CLIMATE NEUTRALITY FORUM 2024

ACCELERATING CLIMATE ACTION NOW

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Authors and contributors: Natasha Lutz, Frank McGovern, Camilla Hyslop, Myles Allen, Tristram Walsh, Petra Manderscheid, Maria José Sanz, and Bram Maasakkers.

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Abbreviations

AR6	Sixth Assessment Report of the Intergovernmental Panel on Climate Change
AFOLU	Agriculture, forestry and other land use
BECCS	Bioenergy carbon capture and storage
BTR	Biennial Transparency Reports
CO_2	Carbon dioxide
CDR	Carbon dioxide removal
CH_4	Methane
DAC	Direct air capture
DACCS	Direct air carbon capture and storage
ERW	Enhanced rock weathering
EU	European Union
F-gases	Fluorinated greenhouse gases
GCB	Global Carbon Budget
GMSL	Global mean sea-level
GMST	Global mean surface temperature
GHG	Greenhouse gases
GNZ	Geological net zero
Gt	Gigaton
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
LULUCF	Land use, land-use change and forestry
N_2O	Nitrous oxide
NDC	Nationally Determined Contribution
MRV	Monitoring, verification and reporting
SST	Sea surface temperatures
SR1.5	Special Report on Global Warming of 1.5 °C, in the 6^{th} Assessment Cycle of the IPCC
UNFCCC	United Nations Framework Convention on Climate Change
VCM	Voluntary carbon market
VCMI	Voluntary Carbon Markets Integrity Initiative

Glossary

Additionality
The extent to which greenhouse gas emissions reductions or removals would have occurred in the absence of an associated policy intervention or activity. Additionality is applied to carbon projects for mitigation that would *not* have occurred without the sale of the carbon credit (Smith et al., 2024).

Aerosols
A suspension of airborne solid or liquid particles, typically in the size range of a few nanometres to several tens of micrometers, and with atmospheric lifetimes of up to several days in the troposphere and several years in the stratosphere. They may be of natural or anthropogenic origin, and influence the climate directly through scattering and absorbing radiation, and indirectly through acting as a condensation nuclei for cloud formation (IPCC AR6 WGI Glossary, 2021).

Afforestation
The conversion to forest land that has historically not contained forests, or the practice of planting trees on land that was not previously, or not recently, forested (IPCC, 2019).

Albedo
The fraction of sunlight (solar radiation) reflected by a surface or object, often expressed as a percentage. Cloud, snow and ice usually have a high albedo; photosynthetically active vegetation and oceans have a low albedo (IPCC AR6 WGI Glossary, 2021).

Anthropogenic emissions
Emissions of greenhouse gases derived from human activities. These activities include the burning of fossil fuels, deforestation, land use and land use changes, livestock production, fertilisation, waste management and industrial processes (IPCC AR6 WGI Glossary, 2021).

Ambition gap
A gap between the level of ambition evident in policy and nations' willingness to undertake climate action and the degree of action that is necessary to effectively address change.

Biochar
A relatively stable, carbon rich material produced by heating biomass in a low-oxygen environment (Smith et al., 2024).

Bioenergy with Carbon Capture and Storage (BECCS)
Process by which biogenic carbon dioxide (CO_2) is captured from a bioenergy facility, with subsequent geological storage (Smith et al., 2024).

Carbon credit
A tradeable certificate representing one tonne of CO_2 or other greenhouse gases avoided, reduced or removed. Most carbon credits currently traded are for emissions reductions (Smith et al., 2024).

Carbon dioxide (CO_2)
A naturally occurring gas, and a by-product of burning fossil fuels (such as oil, gas or coal), biomass burning and industrial processes. Carbon dioxide is the principal anthropogenic greenhouse gas causing global warming (through increased radiative forcing), ocean acidification, and changes to terrestrial carbon systems and stocks. These impacts will continue to increase until emissions of additional CO_2 no longer occur (net zero CO_2) (IPCC AR6 WGI Glossary, 2021).

Carbon dioxide removal (CDR)
Anthropogenic activities that remove CO_2 from the atmosphere and store it in geological, terrestrial or ocean reservoirs, or in products. The long-term durability or permanence of such storage determines its role in addressing climate change. CDR is considered to include existing and potential anthropogenic enhancement of biological or geochemical sinks and direct air capture and storage. The term excludes natural CO_2 uptake by ocean and terrestrial sinks that is not directly managed or caused by human activities but whose stability is central to current analysis and actions to address climate change. See also: *conventional CDR*; *novel CDR*.

Climate neutrality
A state in which human activities result in no net effect on the climate system. In terms of emissions, climate neutrality entails a balance between emissions and removals of GHGs from the atmosphere. In terms of a temperature limit, climate neutrality can be considered to denote a state in which human activities cause no additional increase to the global average surface temperature.

Climate-resilient development pathways (CRDPs)
Trajectories that strengthen sustainable development at multiple scales and efforts to eradicate poverty through equitable societal and systems transitions and transformations while reducing the threat of climate change through ambitious mitigation, adaptation and climate resilience (IPCC AR6 WGII Glossary, 2022).

Conventional CDR
CDR methods that are well established, already deployed at scale and widely reported by countries as part of land-use, land-use change and forestry activities. Conventional CDR methods include afforestation/reforestation; agroforestry; forest

management, soil carbon sequestration in croplands and grasslands; peatland and some coastal wetland restoration; durable wood products (Smith et al., 2024).

Direct Air Capture
Chemical process by which carbon dioxide (CO_2) is captured from the ambient air. This CO_2 can then be stored geologically or used in products (Smith et al., 2024).

Direct air carbon capture and storage (DACCS)
A chemical process by which carbon dioxide (CO_2) is captured from the ambient air, with subsequent geological storage (Smith et al., 2024).

Durability
The capacity to store carbon over time without releasing it back to the atmosphere. Some assessments consider durability to include carbon pools with storage timescales on the order of decades or more (Smith et al., 2024).

Emission pathways
The modelled trajectories of global anthropogenic emissions over the 21st century (IPCC AR6 WGI Glossary, 2021).

Enhanced rock weathering
Increasing the natural rate of removal of CO_2 from the atmosphere by applying crushed rocks, rich in calcium and magnesium, to soil or beaches (Smith et al., 2024).

Geological net zero (GNZ)
Achieving a balance between any remaining CO_2 production from geological sources and CO_2 committed to permanent geological storage. This means one tonne of CO_2 is permanently restored to the solid Earth for every tonne still generated from fossil sources (Allen et al. 2024).

Human influence
Human activities that lead to or contribute to a climate response; for example, the increased concentrations of GHGs in the atmosphere, as a result of emissions due to human activities. This has altered the Earth's energy balance causing global warming. Human influences also include emissions of aerosols (microscopic particles) or gases that change the aerosol composition of the atmosphere, and land-use change including deforestation and urbanisation (IPCC AR6 WGI Glossary, 2021).

Long Term Global Goal
A goal under the UNFCCC, which was adopted at COP21 in parallel with the Paris Agreement. The aim is to limit global warming to well below 2°C and to make efforts to limit global warming to 1.5°C. It reflects the wording of the Paris Agreement Temperature Goal. See also: *Temperature Goal* (IPCC, 2018).

