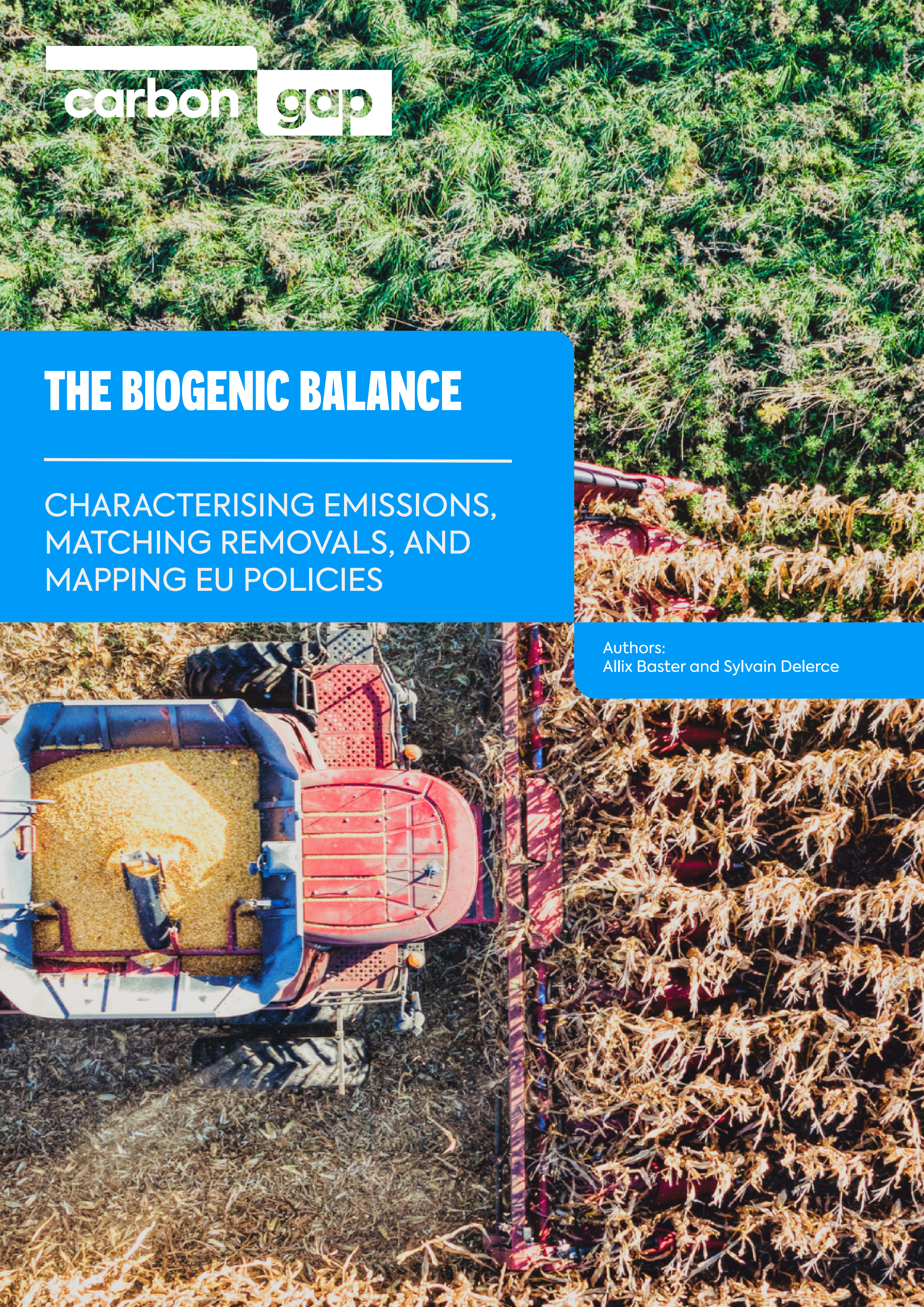

carbon gap

THE BIOGENIC BALANCE

CHARACTERISING EMISSIONS, MATCHING REMOVALS, AND MAPPING EU POLICIES

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KEY TAKEAWAYS

- Anthropogenic biogenic emissions originate from the burning or decomposition of (recently) living organic material or biological processes as a result of human behaviour.
- In GHG inventories, these biogenic emissions are most prominent in the agriculture sector, with additional volumes coming from the waste and LULUCF sectors.
- Currently, GHG inventories generally distinguish emissions by sector, and aggregating biogenic emissions across sectors at the global scale is challenging.
- Enhanced microbial activity in wetlands due to climate change is a source of anthropogenic biogenic emissions which may not be (fully) reported in GHG inventories; it is likely that other sources of emissions from ecosystem disturbance are also not captured.
- Achieving durable net-zero requires a like-for-like balancing of removals and emissions, meaning permanent removals are used to neutralise fossil-fuel emissions, and temporary removals, which capture carbon in biosphere or products, are used to neutralise human-caused biogenic emissions.
- Our analysis suggests that anthropogenic biogenic emissions are currently roughly 9 times greater than temporary nature-based removals globally.
- A large portion of these biogenic emissions are considered hard-to-abate and will likely persist in the future, meaning temporary biogenic removals will be an important tool for reaching net-zero.
- In the context of the EU, biogenic emissions and removals are covered by several key policy frameworks (e.g., the Effort Sharing Regulation (ESR), Land Use, Land Use Change and Forestry Regulation (LULUCF-R), Common Agricultural Practice (CAP), and forthcoming Carbon Removal Certification Framework (CRCF).
- These frameworks provide limited clarity on the future role and pricing of temporary removals but should ideally be leveraged to ensure temporary removals support a like-for-like approach.

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GLOSSARY OF TERMS

Anthropogenic biogenic emissions: includes GHG emissions produced directly or indirectly by human activities which lead to 1) the decomposition or burning of living or recently living organic material, 2) the enhancement of microbial activity, for example, due to global warming or agricultural practices. This report focusses only on biogenic emissions related to human activities in contrast to natural biogenic emissions, for example, caused by seasonal decomposition and respiration, or other biological processes effecting the carbon cycle.

CDR: carbon dioxide removal

Durable net-zero: a state where carbon fluxes in and out of carbon pools reach an equilibrium through the implementation of the like-for-like principle, creating long-lasting stability that effectively halts global warming.

FAO: Food and Agricultural Organization

GHG: greenhouse gases, the four main ones being carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and chloro-fluorinated gases (f-gases).

IPCC: Intergovernmental Panel on Climate Change

Like-for-Like Principle (LfL): the concept that anthropogenic GHG emissions should be neutralised with anthropogenic removals meanwhile matching the particular carbon storage pool (geosphere, biosphere) and overall climate impact of the emitted gas.

LULUCF: Land use, land use change and forestry – the term is used in GHG inventory reporting to describe emissions and removals from land-based activities (e.g., forests, cropland, grassland, wetlands, settlements) and changes between these land uses. In the EU context, "LULUCF" can refer both to the LULUCF sector in national/EU GHG inventories and accounting, and the EU's LULUCF Regulation, which sets binding rules and targets for how Member States account for and manage LULUCF emissions and removals.

Temporary biogenic removals: carbon removal strategies which temporarily store carbon in the living biosphere or products.

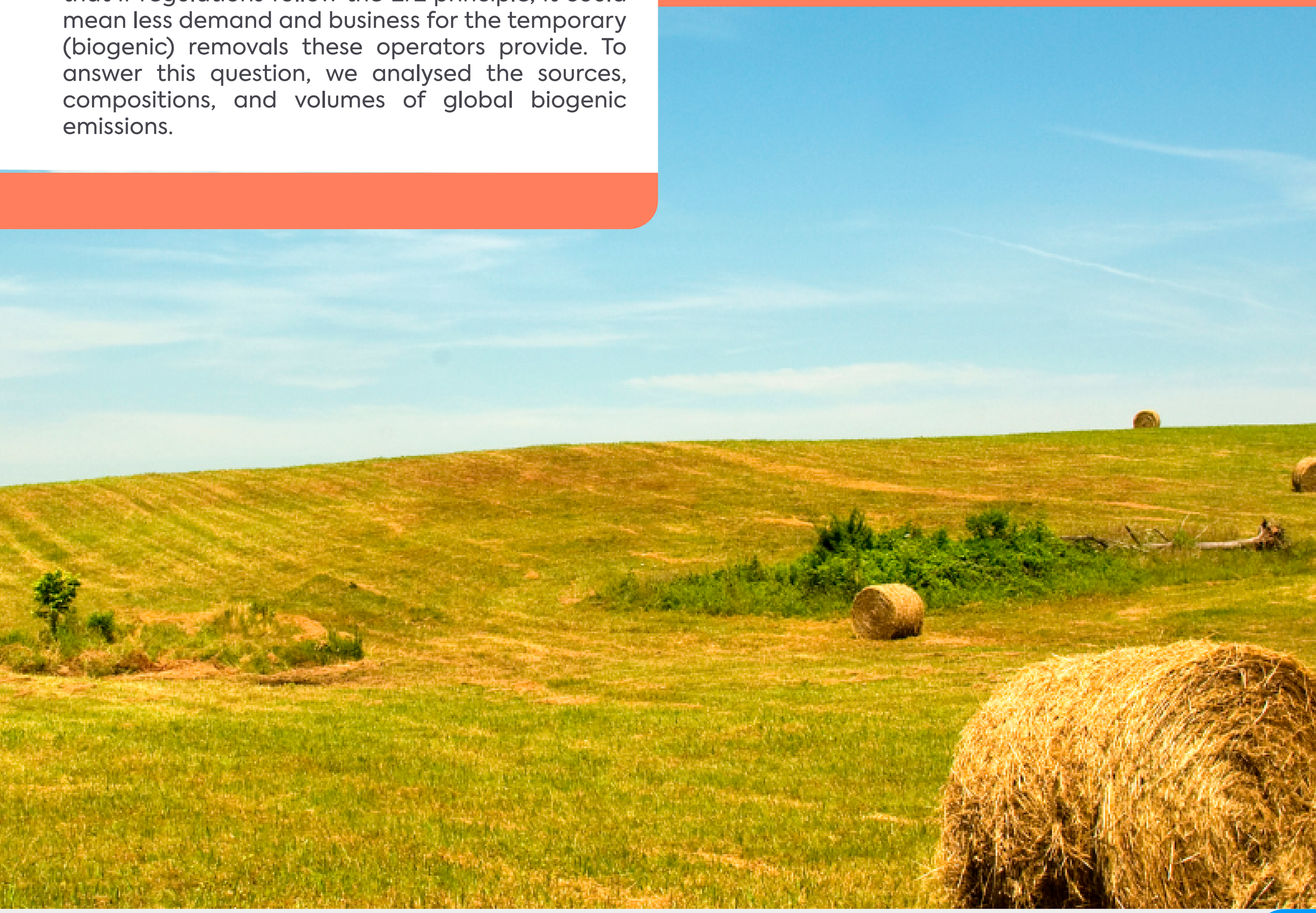
UNFCCC: United Nations Framework Convention on Climate Change

EXECUTIVE SUMMARY

Reaching net-zero emissions worldwide will require removing as much greenhouse gas from the atmosphere as we emit, but ensuring net-zero is sustained will require matching the right emissions with the right removals. This scientifically established concept, known as the Like-for-Like (LfL) principle is crucial for achieving durable net-zero. In simple terms, the LfL principle outlines that permanent carbon removal methods, such as capturing and storing CO_2 underground, should be used to balance out fossil fuel emissions. Meanwhile, temporary carbon storage in soils, forests, or wood products should help balance out biogenic emissions. These biogenic emissions are part of the short-term carbon cycle and come from the burning or breakdown of recently living material.

Putting the LfL principle into practice faces some barriers. Because today the largest portion of emissions by far are fossil fuels, there is some concern from Nature Based Solution operators that if regulations follow the LfL principle, it could mean less demand and business for the temporary (biogenic) removals these operators provide. To answer this question, we analysed the sources, compositions, and volumes of global biogenic emissions.

Our analysis shows that farming, waste, and ecosystem change are the biggest sources of biogenic emissions today—emitting more than nine times what temporary removals are currently storing. Despite their prevalence, the current EU policy frameworks in place do not adequately target biogenic emissions either through targeted reduction measures or by appropriately counterbalancing them with removals. Many of these biogenic emissions will be hard to get rid of going forward, meaning temporary removals will play a vital role in balancing the books, and must be adequately addressed in the EU's policy mix. Policies like the Effort Sharing Regulation (ESR), Land Use, Land Use and Forestry (LULUCF) Regulation, Common Agriculture Practice (CAP), and the new Carbon Removal and Carbon Farming (CRCF) Regulation should work together to give temporary removals a clear, fair place in the path to net-zero.



1. MOTIVATION AND BACKGROUND

1.1 The importance of the Like-for Like Principle

The concept of **durable net-zero** refers to a long-term approach for achieving **net-zero emissions** that accounts for the durability or permanence of carbon removal efforts. It recognises the varying storage capacities and timescales of the biological and geological spheres and proposes that anthropogenic carbon flows in and out of each sphere need to be equilibrated at the point of reaching net-zero.[1] Reaching this equilibrium ensures lasting stability of atmospheric CO_2 levels.

Carbon dioxide removal (CDR) plays a crucial role in this process since it is needed to balance any remaining emissions and stabilise global temperatures. Additionally, CDR could theoretically be used to reach a net-negative state, helping bring temperatures back down after any potential future overshoot of climate goals. On the other hand, misuse of CDR could jeopardise reaching an equilibrium state and undermine climate goals, highlighting the importance of clear definitions and uses.

Within the political debate surrounding how to sustainably achieve durable net-zero, the **Like-for-Like** (LfL)[2] principle has gained traction. We recently clarified its interpretation and practical application, concluding that the LfL principle is best interpreted as the balancing of remaining emissions with removals considering the durability and reversal risk of the relevant storage pools.[3] This definition is rooted in the natural carbon cycle, recognising that carbon moves between storage pools at different timescales, and that matching emissions and removal types helps maintain the long-term balance of these cycles.

In practical terms, this principle means that the sinks used to neutralise remaining CO_2 emissions must have equal or greater permanence than the carbon pool the emissions originate from. Additionally, the temporary warming effect of non-CO_2 gases could be neutralised with an equivalent amount of CO_2 removals for at least the same duration. In this way, the relevant GHG volume, source/sink, and climate impact, must match between the emissions and removals, but the particular gas species (e.g., CO_2, CH_4) may differ. Yet, determining such equivalencies between CO_2 and non-CO_2 pollutants is non-trivial: the choice of the climate impact metric (e.g., Global Warming Potential; GWP or similar) strongly influences the assessed balance, with different gases exhibiting different lifetimes, radiative efficiencies, and atmospheric behaviours.

Nonetheless, following the LfL principle, residual biogenic emissions could be appropriately offset by temporary removal methods (i.e., storage in the living biosphere or products), provided they sequester, at minimum, an equivalent amount of carbon over the duration of the pollutants' climatic impact. By contrast, fossil-fuel emissions must be neutralised with the permanent removal and storage of carbon, for example, in geological formations.

1.2 The current mismatch

Currently, temporary biogenic removals (generally consisting of conventional methods such as afforestation, ecosystem restoration, and agroforestry) account for almost all anthropogenic carbon removals, yet their low permanence and risk of reversibility is increasingly questioned. Meanwhile, permanent removals (e.g., Direct Air Carbon Capture and Storage; DACCS, and Bioenergy with Carbon Capture and Storage; BECCS) reflect less than 1% of captured carbon[4] despite most emissions originating from fossils fuels previously stored in the lithosphere for many millions of years.

