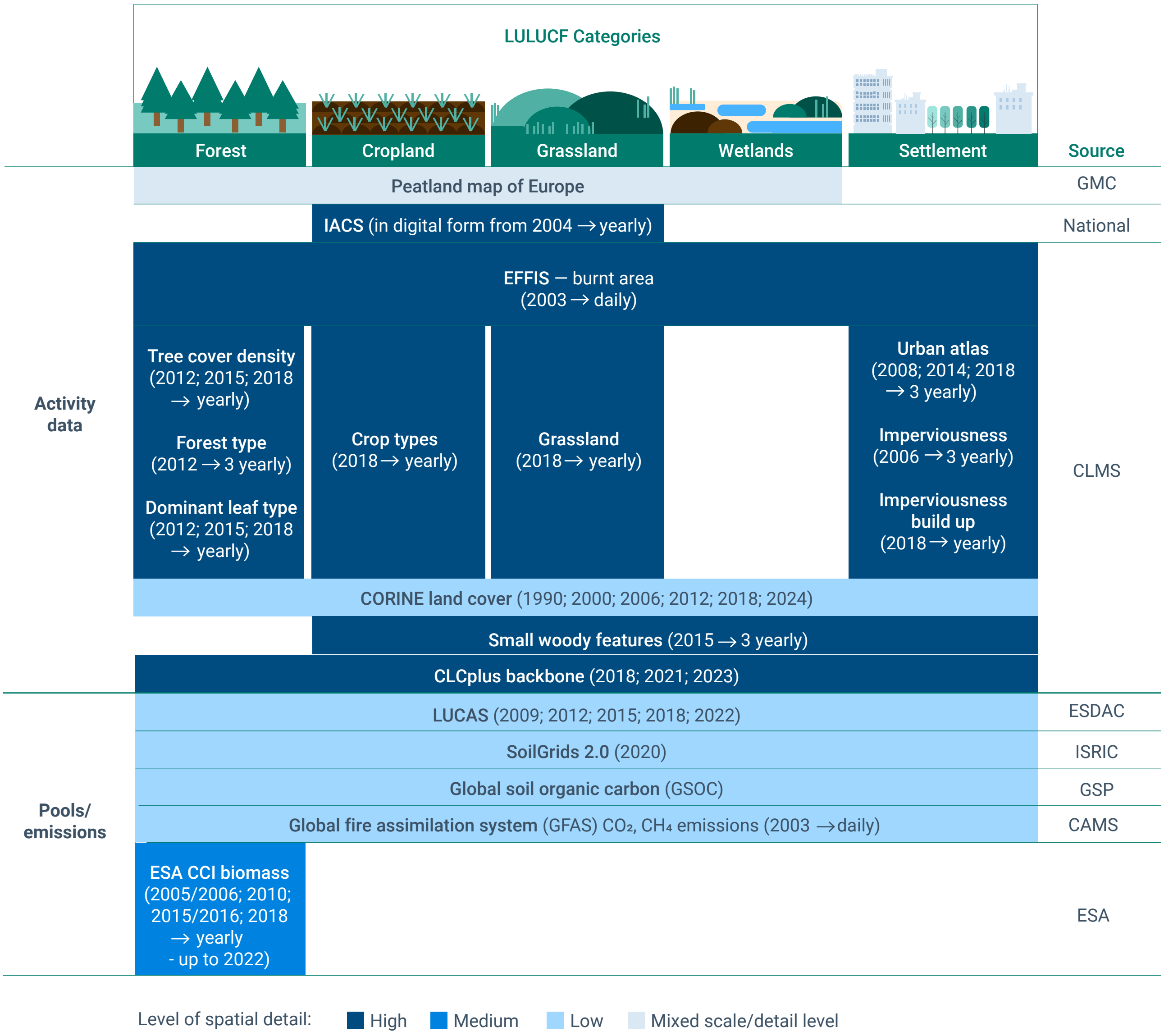
This chapter provides an overview of the most relevant EU geospatial products and their potential use. Section 5.2 presents several key pan-European geospatial datasets to identify land cover and changes in land cover, to understand land cover change in relation to specific drivers (e.g. harvesting, clearing, fire) and to quantify biomass stock and carbon fluxes. The section also discusses the importance of using thematic geospatial datasets that can inform other policy areas and avoiding duplication efforts to monitor the same phenomena in various thematic policy settings (e.g. linking climate change mitigation with biodiversity). Section 5.3 reflects on the role of EO in LULUCF reporting.

5.2 Europe-wide products

Geospatial data play a crucial role in tracking land use changes and their impact on land-based CO_2 removal as well as improving carbon stock change assessments for both national and plot-level verification (such as under the CRCF Regulation). Key datasets, such as those provided by the CLMS, offer valuable land cover information, including specialised products like LULUCF Instances, which integrate land use and land cover data.

Other critical sources, including biomass stock estimates from the European Space Agency (ESA) Climate Change Initiative (CCI), fire emissions data and soil carbon maps from LUCAS and GSOC, help assess carbon stocks and removals. Additionally, real-time atmospheric GHG data from the CAMS aid GHG emission estimates and verification. LULUCF efforts are further enhanced by integrating agricultural datasets from the CAP, although there are still challenges related to the resolution and integration of data as well as harmonising data definitions.

Figure 5.1 Overview of Europe-wide datasets relevant for LULUCF, considered in this report



Note: Sources' acronyms, links and references: GMC: Greifswald Moor Centrum, (Tanneberger 2017); CLMS: Copernicus Land Monitoring Service; ESDAC: European Soil Data Centre; ISRIC: International Soil Reference and Information Centre; GSP: Global Soil Partnership; CAMS: Copernicus Atmosphere Monitoring Service, details on products in Annex 3; ESA: European Space Agency.

Source: Author's compilation based on expert review.

This section provides an overview of a selection of the main data sources at European level (Figure 5.1) that can serve as input data for estimating emissions and removals from the land sector at country level.

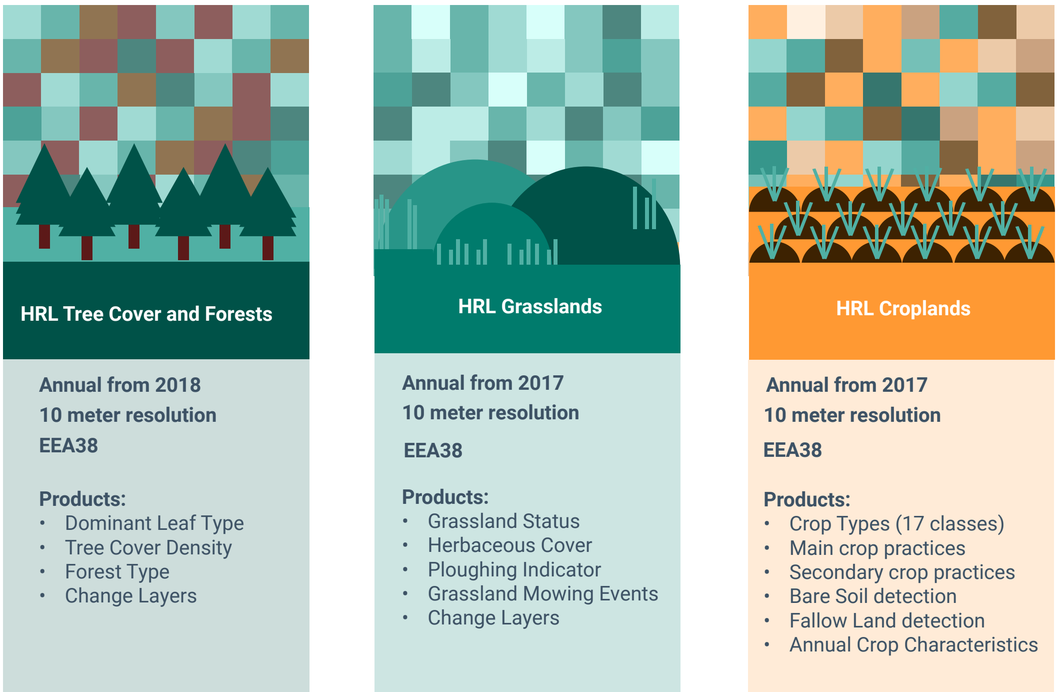
5.2.1 Land cover and land use mapping products to support monitoring and verification

The CLMS is one of the six operational services of Copernicus, providing services and datasets derived from satellite data for the land domain as part of the European Space Agency's Climate Change Initiative (CLMS, 2025). The CLMS makes available geographical information on various parameters related to land: land cover and its changes; land use; ground motion; vegetation state; and water cycle and earth surface energy variables, both at European and global level.

CLMS has been operational since 2012 and some of its products go back as far as 2006. The Sentinel-2 (optical) and Sentinel-1 (radar) satellite data that have allowed for improved spatial, temporal and spectral resolution imagery for free and open use have enabled major improvements to the portfolio, including the evolution of existing products and creation of new ones. These improvements became available from 2015-2017 onwards. Most of the products present a rather high spatial resolution (10m) and they are updated frequently (every 1-3 years). An overview of CLMS products which are specifically relevant for LULUCF and their main characteristics is provided in Annex 3.

All CLMS products are available free of charge and they can be accessed by all users. They are also guaranteed to be operational long-term. This is an important detail because operational monitoring systems rely on consistent and repeated updates of comparable products.

Figure 5.2 Illustration of the current CLMS portfolio of high-resolution datasets relevant for the LULUCF sector



Note: HRL VLCC stands for the new High Resolution Layer (HRL), Vegetated Land Cover Characteristics (VLCC). This follows a more consistent grouping of all vegetation related CLMS HRL's into one overarching category. More details are provided in Annex 3.

Source: CLMS, 2025, Courtesy CLMS, see https://land.copernicus.eu/en/products for more detailed information and data access.

In general, satellite-derived products can effectively classify land cover and land cover change. In contrast the main aim of a national GHG inventory is to report on land use and land management (e.g. whether an area is cropland or managed forest), since managed lands are those identified as sources of and sinks for anthropogenic emissions and removals (GFOI, 2016; Romijn et al., 2018). In other words, land cover refers to the observed physical cover on the ground (vegetation, water etc), while land use refers to socio-economic or functional aspects of the land (e.g. golf course, airfield, pasture etc.). For example, satellites detect a change in land cover over a forest that was harvested even if no land use change occurred. Likewise, satellites cannot easily differentiate a pasture from a golf course.