Land use, land-use change and forestry (LULUCF)
In the context of national greenhouse gas (GHG) inventories under the UNFCCC, LULUCF is a GHG inventory sector that covers anthropogenic emissions and removals of GHG from carbon pools in managed lands, excluding non-CO_2 agricultural emissions. Following the 2006 IPCC Guidelines for National GHG Inventories, 'anthropogenic' land-related GHG fluxes are defined as all those occurring on 'managed land', i.e., 'where human interventions and practices have been applied to perform production, ecological or social functions' (IPCC, 2018).

Managed land proxy
In the Agriculture, forestry and other land use (AFOLU) sector, anthropogenic greenhouse gas emissions by source and removals by sinks are defined as all those occurring on 'managed land.' i.e. managed land is used as a proxy for identifying anthropogenic land based removals (IPCC, 2006).

Monitoring, Reporting & Verification (MRV)
Procedures for quantification, documentation and independent review of reported GHG emissions and removals, in the context of national inventory reporting, emissions trading and voluntary claims such as net zero (Smith et al., 2024).

Net zero (CO_2)
Net zero carbon dioxide is achieved when anthropogenic CO_2 emissions are balanced globally by anthropogenic CO_2 removals over a specified period (IPCC AR6 WGI Glossary, 2021).

Novel CDR
CDR methods where the captured carbon dioxide is stored in geological formations, the ocean or products. Novel CDR methods generally have a lower level of readiness for deployment and are therefore currently deployed only at smaller scales. Examples of novel CDR include bioenergy with carbon capture and storage, direct air capture, enhanced rock weathering, biochar, mineral products, and ocean alkalinity enhancement (Smith et al., 2024).

Offset
A term used under the 1997 Kyoto Protocol in which removals of atmospheric carbon dioxide as determined under the LULUCF accounting rules could be used to offset emission of carbon dioxide from other sources. The term Removal is mainly used under the Paris Agreement.

Radiative forcing
The net energy imbalance in the climate system, caused by changes in the Earth's atmosphere and surface such as GHG concentrations or the concentration of volcanic aerosols. Adjustments to this

energy imbalance include adjustments to the global temperatures (IPCC AR6 WGI Glossary, 2021).

Remaining carbon budget
The maximum estimated cumulative net global anthropogenic CO_2 emissions (from a given start date to the time that anthropogenic CO_2 emissions reach net zero) that would result in limiting global warming to a given level with a given probability, accounting for the impact of other anthropogenic emissions (IPCC AR6 WGI Glossary, 2021).

Residual emissions
Remaining gross emissions when net zero and subsequently net negative emissions are reached. This can apply to both net zero CO_2 and net zero GHG emissions, from local to global scales and at company or sector level. At net zero emissions, the amount of CDR equals the amount of residual emissions over a given period. At net-negative emissions, the amount of CDR must exceed residual emissions (IPCC, 2018).

Temperature Goal
The goal expressed in Article 2.1 (a) of the 2015 Paris Agreement is to *'hold the increase in the global average temperature to well below 2°C above pre-industrial levels and pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels*.' The wording is similar to that of the Long Term Global Goal under the UNFCCC. The Paris Agreement specifies that reaching a global balance of GHG emissions and removals is required during this century to achieve the Temperature Goal. See also: *Long Term Global Goal*. (IPCC AR6 WGI Glossary, 2021).

Tipping Point
A level of change in system properties beyond which a system reorganises, often abruptly and/or irreversibly (IPCC AR6 WGI Glossary, 2021).

UN Framework Convention on Climate Change (UNFCCC)
The UNFCCC was adopted by Governments in 1992 and was ratified in 1994. Its objective is to stabilise greenhouse gas concentrations in the atmosphere at a level that will prevent dangerous human interference with the climate system, in a time frame which allows ecosystems to adapt naturally and enables sustainable development.

Paris Agreement
The Paris Agreement was adopted in 2015 and entered into force in 2016. The three primary goals of the Paris Agreement are: (1) to hold the increase in the global average temperature to well below 2°C above pre-industrial levels and pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels; (2) increase the ability to adapt to the adverse impacts of climate change and foster climate resilience and low greenhouse gas emissions development, in a manner that does not threaten food production; and (3) make finance flows consistent with a pathway towards low greenhouse gas emissions and climate-resilient development (UNFCCC, 2015). To achieve the *Long-Term Temperature Goal*, Parties aim to reach global peaking of greenhouse gas emissions as soon as possible, recognizing that peaking will take longer for developing country Parties, and to undertake rapid reductions thereafter in accordance with best available science, so as to achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century. The Paris Agreement is being implemented under the 5-year Global Stocktake process in which Parties assess progress and level of commitments expressed in their Nationally Determined Contributions.

Passive uptake/removals
Passive removals refer to those which occur currently as an ongoing adjustment to past emissions (through processes such as the CO_2 fertilisation of plants), and are not a result of active ongoing human intervention (Allen et al., 2024).

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Executive Summary

The 2024 Climate Neutrality Forum (CNF) took place from 28 - 30 October in Brussels. The gathering facilitated a science-policy-practitioner dialogue to explore the pathways, interventions and enabling environments required to accelerate progress towards climate neutrality. The 2024 CNF provided an update of the best-available science, explored requirements for effective policies for emissions reduction and removals, and elucidated areas for further policy development such that progress towards climate neutrality may be accelerated.

Key insights from the 2024 Climate Neutrality Forum

- **On Observations, Trends, and Indicators of Climate Change.** The Earth's climate system is undergoing unprecedented changes due to human-induced greenhouse gas emissions. The influence of global warming is increasingly apparent as slow onset changes such as sea-level rises and sea and land ice loss, and locally as more frequent and intense weather extremes. The risks of crossing major tipping points are escalating.

- **On the Global Energy Imbalance and Temperature Increase.** The observed annual global temperature increase reached 1.4°C in 2023 above pre-industrial levels; however, this number cannot be directly compared to the Paris Agreement temperature goal which is the long-term human caused contribution to the temperature increase, which was around 1.3°C in 2023 or 1.2°C if averaged over the last 10 years. Global temperatures are increasing at the highest measured rate, at over 0.25°C per decade. As of October, 2024 is the warmest year on record (since 1940) and the annual global mean surface temperature is expected to be in excess of 1.5°C for the first time.

- **Carbon Dioxide Emissions.** Carbon dioxide is the most important GHG contributing to global warming. Global CO_2 emissions continue to grow, although at a slower rate than in recent decades. This high rate of global CO_2 emissions increases the challenge of reaching net zero CO_2 emissions by mid-century.

- **Methane Emissions.** Methane is the second most important anthropogenic GHG in terms of climate forcing after carbon dioxide. Globally, atmospheric methane concentrations continue to increase. However, effective actions to reduce emissions including those adopted under the Global Methane Pledge can play an important and relatively rapid role in limiting warming to the Paris Agreement Temperature Goal. However, even if the pledged reduction in CH_4 emissions of 30% are achieved by 2030, there is still the risk of overshooting 1.5°C, especially if CO_2 and other GHG emissions continue to increase at current rates. Some methane emissions reduction progress is occuring; decreasing emissions have been observed in Europe.