The use of temporary biogenic removals to combat fossil fuel emissions is therefore incongruent with strict adherence to the LfL principle.

1 Fankhauser et al. (2022) *The meaning of net-zero and how to get it right*

2 Fankhauser et al. (2022); Allen et al. (2022; 2025) *Net zero: science, origins, and implications*; *Geological net zero and the need for disaggregated accounting for carbon sinks*

3 Carbon Gap (2026) *Understanding and implementing the Like-for-Like principle: Rules for carbon removal that enable durable net-zero.*

4 Smith et al. (2023) *The State of Carbon Dioxide Removal Report 2023*

In practice, presenting short-lived carbon storage as a substitute for permanent fossil emissions risks being deeply misleading and undermines the environmental integrity of climate mitigation efforts. However, since most of the emissions are currently fossil, there is concern from Nature-Based Solutions (NBS) operators that strictly adhering to the LfL principle could reduce demand for the temporary removal solutions they provide.

To investigate this concern, this review aims to better quantify those human-caused biogenic emissions which may be appropriately neutralised with temporary biogenic removals. By summarising the volumes, specific gases, and sources of biogenic emissions and, where possible, their future trends, this analysis presents a comprehensive view of current biogenic emissions.

We compare these emissions to the current level of temporary removals and the estimated capacities of these methods. With this bird's eye view on biogenic emissions and removals, we then zoom-in on the European context to understand how they are addressed by active and developing regulations and where potential gaps in coverage may exist. This analysis therefore provides a basis for understanding the scale of temporary removals that may be needed, while raising important questions about their appropriate use and the types of incentives required to scale them effectively within the EU regulatory system.

2. SOURCES OF BIOGENIC EMISSIONS

For the purpose of this review, we define anthropogenic biogenic emissions as those emissions released by the burning or decomposition of living or recently living organic material or produced by biological processes, prompted, either directly (e.g., logging) or indirectly (ecosystem change linked to global warming) by human activities. This definition contrasts with emissions generated by the natural decay or productivity of organisms (e.g., seasonal litterfall decomposition, microbial respiration, or other biological turnover processes), which are part of the background biogenic carbon cycle and not attributable to anthropogenic disturbance. This review focuses only on the human-driven biogenic emissions and will refer to them simply as 'biogenic emissions.' Therefore, this definition includes biogenic CO_2 which is part of the short-term carbon cycle but excludes all GHGs from fossil fuels. Other GHGs, namely, CH_4 and N_2O are also known to contribute significantly to biogenic emissions.

To gather the potential sources of biogenic emissions examined by this report (see Table 1), we reviewed the United Nations Food and Agriculture Organisation (FOA) inventory, the UNFCCC GHG Inventory, the EDGAR GHG emissions dataset, and the PRIMAP-PIK Historical Emissions dataset (see section A1 in Annex for further details). Where possible, we provide global (Annex I and non-Annex I) emissions estimates from biogenic activities. Given data restrictions, in some cases the presented totals reflect minimum estimates (i.e., when only Annex I estimated are reported). We also consider potential overlaps in reporting between inventories. This review also aims to identify potential sources of biogenic emissions which are outside the scope of GHG reporting frameworks. The results should be interpreted as a general summary that illustrates the difference in scale between biogenic/fossil emissions and temporary/permanent removals but does not provide an exhaustive review.

2.1 Agriculture

Activities and current emissions

The agricultural sector currently represents the largest contributor of non-fossil fuel emissions by GHG volume and mainly involves emissions of CH_4 and N_2O (Table 1). The practice of **farming livestock** results in CH_4 production from **enteric fermentation**[5] by ruminant cattle. Additionally, the **manure and urine** of livestock enhance N_2O emissions from pasture soils. Another substantial source of GHG emissions in the agricultural sector is **crop production**; the use of nitrogen-based fertilisers increases microbial activity in soils and can lead to higher N_2O emissions. In particular, the **cultivation of rice paddies** is linked to the production of CH_4 by microorganisms that thrive in the water-logged environment. The decomposition and burning of **crop residues** (organic materials left in the field after harvest) can lead to N_2O emissions and/or CH_4 emissions if these residues are left in waterlogged or low-oxygen conditions.

We note that although applying nitrogen-based fertiliser can cause biogenic N_2O emissions from enhanced microbial activity, the source of the applied nitrogen itself is not strictly of biogenic origin. For example, fertilisers may be produced through industrial processes using atmospheric nitrogen and therefore could challenge the consideration of these emissions as truly biogenic.

These agricultural activities causing biogenic emissions are generally well-covered in GHG inventories. In total, our assessment of the inventories found that agricultural practices currently contribute around 7050 $MtCO_2e$ / year of biogenic emissions, with 4579 $MtCO_2e$ from CH_4 emissions, and 2471 $MtCO_2e$ from N_2O emissions (Fig. 1).

5 Enteric fermentation is a natural digestive process in ruminant animals (e.g., cattle, sheep, goats) in which microbes in the stomach break down feed and produce methane (CH_4), which is released into the atmosphere.

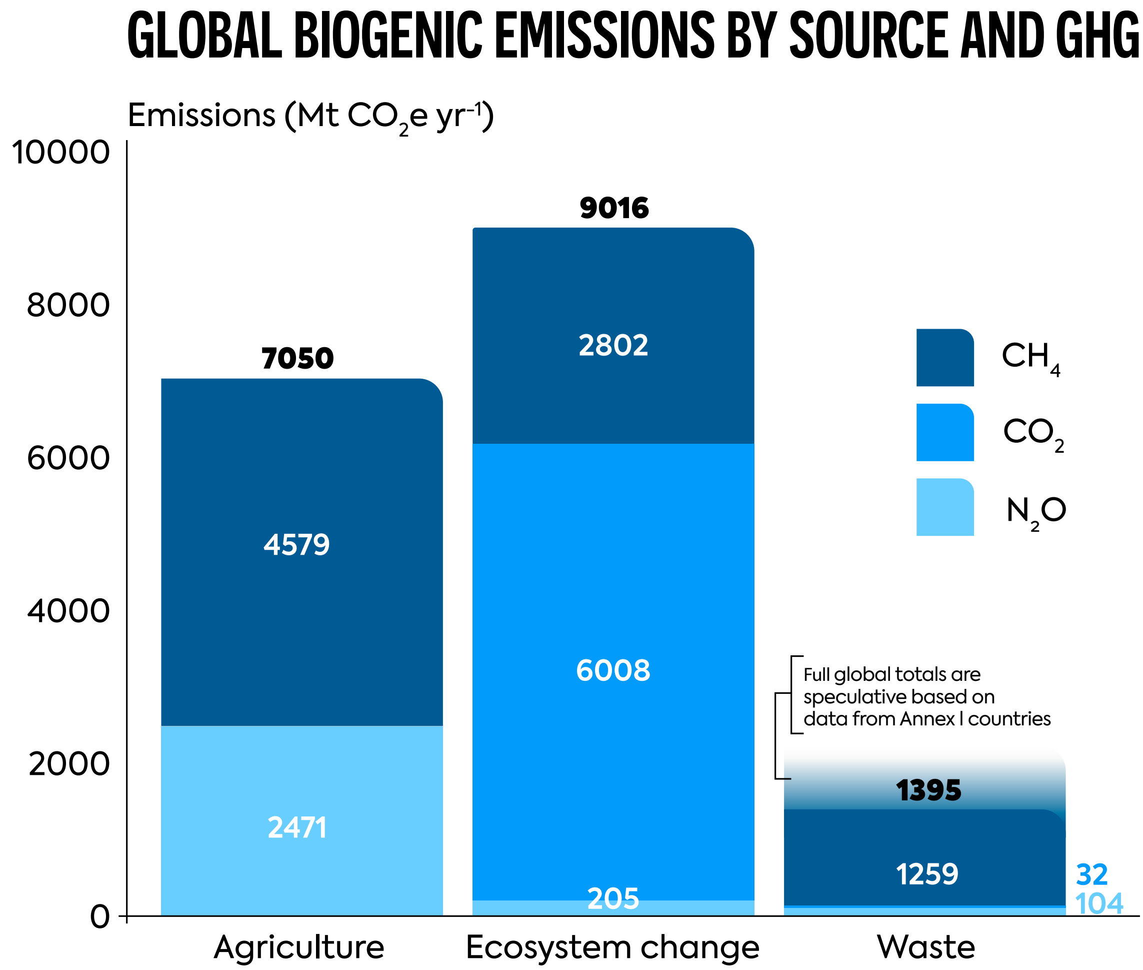


Figure 1: Summary of the current human-caused biogenic GHG emissions by source and GHG in million tonnes (Mt) of CO_2 equivalent per year, aggregating the emissions reported in Table 1 (summed values in the dark blue cells). Emissions from non-CO_2 gases are translated to CO_2e volumes following GWP100 according to AR5 (Table A2). This summary is an indicative estimate of the true emission volumes due to potential gaps and uncertainties in the reporting. For example, certain activities in the waste sector were captured only for Annex I countries, and therefore biogenic emissions from this sector could actually be higher.

Future developments

A substantial share of agricultural emissions is considered hard-to-abate and is therefore projected to be the largest contributor to future residual emissions.[6] Estimates for 2050, indicate that emissions from the agricultural sector are expected to change little—or in some cases increase—compared to current levels[7] (Table 1). According to the FAO, global agricultural production is likely to grow in response to population growth, rising incomes, and changing dietary preferences.[8] At the same time, climate change is expected to exert increasingly negative impacts on crop yields and livestock production.[9]

How agricultural GHG emissions will evolve depends on multiple, interacting factors: implementation of sustainable practices, shifts in consumption patterns, improvements in efficiency, and the adoption of new technologies. These changes require innovation and investment. Yet, when countries estimate their future residual emissions from agriculture, it is often unclear how they factor in these potential mitigation measures, particularly the extent to which they assume behavioural change, such as reduced consumption of livestock products.[10] Therefore, there is a high level of uncertainty about how future emissions for the agricultural sector are likely to evolve.

6 Smith et al. (2024) *Residual emissions in long-term national climate strategies show limited climate ambition*

7 FAOSTAT dataset (Accessed June 2025) *The FAOSTAT domain Emissions Totals*

8 FAO (2018) *The future of food and agriculture – Alternative pathways to 2050*

9 Cheng et al. (2022) *Climate change and livestock production: a literature review*; Hultgren et al. (2025) *Impacts of climate change on global agriculture accounting for adaptation.*

10 Smith et al. (2024); Buck et al. (2023) *Why residual emissions matter right now*

Table 1. Summary of all sources of biogenic emissions reviewed in this paper.

Summary of the sources of human-driven biogenic GHG emissions per sector or activity provided in Mt / year. The values use GWP100 where conversion to CO_2e is needed (see section A4 in the annex for further notes on the use of GWPs). Where possible, we provide global (Annex I and non-Annex I) emissions estimates from biogenic activities. In some cases (such as using the UNFCCC data) the presented totals reflect minimum estimates (i.e., where only Annex-I estimated are reported). (See the annex for further information on data coverage). Current emissions are from the latest reported year of the individual inventories; 2022 for FOASTAT; 2021 for UNFCCC; 2024 for EDGAR; 2020 for the Global Methane Budget; 2021 for permafrost melt. When available, the projected emissions for 2050 are included. Possible overlaps in reporting between the different inventories are noted. The cells highlighted in blue are aggregated to achieve the sectoral/source totals; the activities for which there are currently biogenic emission estimates are summed together meanwhile avoiding potential overlaps between inventories. Permafrost melt is shaded in grey, to reflect that instead it is perhaps best categorised as part of the long-term carbon cycle.

Sector / Source	Activity	GHG	Current emissions Mt CO_2e / year	2050 emissions Mt CO_2e / year	Scope	Inventory / Reference	Note
Agriculture	Livestock farming (enteric fermentation, manure management, manure left on pasture, manure applied to soils)	CH_4	**3,183**	3,670	Global	FAOSTAT	
		N_2O	**1,076**	1,272	Global		
Agriculture	Rice cultivation	CH_4	**683**	657	Global	FAOSTAT	
Agriculture	Crops (residues and burning of residues)	CH_4	**713**	685	Global	FAOSTAT	
		N_2O	**799**	958			
Agriculture	Synthetic fertilizer use	N_2O	**596**	750	Global	FAOSTAT	
Agriculture summed total		CH_4	**4,579**	5,012	Global		
		N_2O	**2,471**	2,980	Global		
Waste	Food waste disposal	CO_2	**32**	NA	Global	FAOSTAT	Overlaps with certain activities reported for the Waste sector by UNFCCC.
		CH_4	**1,183**				
		N_2O	**65**				
Waste	Biological treatment of solid waste (Composting, Anaerobic digestion at biogas facilities)	CH_4	**9**	NA	Annex-I	UNFCCC	Per the reporting requirements, the data is not global in scope but relates to emissions from Annex-I countries only.
		N_2O	**5**				
Waste	Burning biogenic waste (Biogenic waste incineration & open burning of waste - biogenic)	CO_2	**12**	NA	Annex-I	UNFCCC	Per the reporting requirements, the data is not global in scope but relates to emissions from Annex-I countries only.
		CH_4	**1**				
		N_2O	**2**				
Waste	Wastewater treatment and discharge	CH_4	**77**		Annex-I	UNFCCC	Per the reporting requirements, the data is not global in scope but relates to emissions from Annex-I countries only.
		N_2O	**39**				
Waste summed total		CO_2	**32**		Annex-I		
		CH_4	**1,259**				
		N_2O	**104**				

Ecosystem change	Land disturbance	CO_2	3,782	NA	Global	FAOSTAT	Included emissions from fires (forests, tropical forests, savannas, and organic soils), net forest conversion, and drained organic soils. Certain activities overlap with LULUCF emissions from UNFCCC inventory and EDGAR dataset. Also, there is likely some overlap with CH_4 reporting and the Global Methane Budget.
		CH_4	260				
		N_2O	315				
Ecosystem change	LULUCF	CO_2	232	NA	Annex-I	UNFCCC	Per the reporting requirements, the data is not global in scope but relates to emissions from Annex-I countries only, and therfore represents a minimum estimate. Land types linked to CO_2 emissions include croplands, wetlands, grasslands, other land & other. All land types contribute N_2O and CH_4 emissions. The listed subcategories likely overlap with the land distrubance activities from FAOSTAT and EDGAR dataset, and potentially with the Global Methane Budget.
		CH_4	118				
		N_2O	42.5				
Ecosystem change	LULUCF	CO_2	**6,008**	NA	Global	EDGAR	Data reflect CO_2 emissions include deforestation, and organic soil, and also CO_2, CH_4 and N_2O emissions from fires. There is likely overlap with UNFCCC inventory.
		CH_4	**711**				
		N_2O	**205**				
Ecosystem change	Permafrost Melt	CO_2	1,263	2,697	Global	Schuur et al. (2022)	Emissions estimates here reflect the 'medium scenarios' from the cited publication, and are converted using the molecular mass of CO_2 (see Annex). Reporting potentially overlaps with the Global Methane Budget since some permafrost thaw is reported with wetland emissions. Arguably, permafrost is part of the long-term carbon cycle.
		CH_4	448	971			
		N_2O	NA	NA			
Ecosystem change summed total		CO_2	6,008		Global		
		CH_4	2,802				
		N_2O	205				
Chemical industry (i.e., IPPU)	Disposal of chemical byproducts which enhances N2O production by microbes	N_2O	NA	NA			Unclear if/how this component is reported in GHG inventories.