The datasets produced operationally by CLMS are largely mapping land cover, in particular the type of vegetation cover (e.g. grassland, tree cover and forest, cropland), vegetation phenology (plant growth and development), soil sealing (imperviousness), and snow and ice cover. However, some CLMS products also map features of land use (crop rotation, mowing) meaning that the information provided by the products can be closer to the land use categories used by countries under LULUCF reporting (see Table 2.1). For example, the CLMS grassland and cropland High Resolution products can be used to approximate the respective LULUCF categories with the same names.

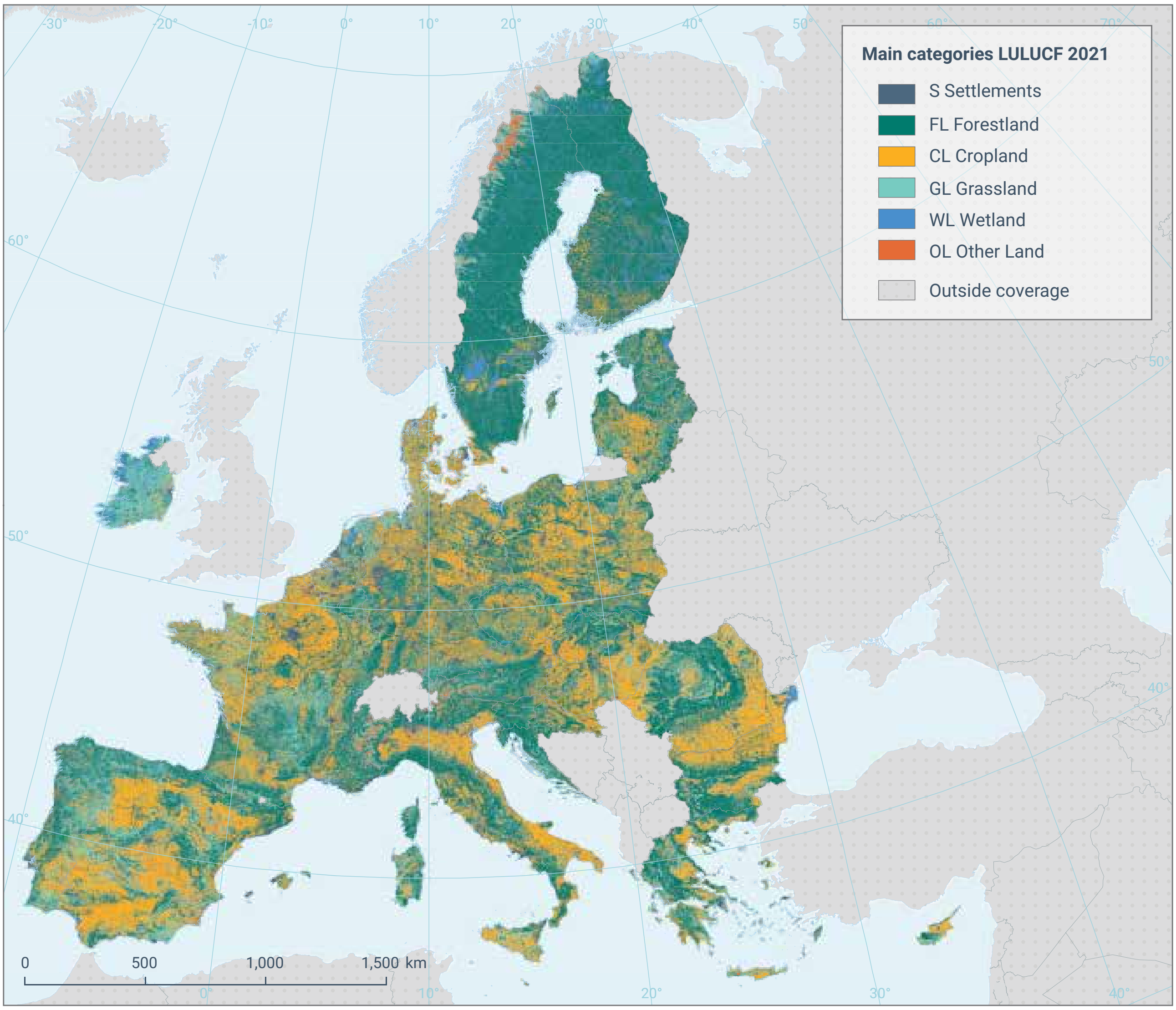
Anticipating the increased policy needs for up-to date and frequently updated land cover and land use information, in 2017 the CLMS began to plan for a set of new products and tools which are better able to support policy needs, like those arising from the revised LULUCF Regulation. This has led to the design and implementation of the next generation CORINE land cover (CLCplus) system.

Instead of being a single product or a portfolio of products, the CLCplus system combines a new land cover product with a two-year update cycle (CLCplus Backbone, BB) with a database and online user interface (CLCplus Core) that allows the production of tailor-made 100m grid products (CLCplus Instances), combining existing input datasets. Tailor-made products, using this system, specific for the LULUCF use case, are called 'LULUCF Instances' and they combine the best land cover and land use information available from different sources.

For the EU-level, CLMS now produces one consistent LULUCF instance annually for the whole EU area as an independent approximation for the LULUCF categories that countries report annually (Map 5.1). The current LULUCF instance is available for the 2018 and 2021 inventory years and classifies the EU-27 territory into 27 subclasses that can be grouped in the main six LULUCF categories (Map 5.2).

In addition to producing an EU-level LULUCF instance, the CLCplus system can also produce country-level instances based on more detailed national datasets. The EU-wide LULUCF instance is constantly improved and (from the 2021 inventory year) available annually in time for the country submissions in January of the inventory year +2.

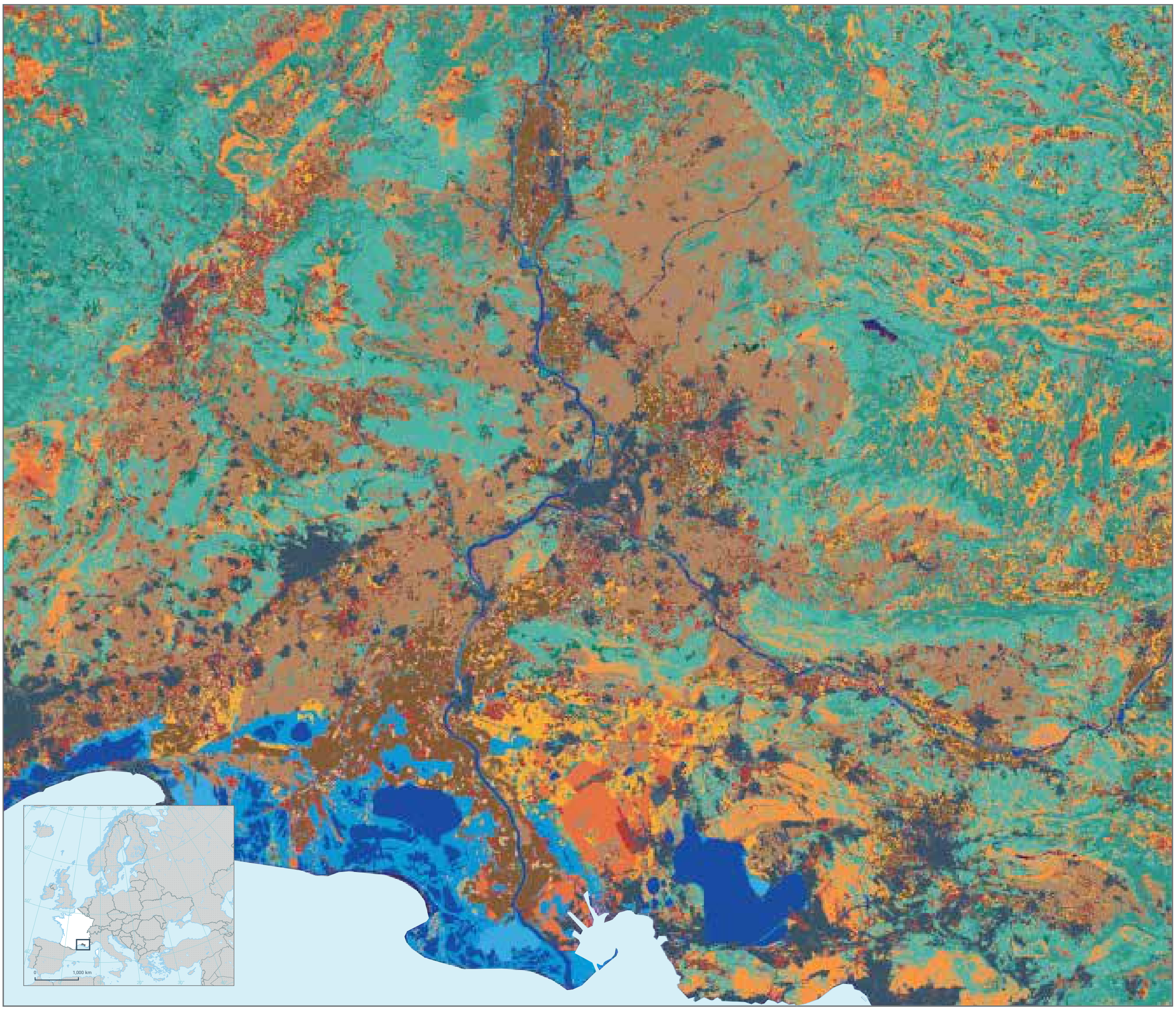
Map 5.1 **2021 LULUCF instance dataset, illustrating both the extent of production and six main LULUCF categories mapped**



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

Source: CLCplus LULUCF Instance 2021 at 100m (URL to dataset not available), Copernicus Land Monitoring Service (EEA/CLMS).

Map 5.2 **2021 LULUCF instance dataset, in more detail and with all sub-categories mapped in the product**



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

LULUCF Land Use classes 2021

- 11: S Burnt areas
- 12: S Settlements
- 13: S Green urban areas
- 14: S Other settlements
- 21: FL Burnt areas
- 22: FL Transitional woodland
- 23: FL Deciduous
- 24: FL Coniferous/Evergreen
- 25: FL Other forestland
- 31: CL Burnt areas
- 32: CL Annual crops
- 33: CL Perennial crops
- 34: CL Other cropland
- 41: GL Burnt areas
- 42: GL Pastures
- 43: GL Shrubs
- 44: GL Natural grassland
- 45: GL Other grassland
- 51: WL Wetland managed
- 52: WL Wetland unmanaged
- 53: WL Water managed
- 54: WL Water unmanaged
- 61: OL Bare soil and rocks
- 62: OL Permanent snow and ice
- 63: OL Lichens and mosses
- 64: OL Other land

0 20 40 60 km

Source: CLCplus LULUCF Instance 2021 at 100m (URL to dataset not available), Copernicus Land Monitoring Service (EEA/CLMS).