- **Nitrous Oxide Emissions.** Nitrous oxide (N_2O) emissions is the third most important GHG contributing to global warming, and its emissions are the leading contributor to stratospheric ozone depletion. Although nitrous oxide emissions have been reduced in Europe, global N_2O emissions are increasing at an unprecedented rate, and faster than the high-emission 'business as usual' scenarios used in the IPCC Sixth Assessment Report. Actions to address emissions of N_2O produced by extensive use of fertilisers have benefits for climate change, protection of the stratospheric ozone layer, and water quality. Enhanced management of land and reduced reliance on synthetic fertilisers is cost effective in many, although not all, agricultural systems. Improved methods of monitoring N_2O will aid management.

- **The Paris Agreement and the Global Stocktake Process.** The Paris Agreement architecture serves as a framework to drive climate policies in line with the long term global goal (a climatological goal assessed over decades to limit warming 'well below' 2°C while pursuing efforts to limit the increase to 1.5 °C) and determine progress towards this goal through the Global Stocktake and Enhanced Transparency Framework processes. The 2023 Global Stocktake (GST) (COP28/CMA5) found that while some progress has been made, current ambition and implementation levels are insufficient to meet the Paris Agreement goals. The GST called for a just, orderly and equitable transition away from fossil fuels, the tripling of renewable energy capacity, and the doubling of energy efficiency.

- **On Global Emissions Pathways Characteristics for 1.5˚C and 2˚C.** Pathways that limit warming to 1.5˚C include clear CO_2 emissions reductions by 2030 and deep reductions in non-CO_2 GHGs. Most modelled pathways include overshoot and temporarily exceed the 1.5˚C limit before 2100. All pathways that limit warming to 1.5°C with minimal or no overshoot require carbon dioxide removal (CDR) to achieve and maintain substantial global net-negative emissions.

- **On the remaining carbon budget.** The remaining carbon budget (RCB) to limit warming to 1.5°C without CDR is becoming untenably small. The remaining carbon budget for a 50% likelihood of limiting global warming to 1.5˚C has halved from 2020 to 2024 and is estimated at 200 $GtCO_2$. This budget could be depleted in seven years if emissions continue unchanged. However, this carbon budget provides an approximation rather than a precise timeline due to uncertainties in climate response and non-CO_2 emissions scenarios.

- **On land ecosystems and their roles in climate change.** Terrestrial ecosystems are vital for stabilising the global climate and are integral to mitigation pathways for 1.5°C or 2°C. However, although the AFOLU sector offers substantial mitigation potential, the biosphere sink is vulnerable to being weakened by climate impacts like extreme heat and wildfires.

  Land-based GHG accounting would benefit from clearer definitions and consistent methodologies across modelling and National GHG Inventory communities, including but not limited to better methods of distinguishing active anthropogenic interventions from passive natural uptake. The current gap between land use emissions estimated between the global modelling and National GHG Inventory communities (~7 $GtCO_2\ yr^{-1}$) has implications for the remaining carbon budget and net zero and undermines achieving the temperature goal of the Paris Agreement.

  Greater collaboration is needed between carbon monitoring and modelling communities. Greater *transparency* of methods and data, *translation* of outcomes between global models and National GHG inventory communities, and *communication of the implications* of these discrepancies is needed to ensure effective climate policies and progress toward stabilising global temperatures.

  Achieving Geological Net Zero (GNZ) is needed to stop global warming and meet the Paris Agreement goals. This requires a balance between any remaining production of CO_2 from fossil sources and storage of CO_2 in geological-timescale sinks. While reducing CO_2 emissions remains the primary mitigation strategy, geological storage must scale up significantly. Distinguishing geological storage from land-based interventions and passive uptake will be crucial for tracking progress towards GNZ.

- **On the energy transition**. Achieving climate neutrality requires a just, orderly and equitable transition away from fossil fuels, the large-scale deployment of renewable energy technologies, improved energy efficiency and security, and the widespread electrification of final energy demand. Global energy sector emissions continue to rise but at a decreasing rate due to the growth in solar PV, wind, nuclear power, heat pumps and electric cars. Current levels of ambition in NDCs, long-term strategies and existing national policies are insufficient to achieve the pledge to triple renewable energy by 2030.

- **On policy pathways to accelerate decarbonisation**. While a mix of policy instruments typically yields greater emissions reductions than individual policies, the effectiveness of specific interventions varies by sector and economy. For example, pricing mechanisms dominate in developed economies' transport and industrial sectors, while regulations and subsidies are more impactful in developing economies, particularly for electricity and buildings. Taxation consistently performs well across sectors, often achieving significant reductions even as a standalone policy.

- **On carbon dioxide removal.** Alongside rapid, deep and widespread emissions reductions, near-term upscaling of carbon dioxide removal (CDR) will be necessary to achieve the Paris Agreement temperature goal. CDR is not a substitute for immediate and deep emissions reductions, but rather has a complementary role along a mitigation timeline. Some CDR deployment is occurring (~2 $GtCO_2$ per year), but not enough. Most of this is land-based CDR through forestry. While there is rising investment in novel CDR methods, particularly DACCS and biochar, they currently remain a small share of CDR deployed. A gap continues to persist between the amount of CDR in IPCC scenarios that meet the Paris temperature goal and the level of CDR in national proposals. Insufficient investment and planning raises concerns about our ability to achieve the required levels.

  Government policies and support is critical for CDR innovation and commercialization, but current commitments and governance frameworks are vague. Improved guidance, monitoring, reporting, and verification (MRV) standards, as well as liability mechanisms, are needed to ensure permanence, build trust, and support equitable global scaling of CDR.

  Sustainability should be foregrounded in CDR policy and implementation. Sustainable CDR deployment must balance technical and economic potential with consideration of environmental, social, and geopolitical trade-offs, including potential impacts on biodiversity, ecosystems, Indigenous and local communities, food security, oceans and equity. Excessive reliance on land-based or high-risk methods like BECCS may harm biodiversity, water availability, and food security.

- **On enabling environments and means of implementation.** Living evidence synthesis and dynamic science-policy dialogues can bridge gaps between scientific research and policymaking, ensuring timely and relevant action. Creating enabling environments for climate action requires robust governance, equitable finance mechanisms, capacity building, and market support. Addressing structural barriers, such as underinvestment in long-term climate solutions and inequities in finance distribution, is critical for fostering innovation and scaling transformative solutions. Policies for climate action should acknowledge the interconnectedness of economic, social, and environmental systems, leveraging co-benefits such as improved health and biodiversity to garner wider support.