Bioenergy	Burning of biomass or biofuel for energy	CO_2	1,143	NA	Annex-I	UNFCCC	Emissions from biomass burning are zero-rated to avoid potential double counting with LULUCF reporting. CO_2 emissions from biomass burning for bioenergy are reported as a memo item for the energy sector to the UNFCCC for Annex-I countries.
Bioenegy	Combustion of biofuels (e.g. primary solid biomass, liquid biofuels, etc.)	CO_2	8,017	NA	Global	EDGAR	Emissions from biofuel combustion are zero-rated to avoid potential double counting with LULUCF reporting. CO_2 emissions from biomass burning for bioenergy are reported as a memo item for the energy sector to the UNFCCC for Annex-I countries. Overlaps with UNFCCC reporting of waste (e.g., activities such as Incineration and Open Burning of Waste.
Harvested wood products (HWP)	End of life of wood products	CO_2	NA	NA			The net emissions from HWPs are reported according to IPCC GHG framework within the LULUCF sector. Possible emissions from HWP's are implicitly included as "outflows" within this net stock-change calculation using decay rates, but are not a direct measure of emissions from the end-of-life of wood products.

2.2 Chemical industry

Activities and current emissions

Another sector which contributes substantially to global GHG emissions is the chemical industry. Within the prescribed definition of biogenic emissions, the **disposal of chemical byproducts** can lead to (indirect) nitrogen enrichment in soils and water bodies, which in turn can enhance N_2O production by microbes.

This biogenic component of GHG emissions relating to the chemical sector is difficult to identify within reported emissions totals. It is unclear if these emissions are considered within the Industrial Processes and Product Use (IPPU) sector in the UNFCCC inventory categories or if they are distributed across multiple categories, particularly Agriculture (indirect N_2O from soils), Waste (wastewater or solid waste disposal), or potentially even the Energy sector if incineration is involved.

2.3 Waste management

Activities and current emissions

The waste management sector includes several activities which produce biogenic emissions resulting from the treatment of biological waste (Table 1). For example, **food waste** is a substantial source of biogenic emissions. When organic material is **composted** or burned, the carbon it contains is released mainly as CO_2, and nitrogen-rich waste can also produce N_2O. In **landfills**, where oxygen is limited, microbes can generate CH_4 as the waste breaks down. **Anaerobic digestion in biogas** plants also breaks down organic waste without oxygen, producing a gas mixture rich in CH_4 and CO_2. Although this CH_4 is usually captured and used for energy, some can leak, and excess CO_2 may be burned off, creating small additional emissions. **Wastewater treatment** can also generate emissions.

The FOA and UNFCCC inventories overlap in their reporting of biogenic sources from waste (Table 1; see Fig. A1 in the annex for details). Namely, the FAO reports substantial emissions globally (> 1000 $MtCO_2e$ per year) from the disposal of food waste within the agri-food system, taking a full supply chain approach to the food industry. This category overlaps with the waste sector reported to the UNFCCC, which shows a more minor contribution of biogenic emissions from Annex-I countries (<150 $MtCO_2e$). Therefore, to avoid overlap between inventories and capture the global perspective of emissions as much as possible, we aggregated the emissions from food disposal (FOA) and wastewater treatment only (UNFCCC) to roughly estimate the total biogenic emissions from the waste sector. According to our data compilation, **the waste sector currently accounts for roughly 1395 $MtCO_2e$/year of biogenic emissions in total, with 1259 $MtCO_2e$ from CH_4, 104 $MtCO_2e$ from N_2O, and 32 Mt/year from CO_2** (Fig. 1).

Future developments

Looking to the future, emissions from the waste sector may be expected to increase, considering the close link between waste production and population size and material well-being, but substantial improvements in waste management (such as in landfills and wastewater treatment) combined with dietary and consumer changes and better waste-to-energy streams, could eliminate a significant share of emissions.[11] For example, it is clear that reducing food waste alone could eliminate a substantial volume of emissions.[12] An analysis from Project Drawdown found that up to 100 Gt CO_2e emission could be avoided by 2050 if there was a largescale reduction in global food loss and wastage.[13]

11 Gautam & Agrawal (2021) *Greenhouse Gas Emissions from Municipal Solid Waste Management: A Review of Global Scenario*; FOA (2018) *The future of food and agriculture – Alternative pathways to 2050*; Ivanovich et al. (2023) *Future warming from global food consumption*; UNEP (2024) *Global Waste Management Outlook 2024: Beyond an Age of Waste — Turning Rubbish into a Resource*

12 OECD/FAO (2024) *OECD-FAO Agricultural Outlook 2024-2033*

13 Project Drawdown *Reduced Food Waste (Accessed September 2025)*

2.4 Bioenergy

Activities and current emissions

Bioenergy refers to the use of organic materials—such as plants, agricultural residues, forestry products, or organic waste streams—as fuel for energy generation. This category includes solid biomass (e.g., wood pellets, wood chips), liquid biofuels from dedicated crops (e.g., ethanol, biodiesel), and biogas produced through the anaerobic digestion of organic matter (e.g., manure, food waste, sewage sludge) or captured from landfill sites. When these fuels are combusted for heat, electricity, or transport, the carbon stored in the material is oxidised and released as CO_2. Therefore, these energy-related practices represent sources of biogenic emissions.

These emissions from bioenergy are not explicitly counted towards the total emissions for the energy sector in national inventories to avoid double counting, since the associated carbon fluxes are assumed to be reported in the LULUCF sector where applicable. Instead, Annex I countries report CO_2emissions from biomass burning for bioenergy as a memo item to the UNFCCC. However, this strategy creates an incomplete linkage between inventories which is problematic for several reasons: namely, imported biomass is not connected to exporting countries' LULUCF accounts, some waste-derived fuels fall outside of LULUCF reporting, key carbon stock changes (such as degradation and indirect land-use change) are often unaccounted for, and annual inventories do not capture the time lag between immediate combustion emissions and delayed forest regrowth. The overall effect is that some biogenic CO_2 emissions from energy use are not fully reflected in national totals.

In the latest available inventory year (2021), the CO_2 emissions from biomass burning reported by **Annex I countries were 1,143 Mt** according the UNFCCC and **8,017 Mt** globally according to the EDGAR data set (Table 1). Understanding how much of this volume could reflect 'missing' emissions which are not fully reflected by LULUCF emissions is currently difficult to estimate and would require updates to reporting requirements.[14] For this reason, these biogenic emissions from bioenergy use are therefore not explicitly reflected in our aggregate total.

14 Pulles et al. (2022) *CO_2 emissions from biomass combustion: Accounting of CO_2 emissions from biomass under the UNFCCC*

Future developments

The demand for bioenergy is expected to increase in the future due to its perceived role in replacing fossil fuels and supporting decarbonisation in hard-to-abate sectors.[15] Yet, the future growth of the bioenergy sector will be impacted by competition with other wood-using industries, such as the building sector and pulp and paper. If not paired with properly implemented carbon capture and storage (CCS), expanding bioenergy use could mean larger gross CO_2 flows from combustion of bioenergy gases and fuels. Only a small number of bioenergy systems use CCS today.

2.5 Harvested wood products

Activities and current emissions

Another source of biogenic emissions comes from the **decomposition of harvested wood products (HWPs)** or other biomass products. HWPs include wood materials used in construction, manufacturing, such as sawn wood, wood panels or paper (but excludes wood pellets). Carbon stored in these products can temporarily (on the timescale of several decades maximum) result in emissions reductions, which may be reflected as emissions reductions in national greenhouse gas inventories.

HWPs are accounted for within LULUCF as a carbon stock, with reported emissions based on the net change in this stock. As a result, countries may report HWPs as negative emissions (i.e. a carbon sink) when the stock of wood products is increasing. In 2021, Annex I countries reported a net sink of around 54 $MtCO_2$ per year from HWPs.

However, this accounting approach does not explicitly report emissions from the physical decay or oxidation of wood products (e.g. through decomposition or incineration). Instead, these emissions are implicitly included as “outflows” within a net stock-change calculation, where reported values reflect the balance between additions to and losses from the HWP pool. As a result, HWP reporting represents a net emissions metric, rather than a direct measure of emissions to the atmosphere in a given year. Consequently, substantial real-world emissions from the end-of-life of wood products can occur even while HWPs are reported as a net carbon sink, provided that inflows exceed outflows.

This lack of transparency can obscure both the magnitude and timing of emissions, and may give the impression of sustained mitigation benefits, even though the underlying carbon storage is temporary and associated emissions are delayed rather than avoided. At the end of life of these products (i.e., upon burning or decomposition), this carbon is released back into the atmosphere in the form of CO_2. In this way, the current accounting may overstate mitigation benefits and undermine the accuracy of greenhouse gas inventories.

Future developments

The carbon stocks stored in HWPs are growing globally[16] as more wood is entering this pool from use in building construction, furniture, paper and other materials. Wood is often promoted as a lower-GHG alternative to concrete or steel in construction, based on the assumption that it can substitute emissions-intensive materials and store carbon in the short-term.

However, the actual climate benefit from mass timber use in construction is far from assured.[17] Large losses of biomass occur during harvesting and processing, leading to substantial near-term emissions. These short-term atmospheric impacts, combined with biodiversity risks and land-use competition, cast doubt on the overall mitigation value of expanded mass-timber use.

The climate impact of HWPs also depends heavily on what happens at the end of their life. Emissions vary with the volume of material stored, the longevity of different product types, and the pathways used for disposal or bioenergy. As a result, future inflows to and outflows from the HWP carbon pool will depend on assumptions around product lifespans, wood-use trajectories, and bioenergy strategies. Under different scenarios, the contribution of HWPs to climate mitigation could either grow or decline in the coming decades.[18]

15 Riahi et al (2022) *Mitigation pathways compatible with long-term goals. In Climate Change 2022: Mitigation of Climate Change*; IEA (2023) *Net Zero Roadmap: A Global Pathway to Keep the 1.5 °C Goal in Reach*

16 Steel et al. (2021) *Carbon Storage and Climate Change Mitigation Potential of Harvested Wood Products*

17 WRI (2023) *Wood Is Not the Climate-friendly Building Material Some Claim It To Be*

18 Bozzolan et al. (2024) *Options to improve the carbon balance of the harvested wood products sector in four EU countries*

2.6 Human-driven ecosystem change

Activities and current emissions

Climate change and human activities have led to the disturbance of many natural ecosystems, resulting in sizeable changes in carbon stocks and GHG emissions. The consequences are wide-ranging: ecosystems lose biodiversity, forest fires increase, soil and water systems are altered, and greenhouse-gas (GHG) fluxes change, affecting not only CO_2 emissions but also potent gases such as CH_4 and N_2O.

The emissions and removals associated with different land types are reported under the **LULUCF** sector. Considering the reported estimates to the UNFCCC for Annex-I countries, the categories which contribute to GHG emissions (in 2021) are cropland, grassland, wetlands, and those covered by 'Other Land' and 'Other' (Table 1). However, these emissions are fully compensated by removals from Forest Land, Settlements and Harvested Wood Products, resulting in net-negative emissions from LULUCF for Annex-I countries overall.

On the global scale, the LULUCF sector is a net source of emissions. For example, according to the PRIMAP-PIK historical emissions data, net LULUCF emissions globally were 6.6 ± 4.6 Gt CO_2 in the last inventory year (2019) and emissions levels have remained relatively stable since 1990, albeit with substantial uncertainties in the calculations.[19] Considering the positive emissions component from this net estimate, according to EDGAR data estimates, the GHG emissions coming from deforestation, organic soils, and fires are currently 6.9 Gt (based on data from 2024), mainly in the form of CO_2 and also a smaller contribution of CH_4 and N_2O from fires (Table 1). Similarly, the FAO also estimates substantial emissions from land disturbance (fires, draining organic soils, and net forest conversion), but with much lower emissions estimates likely due to the only partial overlap with LULUCF reporting (see Fig. A1).

On the other hand, some carbon-stock changes in LULUCF land categories are likely not fully captured in current GHG inventories. For instance, evidence suggests that in Europe most soil carbon changes are currently not monitored.[20] Better monitoring could reveal large hidden emissions from croplands and removals from grasslands and forests on a similar order of magnitude, but which may not fully cancel out and could significantly shift the EU's GHG balance. These large volumes are likely driven by past land-use changes and climate change impacts.

Other sources of emissions from ecosystem change

Among land categories linked to GHG emissions, wetlands have received particular attention. While they are well known as important CO_2 sinks, wetlands can also be significant sources of greenhouse gases through two main pathways. First, the drainage or conversion of wetlands, for example for agriculture, urban development, or in response to climate change, leads to the release of CO_2, as previously preserved organic material decomposes. Second, intact wetlands such as peatlands host methane-producing microbes and are therefore a source of CH_4 emissions. As a result, the net emissions contribution from wetlands depends on the balance between these components.

According to the UNFCCC reporting for Annex I countries, wetlands currently emit 80 Mt CO_2e per year.[21] However, not all wetland-related emissions are fully covered under current LULUCF reporting. While managed wetlands must be reported, emissions from unmanaged wetlands, drained organic soils (peatlands), and coastal "blue carbon" ecosystems (saltmarshes, mangroves, seagrasses) are often missing or underestimated due to data gaps and limited use of the 2013 IPCC Wetlands Supplement.[22]

Additionally, these emissions reported under the LULUCF mainly focus on carbon stock changes from wetland conversion or management practices. On the other hand, rising average temperatures in certain wetland environments relating to human-induced global warming causes increased microbial activity resulting in the net effect of elevated CH_4 emissions. Scientists are working to determine what level of GHG emissions from wetlands and inland

19 Dhakal et al. (2022) *Summary for Policymakers*

20 Bellassen et al. (2022) *Soil carbon is the blind spot of European national GHG inventories*

21 based on 2021 data

22 IPCC (2014) *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands. Provides methods for wetlands, rewetting, and coastal ecosystems, but acknowledges that many countries do not yet apply them in national inventories*; Barthelmes et al. (2018) *Reporting greenhouse gas emissions from organic soils in the European Union: challenges and opportunities* waterbodies is above the baseline of the natural system and therefore can be indirectly attributed to human causes. The most recent report from the Global Methane Budget[23] includes an average estimate of global emissions from inland freshwater system, such as lakes and wetlands of 3,808 Mt CO_2e/year, with an estimate range of 1,666 – 6,868 Mt CO_2e/year[24]. Of this total volume, likely more than two thirds[25], **or roughly 2,550 Mt CO_2e/year**, can be attributed to anthropogenic actions (relating to climate change, CO_2 fertilisation, eutrophication, and human-built reservoirs).