The CLMS datasets and CLCplus products could be useful for several types of use case in the context of LULUCF monitoring and verification activities. The datasets could support national geospatial systems for LULUCF monitoring and reporting by, for example, filling national data gaps. Likewise, the CLMS datasets could be used synergistically with existing national geospatial datasets, for example to supplement (not replace) data derived from infrequently compiled land use inventories with more frequently updated remote-sensing based tree cover density products.

The use of CLMS datasets, in particular the tailor-made and annually updated 'LULUCF instance' datasets, can also provide (country) independent, EO-based proxies for the activity data reported by countries, to be used for verification purposes at the EU level. This use is currently being piloted and tested by the EEA as one element of LULUCF verification activities, within the QA/QC process for the Member States' GHG inventories.

Individual countries may also use CLCplus Core themselves to create country-specific LULUCF instances. This online system allows existing land cover and land use data from various sources to be input (ingested) and harmonised using a common nomenclature (EAGLE). The land use and land cover data in the system are then combined in creative and novel ways. For example, an existing pan-European forest LULUCF instance rule set in CLCplus Core can be taken and improved by adjusting the rules according to a national definition of a forest; national forest datasets can then also be added to the system.

Testing and implementation of the system/workflow are ongoing and as such there are currently still a number of unknowns and possible limitations around the use of CLMS datasets to support MRV for LULUCF. In terms of Europe-wide harmonised data, the main limitation and challenge is around gaps and incomplete land use (and land use change) data availability and also around the timing of available updates for the input data and the degree to which countries' definitions for LULUCF categories vary. All CLMS input datasets, indirectly used to create the LULUCF instance, have very high overall accuracy, with detailed information on validation and classification accuracy provided. Additional steps to evaluate the accuracy of the results for LULUCF instances are currently being explored and implemented.

To facilitate the use of the LULUCF instances, the EEA offers training to support countries to use the CLCplus system. This training can help countries to evaluate the usefulness of available datasets or systems in order to develop their own geospatial LULUCF monitoring and reporting.

5.2.2 Data on biomass carbon stocks and emissions

The living biomass of terrestrial ecosystems is an important pool of carbon that is influenced by land use management (e.g. deforestation, harvesting) and natural disturbances (e.g. tree mortality, fires, pest and diseases). At the European level there is a set of EO-derived products that can support the assessment of stocks and emissions of living biomass, especially AGB that is more easily detectable from space. This section of the report gives an overview of the most relevant datasets for carbon monitoring and verification.

The ESA CCI biomass project provides global estimates of woody vegetation, AGB in Mg/ha (megagram per hectare, equivalent to tonnes per hectare) at a fine spatial resolution of 100m, for multiple epochs (2005/6, 2010, 2015/16) and annually from 2018 to 2022 (ESA, 2025). These data can be used to quantify biomass at various time steps and understand biomass changes over time. Two global layers are provided: one for AGB and the other for per-pixel uncertainty (standard deviation), allowing for a detailed analysis of biomass distribution and the associated uncertainties. Despite the large uncertainties in AGB change products, particularly at finer scales, the fact that the data are updated annually and have global coverage make them one tool for biomass monitoring at the global level. However, estimates need to be consistently repeated to guarantee the data are comparable and available through time.

A great improvement is expected with the ESA's Biomass Earth Explorer mission (BIOMASS), with a planned launch around the end of 2025; this will be the first Spaceborne P-band Radar mission (synthetic aperture radar (SAR)). The main aim is to determine the worldwide distribution of forest AGB to reduce the major uncertainties in calculations of carbon stocks and fluxes associated with the terrestrial biosphere, including carbon fluxes associated with land use change, forest degradation and forest regrowth.

In general, biomass maps can be used as an independent data source for verification (if field data have not been applied to predict the biomass maps used for stratification); to improve the estimation of carbon emissions by increasing data density in under-sampled or inaccessible areas; and to improve the stratification of ground carbon inventories (IPCC, 2019a). However, some global maps frequently show significant systematic errors in the calculation of carbon stock and changes for local and national assessments, that need to be checked with the use of national data (Avitabile and Camia, 2018).

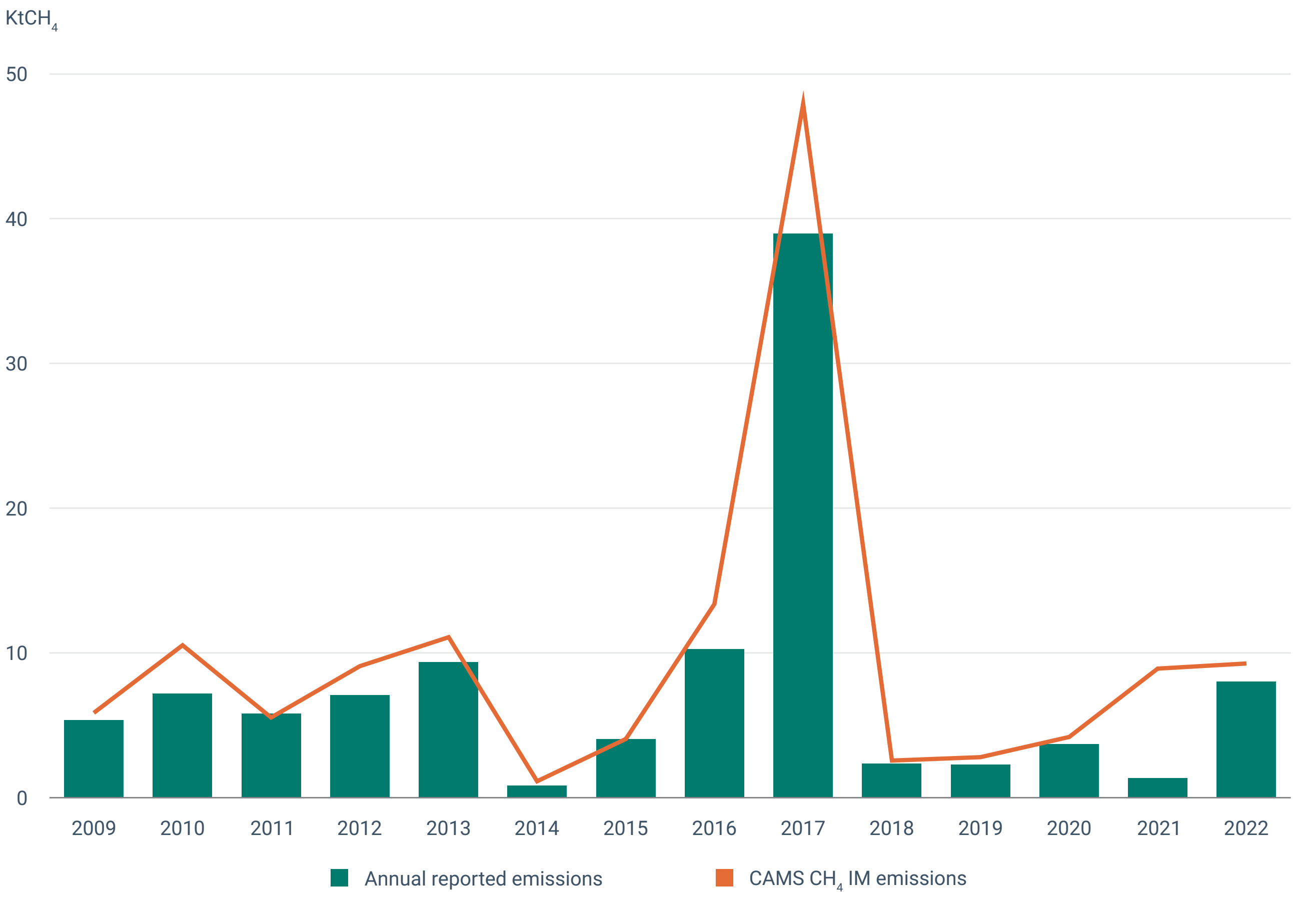
The CLMS products also provide information on other vegetation characteristics related to biomass carbon stocks and fluxes such as Tree Cover Density as well as the 10-daily Leaf Area Index or the productivity parameter of the High-Resolution Vegetation Phenology and Productivity (HR-VPP) product suite at high spatial (10m x 10m) and temporal resolutions. Those products, although not directly usable in LULUCF reporting, can provide information for the assessment of the state and development of ecosystems, habitats and land cover. Remote sensing-derived phenological and productivity measures can reveal patterns of land use, capture changes in ecosystems up to local scales and provide information on the health and interannual variability of ecosystems (Smets et al., 2024).

Wildfires can have a significant impact on emissions from grassland and forest land. In certain regions, like the Mediterranean basin, wildfires are common and recurrent, preventing the evolution of the vegetation towards natural tree stands (Chapter 2).

The Global Fire Assimilation System (GFAS) of CAMS (2025) provides daily estimates of emissions from burning biomass, using satellite-derived fire radiative power data across Europe. The data have been available since 2003 at a resolution of 10km and thus GFAS offers a consistent and homogeneous dataset for estimating fire-related biomass emissions independently of burned area assessments. Although the data are limited to cloud-free days, integration with other data, such as burned area data provided by EFFIS (see Figure 5.3), allows for more comprehensive emission estimates, particularly when broken down according to LULUCF categories at the country level.

In the figure below, an example is given of a comparison between CAMS CH_4 data and fire emissions reported by Portugal. The figure shows a comparison between the GFAS data and the reported emissions. However, the discrepancy between the reported and CAMS-estimated emissions requires further investigation.