1 Introduction

Since its adoption in 2015, the Paris Agreement has provided a global framework for coordinated collective action to address the causes and consequences of climate change. Article 2 of the Paris Agreement outlines the goal to limit the increase in global average temperature to well below 2˚C and pursue efforts to limit temperature increase to 1.5˚C above pre-industrial levels. It also articulates the need for increased adaptation and finance flows to enable low emissions and climate resilient development. Article 4 provides guidance on how to achieve the Paris temperature goal through the peaking of global GHG emissions as soon as possible (recognising that peaking will occur later in developing economies), with subsequent rapid reductions in emissions, to achieve a balance between anthropogenic emissions by sources and anthropogenic removals by sinks. The IPCC Sixth Assessment Report (AR6) reiterated that limiting warming to 1.5˚C with no or limited overshoot requires deep, rapid, immediate and sustained emissions reductions.

The first global stocktake (GST) under the Paris Agreement assessed collective progress towards achieving the Paris Agreement's long-term mitigation, adaptation and finance goals. The GST recognised that significant progress has been made by Parties but concluded that much more is needed. In addition to an emissions gap between the levels of mitigation implied by current Nationally Determined Contributions (NDCs) and the levels consistent with limiting warming to 1.5 or 2˚C, the GST emphasised an implementation gap between stated NDC targets and observed progress in the form of currently enacted policies and achieved emissions reductions. Transformative systems change is required, including transitioning away from all fossil fuels in energy systems, in a just, orderly and equitable manner. Action is needed in this critical decade to enable the world to keep close to 1.5˚C and achieve climate neutrality.

2024 Climate Neutrality Forum

The 2024 Climate Neutrality Forum (CNF) facilitated a science-policy-practitioner dialogue to explore the pathways, interventions and enabling environments required to achieve climate neutrality. The 2024 CNF provided an update of the best-available science, explored requirements for effective policies for emissions reduction and removals, and elucidated areas for further policy development such that progress towards climate neutrality may be accelerated. It took place within the context of an evolving landscape of national and regional climate policies and regulations. Recent developments included the conclusion of the first GST at COP28, the establishment of the Loss and Damage Fund and intense consideration of the New Collective Quantified Goal (NCQG) on climate finance, for which some agreement was reached at COP29. A new round of Nationally Determined Contributions (NDCs) are expected early in 2025 with more information being provided by all Parties to the Paris Agreement under its transparency framework via the Biennial Transparency Reports (BTRs) from 2024.

The 2024 CNF built on the knowledge synthesised by the 2021 CNF and associated report: *Sensitive Intervention Points for Achieving Climate Neutrality* (see Appendix A). The 2021 CNF occurred in the lead-up to COP26 and was informed by early outputs of the IPCC AR6 cycle. The 2021 forum was framed by the objective of identifying interventions in socio-economic, technological and political systems that could facilitate breakthroughs or positive tipping points such that the outcome is amplified and transformative progress towards climate neutrality achieved. Potentially effective interventions include policies that: (*i*) are politically, technologically or economically feasible; (*ii*) have high impact potential, in terms of expected emissions reductions; and (iii) a low risk potential, or limited unintended detrimental outcomes. The 2024 CNF continued to build on this systems approach for evaluating policy options, with an increased focus on evidence-based policy decision-making.

Many of the overarching goals of the 2021 CNF remain relevant, if not more pertinent. Rapid emissions reductions and targeted investment in hard-to-abate sectors remains an urgent task. Long-standing concerns of equity, inclusion and multilateral effort-sharing relating to the historical and current emissions contributions of nations continue to be salient. As the wider climate governance landscape shifts towards ensuring effective implementation of policies and goals, there is increased focus on enhanced accountability and transparency. Consequently, the need for appropriate monitoring, verification and reporting mechanisms are increasingly important to ensure policy effectiveness and impact. Further, with advancements in science observation and understanding comes a continued need and opportunity to improve pathways of knowledge transfer from science to decision making spaces. While progress on some avenues of climate governance has been sluggish, progress has been made on several fronts since COP26 and CNF2021, including but not limited to:

- A groundswell of national and sub-national net zero climate pledges; 148 countries have pledged a net zero or climate neutrality target. The proportion of countries with net zero or climate neutrality targets has risen from 25% prior to COP26 to 75% prior to COP29 (Net Zero Tracker, 2024).
- The European Union's 'Fit for 55' package of legislation that aims to reduce greenhouse gas emissions by 55% by 2030 was formally adopted in October 2023, and its implementation is progressing.
- Several key policy instruments highlighted during the 2021 CNF are in the process of being implemented, these include the European Union's use of the Carbon Border Adjustment Mechanism (CBAM) within its borders to address carbon leakage.
- Advances in the deployment of renewable energy technology. Renewable energy sources accounted for 30.4% of electricity generation globally in 2023, 7.4% higher than in 2021 (IEA, 2024a).
- A steady intensification of carbon dioxide removal (CDR) research, innovation and investment (although with a recent slowdown) and diversification of methods (Smith et al., 2024).
- Continued use of climate litigation as an instrument to instigate climate policy and justice. Although the rate of new climate litigation cases has slowed since 2021, the diversity of jurisdictions is expanding; cases were filed for the first time in Bulgaria, China, Finland, Romania, Russia, Thailand and Turkey during 2022, and in Panama and Portugal in 2023 (Setzer and Higham, 2024).

Approach and structure of this report

This report was initially created to provide background material for the discussions at CNF2024, and has subsequently been updated based on the discussions held at the forum. Its structure largely reflects the agenda and structure of that event. After this introduction, Section 2 provides framing material based on the latest science on the indicators of climate change, and Paris Agreement temperature goal-aligned emissions pathways. Section 3 explores the role of land in climate mitigation and the emerging roles of observation systems in policy. Section 4 outlines progress towards emissions reductions and the energy transition. Section 5 summarises the current state of knowledge on carbon dioxide removal (CDR) deployment and upscaling. Section 6 explores the political economy required for enabling transformative change and accelerating progress. The report closes with a consideration of areas for development ahead of the next CNF in 2026 and the current IPCC 7th Assessment Cycle. Steps to address gaps will be subsequently considered by JPI Climate and its partners including the European Commission. This report will inform ongoing and future research, needed to inform progress during this critical decade of climate action and beyond.

2 Framing the state of play

Introduction

The Intergovernmental Panel on Climate Change (IPCC) is the authoritative source of scientific and socio-economic information for the development of global policy and responses to climate change. The IPCC publishes major Assessment Reports (ARs) on a five to seven year cycle. However, due to the rigorous procedures employed by the IPCC – including the use of cut-off dates for contributing publications – the information in IPCC assessments can significantly predate the report publication date. To address this time lag and meet the growing demand for up-to-date and policy relevant scientific information, several initiatives within the scientific community have been established utilising IPCC approaches and methods. These include the annual Indicators of Global Climate Change assessment (Forster et al., 2024), and the work of the Global Carbon Project on the key greenhouse gases, specifically the carbon dioxide (Friedlingstein et al., 2024), methane (CH_4) (Saunois et al., 2024) and nitrous oxide (N_2O) budgets (Tian et al., 2024). The following section provides a summary of the key messages from these initiatives as presented at the 2024CNF, and updates the related analysis provided in the IPCC AR6.