Another landscape which may not be fully included within LULUCF reporting are **permafrost** regions. As temperatures rise, large areas of permafrost in the arctic and sub-arctic are beginning to melt, making previously frozen organic material accessible to microbes. This phenomenon is predicted to accelerate in the future.[26] Decomposition of this organic material can lead to CO_2 emissions in aerated environments and CH_4 emissions in waterlogged environments. It's estimated that **permafrost thaw currently contributes roughly 1,300 Mt CO_2e /year** of emissions from CO_2 and CH4 and that this figure could more than double by 2050 (Table 1).[27]

However, it is not entirely clear whether permafrost should be considered part of the short-term carbon cycle because its behaviour spans both fast and slow timescales. On the one hand, it functions as a long-term store, containing organic matter that has remained frozen for centuries to tens of thousands of years, giving it residence times similar to deep-soil or geological carbon pools. On the other hand, once permafrost thaws, the carbon it holds can rapidly enter the short-term carbon cycle over timescales ranging from seasons to decades through its interaction with microbial processes. Also, the seasonally thawed 'active layer' of permafrost already exchanges carbon with the atmosphere every year, and abrupt thaw events can mobilise deep carbon even more quickly. Taken together, permafrost is best understood as a hybrid carbon reservoir, storing carbon over millennia yet can release it on short, climate-relevant timescales once it is disturbed.

Therefore, there are strong arguments that these emissions should ideally be compensated with permanent removals under the LfL principle. For this reason, we presently exclude them from our aggregate total, but note that they represent a sizeable source of emissions not captured in GHG inventories.

To gauge the global emissions relating to human-driven ecosystem change and avoid potential overlaps in data sources, we aggregate data from the LULUCF sector from the EDGAR dataset and from wetlands reported by reported by the Global Methane Budget, (Table 1). **These emissions sum to a total of 9,016 Mt CO_2e /year, with 6,008 Mt from CO_2, 2,802 Mt from CH_4 and 205 Mt from N_2O** (Fig. 1).

Future emissions

Emissions from wetlands, inland water bodies[28] and melting permafrost[29] are generally expected to increase in the future as global warming continues (Table 1). On the other hand, the net emissions world-wide from the LULUCF sector remain uncertain. Depending on future land-use trajectories, natural ecosystems could expand and strengthen the carbon sink, or continued conversion and degradation could cause the sector to remain a net source of emissions at the global scale[30]. These large differences in predicted LULUCF capacity relate to uncertainties about changing land use practices, food security, lifestyle and diet, and the impact of climate change on the sector in the future.

23 Saunois et al. (2025) *Global methane budget 2000–2020*

24 *see section A3 in the annex for notes on conversion method*

25 Jackson et al. (2024) *Human activities now fuel two-thirds of global methane emissions*

26 Schuur et al. (2023) *Permafrost and climate change: carbon cycle feedbacks from the warming Arctic*

27 Schuur et al. (2023); data for 2021; see section A3 in the annex for notes on conversion method

28 Zhang et al. (2017) *Emerging role of wetland methane emissions in driving 21st-century climate change*; Saunois et al. (2025) *Global methane budget 2000–2020*; Jackson et al. (2024) *Human activities now fuel two-thirds of global methane emissions*; Bastviken et al. (2025) *Future methane emissions from lakes and reservoirs*

29 Schuur et al. (2023) *Permafrost and climate change: carbon cycle feedbacks from the warming Arctic*

30 IPCC (2019a) *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems*

2.7 Summary of sectors contributing to biogenic emissions

This data collection exercise demonstrates the difficulty of extracting the biogenic emissions component from GHG inventories at the global scale and the potential need for better activity level information from non-Annex I countries. Although the aggregated totals reflect global estimates as much as possible as discussed above, certain limitations in coverage mean that **the total values reflect a conservative estimate of biogenic emissions, and that actual volumes could be considerably larger.** For example, other sources of biogenic emissions, such as activities in the chemical industry, bioenergy use, and the breakdown of harvested wood products are potentially (partially) neglected in GHG inventories and precise estimates of these missing emissions are difficult to obtain. Other ecosystems, for example, the marine environment, may also be a source of unaccounted anthropogenic emissions. Also, permafrost thaw is a growing source of unreported GHG emissions, but which is perhaps best placed in the long-term carbon cycle.

Nonetheless important insights can be gleaned about the relevant sectors, gases, and volumes of the current biogenic emissions at the global scale. In total, we found that globally, humans are currently responsible for over 17 $GtCO_2e$ of biogenic emissions per year (roughly 30% of our total emissions). Ecosystem change contributes the largest proportion of GHG emissions from biogenic sources (52%), consisting mainly of CO_2 (67%) and CH_4 (31%; Fig. 1), with a small contribution of N_2O (2%). These contributions are followed by emissions from agriculture (41%), in the form of CH_4 (65%), with substantial volumes of CO_2 (35%). The waste sector also contributes substantially to biogenic emissions (8%), overwhelmingly in the form of CH_4 (90%) with smaller contributions from N_2O (7%) and CO_2 (2%). Considering the relative contribution of the different GHGs overall (Fig. 2), nearly half of the biogenic emissions are CH_4 (49%), followed by CO_2 (35%) and N_2O (16%).

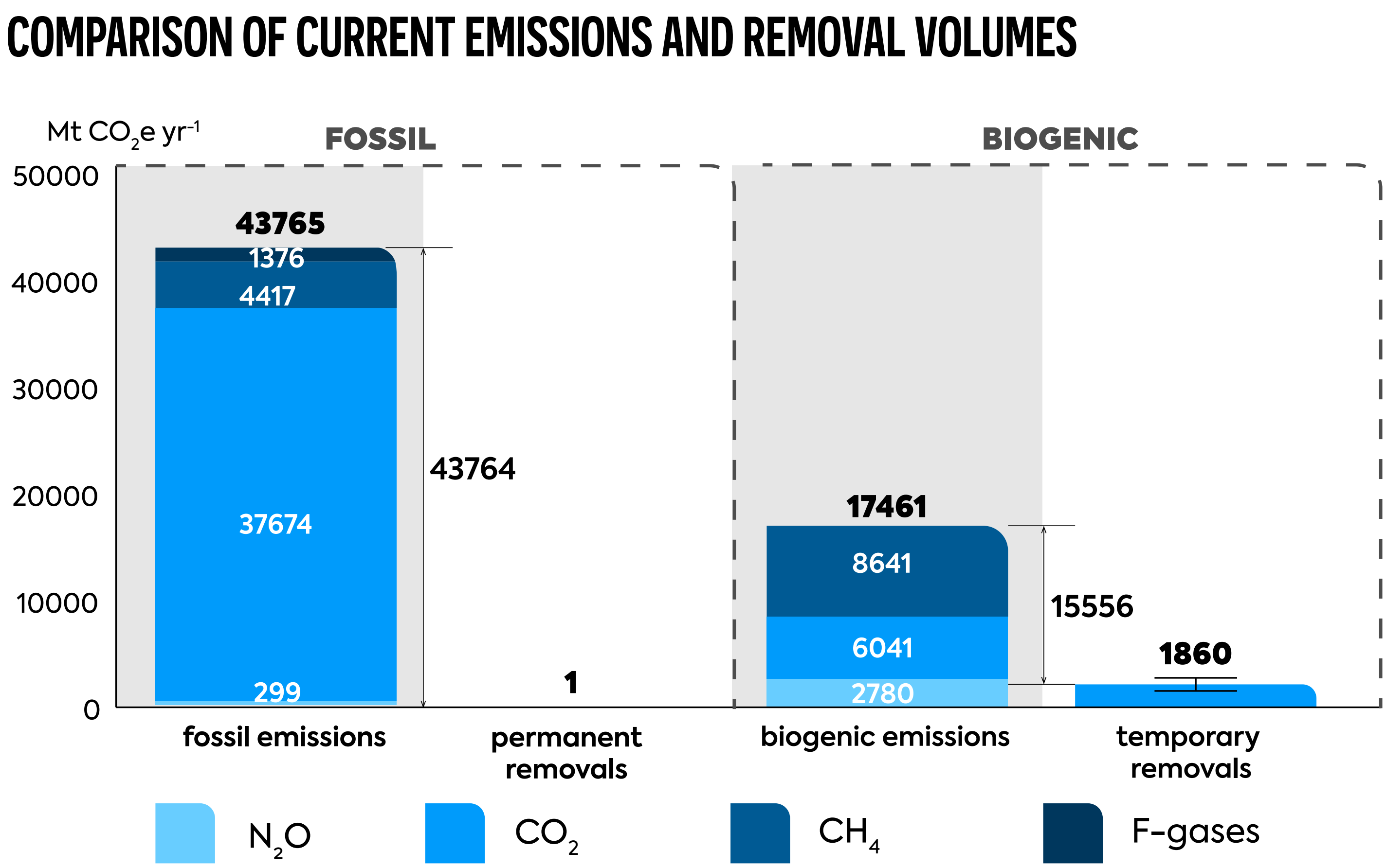


Figure 2: Comparison of GHG volumes emitted from fossil sources with the current amount of permanent removals (left) and comparison of current biogenic emissions caused by human activity (Table 1) and temporary removals. The current level of permanent and temporary removals comes from Smith et al. (2023); we plotted temporary removals to show the mean (bar height) and standard deviation (whiskers) of several reported model outcomes.

3. TEMPORARY BIOGENIC REMOVALS

3.1 Current levels

There are several methods for temporary carbon removal and storage. Most prominent, land-based carbon removal methods—such as afforestation, reforestation, peatland restoration, and improved soil management on cropland, grassland, and agroforestry systems—draw CO_2 from the atmosphere and store it temporarily in vegetation and soils. Blue-carbon options like mangrove restoration or kelp farming can similarly enhance CO_2 uptake in coastal and marine ecosystems. Temporary carbon storage in long-lasting wood products is also comparable to those of forest biomass, typically on the order of decades. In general, these activities reflect short-term removals with heightened reversal risk, for example from ecosystem loss, decomposition, or forest fires. Current estimates for the level of temporary removals, predominantly from afforestation/reforestation, range between **1160 and 2230 Mt CO_2e /year** (Fig. 2).[31]

It is important to note that several carbon removal methods initially store carbon in living biomass but subsequently convert it into a more stable form through chemical processes and/or long-term physical storage. Examples include bioenergy with carbon capture and storage (BioCCS), biomass sinking in the deep ocean, and permanent wood burial. When carried out appropriately, these approaches are considered permanent carbon removal methods and are therefore distinct from temporary biogenic removals. Additionally, under certain conditions the application of biochar to soils can deliver longer-term removals depending on how the biochar is produced, its stability, and where it is applied, but shorter residence times are also likely.

New techniques for capturing CO_2 in the biosphere are continuously being developed. On the other hand, removing other GHGs (i.e., CH_4 and N_2O) from the atmosphere presents unique challenges. Although several techniques are emerging[32], they are comparatively novel and underdeveloped, meaning their future capacity is somewhat uncertain.

31 Smith et al. (2023) *The State of Carbon Dioxide Removal Report 2023*; The range between different model outcomes is given.

32 Spark Climate Solutions (2024) *Atmospheric Methane Removal Primer: Methane Removal Climate Motivation*; Crop Intellect (2024) *R-Leaf*

3.2 Potential removal capacity

There are a handful of assessments which address the future potential of a variety of nature-based solutions at the global scale to remove and store carbon, mainly in the living biosphere on land and soils.[33] It should be noted that frequently these assessments group avoided emissions and carbon storage together to determine a net climate mitigation potential from nature-based methods. For example, one study estimates that between 2020 and 2050 cost-effective land-based measures (available up to $100/t$CO_2$e) have the potential to mitigate around 8,000 to 13,800 Mt CO_2e/year.[34] More recently, researchers estimated that the global potential for net carbon storage from reforestation alone is 2225 Mt CO_2e/year but drops to just 53 Mt CO_2e/year if considering only statutorily protected areas[35] where government policies are likely most effective.

Hence, some studies suggest that a massive scale-up of temporary removals is theoretically possible, but there are practical limitations which will likely hinder their implementation. Relying too heavily on land-based CDR may carry substantial risks. For example, large-scale biomass and land interventions can accelerate biodiversity loss and also face major economic, technological, and social feasibility constraints, while posing threats to food security and human rights.[36]

33 E.g., Griscom et al. (2017) *Natural climate solutions*; Roe et al. (2021) *Land based measures to mitigate climate change: Potential and feasibility by country*

34 Roe et al. (2021) *Land based measures to mitigate climate change: Potential and feasibility by country*; Land-based mitigation measures defined by Roe et al. avoid emissions or lead to carbon removals through practices such as sustainable agricultural practices, restoration/management of forests or other ecosystems, and biochar application.

35 Fesenmyer et al. (2025) *Addressing critiques refines global estimates of reforestation potential for climate change mitigation*

36 Deprez et al. (2024) *Sustainability limits needed for CO_2 removal*

4. THE CURRENT MISMATCH AND FUTURE OF BIOGENIC TEMPORARY REMOVALS

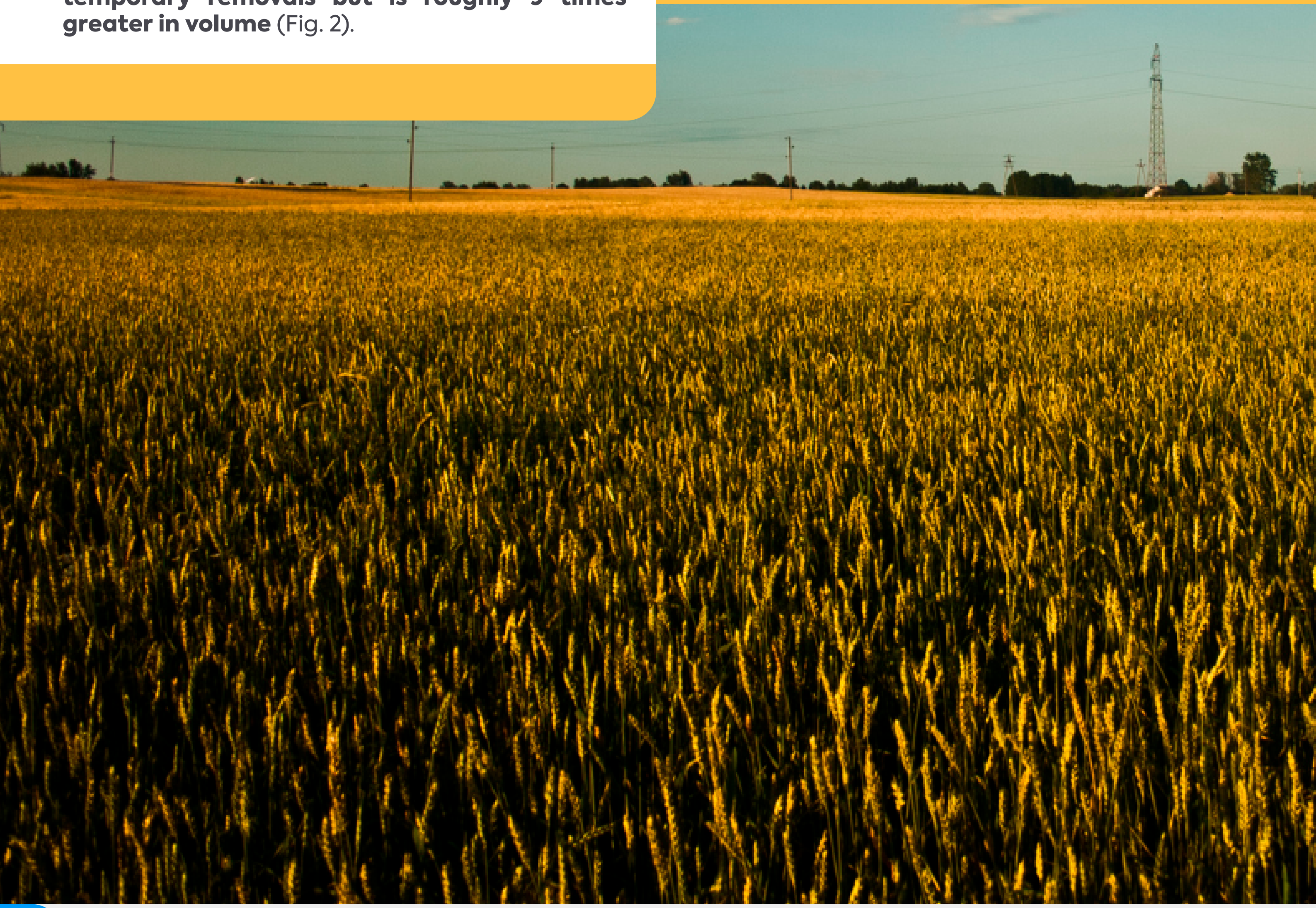
According to our analysis, total GHG emissions currently exceed total removals by one order of magnitude (Fig. 2). The closing of this gap to reach net-zero emissions in the future will be chiefly determined by largescale emissions reductions as outlined in the Paris Agreement. Additionally, removal efforts will need to increase in order to balance residual emissions and reach net targets.[37] Currently, only roughly 29% of these emissions can be categorised as biogenic whereas the majority of emissions (71%) originate from fossil fuels or other non-biogenic sources (Fig. 2). On the other hand, currently nearly all removals come from conventional carbon removal methods involving ecosystem restoration and management, whereas novel CDR methods capable of more permanent CDR storage currently reflect less than 0.1% of removals (or 1300 Kt).[38] Importantly, this comparison shows that **at present, the total rate of yearly biogenic emissions is not fully neutralised by temporary removals but is roughly 9 times greater in volume** (Fig. 2).