Figure 5.3 **Annual CH_4 emissions from biomass burning (2009-2022) for Portugal from CAMS and GHGI in $ktCO_2e$**



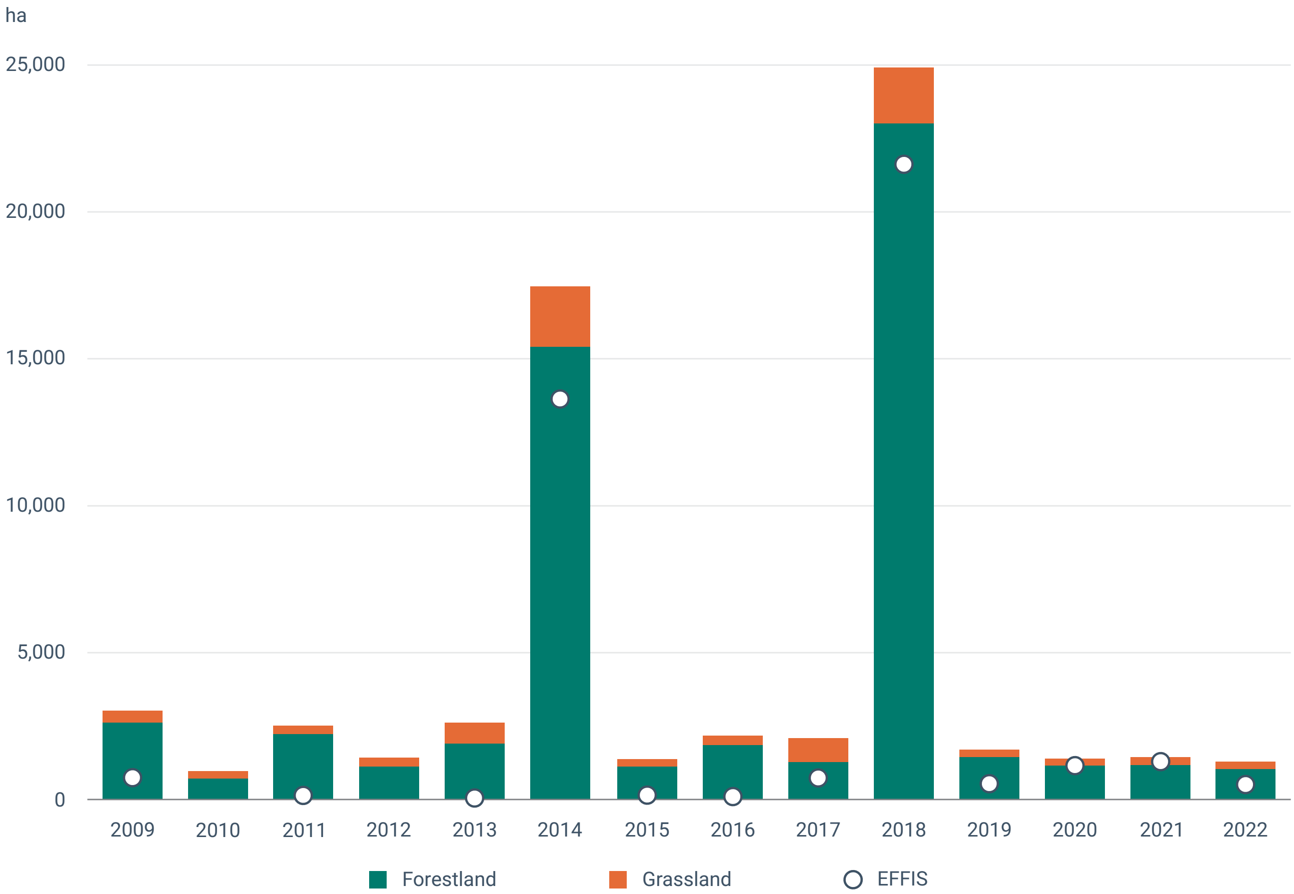
Source: Authors' analysis on the basis of Portugues GHGI 2024 submission (Portuguese Environment Agency 2024) and CAMS CH_4 IM emissions.

The coarse spatial resolution of GFAS goes some way towards explaining these discrepancies and it could be a barrier to the direct use of the data in LULUCF reporting, where the emissions for biomass burning need to be linked to the land categories at a finer resolution (<100m²) and to reported pools.

On the other hand, these GFAS data may be a relevant source for assessment of the overall quality of the inventory in capturing the magnitude and trends of fires at the country level. Additionally, the daily GFAS updates ensure that emission estimates are timely and reflective of current fire activities, making them an essential resource for real-time monitoring and response.

Another data source on forest fires is the EFFIS burned area dataset. This is a key resource for assessing the extent of wildfires and their impact on biomass, with daily updates since 2000 (EFFIS, 2025). This dataset provides detailed spatial information on fires, with a resolution of 250m pre-2017 and 20m from 2018 onwards.
By intersecting EFFIS data with land cover/land use data (i.e. CLC data, LULUCF instances), analysts can accurately quantify burned areas according to land cover type, including those relevant to LULUCF categories. An example of this comparison is provided in Figure 5.4.

Figure 5.4 **Area of forest and grassland burned in Sweden (1990-2022), comparing data from burned areas reported in the inventories and EFFIS, in ha**



Source: Authors' compilation based on (Sweden, 2024) and EFFIS data.

This intersection is particularly useful for understanding the role of wildfires as a natural disturbance affecting biomass stocks in Europe.

5.2.3 Soil carbon data

Soil data are crucial for understanding and managing the environment, agriculture and land use across Europe. Several key datasets and initiatives provide comprehensive soil information at the European level. The main dataset is the LUCAS, an EU-wide point survey undertaken every three years based on in-situ observation of land cover/land use types and the photographic record (Orgiazzi 2018). LUCAS reference years are 2009, 2015, 2018 and 2022. The surveys included a soil module, for which a topsoil sample was collected for around 10% of the survey points.

The LUCAS soil module was implemented in cooperation with the JRC and feeds into further data products (e.g. the pan-European SOC of agricultural soils) (Lugato et al., 2013). The objective of the soil module is to improve the availability of harmonised data on soil parameters in Europe. Over the years, LUCAS has been adapted in several ways to make the dataset more suitable and relevant for the LULUCF inventory (e.g. inclusion of a bulk density analysis and an increase in the measurements of the organic horizon). The new LUCAS 2022 survey will provide improved soil data because the number of points in the LUCAS soil survey was doubled in 2022 to reach total of 41000 in the EU.

The primary repository for soil data and information in Europe, including LUCAS data, is the European Soil Data Centre (ESDAC), managed by the JRC (2025b). ESDAC is an online platform hosting a series of pan-European and global datasets, maps and soil-related documents. Since its launch in 2006, ESDAC has grown in an ad-hoc fashion and aims to include the latest state-of-the-art know-how on soils at the pan-European scale. Since 2013 several modelled products have been published by the JRC under the ESDAC umbrella (Fernández-Ugalde et al., 2020; Aksoy et al., 2016).

At the global level, the Global Soil Partnership (GSP) created the GSOC map (FAO and ITPS, 2018). This is the result of a country-driven mapping effort for which countries from across the globe have produced SOC maps based on their own data, following a prescribed recipe or 'cookbook'. The GSOC estimates in subsoil provide global predictions of subsoil (30-100cm) SOC (tC/ha).

Another relevant soil information system is SoilGrids 2.0, a global gridded soil dataset that provides predictions for standard soil properties and classes at multiple depths, developed by ISRIC — World Soil Information (Poggio et al., 2021). Among other soil properties, SoilGrids provides SOC estimates at six standard depths globally with a spatial resolution of 250m. SoilGrids SOC predictions are obtained from machine learning models calibrated with over 230,000 soil profile observations (World Soil Information Service (WoSIS) database, see Batjes et al., 2024).

SoilGrids estimates are generated using a reproducible workflow, so they can be regularly updated as new soil data or covariates become available. The most important tasks undertaken by SoilGrids include: (1) extending the list of soil properties based on user requests (e.g. maps for subsoil carbon stocks) and (2) delivering maps at a resolution of 100m. A new methodology is currently under development towards a unified soil classification map of the world that would be more accurate and easier to use. However, this is currently hampered by a lack of reliable soil class observations.

Organic soils (i.e. soils that contain an organic carbon content >12% (including histosols and peatland) represent a significant emission source in the EU. It is crucial to map these soils and their water conditions accurately to estimate GHG emissions in the land sector (see Chapter 2). In Europe, historical and modern uses of peatland have led to substantial drainage and degradation, complicating accurate mapping. Countries such as Finland, Denmark and Germany have detailed local maps as a result of extensive research and policy-driven monitoring. However, much of the remaining peatland in Europe has been affected by agriculture and forestry, with over 90% drained in some areas. Mapping of organic soils and peatlands across Europe is supported by several initiatives and databases, though the coverage and detail vary significantly by region.

Information on the distribution of peatlands and organic soils in Europe is provided by the peatland map of the Greifswald Moor Centrum (Tanneberger et al., 2017). The dataset is not based on a single definition of organic soil as it uses the definitions, as well as the spatial scale, applied by each country.

Another important ongoing project is the Global Peatland Database (GPD) of the International Mire Conservation Group (IMCG) located and maintained at the Greifswald Mire Centre. The GPD collates and integrates data on the location, extent and drainage status of peatlands and organic soils worldwide and for 268 individual countries and regions. The GPD has produced a Global Peatland Map that integrates data from regional surveys and advanced remote sensing, but gaps remain, particularly in under-researched areas.

Land use change can have a large effect on the size of soil pools through activities such as conversion of native grassland and forest land to cropland, which can lead to the loss of 20-40% of the original soil carbon stocks (IPCC, 2019a). Repeated surveys are needed to detect such changes and currently soil maps comprising various properties, including carbon content, provide only static assessment of C stocks. Given the low level of detail and high uncertainty of these maps, they should not be considered reliable at plot level, where the variability in carbon content is high, but they do offer a general indication of the stock in the region, and they can be used for the application of IPCC methods that require SOC for reference conditions.

5.2.4 CAMS inverse modelling products for verification of national net GHG emissions and removals

Atmospheric measurements from remote sensing and point measurements can be used to provide useful quality assurance for national GHG emission estimates through the use of inverse modelling (IM) (German et al., 2021). Inverse modelling is a method utilised to estimate GHG emissions by tracing atmospheric concentration measurements back to their sources and sinks. It combines observational data, atmospheric transport models and existing knowledge of emission patterns to produce refined estimates of GHG emissions. In the LULUCF sector, inverse modelling can be instrumental in quantifying net emissions or removals of GHGs such as CO_2, CH_4 and N_2O through consideration of various land use practices and forest carbon dynamics (Deng et al., 2022).