2.1. Observations, Trends, and Indicators of Climate Change

Global climate indicators provide insights into why and how the climate system is changing. Since the start of the industrial revolution in the 19th century, increasing emissions of greenhouse gases (GHGs) have resulted in rising concentrations of GHGs in the atmosphere. This has changed the Earth's energy balance relative to pre-industrial times, with more energy in the Earth's climate system and is termed global warming. Global warming has resulted in a range of observed changes and responses within the global atmosphere, land, ocean and cryosphere. Some responses are clearly evident, such as the increase in the global temperature as shown by the temperature records. Some impacts, such as the rise in sea-level and the loss of ice sheets, will continue for centuries, even following stabilisation of the Earth's energy balance and global temperature. The scale and nature of these 'locked in' long term responses are a major concern for future generations and will continue to increase as GHG levels in the atmosphere increase.

2.2.1. **The magnitude and rate of recent changes to the climate system are unprecedented in the past hundred to many thousands of years.** Human-induced climate change has led to an increase in the severity and frequency of some weather and climate extremes (IPCC AR6 WGI, 2021).[1] Human activities have impacted the cryosphere, ocean, atmosphere and biosphere. Extreme weather and climate events are occurring in every region of the globe.

2.2.2. **Changes in the cryosphere have broken records in the past decade.** The annual minimum **Arctic sea ice extent** in September 2024 was the seventh lowest in the 46-year-satellite observation record (NSIDC, 2024). The **Antarctic sea ice extent** reached in February 2024 was the second lowest annual level since records began in 1978, with the lowest occurring in 2023 (NSIDC, 2024). The annual maximum Antarctic sea-ice extent in 2023 was 1 million km^2 below the previous low and was well outside the previous range of observations since 1978 (**Figure 1**) (WMO, 2024a). **Ice sheets** (expanses of ice originating on land) in the two principal regions of Antarctica and Greenland have had the seven highest melt years on record since 2010 (WMO, 2024a), and ice loss from these sheets has accelerated since the 1990s (Otosaka et al., 2023). **Glacier loss** is

[1] See glossary for definition of human influence in this context.

accelerating; the glacier mass loss over 2022/23 was nominally the largest loss on record (1950 - 2023) (WMO, 2024a).

2.2.3. **Sea surface temperatures (SST) reached record highs in 2023 and 2024, well outside the previous range of observations since 1979** (see **Figure 2**; Copernicus, 2024). SSTs in the North Atlantic Ocean were the warmest on record since 1900 (Kuhlbrodt et al., 2024). Monthly anomalies above average in the north and tropical Atlantic Oceans were associated with a more severe hurricane season and marine heat waves were also observed in parts of the North Pacific and Indian Oceans and in the Gulf of Mexico and the Mediterranean. This trend reflects the increasing accumulation of heat in the ocean due to additional heat being taken up by continuing greenhouse gas increases (Forster et al., 2024).

2.2.4. **Global mean sea-level (GMSL) rise is accelerating.** The combination of thermal expansion and meltwater from ice sheets has contributed to a rise at a rate of 4.77 mm per year between 2014 - 2023 (WMO, 2024a). Prior to this period, the GMSL has increased at a faster rate since 1900 (0.2 [0.15 to 0.25] m) than over any previous century within the last 3000 years (IPCC AR6 WGI, 2021). Further global mean sea-level rise is projected.

2.2.5. **Record extreme weather events occurred across the world in 2023 and 2024**. Hot extremes, such as heatwaves, large wildfires and drought, are occurring with increasing severity and frequency (Copernicus, 2023). Cold extremes are increasingly less frequent and less severe. The frequency and intensity of heavy precipitation events has increased since the 1950s over most land areas for which sufficient observation data is available (IPCC AR6 WGI, 2021).

2.2.6. **Extreme weather events are leading to severe socio-economic impacts, loss of life and destruction of homes and property.** Projections of the macroeconomic damage caused by future climate change until 2049 indicate that the damages from climate change greatly outweigh the cost to mitigate emissions within the 2˚C target (Kotz et al., 2024).

2.2.7. Additional warming is projected to further amplify extreme conditions. Even small increases in warming, such as 0.5°C, can be associated with discernible increases in the intensity and frequency of hot extremes, including heatwaves, heavy precipitation, intense tropical cyclones, and droughts in some regions (IPCC, 2018; IPCC AR6 WGI, 2021).

2.2.8. Continued global average temperature rises are expected to increase permafrost thawing and loss of seasonal snow cover, as well as reducing land and sea ice extents. Future global warming is expected to result in an increasing occurrence of extreme weather and climate events unprecedented on the observational record, even at a stabilisation of 1.5˚C of warming (IPCC AR6 WGI, 2021).

2.2.9. The increasing concentration of GHG levels in the atmosphere, as a result of ongoing GHG emissions have created long term commitments to global changes. The global ocean will continue to warm, while mountain and polar glaciers are expected to continue melting for decades or centuries. These will result in sea-level rise and loss of freshwater resources. The scale of lock-in to future sea-level rise and cryosphere losses will continue to increase with increased GHG induced global warming (IPCC AR6 WGI, 2021).

2.2.10. The IPCC AR6 provides increased confidence in the existence of tipping points in the Earth's system, which corresponds to abrupt, self-perpetuating, and irreversible changes. The probability of such qualitative changes within the Earth system all increase with higher warming levels. Once tipping points are passed, the resulting changes are both large and lead to a new system state that appears and functions qualitatively differently from before, as the system has moved beyond the regime of linear incremental changes (Climate Overshoot Commission, 2023; Global Tipping Points, 2023).

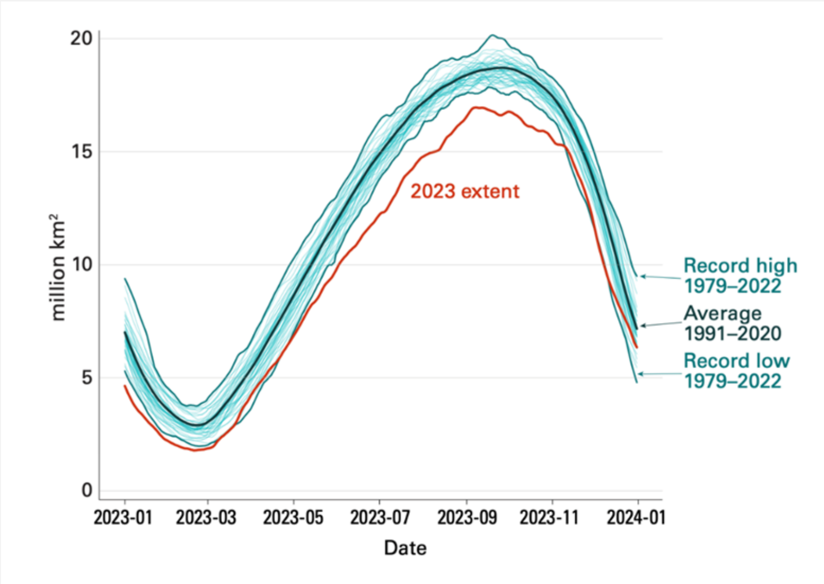

Figure. 1. Daily Antarctic sea-ice extent from January through December 2023; showing 2023 conditions (red line) against the 1991–2020 climate normal (dark blue), and the record highest and lowest extents for each day (mid-blue). Source: WMO 2024.