4.1 Matching Biogenic Emissions and Removals

Figure 3 illustrates how the LfL principle could be implemented to strive for durable net-zero, with the emissions trajectories determining the level of CDR need in the future. Both permanent and temporary CDR will need to scale dramatically to meet this future demand, balancing residual emissions and potentially addressing historical emissions. This hypothetical pathway towards a LfL approach of matching emissions and removals also highlights some technological challenges and potential future gaps.

37 IPCC (2022) _Climate change 2022: Mitigation of climate change. Contribution of working group III_

38 Smith et al. (2023) _The State of Carbon Dioxide Removal Report 2023_



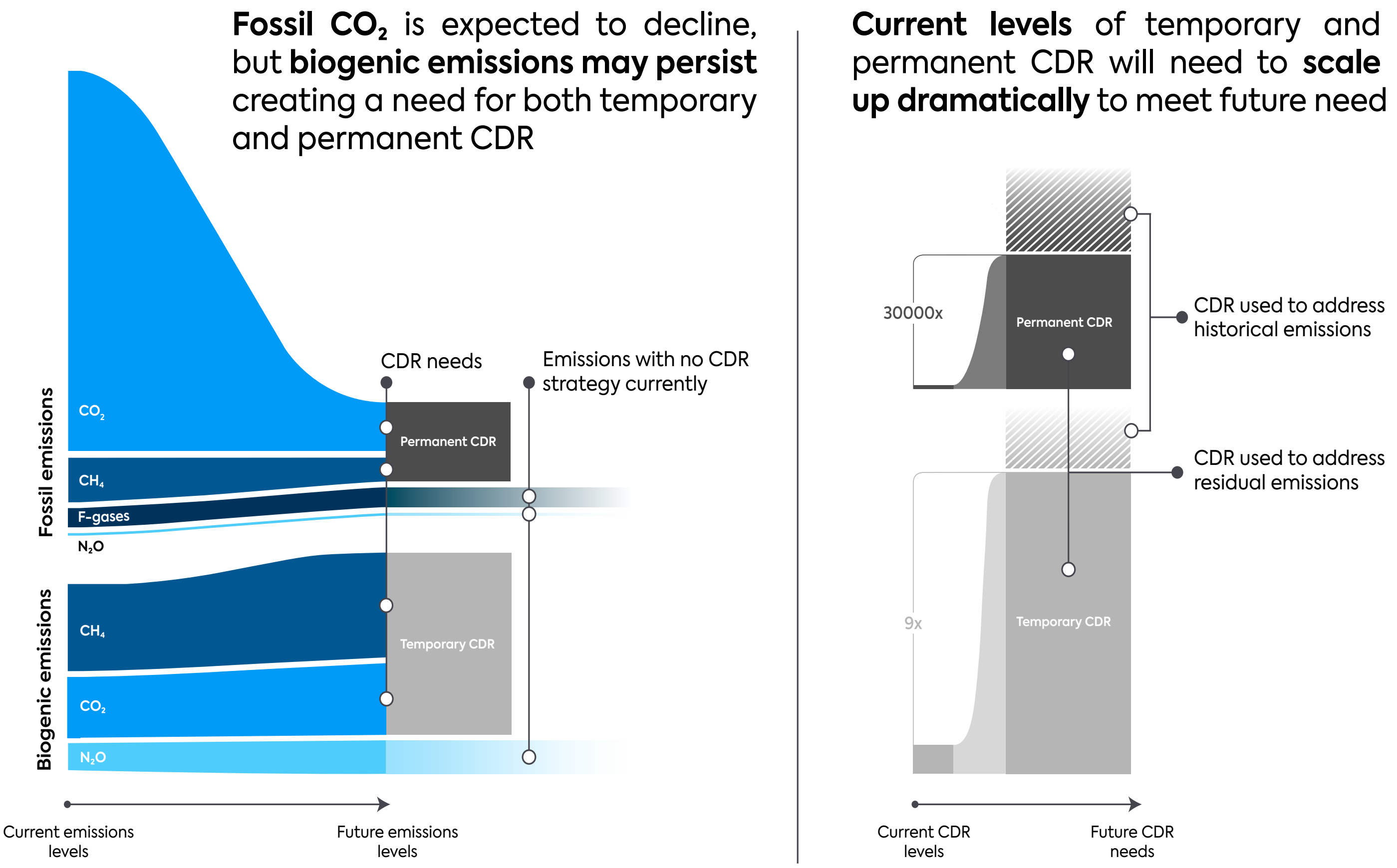


Figure 3: Illustrative pathway showing the evolution from today's fossil and biogenic emissions to future levels, showing the implications of striving for a like-for-like (LfL) balancing of emissions and removals. The figure shows steep projected reductions in fossil emissions alongside comparatively persistent biogenic emissions. It illustrates a LfL framing in which permanent CDR is used to neutralise residual fossil CO_2 (and, where applicable, fossil CH_4), while temporary removals are used to neutralise residual human-driven biogenic CO_2 and CH_4. The figure also signals that certain gases (e.g., N_2O and F-gases) are generally not well suited to mitigation through CDR, and that using CO_2 removals to counterbalance non-CO_2 gases remains an evolving area with no agreed best practice or robust equivalence methods. Current levels of both permanent and temporary CDR will need to scale dramatically to reach future need.

A central challenge of enacting the LfL principle is that essentially all mature GHG removal techniques target CO_2, whereas the majority (roughly 65%) of biogenic emissions consist of CH_4 and N_2O. The question therefore arises whether biogenic CH_4 and N_2O emissions can be appropriately countered with temporary CO_2 removals given their differing lifetimes, radiative efficiencies, and climate impacts. Addressing this question requires selecting a metric to place different gases on a comparable scale, which a complex and consequential choice.

In this analysis, we express emissions in CO_2-equivalent terms using the IPCC AR5 GWP100 values for CH_4 (28) and N_2O (265) (see Table A2 in the annex). The GWP100 metric estimates the average warming effect over 100 years of a one-time "pulse" emission of a gas, relative to CO_2, which is assigned a value of 1. This conversion provides a practical basis for comparison and for planning CDR strategies. For example, under this framework, offsetting one tonne of CH_4 emissions would require removing 28 tonnes of CO_2.

However, this approach involves important trade-offs. CH_4 is far more potent than CO_2 in the short term but breaks down relatively quickly, within about 12 years. This difference is reflected in its high GWP20 value (>80). Using GWP20 instead of GWP100 the resulting biogenic CH_4 emissions, would nearly double (See section A4 and Fig. A2). By contrast, CO_2 has a much lower per-molecule warming effect but remains in the atmosphere for hundreds to thousands of years, giving it a far greater cumulative impact on climate over long timescales. These differences have led some to argue that CH_4 emissions should ideally be countered with CH_4 removals, which would yield more immediate climate benefits—an important consideration for limiting near-term warming. Yet, such technologies are still in their infancy. As a result, the idea of balancing biogenic CH_4 emissions with biogenic CO_2 removals is a pragmatic approach, though one that comes with important caveats and considerations.

For N_2O, the picture is different again. This gas is far more potent than CO_2 on a per-molecule basis and, like CO_2, it persists in the atmosphere for centuries, with GWP500 around 153 (Table A2). In addition to its direct warming effect, N_2O also has important indirect impacts on the climate system because it participates in chemical reactions that deplete stratospheric ozone. While ozone depletion does not itself increase global warming, it weakens the atmosphere's ability to absorb harmful UV radiation, leading to higher risks of UV-related health impacts and damage to ecosystems such as crops and marine phytoplankton.[39]

Countering biogenic N_2O emissions with CO_2 is therefore also a practical choice which carries important implications. Other opportunities for N_2O mitigation would be to deploy a circular life-cycle approach for nitrogen fertilisation in agriculture, which emphasises reducing losses at every stage of production, recycling nutrients, and closing the nitrogen loop to minimise environmental impacts. Emerging technological solutions, such as nitrous oxide destruction using photocatalysts,[40] deserve further exploration, since they could complement circular practices by directly targeting emissions that are otherwise difficult to mitigate.

39 UNEP & FOA (2024) *Global Nitrous Oxide Assessment*

40 Crop Intellect (2024) *R-Leaf*

Besides the GWP metrics defined for specific time horizons (e.g., GWP20, GWP100), several other climate-impact metrics have been developed, each serving a slightly different purpose. For example, GWP* links a pulse emission of long-lived gases such as CO_2 with a change in the emissions rate of short-lived gases like CH_4[41]. This method allows the cumulative warming effects of both gases to be compared more consistently under the traditional GWP framework and provides a more accurate reflection of the climate impact of short-lived pollutants. It is particularly applicable for carbon-budget accounting. More recently, Sum44 (the 44-year lagged cumulative sum of methane emissions) has been proposed as a simple and robust predictor of methane-driven temperature change, offering advantages for designing policy controls aimed at meeting near-term climate targets.[42]

We recently recommended[43] that biogenic residual emissions be offset by those biogenic carbon removal methods that match in terms of the sphere of origin, equivalent carbon volume, and minimal duration of the pollutants' climatic impact. Further work should focus on creating concrete recommendations and create practical guidelines for best matching emissions and removal strategies based on equivalences.

4.2 The future of biogenic emissions

Although there are large uncertainties in how the sources of biogenic emissions will evolve, there is cause to believe that many of these emissions will persist or increase due to increasing population size, pressures on land use, and negative climate impacts on ecosystems. In particular, the agricultural sector which currently contributes most biogenic emissions is seen as a hard-to-abate sector. There is enormous potential from nature-based solutions to mitigate climate change through carbon storage in the biosphere,[44] but real-world blockers and competing land uses will likely limit this potential.

41 Allen et al. (2018) *A solution to the misrepresentations of CO2-equivalent emissions of short-lived climate pollutants under ambitious mitigation*

42 Miller et al. (2025) *Assessing alternative methane emission metrics conducive to quantifying*

43 Carbon Gap (2026) *Understanding and Implementing the Like for Like Principle*

44 Roe et al. (2021) *Land based measures to mitigate climate change: Potential and feasibility by country*; Griscom et al. (2021); Fesenmyer et al. (2024)

On the other hand, fossil emissions from CO_2 must be rapidly and dramatically cut in the coming decades. Most mitigation is expected to come from sectors such as energy, although the magnitude and pace of decarbonisation remain uncertain across future scenarios. This balance could have implications for the future role of permanent removals to tackle the shrinking residual emissions from fossil sources. Yet, it also appears unlikely that the reduction of fossil fuel emissions will be successful enough to limit the need to continue growing the nascent permanent removal methods; rapid scale-up of this industry must remain a priority. Beyond durable net-zero, permanent CDR will still have the leading role in neutralising historical fossil-fuel emissions.

With these caveats and uncertainties in mind, this analysis shows that scaling the amount of annual temporary removals to fully compensate for biogenic emissions in the coming decades in order to reach durable net-zero presents a huge challenge. On the other hand, the concern from nature-based solution providers that setting strict rules for temporary and permanent removals following a LfL approach might reduce demand for their services is not supported by our analysis. Ample biogenic emissions are likely to persist in the future, providing suitable demand for temporary removals. In practice, **both temporary and permanent CDR will need to scale significantly to address future biogenic and fossil emissions, respectively.**

5. RELATED EU POLICIES

The future of biogenic emissions and removals is shaped by international climate agreements, evolving accounting rules, and national policy frameworks that govern land use, forestry, agriculture, waste, and bioenergy. Within this global landscape, the EU plays a key role through a set of policies that regulate and monitor biogenic emissions, several of which are reviewed below and summarised in Table 2. For each, we explain how it regulates or interacts with biogenic removals or emissions and spotlight their limitations. This preliminary review focusses on the main regulations, mainly at the EU level, and does not yet assess additional policies which may exist at the Member-State level.