The Copernicus programme plays an important role in supporting IM by supplying essential data through its satellites (Sentinels), in-situ measurements and services such as the European Centre for Medium-Range Weather Forecasts (ECMWF) and CAMS. CAMS offers near-real-time information on GHG concentrations and fluxes (ECMWF, 2020). By integrating these datasets with atmospheric transport models, it is possible to achieve more accurate estimations of GHG emissions and removals within the LULUCF sector (German et al., 2021). However currently IM in the GHGI is only used by a few countries (UK, Switzerland and Australia) to verify non-CO_2 gases outside the LULUCF sector (Perugini et al., 2021).

While IM offers valuable insights, there are limitations, relating to data uncertainty (which is not provided), model complexity, spatial resolution issues (coarse, in the order of km^2) and challenges in attributing the origin of the emissions (e.g., industry, agriculture, or transport). To improve the application of IM in GHG monitoring and reporting, efforts are underway to increase data availability with new satellites, improve computational infrastructure for more frequent model inversions and support EU-funded projects which aim to enhance GHGI processes (Walter et al., 2024).

5.2.5 Policy-driven data and information: the CAP

The IACS developed under the CAP contains spatially explicit data about land cover, land use and agriculture management which can provide relevant and detailed information which is regularly updated and validated by Member States. Tailored systems that hold national information about agricultural land have been implemented and enforced by several reforms to achieve the various policy goals. The IACS manages, monitors and serves the EU Member States to control CAP payments (such as: direct payments and area- and animal-based rural development interventions) but also ensures that comprehensive data about land use and management is available throughout the EU.

Each member state had set up and is operating a database system to administer and control direct payments as well as certain rural development payments to ensure that they are made correctly, to prevent and deal with irregularities and to ensure that CAP beneficiaries comply with management commitments (conditionality) ([37]). The IACS consists of several digital and interconnected elements and databases; from the perspective of land-based carbon removals, the following components are relevant:

- The LPIS is a geographic information system that uniquely identifies agricultural land ready for production. In the LULUCF context, LPIS holds relevant information associated with land use at a single parcel level or a set of neighbouring parcels represented as a block (arable land, permanent crops or permanent grassland); elements within the parcel excluded from CAP payments (i.e. constructions) and information regarding the obligations from farmers under the CAP (elements relevant under conditionality like presence of organic soils or landscape elements). The LPIS has been mandatory for Member States since 2004 in a digital form and from 2015 onwards at a scale of 1:5,000. The geographically explicit information, including land use data, contained in the LPIS, is subject to rigorous update cycles varying from 1-3 years. The data are quality assessed every year.

- The geo-spatial application (GSA) is an aid management system with corresponding graphic material (provided by a web-based application, including: remote sensing imagery and corresponding parcel data) that allows beneficiaries to visually indicate the areas for which they are applying for aid and provide information (e.g. crop declaration). In addition to crop types, the aid application consists of relevant information about management commitments (the adoption of practices) financed under the CAP.

- The area monitoring system is an MRV system for agricultural areas which has been fully implemented and is operational at the Member State level. It is based on systematic observations (every 3-6 days) based on Copernicus Sentinel data or other equivalent data that are analysed automatically to provide assessment of agricultural activities for all parcels concerned. The ongoing monitoring ensures that the applications are correct so at the end of the process, each parcel contains validated land cover information (crop types) together with data on detected agricultural activities and associated practices (i.e. green cover, ploughing, number of mowing events, harvest, etc.).

In terms of potential data use cases (see Table 4.5 in Chapter 4), IACS data can provide valuable information for GHG inventories and improvements or verification. Relevant information includes land use, land cover and information about land management practices (i.e. practices supported or requested under the CAP). The information could be available at the level of parcel, updated annually, quality checked and verified.

The LPIS is designed based on a common conceptual model and vocabulary (Sagris et al., 2013); as such, it is interoperable across the sectors, so the information has the potential to be reused. However, there are differences in implementation of IACS among the Member States and this may require an additional effort to ensure that data are harmonised across the EU to provide a pan-European dataset (Toth

([37]) The legal requirements for an IACS were set out in Regulations (EU) 1306/2013 and 640/2014(EU, 2013b) (EU, 2014). The contents of the IACS after the last CAP reform are described in Regulation 2021/2116 and EC delegated and implementing regulations (EU) 2022/1172 and 2022/1173(EU, 2022a;EU, 2022b).

and Milenov, 2020) (e.g. harmonisation of the crop types declared by farmers or management commitments declared by farmers across Member States). However, these additional needs should not be an obstacle to reusing it within a single Member State. At Member State level, IACS data reflect specific characteristics and capture local aspects in detail. This represents valuable input for tailored solutions for implementing other policies (e.g. related to the LULUCF sector).

In light of the growing importance of data collected under the IACS, Regulation 2021/2116 (EU, 2021b) established that IACS data relevant for monitoring EU policies shall be shared by Member States free of charge between public authorities and made publicly available at the national level. Furthermore, EC Implementing Regulation (EU) 2023/138 (EU, 2022c) on high-value datasets regards data under the LPIS and GSA as part of the high-value datasets that should be made available. With legislation like this in place a growing number of Member States are likely to make their IACS data publicly accessible over time.

5.2.6 Data interoperability

Member States are encouraged to explore synergies and opportunities to consolidate reporting with other relevant policy areas and strive towards GHG inventories which allow for interoperability with relevant electronic databases and geographic information systems (Governance Regulation 2018/1999 Annex V, Part 3) (EU, 2018c). In return, the GHGI strives to enable the exchange and integration of data between the electronic databases and geographic information systems, in order to facilitate their comparability and public accessibility as part of data interoperability.

The INSPIRE Directive defines interoperability (Article 3(7) of Directive 2007/2/EC) as follows: 'interoperability means the possibility for spatial data sets to be combined, and for services to interact, without repetitive manual intervention in such a way that the result is coherent, and the added value of the datasets and services is enhanced' (EU, 2007).

The analysis presented in Chapter 4 and the different data use cases identified point (among other requirements) to the need for high-quality geographically explicit data (e.g. annual GSA data) providing information about land use, land use change and management practices. In the context of land use policies, it should be assumed that both data sharing (the ability for multiple applications or domains to access and use the same data resource) and data reuse for different purposes are already a common practice within Member State administrations. From a practical perspective, reuse of existing data can decrease the cost of data acquisition and maintenance and may reduce redundancy and reporting obligations in common cross-policy areas.

Key requirements/concrete steps can facilitate interoperability: the use of common formats, creation of metadata and improved documentation and definitions (EEA, 2024d). Good practices, like the use of mandatory keywords when creating metadata, facilitate data discovery from the semantic point of view. The potential user needs to understand the nature of any data they use and their fitness for the purpose and conditions of use. In this process, data semantics help users to find actual correspondence between two datasets via metadata and corresponding definitions of matching representations (e.g. between LULUCF categories and crop type datasets).

As discussed earlier, there are several Member States that use geographically explicit data, including the IACS data, for their LULUCF inventories (Zielinski, 2024).

The challenges related to creating a dataset from multiple sources are summarised below:

- Harmonisation of data created with different definitions, parameters for a single class (i.e. minimum mapping unit) and originating in another domain (e.g. providing land cover instead of land use information) can be partly addressed through semantic mapping and an appropriate level of disaggregation of the resulting classes or categories. However, this process will not cover for missing data or modify the data content.

- Data-related properties, like the completeness or spatial and temporal resolution, should be examined early on during analysis in line with the minimal requirements of the end-product.

- Data harmonisation requires a large volume of geographical data to be dealt with; it also requires non-harmonised archive cartographies with diverse datasets, using different data models, scales and datasets created for different purposes (semantically inconsistent) to be integrated. Addressing this challenge requires high-level competencies and resources which are often not available.

- In addition, it might be a challenge to achieve clarity around typology while merging large datasets from several data sources to avoid double counting in activity data. This might be especially true when following the LULUCF requirements for consistent time series data.

Despite the obvious challenges, there are already several examples of Member States gaining experience of reusing existing geographically explicit data operationally in the LULUCF inventory setup. For example, Denmark (Levin G., 2022), Spain (Spain, 2024) and France (France, 2024) use CAP data to support implementation of the climate policy by providing country-specific solutions to create dedicated land use products based on the available data sources. In all mentioned cases, the LPIS and GSA form the backbone of the solutions by providing most of the information about agricultural land.

5.3 Challenges in LULUCF reporting

EO-derived datasets in the LULUCF sector can have multiple uses in supporting the compilation of inventories beyond the identification of land cover categories and their changes:

- They can attribute land cover changes to specific drivers.

- They can support the stratification of land use categories into logical units that facilitate the estimation of emissions and removals, such as forest condition and types, growth stage, time since disturbance etc.

- They can be used for the assessment of carbon stock change by comparing carbon stock datasets (e.g. on SOC or biomass) consistently and repeatedly over time.

- They can be used as independent sources of data for verification purposes.

However, challenges remain in relation to spatial resolution and land classes used in the EO-derived datasets: information needs to be consistent with the land category classification used by countries under the LULUCF Regulation, including its minimum area in the classes' definitions (see Table 2.1 and Figure 5.5). Another issue is related to the temporal scale of the datasets. One of the reporting requirements of the UNFCCC and EU relates to the consistency of data reported throughout the time series, that goes back to 1990 (see Table 2.2). The availability of data at a finer resolution in more recent years means it is necessary to ensure the synergistic use of 'older' technology with other newer types of remote sensing technology to guarantee time series consistency. This principle is often perceived as a limitation in the use of more detailed datasets that only cover more recent years.

The IPCC guidelines propose various methodologies to realign the new data with the time series. For example, the IPCC 2019 refinement proposes the overlap method whereby data from the old and new approach are overlapped in the years where both can be used, in order to establish a relationship between the methods. In other words, for those years in which the new method cannot be used directly, a correction should be applied to the emission or removal estimates in the time series by proportionally adjusting the previously developed estimates, based on the relationship observed during the period of overlap. This approach can be used when it can be assumed that there is a consistent relationship between the results of the previously used and new method. To apply this method, it is important to fully understand the differences to be sure that the new method improves the accuracy of emission estimates. This is a practical approach that can guarantee that countries can continuously improve their reporting using more detailed datasets, while still fulfilling the time consistency obligation.

While encouraging the use of nationally derived land use maps, the IPCC 2019 refinement provides good practice guidance when using global datasets, requiring users to: (1) assess the consistency of the global dataset alongside national definitions of land use and suitability for reporting (e.g. time-series consistency, spatial scales, update processes); (2) assess the accuracy of the products for the mapped land use categories and correct for bias by using ground or other reference data; and (3) ensure that the processes to assess accuracy represent not just the IPCC land use categories but also the strata (e.g. forest types, areas impacted by disturbances, soil classes) used to estimate emissions and removals.