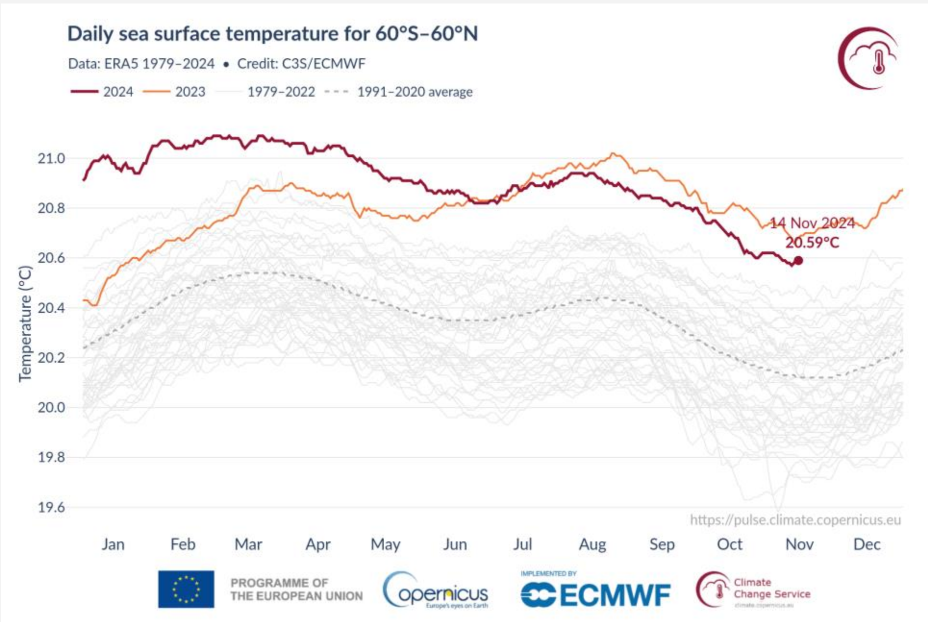

Figure. 2. Daily sea surface temperature (°C) averaged over the extra-polar global ocean (60°S–60°N) for 2023 (orange) and 2024 (dark red). All other years between 1979 and 2022 are shown with grey lines. The daily average for the 1991–2020 reference period is shown with a dashed grey line. Data source: ERA5. Source: Copernicus Climate Change Service/ECMWF, 2024.

2.2.11. **On the current climate path, several tipping points are at risk of being breached.** The Paris Agreement's 1.5˚C and 2˚C temperature thresholds are important markers of escalating climate risk; these temperature thresholds do not correspond directly to tipping thresholds. Even at current levels of warming, tipping vulnerability cannot be ruled out for warm-water coral reefs, the ice sheets of both Antarctica and Greenland, the North Atlantic Subpolar Gyre circulation, and permafrost thaw. Above 1.5°C, vulnerabilities increase for boreal forests, mangroves, and seagrass meadows. At 2°C and beyond, these systems become increasingly likely to have tipped, and more elements of the Earth system may become vulnerable. Early warning signals have been detected that are consistent with the Greenland Ice Sheet, Atlantic meridional overturning circulation (AMOC), and Amazon rainforest heading towards tipping (Global Tipping Points, 2023).

> **Key insight:** The Earth's climate system is undergoing unprecedented changes due to human-induced greenhouse gas emissions. The influence of global warming is increasingly apparent as slow onset changes such as sea-level rises and sea and land ice loss, and locally as more frequent and intense weather extremes. The risks of crossing major tipping points are escalating.

2.2 The Global Energy Imbalance and Temperature Increase

The increased concentration of greenhouse gases (GHGs) in the atmosphere has altered the Earth's energy balance - the equilibrium between the uptake of energy from the sun and the energy radiated back into space. The Earth's energy imbalance relative to pre-industrial levels is estimated here in Watts per square metre, and is termed positive radiative forcing. The additional energy can be considered to be the driver of 'global warming' that is responsible for the recent changes observed across the Earth's system. The clearest response to the energy imbalance is provided by the global temperature record, which is central to climate policy under the UNFCCC and Paris Agreement. Other long-term consequences of global warming include sea-level rise and cryosphere loss, which are expected to continue for centuries even if global temperatures stabilize.

2.2.12. **Anthropogenic emissions of GHGs have unequivocally caused an increase in global mean surface temperatures (GMST). Over the period 2014–2023, the average GMST was 1.19 [1.06 – 1.30] ˚C of which 100% was attributable to human influence. The global average temperature was 1.43 [1.32 to 1.53]°C in 2023, 1.31 [1.1 - 1.7]°C of which was human induced (Forster et al., 2024).**

2.2.13. The observed increase in global mean surface temperatures (GMST) since the pre-industrial period is mainly caused by increased atmospheric concentrations of GHGs from human activities, particularly carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O).

2.2.14. Atmospheric aerosols, which are microscopic particles in the atmosphere, can cause cooling which temporarily masks some warming by GHGs (IPCC AR6 WGI, 2021). Elevated aerosol levels in the atmosphere from human activities are being reduced through the implementation of policies and measures adopted to address air pollution and minimise adverse impacts on human health and natural systems (EU NEC Directive, 2016; UNECE CLRTAP, 1979).

2.2.15. Increased atmospheric GHGs dominated the energy imbalance in 2023. The influence of GHGs and aerosols on the Earth's energy balance is shown in **Figure 3a** with recent trends in GHG influences shown in **Figure 3b**. Carbon dioxide contributed 2.28 Wm^{-2}, methane 0.56 Wm^{-2}, and nitrous oxide 0.22 Wm^{-2}. Aerosol cooling of around -1.17 Wm^{-2} is both uncertain and decreasing at least in some regions. The impacts of short lived GHGs such as ground level ozone is also important at 0.51Wm^{-2}. Uncertainty ranges are provided in **Figure 3**.

2.2.16. **The global temperature increase was 0.26 [0.2–0.4] °C per decade over 2014–2023, a rate that is unprecedented in the instrumental record (since 1850).** This is owing partly to GHG emissions being at a persistent high, resulting in record atmospheric concentrations, as well as some reductions in cooling effects due to decreasing aerosol levels in the atmosphere (Forster et al., 2024)

2.2.17. **As of October, 2024 is on track to be the warmest year on record (ERA5, 1940 - 2024) (WMO, 2024b). The annual temperature for 2024 is expected to be more than 1.5˚C relative to pre-industrial levels (1850 - 1900) (Copernicus, 2024), boosted by a strong El Nino event. Prior to this, the GMST in 2023 was the hottest on record, reaching 1.43˚C [1.32 to 1.53]˚C above the 1850–1900 pre industrial average.** While 1.31°C of warming in 2023 was human-induced, a considerable contribution was due to internal variability in the climate system from the change from La Niña (active from mid-2020 until early 2023) to El Niño (Forster et al., 2024). The 2022–2023 increase in observed temperature was the third-largest annual increase in the instrumental record after 1876–1877 and 1976–1977, both of which also featured a strong transition from La Niña to El Niño conditions. The decade prior to 2023 was the warmest on record and included the two previous warmest years: 2016 (1.29 ± 0.12˚C) and 2020 (1.27 ± 0.13˚C) (WMO, 2024a).