REGULATION	POLICY SNAPSHOT	RELEVANCE FOR BIOGENIC EMISSIONS / REMOVALS	
EFFORT SHARING REGULATION (ESR)	Under the ESR, each EU country has its own binding target to cut emissions compared to 2005 levels. Together, these targets aim to reduce total EU emissions by 40% by 2030.	The ESR includes sectors outside of the ETS and LULUCF, including agriculture and waste which are important sources of biogenic emissions.	SECTOR-SPECIFIC BINDING EU TARGETS
LAND USE, LAND USE CHANGE, AND FORESTRY REGULATION (LULUCF-R)	Until 2030, EU countries must make sure that emissions from LULUCF do not exceed the amount of CO_2 they remove — known as the "no-debit" rule. Countries can trade surplus removals under the Effort Sharing Regulation (ESR). In 2023, the revised LULUCF-R set an EU-wide target of –310 Mt CO_2e of net removals by 2030.	Since the LULUCF-R sets out a net removals target, it is relevant for both biogenic emissions and removals from the land sector. LULUCF covers land conversion or disturbance on various managed and natural land types and includes also removals from harvested wood products (HWPs).	SECTOR-SPECIFIC BINDING EU TARGETS
NATURE RESTORATION LAW (NRL)	Under the NRL the EU has a set target to report 20% of degraded land and seas, restore at least 25,000 km of rivers into free-flowing rivers and plant at least 3 billion additional trees by 2030. By 2050, all ecosystems in need of restoration must be restored.	Restoring natural ecosystems can remove large amounts of emissions and store them in the biosphere.	SECTOR-SPECIFIC BINDING EU TARGETS
RENEWABLE ENERGY DIRECTIVE (RED)	The RED is the EU's main policy for boosting renewable energy which sets binding targets for renewable energy use and provides rules for sectors. The latest update, RED III (2023), raises the EU's goal to at least 42.5% renewables by 2030 (with a voluntary target of 45%).	Renewable energy based on biomass is promoted through the RED, with key sustainability guardrails. The RED and other European policy frameworks (ETS and ESR) consider biomass burning for energy as carbon-neutral. This is problematic for accurate emission reporting and effective climate mitigation strategy.	SECTOR-SPECIFIC BINDING EU TARGETS
EUROPEAN CLIMATE LAW (ECL) & 2040 TARGETS	The ECL sets the EU's path to climate neutrality by 2050, requiring least a 55% net emissions reduction by 2030 (vs. 1990 levels) and guides progress through rules linking major policies like the ETS, ESR, and LULUCF. The recent amendment set a 90% net GHG emissions reduction target by 2040 (compared to 1990 levels).	The net emission reduction targets must be met by cutting emissions, and removing/storing carbon via the LULUCF sink, or permanent removals. The structure and ambition of the 2040 target, through its impact on sectoral and member state planning, will impact the level of biogenic emissions and removals in the future.	BINDING NET EMISSIONS TARGET
COMMON AGRICULTURAL POLICY (CAP)	The CAP is the main funding instrument to meet LULUCF and ESR targets. It provides financial support to help farmers produce food sustainably, enhance biodiversity, and contribute to climate goals.	Land management measures supported by the CAP influence major sources of biogenic emissions and carbon removals, mainly within the LULUCF and agriculture sectors.	VOLUNTARY INCENTIVE SCHEMES
CARBON REMOVAL & CARBON FARMING REGULATION (CRCF)	The CRCF will establish EU-wide rules for monitoring, reporting, and certifying carbon removals to ensure credibility and consistency. It will allow certification of permanent industrial removals, carbon farming practices, and carbon storage in long-lasting products.	The CRCF aims to provide a monetary incentive for high-quality carbon removal activities, including temporary biogenic removals through carbon farming practices. Moreover, avoided emissions from via peatland rewetting are included within the scope of CRCF eligible activities.	VOLUNTARY INCENTIVE SCHEMES

Table 2: Overview of the major EU regulations and policies which currently shape the relevant to biogenic emissions and removals.

5.1 Effort Sharing Regulation

Scope

The **Effort Sharing Regulation** (ESR)[45] oversees GHG emissions from sectors that fall outside the scope of the EU Emissions Trading System (ETS) and LULUCF. These sectors[46] include transport, buildings, agriculture, non-ETS industry, and waste, and are collectively responsible for nearly 60% of the EU's total GHG emissions.[47] As shown above, the most important ESR emission categories for biogenic sources are the agricultural and waste sectors. Under the ESR, each Member State has a binding emissions target, expressed as a reduction from 2005 levels, which collectively must deliver the EU-wide ESR target (–40% by 2030 relative to 2005 under the revised ESR[48]).

Impact and limitations

A key limitation of the Effort Sharing Regulation (ESR) is that it sets a single overarching target for all the sectors it covers and largely leaves Member States to decide where and how reductions are delivered across that aggregate group. In this sense, the ESR effectively outsources governance of biogenic emissions to national decision-making. This lack of guidance makes it difficult to drive emissions reductions in the agriculture and waste sectors, where biogenic emissions are most significant. Emissions of N_2O and CH_4 from these sectors are technically much harder to reduce than fossil CO_2 emissions, yet Member States are still required to meet their overall ESR reduction pathways. As a result, the agriculture and waste sectors often face weaker reduction pressure, unless explicitly targeted through national policies, while most Member States tend to prioritise mitigation efforts in transport, buildings, and industry, where abatement options are more readily available.

In particular, the use of a single aggregate target across all greenhouse gases hinders the development of EU level policies that are fit for purpose in addressing different emission types. As discussed above, N_2O emissions constitute a large portion of the emissions from agriculture, yet arguably there is currently no suitable removal method to neutralise them if striving for a LfL balancing of emissions. There is no explicit EU-level plan for N_2O within the ESR framework itself. Instead, mitigation depends largely on national measures and sectoral regulations. These can include improving fertiliser efficiency, promoting precision farming, or strengthening manure management practices.

Another complicating issue is that the ESR accounting does not distinguish between fossil and biogenic emissions. For example, on-farm fossil fuel use (e.g. tractors, heating) is counted alongside N_2O and CH_4 from crops and livestock in a country's ESR balance. The accounting is carried out purely by gas and sector, without separate treatment for biogenic versus fossil origin. This lack of distinction poses a hurdle to pursuing a LfL balancing of emissions and removals through the ESR. In principle, the ESR could serve as a central EU framework for biogenic emissions governance, but in its current form it is not designed to do so.

5.2 LULUCF Regulation

Scope

The LULUCF sector covers land conversion or disturbance of forest land, cropland, grassland, wetlands, settlements, and 'other land' as well as uses from HWP, atmospheric deposition, nitrogen leaching and run-off, and 'other emissions'. Therefore, LULUCF encompasses both biogenic emissions and removals from the land sector. The first binding **LULUCF Regulation** adopted in 2018 is designed to ensure that emissions and removals from LULUCF are accounted for within the EU's climate targets. According to this regulation, Member States are obliged to ensure that emissions from the LULUCF sector do not exceed removals (the so called "no-debit" rule), with the ability to trade surplus removals under the ESR.

45 European Union (2018) *Regulation (EU) 2018/842 of the European Parliament and of the Council of 30 May 2018 on binding annual greenhouse gas emission reductions by Member States from 2021 to 2030 (Effort Sharing Regulation)*

46 Note that the buildings and transport sectors will be included in the new trading system named ETS2 as part of the 2023 revision of the ETS Directive

47 EEA (2024a) *Greenhouse gas emissions from land use, land use change and forestry in Europe*

48 European Union (2023) *Regulation (EU) 2023/857 of the European Parliament and of the Council of 19 April 2023 amending Regulation (EU) 2018/842 on binding annual greenhouse gas emission reductions by Member States from 2021 to 2030*

Since 2021, the LULUCF Regulation has been connected to the ESR through two flexibility options. Member States that exceed their LULUCF targets may transfer part of the surplus—up to a capped share—towards fulfilling ESR commitments. Conversely, if they fall short on LULUCF obligations, they can draw on ESR emissions allowances to cover the gap, a mechanism especially important from 2026 to 2030.

In 2023, the regulation was revised to align with the ambition of the new European Climate Law which set a target of 55% net emissions reductions for 2030. Therefore, a new binding EU-wide LULUCF removal target was set for 310 Mt/CO2e by 2030, reflecting a considerable expansion from the estimated 2023 capacity of 200 Mt CO_2/year.[49] Under this revision, Member States are also meant to set net removal targets for the LULUCF sector from 2026 onwards.

Impact and limitations

A primary limitation of the LULUCF Regulation is its narrow focus on net removals, rather than distinguishing between gross emissions and gross removals. This net accounting approach effectively enables internal offsetting within LULUCF, where increases in removals in one land category can compensate for persistent or rising gross emissions elsewhere. While this net accounting approach simplifies compliance, it is largely a political choice that acts to hide land-use emissions. As a result, it can obscure major, addressable sources of land-based emissions and reduce visibility on where targeted mitigation could deliver the greatest impact. For instance, peatland degradation emits substantial volumes of CO_2 in countries such as Germany,[50] and mitigating these gross emissions could be one of the most effective ways to strengthen the net land sink. Yet, because the regulation primarily recognises increases in net removals, it provides limited incentive to prioritise emissions reductions within the land sector itself.

Considering the effectiveness of the LULUCF Regulation, it is clear that it has not yet led to a measurable expansion of the land-sink in Europe. In fact, recent studies have indicated that the LULUCF carbon sink has weakened in past decade, and its future development is highly uncertain.[51] Factors contributing to this decline include increasing harvest levels, reduced uptake in ageing forests, and climate stressors such as drought and pest damage.[52]

Several modelling studies suggest that maintaining current forest management practices could further diminish the sink in the coming years,[53] while others point to potential for enhanced capacity, underscoring the considerable uncertainty around this carbon pool.[54] According to the European Environment Agency,[55] even with additional measures, expected removals are unlikely to meet policy objectives, with projections estimating roughly 230 MtCO_2 per year by 2040 (dropping to around 200 MtCO_2 annually if no new measures are adopted).

Considering the limitations and performance of the current LULUCF framework, one could argue that LULUCF should not remain solely a net sink target but should evolve toward a framework that requires transparent gross emissions reductions alongside robust tracking of gross removals. Without greater granularity into the gross emissions and removals of LULUCF, it would not be possible to incorporate a LfL approach into EU target-setting or into credible balancing rules.

5.3 Common Agricultural Policy

Scope

The Common Agricultural Policy (CAP) has historically been the EU's primary instrument for ensuring food security. Over the years, it has progressively included stricter conditionality on payments and more instruments to encourage sustainable practices and ecosystem services. It is the EU's largest public spending programme for shaping land-management decisions at a scale that currently exceeds any single law. CAP is the main funding instrument for LULUCF-related actions and meeting ESR targets through supporting eco-schemes and rural development programmes that encourage sustainable land practices, agroforestry, soil protection, forest recovery, and peatland restoration.

49 *EEA (2025) Europe's land carbon sink declines, but its potential stays high. European Environment Agency*

50 Heinrich-Böll-Stiftung et al. (2023) Facts and Figures on Wet Climate Guardians

51 EEA (2024a) *Greenhouse gas emissions under the Effort Sharing legislation (ESL). European Environment Agency Datahub (2024a)*; EEA (2025)

52 *EEA (2024b) Greenhouse gas emissions from land use, land use change and forestry in Europe*

53 Kurosuo et al. (2023) *The role of forests in the EU climate policy: are we on the right track?*; EEA (2024b) *Greenhouse gas emissions from land use, land use change and forestry in Europe*

54 Pili et al. (2022) *The European forest carbon budget under future climate conditions and current management practices*; IEEP (2025) *EU LULUCF sink development until 2040: Trends, projections and uncertainties*

55 *EEA (2024b) Greenhouse gas emissions from land use, land use change and forestry in Europe*

Therefore, land management policies supported by CAP can impact key sources of biogenic emissions and carbon removals mainly reported in the LULUCF and agricultural sectors. At the same time, CAP is primarily a spending and income-support policy rather than a climate instrument designed around quantified mitigation or removal outcomes.

The EU's Common Agricultural Policy (CAP) is structured around two pillars: Pillar I, which provides direct payments and market support to ensure farm income stability and encourage sustainable practices, and Pillar II, which co-finances rural development programmes with Member States to promote environmental, social, and structural improvements in rural areas. Together, they aim to balance agricultural productivity, environmental protection, and rural viability across the EU.

Unlike carbon markets, CAP does not put a price on carbon removals. Incentives are instead indirect, delivered through subsidies, activity-based payments, and conditionality. Under Pillar I, farmers can participate in voluntary eco-schemes that provide annual area-based payments (€ per hectare) for practices set by each Member State. Activities relevant to carbon removal include agroforestry, tree planting, extensive grassland management, maintaining wetlands and peatlands, and cultivating cover or catch crops to build soil carbon. However, payment levels vary widely and are not linked to the carbon value of these practices.

Under Pillar II, rural development programmes support more ambitious or longer-term carbon-relevant measures such as rewetting peatlands, organic farming, or carbon farming pilots, typically through multi-annual contracts (5–7 years). Payments remain area- or activity-based and usually compensate for costs incurred and income foregone. Some CAP Strategic Plans[56] introduce result-based payments, rewarding measurable improvements. While these approaches move CAP closer to a performance-based incentive, implementation remains limited and is not designed to function as a carbon-pricing mechanism.

Impact and limitations

In principle, the practices incentivised under CAP can increase carbon sequestration in living biomass and soils and further reduce biogenic emissions from land use change and agriculture. However, in reality, emissions from agriculture have stagnated over the last few decades[57] signaling that CAP has not delivered measurable mitigation or removals[58] even though ~40% of the CAP budget is earmarked for "climate and environment." Despite mechanisms to encourage carbon-positive practices, CAP simultaneously supports productivity-oriented models of agriculture that rely on higher input use, mechanisation, and intensification, potentially undermining some the environmental benefits it aims to promote.

As CAP needs to balance farmer income support, food security, and rural development, climate and removals goals often lose priority. Partly to blame is the short-term nature of CAP programming cycles (typically five to seven years) which constrains investment in long-term carbon sequestration strategies that require decades to materialise, such as afforestation or soil carbon accumulation. Combined with the administrative complexity of accessing funds and the limited uptake of result-based payment schemes, these factors have restricted CAP's effectiveness as a climate instrument.

As CAP does not take a carbon accounting approach, there is no clear pathway for directly introducing a LfL understanding of balancing removals and emissions to this policy. CAP's subsidy logic will also need to be clarified alongside the EU's emerging carbon credit logic under the CRCF. Without clear rules on additionality, stacking, and transparency, there could be a risk of creating double incentives, where operators receive financial incentives once through CAP support and again through CRCF units for the same underlying activity or outcome. A clearer division of labour could position CAP to fund transition costs and enabling conditions (e.g., advisory services, monitoring infrastructure, and MRV capacity), while CRCF crediting rewards verified net removals that go beyond subsidised baselines and are demonstrably additional.

56 For example, pilot projects using *results based point system* in the Netherlands

57 Scheffer & Wiegmann (2024) *EU 2040 Climate Target: Contributions of the Agriculture Sector*

58 European Court of Auditors (2021) *Common Agricultural Policy and climate: Half of EU climate spending but farm emissions are not decreasing*

59 WWF (2022) *Nature Restoration – The Missing Piece in the EU Climate Action Puzzle*

5.4 Nature Restoration Law

Scope

The Nature Restoration Law (NRL; also often called the Nature Restoration Regulation) entered into force in 2024 and set targets for the EU to restore 20% of degraded land and sea areas by 2030, and all ecosystems in need of restoration by 2050. Additionally, the EU must restore at least 25,000 km of rivers into free-flowing rivers by 2030, as well as plant at least 3 billion additional trees by 2030. Member States must design their national restoration plans in order to contribute to these EU targets. As the WWF promotes,[59] restoring nature can remove large amounts of emissions and the level of ambition adopted by the NRL has an important impact on reaching our climate goals.
While the law does not obligate Member States to guarantee ongoing improvement of restored areas or to permanently maintain their quality, they are required to show that, where feasible, they have taken steps to prevent substantial deterioration of those areas at the national level. The NRL therefore promotes temporary biogenic removals through tree planting and ecosystem restoration and helps protect those restored lands to avoid potential emissions from land-use change.

Impact and limitations

Although the NRL has strong potential to enhance carbon storage and prevent emissions from degraded ecosystems, its climate impact is largely indirect. The regulation focuses on ecological conditions rather than explicit carbon outcomes, and it lacks a unified framework for MRV of GHG sources and sinks. As a result, the carbon benefits of restoration, such as avoided emissions from drained peatlands or increased soil carbon, are not directly attributed to the NRL as a policy instrument, even though they are expected to be reported in the EU's GHG accounting. This disconnection makes it difficult to isolate and quantify the specific contribution of the NRL to observed emissions reductions.

A further challenge lies in the temporal mismatch between restoration timelines and climate targets. Ecosystem recovery and soil carbon accumulation occur over decades, meaning that measurable climate benefits will materialise only gradually, limiting the contribution of the NRL to short-term milestones such as the EU's 2030 and 2040 climate goals.