Interesting considerations emerged during the conference held in October 2024 in Copenhagen on 'Earth Observation for Monitoring, Reporting, and Verification of Carbon Removals' The conference underscored the crucial role of EO in supporting policy frameworks like LULUCF and CRCF. However, several important areas were discussed:

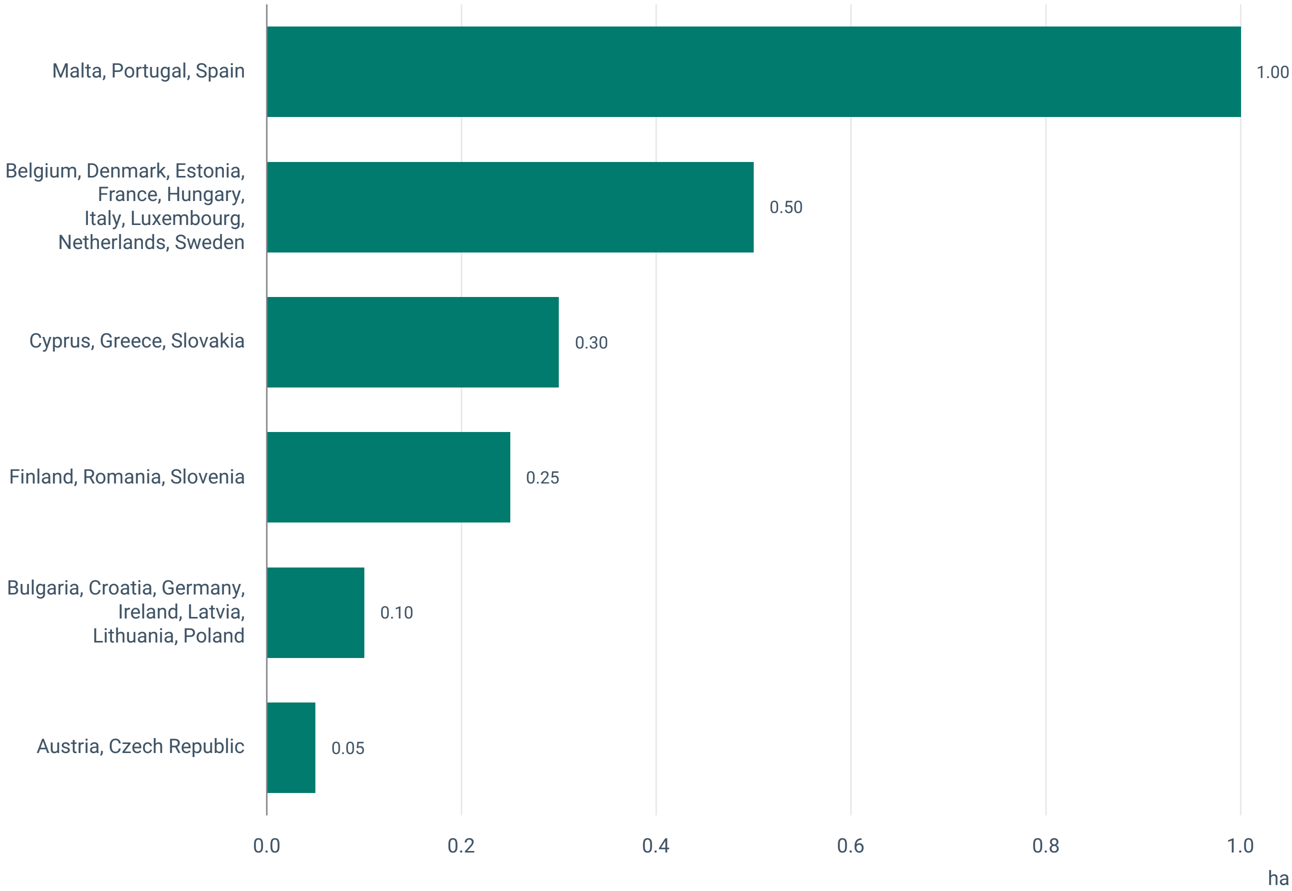
- Tailored solutions: Different policies require customised EO solutions. The LULUCF Regulation and the CRCF Regulation, while both focused on carbon removals, have distinct requirements in terms of scale, accuracy and methodology, with LULUCF reporting focusing on the national level, while the CRCF Regulation is required to track each single plot.

- Timely and accurate delivery: EO data need to be delivered quickly, accurately and derived using transparent, repeatable methodologies to be useful for policymakers and stakeholders. While the details of monitoring frequency for CRCF still need to be defined, the LULUCF inventories are compiled annually for the whole time series from 1990 until the reporting year -2. Any product should be available on a regular basis and in time (preferably in January) to be processed for use in the inventory.

- Spatial Adequacy: EO solutions must be at a spatial resolution capable of supporting national and/or project-specific carbon accounting systems. Finer resolution capable of capturing land use change at a level of detail consistent with each country's definition of a forest is a general requirement for LULUCF reporting (see Figure 5.5). This is the same scale that is required for the CRCF MRV.

- Improved communication across communities: There is a clear need for better communication and collaboration between the EO community, GHGI reporting institutions and policymakers to ensure that EO data are used effectively in carbon accounting.

Figure 5.5 Five country-specific definitions of the minimum area for a forest in ha



Source: EU, 2018a.

Overall, the increasing availability of pan-European geospatial products enables policymakers and stakeholders to gain deeper insights into the effects of measures to increase carbon removals or mitigate land-based emissions.

6 Conclusion and outlook

Key messages

More action from Member States and private actors is needed to reverse the trend of a declining EU LULUCF sink and safeguard the role of LULUCF for climate change mitigation in the coming decades. Successful LULUCF strategies will depend on their effectiveness to:

- Ensure farmers and foresters are adequately supported to change their management practices, both practically and financially. The focus should be on the rapid implementation of the various (policy) instruments that have recently been put in place and leveraging public and private financial investment.
- Pursue optimal environmental and socio-economic outcomes (e.g. reduction and distribution of climate change mitigation costs) in the long term, and a policy framework that delivers on different objectives simultaneously, i.e. climate change mitigation, increasing the resilience of ecosystems (and supply chains) to climate change, biodiversity protection and a sustainable bioeconomy.
- Capitalise on the potential of an evolving technological and data landscape to increase the effectiveness and cost-efficiency of LULUCF mitigation action by public and private actors. Reporting and data developments also give scope for improving administrative efficiencies, such as by enhancing data interoperability and creating reporting synergies across different land-related policies.

While all relevant climate change mitigation scenarios show the need for rapid, deep reductions in gross GHG emissions, they also show varying needs for CO_2 removals to counterbalance residual emissions — largely from the agricultural sector — by 2050, to reach climate neutrality by that year. The EU target to achieve net climate neutrality as enshrined in EU Climate Law integrates removals and their role in contributing to climate targets as well as achieving net-negative emissions beyond 2050. While industrial carbon removals are not yet fully mature and/or ready to be scaled up, in the short to medium term, climate scenarios depend predominantly on carbon removals from the LULUCF sector.

However, while the LULUCF sector in the EU provided a relatively stable sink in the first two decades since 1990, this sink has declined substantially in the last decade. Between 2013 and 2024 the average annual sink was approximately 30% lower compared to the average in the previous decade, largely due to dynamics in forest land (Section 2.2.).

Member States' projections (reporting years 2023-2024) indicate that the EU is not on track to reach its cumulative removals target for LULUCF by 2030 (Section 4.4.). A recent Commission assessment of the final NECPs indicated that several Member States have stepped up efforts in the sector, but the gap to the 2030 target remains 45-60 $MtCO_2e$ (EC, 2025b). This suggests additional action is needed to reach the 2030 climate targets, as well as to allow the sector to contribute effectively to mitigation in the decades thereafter. The governance challenge to manage and scale up removals is vast and complex, and involves managing budgets, enhancing distributional fairness, ensuring the quality of removals ('environmental integrity'), enhancing the land sink in a changing climate and institutional governance (ESABCC, 2025).

This report has aimed to inform successful governance strategies by assessing:

- Chapter 1: the role of anthropogenic and climate/natural influences on LULUCF;
- Chapter 2: the status of reported emissions and removals in LULUCF, as well as reporting practices by EU Member States;
- Chapter 3: Options to enhance removals and reduce GHG emissions in LULUCF;
- Chapter 4: EU governance and policy frameworks impacting carbon removals in LULUCF;
- Chapter 5: Europe-wide geospatial datasets for MRV.

This final chapter presents some concluding cross-cutting messages resulting from this report, in the context of future policy development at the EU level.

Ongoing efforts from Member States are needed to implement adopted policy instruments

As outlined in Chapter 4, since the adoption of the Climate Law, new regulatory and governance frameworks have been established in the early 2020s, aiming to address some of the key barriers for the uptake and scaling of these options. Currently, at Member State level, emphasis is placed on implementing these frameworks and ongoing efforts in this regard are crucial to ensure that farmers and foresters are adequately supported to change their management practices, both practically and financially. Considering the potential to enhance the role of terrestrial ecosystems to deliver a variety of ecosystem services simultaneously, it will remain essential to recognise the limitations and risks in consideration of various policy objectives for land. An excessive reliance, either on biomass resources or on LULUCF mitigation, can result in unintended negative consequences, such as carbon leakage from an increase of land use in or biomass imports from third countries.

At the same time, policy discussions are emerging around possible design options for climate governance for the period 2031-2040, with a view to keeping the EU on track to reach climate neutrality by 2050. In the course of 2025, the EC will propose a climate target to 2040, evaluate the LULUCF Regulation, and start developing a new package of proposals for climate- and energy instruments to support achieving this target. Forthcoming EC proposals for the new Multiannual Financial Framework and the CAP, as well as a new EU bioeconomy strategy are all expected to be relevant for the LULUCF sector.

Ensuring optimal environmental and socio-economic outcomes in the long-term

The condition of most ecosystems in Europe is unfavourable and many are under increased pressure from land use and management, climate change and natural disturbances. The degradation of ecosystems undermines their role in delivering a multitude of ecosystem services. Agricultural yields and biomass harvests are becoming less predictable and less stable, with higher variability from year to year, as is the LULUCF sink.