2.2.18. The occurrence of global temperature approaching or surpassing 1.5˚C for a single year, or over several consecutive years, does not mean a key Paris Agreement threshold, which is a climatological decadienal average, has been breached. The temperature in any single year is likely to vary above or below the average human induced level. This is due to natural variability, including changes in volcanic activity, solar cycles and interannual variability including oscillations between El Niño and La Niña conditions (WMO, 2024a).

2.2.19. At current warming rates, human-induced warming is estimated to reach 1.5˚C in the early 2030s unless rapid and immediate emissions reductions are undertaken (Forster et al., 2024). AR6 estimated that global surface temperatures will continue to increase until at least the mid-century under all emissions scenarios.

2.2.20. The global mean surface temperature will continue to increase until net-positive radiative forcing peaks and starts to decline. This requires the concentration of atmospheric GHGs to peak and decline and that other factors which influence the climate system remain stable (Forster et al., 2024).

Key insight: The observed annual global temperature increase reached 1.4°C in 2023 above pre-industrial levels; however, this number cannot be directly compared to the Paris Agreement temperature goal which is the long-term human caused contribution to the temperature increase, which was around 1.3°C in 2023 or 1.2°C if averaged over the last 10 years. Global temperatures are increasing at the highest measured rate, at over 0.25°C per decade. As of October, 2024 is the warmest year on record (since 1940) and the annual global mean surface temperature is expected to be in excess of 1.5°C for the first time.

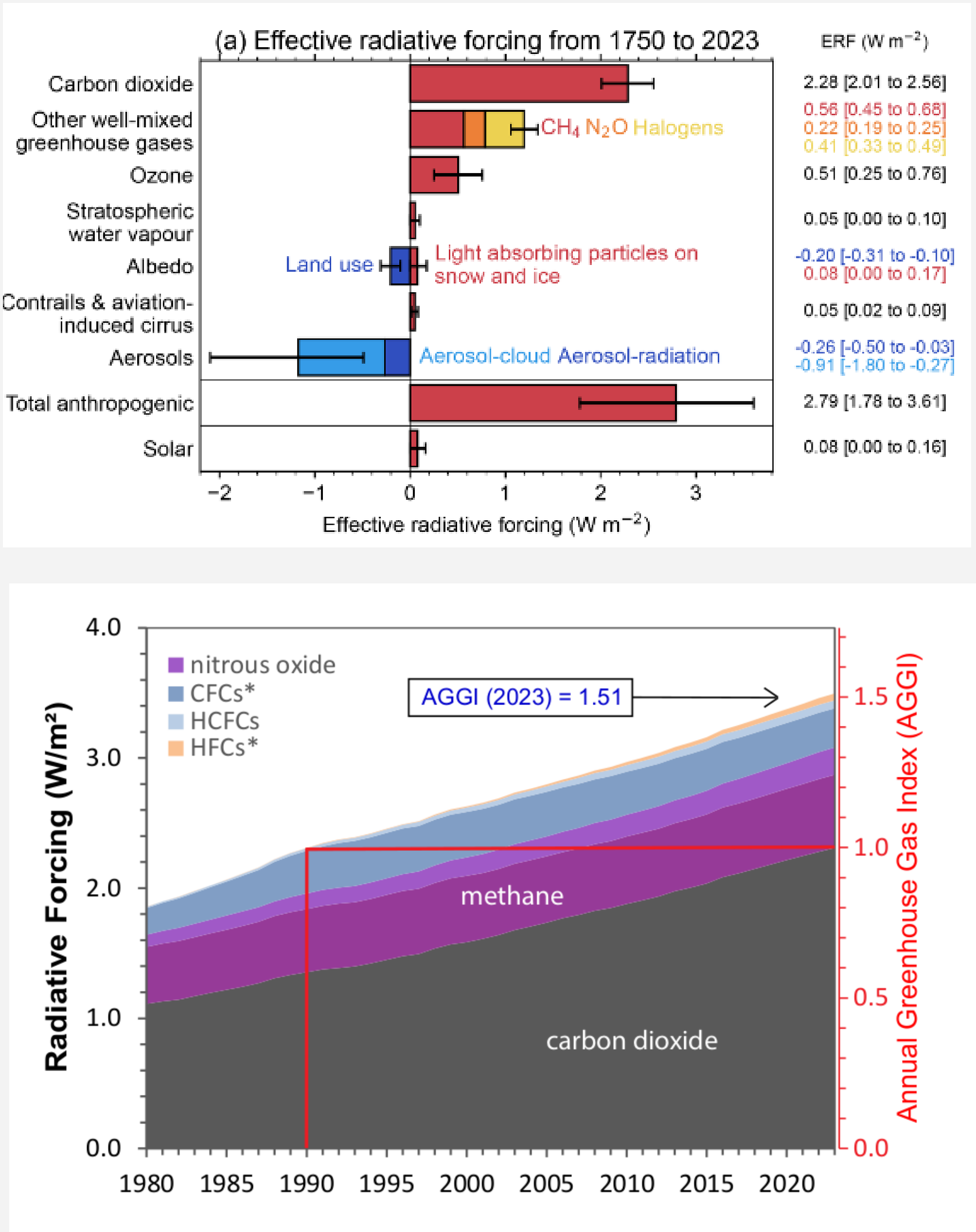

Figure 3. (a) The effective radiative forcing by the main atmospheric species that act to warm and cool the Earth in 2023 from 1750–2023. Source: Forster *et al.*, (2024). **(b) Radiative forcing relative to 1750, over the period 1980 to 2023 of virtually all long-lived greenhouse gases**. Source: NOAA 2024.

2.3 Greenhouse Gas Emissions and Atmospheric Concentrations

The atmospheric concentrations of the three main GHGs responsible for climate change – carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) – have increased rapidly since the industrial revolution. The primary causes for this are GHG emissions from fossil fuel use for energy, unsustainable land management, and unsustainable food production systems. The atmospheric increase in GHG is ameliorated by a number of factors including the unmanaged uptake of additional carbon dioxide by the oceans and terrestrial sinks such as forests and land. The atmosphere itself provides a natural sink for methane and nitrous oxide, which are broken down into other atmospheric species over their atmospheric lifetimes of around 9 and 120 years respectively. The atmospheric concentration of CO_2, CH_4 and N_2O continued to increase in 2023 (**Figure 4**; Forster et al., 2024) and thereby increasing their contribution to global warming.

Carbon dioxide is the most important driver of global warming. In 2023, the atmospheric concentration of CO_2 reached 419.3 [± 0.4] parts per million (ppm), and reached 425 pm in December 2024 (Forster et al., 2024; NOAA, 2025**).** This constitutes an increase of 51% above the pre-industrial concentration of 278 ppm in 1750, and is likely the highest concentration for the past two million years. Despite this increase, there is evidence that the *rate of increase* in CO_2 emissions in the past decade has slowed relative to emissions in the 2000s (Forster et al., 2024).