Implementation will depend on national restoration plans and coordination with other instruments such as CAP and the LULUCF Regulation. Without clear integration of carbon metrics and sustained funding, the NRL's potential to contribute meaningfully to EU climate targets may remain underrealised.

Ultimately, while the NRL can make a meaningful contribution to carbon storage and the avoidance of land-use emissions, it should not be seen primarily as a carbon removal policy. Framing restoration mainly in terms of carbon accounting risks narrowing its purpose and undervaluing the many co-benefits it delivers, such as biodiversity recovery, soil and water protection, flood prevention, and ecosystem resilience. Many ecosystems targeted by the NRL, including grasslands, dunes, and certain wetlands, provide limited annual carbon sequestration but are nevertheless essential for ecological stability and adaptation.

5.5 European Climate Law and 2040 targets

Scope

The European Climate Law (ECL) establishes the legal framework for achieving the EU's long-term climate objectives. It makes the goal of climate neutrality by 2050 legally binding for all Member States and sets net greenhouse gas reduction targets of at least 55% by 2030 and 90% by 2040 compared to 1990 levels. The law also introduces mechanisms for monitoring progress, aligning EU and national policies, and ensuring consistency across sectoral legislation such as the ETS, ESR, and LULUCF regulations.

However, the Commission has not specified how these net targets should be divided into sub-targets for (1) cutting emissions, (2) using the LULUCF sink, and (3) scaling up permanent/industrial removals.[60] On the other hand, the structure and ambition of the 2040 target(s) will be highly relevant for the future of biogenic emissions and removals. Because the ECL targets are defined in net terms, decisions on how much of the net pathway is delivered through the different approaches directly shape the role and governance of biogenic emissions and biogenic removals.

59 WWF (2022) _Nature Restoration – The Missing Piece in the EU Climate Action Puzzle_

60 European Union (2025) _Proposal for a Regulation of the European Parliament and of the Council amending Regulation (EU) 2021/1119 establishing the framework for achieving climate neutrality_

Impact and limitations

Without distinct targets for permanent removals, LULUCF, and gross emissions, the EU's net -90% goal could be jeopardised.[61] Without additional structure, key decisions about how residual biogenic emissions are treated, and what type of removals are expected to neutralise them, remain implicit rather than policy-driven. The EU risks defaulting to land-based balancing by inertia, using the LULUCF sink to compensate residual emissions because it is the most readily available accounting lever, not because it is the most durable or governable.

In this context, stakeholders have emphasised the need to maintain ambition for enhancing the LULUCF sink,[62] while some caution against relying on it too heavily to achieve overall climate goals.[63] Generally, the concerns of the latter are that many land-based removals are short-lived, permanence and future developments are uncertain, and large-scale monitoring remains difficult. From the perspective of promoting biogenic removals, the lack of a separate LULUCF target in the ECL is a missed opportunity to promote expansion of the land sink. Without clearer signals, land-sector actors face limited long-term visibility on how much the EU intends to rely on land-based removals, and under what integrity conditions.

Setting separate targets would also create a concrete opportunity to operationalise the LfL principle[64] within the Climate Law framework. A LfL approach would clarify that the level of temporary removals should ideally match the remaining biogenic emissions, while permanent removals should scale to meet the residual fossil emissions. Allowing full flexibility for using any proportion of either permanent removals, LULUCF, or gross emissions reductions to reach the net target does not provide clarity on the intended role of the different removal categories.

An important addition to the debate is the flexibility to use a limited share of international carbon credits to reach the 2040 net emissions target. The ECL allows a limited contribution of up to 5% of the 1990 EU net emission level from high-quality international credits. However, the European Scientific Advisory Board on Climate Change has advised strongly against such flexibility, recommending that the EU avoid reliance on external credits and instead pursue a reduction range of 90–95% domestically to maintain ambition and accountability.[65] There is a perceived risk that international credits could mask domestic inaction or delay investment in the infrastructure and innovation needed to scale up EU-based CDR.

Overall, the ECL provides the overarching legal framework for achieving climate neutrality, but its current structure offers limited clarity on the treatment of biogenic emissions and removals. The absence of explicit sub-targets for land-based (biogenic) sinks leaves uncertainty over how much of the EU's mitigation effort should come from reducing agricultural and land-use emissions versus enhancing the LULUCF sink. This ambiguity risks overstating the contribution of temporary, reversible removals, such as those in soils and biomass, while underpromoting the need to reduce ongoing biogenic emissions from agriculture, land use and waste. The current net focus also makes it harder to design coherent incentives across CAP, LULUCF governance, and emerging CRCF.

Earlier proposals to broaden the LULUCF Regulation to cover non-CO_2 emissions from agriculture and create a new "AFOLU" (Agriculture, Forestry and Other Land Use) pillar have been rightly criticised.[66] Such an approach could allow agricultural emissions to be offset by the forest sink, masking real emissions increases and ultimately reducing the pressure on the agriculture sector to cut its own emissions.

61 Carbon Gap (2025) *Divide to Deliver: Why 2040 Separate Targets for Carbon Removal Are Feasible and Necessary to Reach EU Net Zero*

62 CAN Europe & co-signatories (2025) *International NGO response to Finnish and Swedish Prime Minister statements on LULUCF*

63 IEEP (2025) *EU LULUCF sink development until 2040: Trends, projections and uncertainties*

64 Carbon Gap (2025) *Divide to Deliver: Why 2040 Separate Targets for Carbon Removal Are Feasible and Necessary to Reach EU Net Zero*

65 ESABCC (2025a) *Scientific advice for amending the European Climate Law – Setting climate goals to strengthen EU strategic priorities*

66 Fern (2022) *Parliament could still push for ambitious forest climate policy*

5.6 Carbon Removal and Carbon Farming Framework

Scope

The EU Carbon Removal and Carbon Farming Framework (CRCF) is a developing regulatory system that sets common rules for monitoring, reporting, and certifying carbon removals to ensure their credibility and comparability across the Union. Under the CRCF, it will be possible to certify a set of permanent industrial technologies, carbon farming practices, and carbon storage in long-lasting products (>35 years).

Carbon farming under the CRCF refers to land management practices that increase carbon storage or reduce emissions in soils, biomass, and wetlands. Eligible methods include restoring peatlands and wetlands, enhancing agroforestry systems, improving forest management, and adopting agricultural practices that build soil organic carbon. These activities must deliver additional carbon benefits, meaning they go beyond existing legal obligations under EU nature and environmental laws and are not practices that would have happened anyway.

The eligible carbon farming practices reflect temporary biogenic removals, meaning stored carbon is at risk of being rereleased. The CRCF sets minimum duration requirements for certifying carbon storage, monitoring obligations, and risk-management rules such as buffer pools. Carbon farming through the CRCF is intended to reward farmers and land managers for climate-beneficial practices, while ensuring that certified removals are credible, traceable, and contribute to EU climate targets.

Impact and scope

If adopted on the largescale, the CRCF could be the most important instrument for promoting temporary removals through carbon farming and storage in wood-based products and limiting biogenic emissions key environments. Yet, the use case for the CRCF credits and how permanent and temporary removals will be valued and priced in the carbon market are currently unresolved. Without distinct treatment and strategic pricing of permanent and temporary removal credits, the potentially cheaper carbon farming credits could be misused for neutralising fossil carbon emissions, making the CRCF out of line with a LfL approach to reaching durable net-zero. Ultimately, only by clearly distinguishing the role, valuation, and accounting of biogenic and permanent removals can the CRCF help build a transparent and durable carbon removal market aligned with the EU's net-zero goal.

5.7 Renewable Energy Directive and zero emissions rating for bioenergy

Scope

The Renewable Energy Directive (RED) is the EU's central policy tool for expanding the role of renewables in the energy mix. It provides a common framework to guide the deployment of renewable energy technologies across Member States and sets binding EU-wide targets for the share of renewables in final energy consumption. Beyond overall targets, the directive also includes sector-specific provisions for electricity, heating and cooling, and transport, introduces sustainability and greenhouse gas criteria for bioenergy, and strengthens rules on permitting and grid integration to accelerate renewable roll-out. With the adoption of RED III in 2023, the EU raised its ambition to reach at least 42.5% renewables by 2030 (with a voluntary target of 45%), making the directive a cornerstone of both the European Green Deal and the Fit for 55 package.[67]

The EU's use of biomass-based energy affects how carbon is allocated between carbon stored in living biomass, carbon released during energy production, and carbon potentially captured and stored as part of the energy system (e.g., BECCS).

67 The European Green Deal is the EU's umbrella strategy for delivering climate neutrality by 2050. Fit for 55 is the legislative package updating EU laws to achieve the 2030 target of at least 55% net emissions reductions (vs. 1990); more recent initiatives (e.g., the Clean Industrial Deal) repackage parts of this agenda under a competitiveness lens.

68 Brack et al. (2022) *Quantifying the loophole and sustainability impacts of bioenergy being rated zero emissions in the EU Emissions Trading System and Effort Sharing Regulation*

Impact and limitations

The RED, along with several other key European policy frameworks (ETS and ESR), considers biomass burning for energy as carbon-neutral. This assumption mainly comes from 1) the assertion that biomass emissions are a natural part of the carbon cycle, and 2) the reporting framework used by international GHG inventories established by the UNFCCC and Kyoto Protocol.[68] To avoid double counting, these emissions are supposedly reported by the land-use sector, being the actor responsible for biomass harvesting.

Several issues have been raised with these assumptions and their implications for accurate emission estimates.[69] Namely, harvesting and burning trees for energy creates a significant initial increase in carbon emissions, known as a "carbon debt." While regrowing trees and replacing fossil fuels can eventually offset this debt, the process takes time. Evidence indicates that burning wood may actually raise global warming levels for decades to centuries due to this "carbon payback period", with a more short-term impact when residues, wastes, or crops grown specifically for biofuel are used,[70] albeit this effect is stronger when assessing a single plot than when looking at the larger forest landscape.[71] Additionally, biomass combustion often releases more CO_2 per energy unit than fossil fuels, and emissions from biofuel feedstocks like vegetable oil-based biodiesel can exceed those from fossil fuels when direct and indirect emissions are combined.

In response to these concerns, there has been some attempt to distinguish between biomass type by promoting the cascading principle within RED III. Following the cascading use principle, higher-value, longer-lived uses of biomass (e.g., wood products) should come before short-lived or energy uses (e.g., burning for heat or electricity). Yet, many stakeholders argue that enshrining this principle in RED III does not go far enough, as it remains non-binding and insufficient to effectively protect biodiversity and climate objectives.[72]

Problematically, the way that bioenergy emissions are reported can lead to gaps in national emissions inventories, for example when biomass is produced in one country and consumed in another. In this way, separating bioenergy lifecycle emissions across different sectors obscures the total GHG impact in national inventories. This concern is also voiced by the Joint Research Centre, which emphasises the need for policies that fully account for the bioenergy-land-use relationship.[73]

These limitations matter for a LfL approach because RED's carbon-neutral treatment of biomass combustion blurs the boundary between residual biogenic emissions that require temporary neutralisation and fossil emissions that require durable neutralisation. By treating stack emissions[74] as zero and shifting accounting to LULUCF, RED can mask real near-term warming impacts and weakens incentives to prioritise durable removals or genuine emissions cuts. In a LfL framing, bioenergy policy would need clearer rules to ensure that claimed "neutrality" is backed by robust accounting of carbon stock changes and time dynamics, and that any neutralisation aligns with the durability of the emissions being balanced. Without these clarifications, the energy rating of bioenergy risks overstating climate benefits and undermining coherent incentives for durable CDR.

69 Brack et al. (2022) *Quantifying the loophole and sustainability impacts of bioenergy being rated zero emissions in the EU Emissions Trading System and Effort Sharing Regulation*

70 Searchinger et al. (2009) *Fixing a critical climate accounting error*

71 Cowie et al. (2021) *Applying a science-based systems perspective to dispel misconceptions about climate effects of forest bioenergy*

72 WWF Europe (2022) *EU bioenergy policy: debunking the myths on forest biomass*; Stockholm Energy Institute (2017) *Cascading of woody biomass: The tricky path from principle to policy to practice*; Fern (2023) *Wiser with Wood A guide on how to transpose the EU's revised Renewable Energy Directive (RED III) to better protect forests, the climate, public health and other wood-using industries*

73 JRC (2021) *The use of woody biomass for energy production in the EU and impacts on forests*

74 Stack emissions refer to greenhouse gas emissions released at the point of combustion or industrial processing (e.g. from a power plant smokestack), representing direct flows of CO_2 to the atmosphere.

6. CONCLUSIONS & REMAINING QUESTIONS

This review of the sources of biogenic emissions in this report offers a better understanding of how we might strive for a LfL balancing of emissions and removals in the future to achieve durable net-zero. According to our analysis, at present there are upwards of roughly 17,500 Mt CO_2e of biogenic emissions per year, which mainly come from human-driven ecosystem change, agricultural practices, and the waste sector. Although CH_4 gas is the most prominent, a sizeable portion of these emissions are CO_2 or N_2O. Annual biogenic emissions caused by humans still far exceed temporary removals (by a factor of roughly 9), indicating that more temporary removals are needed to match them. Although there is a high level of uncertainty around how these biogenic emissions will develop in the future, several sources of emissions are likely to remain or even increase considering growing population sizes and future warming. Without a massive scale up of temporary removals, biogenic emissions could very well continue to exceed the amount of temporary biogenic removals in the coming decades.

These findings correct the common misconceptions that creating clear and distinct roles for temporary and permanent removals, in accordance with a LfL approach, means sidelining NBS operators. Instead, the task now is to build the rules, metrics, and incentives that match temporary removals properly with biogenic emissions, while also scaling permanent CDR to counter residual fossil emissions.

Our review of relevant policies governing biogenic emissions and temporary removals in the EU landscape identifies limitations of the current system. First, there is no overarching legislation that explicitly monitors, regulates, or creates binding incentives to reduce them. Instead, multiple overlapping instruments provide only partial coverage. In particular, the zero-rating of biomass combustion under the RED shifts emissions to the land sector, while their aggregation across the LULUCF Regulation and the Effort Sharing Regulation limits visibility and weakens incentives for targeted mitigation. The general focus on regulating emissions by sector complicates creating targeted plans for those biogenic emissions that originate from several sectors (agriculture, LULUCF, waste) and include several GHG gases (mainly CH_4 but also N_2O and CO_2). Moreover, the absence of carbon pricing for biogenic emissions further constrains the development of effective mitigation and compensation mechanisms.

Secondly, the focus on net targets can mask what is actually driving outcomes. For example, the net targets included in the ESR, LULUCF Regulation, and 2040 target within the ECL mask which components contribute the most to these net values and hinder developing efficient strategies for both biogenic emissions and temporary removals. This aggregation makes it difficult to identify whether progress is driven by emissions reductions or by changes in land carbon sinks and limits the development of targeted strategies for reducing biogenic emissions and scaling removals.

In parallel, several policies, such as the CAP and the NRL, provide indirect incentives to restore ecosystems and enhance carbon sinks. However, their impact on climate outcomes remains difficult to track due to limited uptake and the absence of direct carbon accounting frameworks linking actions to measurable GHG outcomes.