The LULUCF sector has significant potential to contribute to EU climate change mitigation goals through a change in management practices that reduce emissions — such as those aimed at the protection of carbon stocks in soils and biomass — or that enhance removals. These options generally have significant co-benefits for the restoration of degraded ecosystems, biodiversity and crop pollination; income diversification; and the resilience of ecosystems and economic value chains (see Table 6.1). Climate change and biodiversity loss are mutually reinforcing and share common drivers. Resolving either requires consideration of the other. This also implies that strategies that will increase ecosystems' resilience to climate change can help mitigate future emissions or the risk of reversal of carbon stored in those ecosystems.

In this context, successful LULUCF policy strategies at different governance levels will depend on integrating the notion of ecosystem restoration and biodiversity, and effective strategies to increase the resilience of ecosystems to climate change and adaptive management. Areas for such integrated approaches could be the design of certification standards and related methodologies, the development of land management plans, and — at the public level — the design of policies, measures and incentive mechanisms (e.g., in the context of the CAP). In this context, the EC is exploring the development of biodiversity certification and nature credits, further endorsed by the EC Vision on Agriculture (EC, 2025a).

In designing future strategies, it is important to recognise that there could be possible trade-offs in LULUCF mitigation over time, with certain measures resulting in short-term climate benefits but hampering sequestration potential over time or vice versa. For example, a reduction of forest harvests now can build up biomass stock and thus reduce forest climate mitigation potential in the future. Afforestation may initially reduce soil carbon but deliver significant future mitigation potential. To inform LULUCF mitigation strategies at the EU and Member State levels, both in view of these trade-offs and to ensure adequate action towards reaching climate targets over time, it would be helpful to clarify the role of the sector over a longer time period (i.e. beyond 2040). This in turn could allow for more integrated planning for the cross-sectoral transition of the economy and the role of certain technologies, and the reliance on land and biomass. This would avoid the risk of the LULUCF sector being regarded as a 'balancing item', linked to short-term (10-year) action in other sectors (e.g., biomass substitution) and as a result losing momentum for LULUCF mitigation with potentially more cost-efficient results in the medium- to long term. This trade-off must also be taken into account for the design of the forthcoming EU bioeconomy strategy.

Table 6.1 **Summary of mitigation options in LULUCF, and co-benefits and risks**

Range of average sequestration potential in tCO_2e/ha per year over entire implementation period

	Forest protection	Afforestation/ reforestation	Improved forest management	Agroforestry	Improved cropland/ grassland management*	Wetlad/ peatland restoration*	NBS in settlements*
Above-ground biomass		2-35	1-14	0.4-26.7			
Soil organic carbon		3.5-7	0.1-6	0.4-8.5	0-3		
Time lag mitigation							
Biodiversity		○			○		
Water, air and soils		○			○		
Local climate effects		○		○			
Land use, biomass supply**		○	○			○	○
Resource use***					○	○	○
Socio-cultural							
Socio-economic						○	

- Generally providing opportunities
- Generally providing risks
- Combination of positive and negative effects can apply at the same time or in different time periods following implementation
- Not applicable or negligible
- Uncertain or mixed effects
- ○ Highly dependent on implementation/method and/or local circustances

Notes: (*) Individual options for cropland, grasslands, wetlands/peatlands and settlements have been aggregated in this table; (**) And related effects on income or land prices (foregone income); (***) More details regarding the type of resource use per option are available in Chapter 3.

Source: Author's own compilation based on expert judgement.

Improved GHG reporting is essential for improving policy effectiveness

As discussed in the report, reliable data and monitoring can serve a multitude of needs in support of LULUCF action. To some level, quality and timely data provision, such as to inform activity data and emission factors, will be the backbone for more timely and cost-efficient monitoring of public and private action in LULUCF.

In particular, higher quality GHG inventory data are crucial for gaining a better and more comprehensive understanding of the trends and the role of anthropogenic and natural drivers of GHG emissions and removals in LULUCF. Currently, for example, soil carbon is not fully captured by current reporting, which likely results in unreported losses in cropland and unreported gains in grasslands and forest land (Bellassen et al., 2022). Enhanced inventory data will support assessing progress to targets and allowing for targeting and evaluating policies and measures over time, thereby increasing their effectiveness. When GHG inventories reflect parcel-level change, public and private entities are further incentivised to invest in mitigation measures. Recognising this potential, in 2023, the EU adopted new rules requiring Member States to gradually improve their reporting methods. This will result in an increasing need for high-resolution data on emissions and removals (temporal and spatial) and geographically explicit information to inform models and other inventory methods.

This report also identified the new policy and governance framework relevant for LULUCF results as data needs corresponding to all subsequent phases of the ambition cycle: reporting, review, planning and implementation (Table 6.2.). For example, improved modelling of the sector can provide better insights into mitigation potentials in consideration of climate change and broader environmental and economic outcomes, including biomass provision, over time. The required characteristics of these data, e.g. level of detail, geographical and temporal scales, and types of parameter, depend on the specific use case.

Table 6.2 Phases of the ambition cycle and drivers for data needs

Reporting	Timely information, robust GHG inventory data and site-based GHG emissions/removals tracking methods (for carbon certification)
Review	Review of progress to targets, assessment of trends and drivers, evaluation of the effectiveness of policies
Planning	Establishment of targets, design of policy- and policy scenarios (and information for assessment models), projections
Implementation	Quantification of baselines and mitigation effect from an implemented activity, better targeting for interventions, assessing environmental and climate conditions for addressing risks or targeting co-benefits

Source: Author's compilation based on expert judgment.

As discussed in the report, geospatial data play a fundamental role in tracking land use changes and their impact on land-based CO_2 fluxes. They can improve LULUCF carbon stock change assessments at the national level and support plot-level verification of certified removals (e.g. under the CRCF Regulation). These data, derived from EO or sampling methods, can support Member States in improving LULUCF reporting, filling possible gaps and enhancing comparability. However, certain challenges in their use exist, and research and data providers currently experience various barriers to advancing monitoring data, as outlined in Section 5.3.

Successful LULUCF strategies and policies will therefore depend on how they capitalise on the potential of an evolving technological and data landscape. Integrating GHG inventories with other land-related reporting databases and GIS systems presents a valuable opportunity to enhance data interoperability, enabling more efficient data sharing, minimising redundancy and streamlining reporting across multiple policy areas.

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Glossary

Anthropogenic: Caused directly or indirectly by human activites.

Anthropogenic emissions: Emissions of greenhouse gases, greenhouse gas precursors, and aerosols directly or indirectly caused by human activities. These activities include the burning of fossil fuels, deforestation, land use changes, livestock, fertilization, etc., that result in a net increase in emissions.

Biochar: Biochar is defined as a solid carbonised product created through thermochemical conversion by heating to above 300°C with limited air through a gasification or pyrolysis process.

Carbon flux: The transfer of carbon from one carbon pool to another measured in mass per unit area and time.

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

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

Carbon sink: Any natural or technological process, activity or mechanism that removes a GHG, an aerosol, or a precursor to a GHG from the atmosphere. It includes industrial carbon removals and certain nature-based processes that remove CO_2 from the atmosphere. Carbon sinks store carbon in pools.

Carbon stock: The absolute quantity of carbon stored in a carbon pool.

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

CO_2 fertilisation: The enhancement of plant growth and photosynthesis due to increased atmospheric CO_2, though its effect depends on water, nutrients, and temperature.

Dead organic matter (DOM): A carbon pool consisting of non-living plant material, specifically litter and dead wood. In forest land, litter and dead wood are reported as two separate pools. In other land-use categories such as cropland, grassland, and wetlands, they may be reported as a combined pool when separation is not feasible.

Dead wood: Non-living woody biomass not included in the litter, including standing dead trees, stumps, and fallen logs.

Geographically explicit data: Data that includes specific spatial information, such as geographic coordinates or mapped areas, allowing each data point to be located and analysed in relation to its position on the Earth's surface.

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

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

Harvested wood products: Any product of wood harvesting that has left a site where wood is harvested, including paper, wood used for materials or energy.

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

Insetting: The financing of climate change mitigation along a company's own value chain.

In-situ data: Data collected on the ground at the location being studied, such as field measurements of forest biomass or soil carbon, used to support or verify other data sources.

Litter: Includes all non-living biomass with a diameter less than a minimum diameter chosen by the country, lying dead, in various states of decomposition above the mineral or organic soil in forests. Litter is part of the Dead Organic Matter pool reported for Forest land.

Living biomass: The carbon pool consisting of all living biomass. The pool is differentiated according to whether the biomass is above ground (i.e. stems, branches and leaves) or below ground (i.e. roots).

Mineral soils: Soils that are mainly made up of minerals (sand, silt, clay) and have relatively low amounts of organic matter. They typically occur under moderately well to well-drained conditions and predominate in most ecosystems except wetlands.

Natural disturbances: Events such as wildfires, storms, floods, droughts, or pest outbreaks that significantly affect forest ecosystems and are beyond human control. Under the LULUCF regulation, these are disturbances whose occurrence is beyond the control of Member States, and which cause effects on emissions that Member States cannot significantly limit even after they happen.

Nature-based solutions: Actions to protect, sustainably manage, and restore natural or modified ecosystems, that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits (IUCN definition).

Organic soils: Soils with a high concentration of organic matter (minimum 12-20% by mass according to IPCC Guidelines), usually formed under wet or poorly drained conditions such as wetlands. Countries may apply their own national definitions, provided these are consistent with international reporting guidance. Soils not meeting these criteria are classified as mineral soils.

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

Pool/reservoir: A component of the climate system, other than the atmosphere, that has the capacity to store, accumulate or release a substance of concern (e.g. carbon). Examples of carbon pools include vegetation, soils, or wood products.

Primary woody biomass: See roundwood.

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

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

Soil carbon: The solid carbon stored in global soils. This includes both soil organic matter and inorganic carbon as carbonate minerals. Volatile organic compounds (VOCs): a group of organic chemicals that easily evaporate and take gaseous form, and that have the potential to be harmful to human health.

Soil organic carbon (SOC): The carbon pool that includes all organic material in soil, excluding coarse roots of the belowground biomass pool.

Voluntary carbon market: A decentralised market where private actors voluntarily buy and sell carbon credits that represent removals or reductions of greenhouse gases (GHGs) in the atmosphere.

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

Abbreviations and units

ABER	Agricultural Block Exemption Regulation
AGB	Above-ground biomass
BAU	Business as usual
BECCS	Bioenergy with Carbon Capture and Storage
BGB	Below-ground biomass
BIOMASS	Biomass Earth Explorer mission
CAMS	Copernicus Atmosphere Monitoring Service
CAP	Common Agricultural Policy
CCI	Climate Change Initiative
CDR	Carbon Dioxide Removals
CH_4	Methane
CLC	CORINE land cover
Climate-ADAPT	The EU Climate Adaptation Strategy
CLMS	Copernicus Land Monitoring Service
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
CRCF	Carbon Removals and Carbon Farming
CSPs	CAP Strategic Plans
CSRD	Corporate Sustainability Reporting Directive
DACCS	Direct Air Capture and Storage
DNSH	Do No Significant Harm
DOM	Dead organic matter
EC	European Commission
ECMWF	European Centre for Medium-Range Weather Forecasts
EFs	Emission factors
EGD	European Green Deal

EO	Earth observation
ESA	European Space Agency
ESABCC	European Scientific Advisory Board on Climate Change
ESDAC	European Soil Data Centre
ETC CA	European Topic Centre on Climate Change Adaptation and LULUCF
EU	European Union
EUDR	EU Regulation on Deforestation-free Products
FML	Forest Monitoring Law
FUA	Functional Urban Areas
GFAS	Global Fire Assimilation System
GHG	Greenhouse gas
GHGI	Greenhouse gas emission inventory
GPD	Global Peatland Database
GSA	Geo-spatial application
GSOC	Global Soil Organic Carbon
GSP	Global Soil Partnership
GtC	Gigatonnes Carbon
ha	Hectares
HILDA	Historic Land Dynamics Assessment
HRL	High Resolution Layer
HR-VPP	High-Resolution Vegetation Phenology and Productivity
HWP	Harvested wood products
IA	Impact assessment
IACS	Integrated Administration and Control System
ICVCM	Integrity Council for the Voluntary Carbon Market
IM	Inverse modelling
IMCG	International Mire Conservation Group
IPCC	Intergovernmental Panel on Climate Change
ISRIC	International Soil Reference and Information Centre

IUCN	The International Union for Conservation of Nature
JRC	Joint Research Centre
kha	Kilo hectares
$ktCO_2e$	Kilo tonnes of carbon dioxide equivalent
LPIS	Land Parcel Identification System
LTS	Long-term strategy
LUCAS	Land Use Cover Area Survey
LULUCF	Land use, land use change and forestry
Mg	Megagrams
Mha	Million hectares
MRV	Monitoring, reporting and verification
$MtCO_2e$	Metric tonnes of carbon dioxide equivalent
Mtoe	Million tonnes of oil equivalent
N_2O	Nitrous oxide
NBS	Nature-based solutions
NDC	Nationally Determined Contribution
NECPs	National Energy and Climate Plans
NFI	National Forest Inventory
NRR	Nature Restoration Regulation
NUTS	Nomenclature of territorial units for statistics
Ppm	Parts per million
QA	Quality assurance
QC	Quality control
QU.A.L.ITY	Quantification, Additionality, Long-term storage, Sustainability
RED	Renewable Energy Directive
SML	Soil Monitoring Law
SOC	Soil organic carbon
TACCC	Transparency, Accuracy, Completeness, Comparability, Consistency
tC/ha	Tonnes Carbon per hectare

UNFCCC	United Nations Framework Convention on Climate Change
VCM	Voluntary carbon market
VLCC	Vegetated Land Cover Characteristics
WAM	With additional measures
WEM	With existing measures
WoSIS	World Soil Information Service

Annex 1 Climate impact drivers

Table A1.1 Climatic impact drivers, impact indicators, and associated risks and GHG effects

Climate impact drivers	Effects on ecosystem functioning	Risk or positive impact	GHG effects	References
Temperature increase	Changes in vegetation zones, growing season length, forest and crop productivity, soil respiration and decomposition	Increased productivity, changing composition of species	Depending on level of temperature increase and species: increase in GHG uptake by ecosystems and increased carbon sink	Montibeller et al., 2022; Menzel et al., 2020; Rahmati et al., 2023
Temperature extremes	Changes in vegetation zones, growing season length, forest and crop productivity, soil respiration and decomposition	Heat stress for forests and crops, wildfire risk, pest outbreaks, premature dying of trees	Increase in GHG emissions and reduced carbon sink	Montibeller et al., 2022; Hartmann et al., 2022; Hammond et al., 2022; Bednar-Friedl et al., 2022; Senf and Seidl, 2018; L. M. W. Rossi et al., 2023; Singh et al., 2023b
More precipitation	Increasing soil water availability	Increasing forest and crop productivity, soil respiration and decomposition, less wetland degradation	Increased carbon sinks and reduced emissions	Panagos et al., 2021; Romeiro et al., 2022; Seidl et al., 2017
More precipitation extremes	Heavy rain events, hail, flooding, soil erosion and degradation	Decreasing forest and crop productivity	Reduced carbon sink and eventually higher CH_4 emissions	Panagos et al., 2021; Romeiro et al., 2022; Seidl et al., 2017
Less precipitation/ more droughts	Soil moisture, forest and crop productivity, growing season length, water availability for wetlands, soil erosion	More desertification, drought stress for forests and crops, wildfire risk, pest outbreaks, decreasing ecosystem productivity	Increase in GHG emissions (especially peatland), reduced carbon sink	Gallego-Sala et al., 2018; L. M. W. Rossi et al., 2023; Seneviratne et al., 2021; Jones et al., 2022; Singh et al., 2023b
CO_2 level increase	Forest and crop productivity	Increased productivity	Increased carbon sink	Peñuelas et al., 2017
Reduced snow and ice cover	Forest productivity	Frost damage to crops and forests, increasing wind damage in forests	Increase in GHG emissions and reduced carbon sink	Romeiro et al., 2022; Seidl et al., 2017

Source: Author's compilation based on referenced literature.

Annex 2 Legend of co-benefits and risks

Table A2.1 Legend of co-benefits and risks for the purpose of assessment of mitigation options in Chapter 3

	Positive	Negative
Biodiversity	New/improved habitats for wildlife	Loss of habitats, e.g. in grasslands
Water management	Regulation of availability and quality of freshwater and habitats; flood control	Reduced availability of fresh water or water quality
Air quality	Filtering air pollution	Air pollution
Soil conservation	Soil retention- and stabilisation, improved soil quality, prevention of soil sealing	Increased soil erosion, soil degradation, soil sealing
Resilience ecosystems	Increased resilience of agricultural land and forests; diseases and pests control	Increased vulnerability of ecosystems, increased risk of forest fires and natural disturbances
Local climate effects	Local cooling	Local warming effects
Land use and biomass supply	Sustainable biomass provision HWP	Reduced food security or biomass supply for energy; Displacement of land use or biomass mobilisation; risk of carbon leakage.
Socio-cultural	Recreation, cultural-, educational or spiritual ecosystem services	Loss in cultural-, educational or spiritual ecosystem services
Socio-economic	Supporting local communities; income diversification	Job losses; Foregone income
Resource use (energy, water, fertiliser, pesticides)	Decrease in energy, water, pesticides or fertiliser use	Increase in energy, water, pesticides or fertiliser use

Source: Author's compilation based on expert judgement.

Annex 3 Technical details and additional information on relevant CLMS products

Table A3.1 Selection of relevant CLMS land cover and land use mapping products

Product name	Reference years	Update frequency	Spatial resolution	Description
Dynamic land cover	2015 2016 2017 2018 2019	Annually	100m	Annual global land cover dataset
CORINE land cover	1990 2000 2006 2012 2018 2024	Every 6 years	25ha MMU, 5ha MMU for change layers	Flagship land cover and land use mapping by countries, based on consistent change mapping by country experts
CLCplus Backbone	2018 2021 2023	Every 3 years (2 years from 2021)	10m	European land cover product with high accuracy and (from 2021) a two-year update cycle
Imperviousness (soil sealing density)	2006 2009 2012 2015 2018 2021	Every 3 years	10m, 20m, 100m	Long time series of initially 20m, now 10m raster data on soil sealing/imperviousness
Impervious built-up	2018 2021	Every 3 years	10m, 100m	Additional product allowing sealed non-built up areas to be separated from sealed built up areas
Dominant leaf type	2012 2015 2017 2018 2019 2020 2021	Every 3 years From 2018 shift to annual updates	10m, 20m, 100m	Initially 20m, then 10m since 2018: product mapping for dominant leaf type
Forest type	2012 2015 2018 2021	Every 3 years	10m, 20m	Only CLMS product approximating 'forest' as a land use according to FAO definition by combining various datasets
Tree cover density	2012 2015 2017 2018 2019 2020 2021	Every 3 years From 2018 shift to annual updates	10m, 20m, 100m	Mapping (since 2018 in 10m resolution) the density of tree (crown) cover from 0-100%
Grassland	2015 2017 2018 2019 2020 2021	Every 3 years From 2017 shift to annual updates	10m, 20m, 100m	Product mapping grasslands
Vegetation seasonal trajectories	From 2017	10-daily	10m	Gap-filled and function-fitted time series of PPI, with regular 10-day time step.

Table A3.1 Selection of relevant CLMS land cover and land use mapping products (cont.)

Product name	Reference years	Update frequency	Spatial resolution	Description
Vegetation phenology and productivity parameters	From 2017	Annual	10m, 100m	Thirteen parameters for two seasons derived from thresholding the seasonal trajectories describing start/ end-of-season, length, amplitude, productivity, etc.
Crop types	2017 2018 2019 2020 2021	Annual	10m	Mapping 17 classes of crop types annually. Parallel product of cropping patterns mapping seasonal parameters such as emergence/harvest dates, cover crops, bare soil duration, fallow land, cropping seasons
Small woody features	2015 2018 2021 2024	Every 3 years	5m, 20m 100m	Very high resolution imagery-based product mapping small woody features in higher spatial detail
Urban Atlas	2006 2012 2018 2021 2024	Every 3 years (since 2018)	Vector product (1ha MMU rural, 0.25ha urban)	Detailed land cover and land use data for 788 Functional Urban Areas (FUA) with more than 50,000 inhabitants in EEA38 countries and the United Kingdom

Notes: Upcoming products and reference years in grey font. Apart from the Dynamic Land Cover that is available for the whole globe, all other products cover EEA38 and the UK.

MMU: minimum mapping unit; PPI: plant phenology index.

Source: CLMS portfolio.

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