Finally, there is lack of clarity on the role temporary removals will play in the EU and international markets and how the cost and amount of temporary removal credits generated might be regulated in the future. Importantly, applying carbon accounting to ecosystem management could, in some cases, undermine key co-benefits of protecting and restoring natural environments—such as enhanced biodiversity, greater habitat resilience, and improved soil and a balanced water cycle. It is therefore crucial to design scenarios in which carbon accounting is applied in ways that reinforce, rather than compromise, ecosystem protection.

In this context we identify several unresolved questions:

- What political levers, innovations or management practices could best connect biogenic emissions and removals in the future?
- How can the EU speed up the scale up of biogenic removals to meet the levels of biogenic emissions that are expected to persist in the future?
- How should EU policy frameworks treat biogenic emissions that cannot be appropriately neutralised through biogenic removals, for example N_2O emissions from waste and agriculture?
- How should biogenic emissions be priced in the future to incentivise decarbonisation?
- How should temporary removal credits be valued in the future (relative to permanent removals) to ensure they are used appropriately?
- Should permanent CDR methods be used to offset biogenic emissions, or should they be reserved exclusively for fossil emissions?

We follow the ESBACC in recommending the EU should improve the pricing of biogenic emissions and create clearer incentives to develop biogenic removals. Ultimately, **the imbalance between biogenic emissions and removals highlights the need for clearer accounting and dedicated policies that treat biogenic carbon as a distinct part of climate strategy.**

Future work by Carbon Gap will look in depth at the pricing and governance of biogenic emissions and temporary removals and try to identify regulatory gaps and feasible reforms which could put the EU on the right path and support the progressive implementation of the LfL principle towards durable net-zero.

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ANNEX

A1 Compiling sources of emissions

To gather the potential sources of biogenic emissions reviewed by this report, we reviewed the sectors and activities included in the United Nations Food and Agriculture Organisation (FOA) inventory.[75] Additionally, we reviewed emission subsectors included in the UNFCCC GHG Inventory.[76] Both inventories are based on the IPCC guidelines for national GHG inventories.[77] Aggregated sectors and categories reported in GHG inventories often include a mix of fossil and biogenic emissions; therefore, we made an effort to exclude those activities which reflect fossil emissions. For the UNFCCC emissions data, differences in reporting requirements for Annex I and non-Annex I countries make it difficult to separate the biogenic component from the emissions total for certain sectors, since less detailed and frequent reports are required from non-Annex I countries. By contrast, the FAO independently compiles and estimates emissions from agriculture, forestry, and land use based on available national statistics, rather than relying solely on UNFCCC-reported data, and therefore provides detailed emission estimates per activity for both Annex I and non-Annex I countries.

A third source of sector- and country-specific emissions estimates is the EDGAR GHG emissions data compiled by the Joint Research Center (JRC) and International Energy Agency (IEA). They provide separate estimates for the fossil and bio components of emissions from certain sectors on the global scale. An additional source is the PRIMAP-PIK Historical Emissions dataset.[78] Although this dataset provides Annex-I and non-Annex I emissions data, it lacks sufficient granularity to identify the biogenic emission from the sectoral totals.

We calculated fossil emissions by subtracting the determined biogenic emissions from the all-sector total emissions including LULUCF for Annex I and Non-Annex-I countries for the year 2022 from the PRIMAP-PIK historical emissions dataset.

75 FAOSTAT dataset (Accessed June 2025) *The FAOSTAT domain Emissions Totals*

76 UNFCCC dataset (Accessed June 2025) *GHG Data — Greenhouse Gas Data from UNFCCC: Time Series: GHG Profiles for Annex I and Non-Annex I Parties*

77 IPCC (2019b) *Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (eds Calvo Buendia, E. et al.)*

78 Gütschow et al. (2024) *The PRIMAP-hist national historical emissions time series (Version 2.4.1) [data set]*

A2 Overlapping GHG reporting categories

The GHG inventories used for this review overlap in their reporting of certain sectors or activities (Fig. A1). We account for these overlaps and attempt to avoid double counting when aggregating emission totals as much as possible. As stated, due to potential gaps relating to unreported activities or lack of global-scale data, our aggregated totals reflect conservative estimates of global emissions. In reality, the actual annual biogenic emissions worldwide could be higher.

IPCC for NGHGI			FAO categories and gases		FAO aggregates		
LULUCF	AFOLU	Forest land	Forestland	CO_2			
		Burning biomass	Fires, other forest	CH_4 ; N_2O			
			Fires, organic soils	CO_2; CH_4	Land use change	Agricultural land	Agri-food systems
			Fires, humid tropical forest	CH_4 ; N_2O			
		Forest land converted to other land uses (CL, GL, Settlement, Wetlands, etc.)	Net forest conversion	CO_2			
		Drained organic soils	Drained organic soils	CO_2	Farm gate		
Agriculture		Cultivation of histosols		N_2O			
		Inorganic N fertilizers	Synthetic fertilizers	N_2O			
		Crop residues	Crop residues	N_2O			
		Manure deposited on pasture, range and paddock	Manure left on pasture	N_2O			
		Manure applied to soils	Manure applied to soils	N_2O			
		Manure management	Manure management	CH_4 ; N_2O			
		Enteric fermentation	Enteric fermentation	CH_4			
		Prescribed burning of savanna	Savanna fires	CH_4 ; N_2O			
		Burning crop residues	Burning- crop residues	CH_4 ; N_2O			
		Rice cultivation	Rice cultivation	CH_4			
Energy			On-farm energy use	CO_2 ; CH_4 ; N_2O			
			Fertilizers manufacturing	CO_2 ; N_2O			
			Pesticides manufacturing	CO_2 ; CH_4 ; N_2O			
			Food household consumption	CO_2 ; CH_4 ; N_2O			
			Food packaging	CO_2 ; CH_4 ; N_2O			
			Food processing	CO_2 ; CH_4 ; N_2O			
			Food transport	CO_2 ; CH_4 ; N_2O			
			Food retail	CO_2 ; CH_4 ; N_2O			
IPPU				F-gases			
Waste			Food waste disposal	CO_2 ; CH_4 ; N_2O			
Other n.e.c.							
International bunkers							

Figure A1: Methodology for mapping the correspondence between IPCC (UNFCCC in their national GHG inventories) and FAO emissions categories and aggregates provided by the FAO.

A3 GHG volume conversions

Estimates for current and future emissions originating for permafrost melt were source from Schuur et al. (2023) where they are reported in Teragrams or Petragrams of carbon (C), attributed to carbon dioxide (CO_2) fluxes (Tg or Pg C from CO_2 or CH_4). Therefore, these estimates are converted using the molecular mass ratio between carbon and CO_2 (3.6667) or CH_4 (1.3333; Table A1).

The Global Methane Budget reports fluxes of methane in Tg CH_4/year. We convert roughly two-thirds of the 112 Tg CH_4 total emissions from inland water bodies which can be attributed to human causes[81] using a GWP100 for methane of 28 (IPCC AR5) to align with the UNFCCC, FAOSTAT and EDGAR data sets. Although there is now a more updated estimation from IPCC AR6 (Table A2) , we use the AR5 value since this remains the official reporting value until the UNFCCC and EU formally update their inventory guidelines.

79 FAO (2023) FAOSTAT Domain Emissions Totals. Methodological note, release October 2023

80 Saunois et al. (2025) Global methane budget 2000–2020

81 Jackson et al. (2024) Human activities now fuel two-thirds of global methane emissions

Table A1: Conversion method followed for determining CO_2e in Mt of emissions annual from wetlands and inland water bodies and permafrost thaw.

Reported annual emission volume	Activity and year	Source	Conversion factors used	Converted annual emission used in aggregate totals (Mt CO_2e/year)
0.344 Pg C–CO_2/year	Permafrost thaw in 2021 (medium CO_2 scenario)	Schuur et al. (2022)	1 mol C: 1 mol CO_2 = 3.6667 1 Pg = 1000 Mt	1263
12 Tg C–CH_4/year	Permafrost thaw in 2021 (medium CH_4 scenario)	Schuur et al. (2022)	1 mol C: 1 mol $CH_4$4 = 1.3333 GWP_{100} of CH_4 = 28 (AR5) 1 Tg = 1 Mt	448
0.736 Pg C–CO_2/year	Permafrost thaw in 2049 (medium CO_2 scenario)	Schuur et al. (2022)	1 mol C: 1 mol CO_2 = 3.6667 1 Pg = 1000 Mt	2697
26 Tg C–CH_4/year	Permafrost thaw in 2049 (medium CH_4 scenario)	Schuur et al. (2022)	1 mol C: 1 mol CH_4 = 1.3333 GWP_{100} of CH_4 = 28 (AR5) 1 Tg = 1 Mt	971
112 Tg CH_4/year	Total emissions from inland water bodies	Saunois et al. (2025)	GWP_{100} of CH_4 = 28 (AR5) 1 Tg = 1 Mt	3136
75 Tg CH_4/year	Roughly two-thirds of total emissions from inland water bodies attributed to human causes	Saunois et al. (2025)	GWP_{100} of CH_4 = 28 (AR5) 1 Tg = 1 Mt	2091
231 Tg CH_4/year	Wetland emission in 2050; mean of model ensemble outputs estimate for RCP4.5	Zhang et al. (2017)	GWP_{100} of CH_4 = 28 (AR5) 1 Tg = 1 Mt	6468

A4 Global Warming Potential (GWP)

The climate warming metric known as Global Warming Potential (GWPx) provides a practical way to place different greenhouse gases, with their different potencies, atmospheric lifetimes, and behaviours, on a common scale expressed in CO_2-equivalents. In the main text of this report, we report non-CO_2 gases using GWP100. However, there are strong arguments for alternative metrics, particularly for short-lived gases such as methane (CH_4). While EU regulations and reporting typically follow IPCC AR5 GWP100 values, using different time horizons (e.g., GWP20) or updated values (e.g., AR6) can materially change estimated emissions volumes (Table A2). For example, for the biogenic emission sources compiled here, applying GWP20 instead of GWP100 for CH_4 almost doubles the total biogenic emissions presented (Figure A2).

For policymakers, metric choice directly affects emissions inventories, carbon budgets, the relative weight placed on methane mitigation versus CO_2 removal, and the interpretation of progress toward climate targets—making it a strategic decision, not a technical detail. Ultimately, the selected metric influences how emissions are priced and traded, which mitigation or removal options are rewarded, and whether market mechanisms deliver credible climate outcomes.

COMPARING GLOBAL BIOGENIC EMISSIONS USING GWP20 OR GWP100 FOR CH4

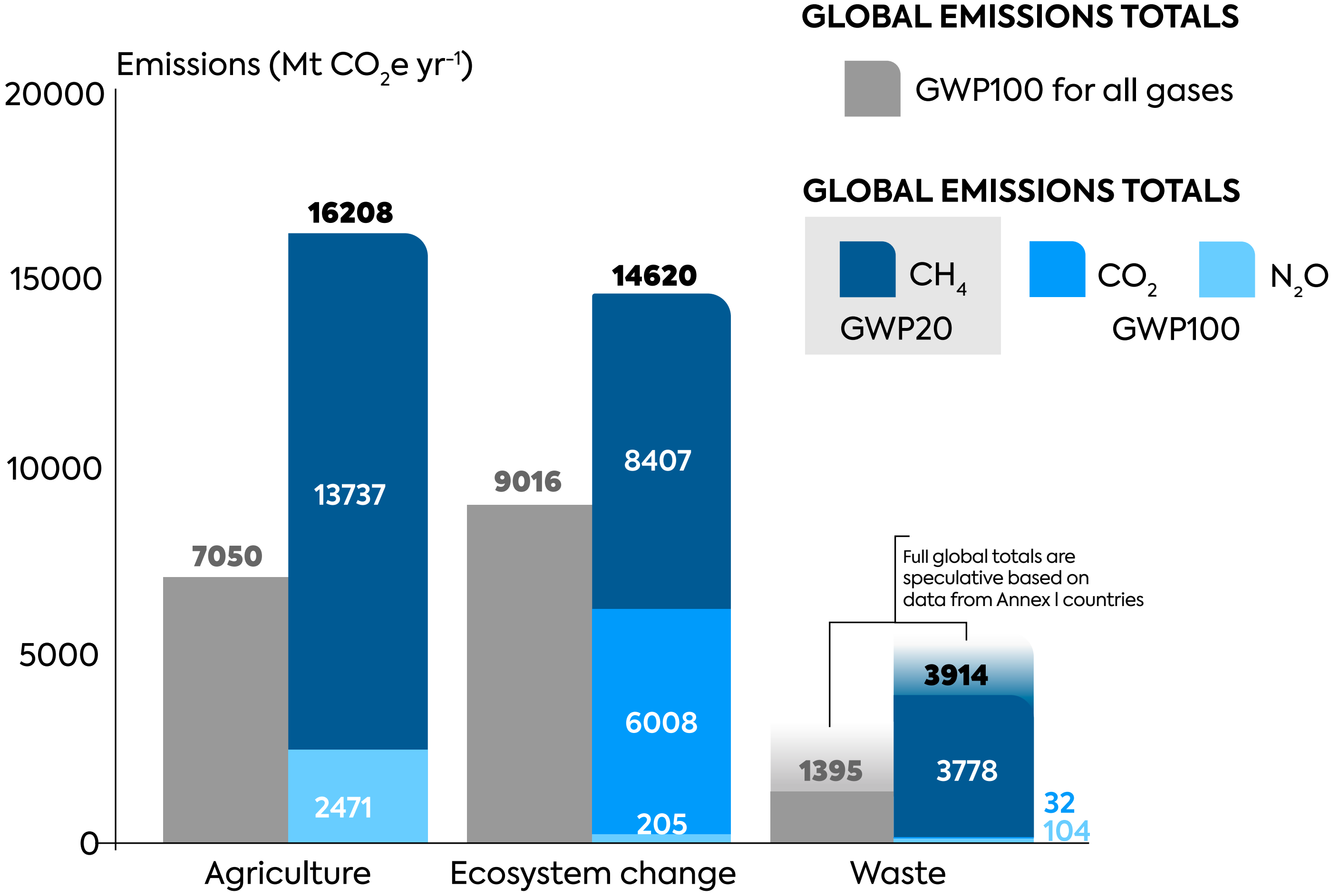

Figure A2: Comparison of the biogenic GHG emissions by sector and GHG in million tonnes (Mt) of CO_2 equivalent per year when using different GWP metrics for CH_4. The grey bars shows the total emission volumes of the sectors if the GWP100 (AR5; without feedbacks) is used for all gases, as shown by the bar height in Figure 1. For the stacked blue bars, N_2O emissions are translated to CO_2e volumes following GWP100 (265), but for CH_4 the GWP20 (84) is used (Table A2). This comparison illustrates the potential effect of choosing different climate impact metrics.

	AR5			
	without climate feedbacks		with climate feedbacks	
gas	GWP20	GWP100	GWP20	GWP100
CO_2	1	1	1	1
CH_4	84	28	86	34
N_2O	264	265	268	298

	AR6		
	with climate feedbacks		
gas	GWP20	GWP100	GWP500
CO_2	1	1	1
CH_4 (fossil)	82.5	29.8	8.2
CH_4 (biogenic)	80.8	27.2	7.5
N_2O	273	273	153

ABOUT US

Carbon Gap is an independent, Brussels and UK-based non-profit organisation supporting Europe's unique opportunity to lead the responsible deployment of carbon dioxide removal (CDR) to fight climate change through independent and science-led advice.

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