Methane is the second most important GHG driving global warming. Concentrations of CH_4 reached 1922.5 [±3.3] parts per billion (ppb) in 2023 (Forster et al., 2024). **Nitrous Oxide is considered to be the third most important GHG in terms of global warming. Concentrations of N_2O in the atmosphere reached 336.9 [±0.4] ppb in 2023** (Forster et al., 2024)**.** The latest information on these GHGs, as provided by the Global Carbon Project (Friedlingstein et al., 2024; Saunois et al., 2024; Tian et al., 2024) is summarised below.

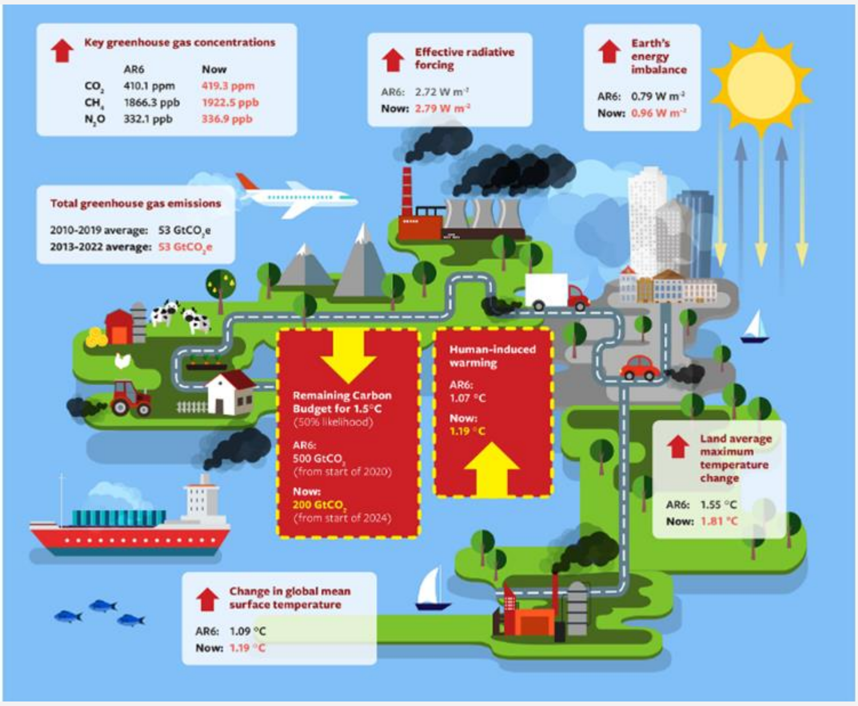

Figure 4. Changes in key climate indicators since AR6. Source: Forster et al., (2024)

Carbon Dioxide (CO_2)

The ongoing build up of CO_2 in the atmosphere constitutes a long term commitment to climate change (IPCC, AR5, AR6). CO_2 currently contributes ~0.8 [0.5 - 1.2]°C to warming relative to pre-industrial temperatures (1850 - 1900) (IPCC, 2023a). It is also driving ocean acidification and leading to increased accumulation of carbon in terrestrial and fresh water systems. The build-up of CO_2 in the atmosphere will continue, along with its increasing contribution to global warming, until net zero CO_2 is achieved. This imperative has been recognised under the UNFCCC and Paris Agreement. Many governments, cities, regions, institutions and private sector actors have adopted net zero CO_2 or wider net zero GHG goals. The Global Carbon Budget provides an annual update of the major components of the global carbon cycle and budget. These are CO_2 emissions from fossil sources and land-use and land-use change, atmospheric CO_2 concentrations, the ocean sink and the terrestrial CO_2 sink. The information provided here is based on Friedlingstein et al. (2023) and Friedlingstein et al., (2024) (pre-print).

2.3.1. **Total anthropogenic CO_2 emissions[2] for the period 1850 – 2023 were 2605± 260 Gt CO_2, of which 70% has been emitted since 1960 and 34% since 2000**. The growth rate of total anthropogenic emissions has been stable over the past decade (2014-2023) (zero growth rate), following a growth rate of 2% during the decade previous (2004 - 2013) (Friedlingstein et al., 2024).

2.3.2. **Fossil emissions.** Global fossil CO_2 emissions increased in 2023 by 1.4% relative to emissions in 2022, and are expected to increase further by 0.8% in 2024, relative to 2023 (Friedlingstein et al., 2024, 2023). The 2024 increase in emissions from coal, oil, gas and cement are anticipated to be 0.2%, 0.9%, 2.4%, and -2.8% respectively, above 2023 levels.[3] Cumulative fossil emissions over the period 1850 – 2023 were 490 ± 25 Gt C.

2.3.3. In 2023, China made the greatest absolute contribution to global fossil CO_2 emissions (31% of total), followed by the USA (13%), India (8%) and the EU27 (7%).

2.3.4. Major regional variation in fossil CO_2 emissions are anticipated for 2024. Most notably, a decrease in emissions by 3.8% in the **European Union** to reach 2.4 GtCO_2 (Friedlingstein et al., 2024). This follows a 8.4% decline in the EU in 2023 (Friedlingstein et al., 2023). Fossil CO_2 emissions are expected to decline by 0.6% in the **United States** (4.9 Gt CO_2),following reductions by 3.5%, 0.7%, and 5.8% for coal, oil and cement, but an increase in natural gas emissions by 1.0% (Friedlingstein et al., 2024). Emissions from fossil sources are expected to increase slightly by 0.2% in **China** in 2024, following an increase by 4% in 2023. India is expected to increase fossil fuel emissions by 4.6%, following an increase of 8.2% in 2023. Emissions from the rest of the world are expected to increase by 1.1% in 2024, after a decrease by 0.4% in 2023.

2.3.5. **International aviation and shipping emissions,** which make up 2.8% of global CO_2 emissions, increased by 14% in 2023, following an increase of 28% in 2022 from pandemic lows. They are anticipated to increase further by 7.8% in 2024 (Friedlingstein et al., 2024).

2.3.6. Land currently accounts for a net sink on average of approximately 2 Gt C per year, and stores a large stock of carbon (an estimated 3550 GtC in vegetation, soils and permafrost combined) (**Figure 5**, Friedlingstein *et al* 2023).

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[2] Total anthropogenic emissions comprise fossil and LULUCF including the carbonation sink.

[3] The GCB (Friedlingstein *et al.* 2024) estimates of global fossil CO_2 emissions include emissions from the oxidation (combustion and chemical) of fossil fuels, and the decomposition of carbonates in industrial processes such as the production of cement.

2.3.7. Global net CO_2 emissions from land-use change remain high at a projected 4.2 $GtCO_2$ in 2024, but they have decreased every decade since the 1990s, in particular in the past decade (-20%) (Friedlingstein et al., 2024). The reduction in land-based emissions (predominantly deforestation emissions) in the past decade (2014 - 2023) resulted in a plateauing in the combined emissions from land-use and fossil fuels, despite an increase in fossil emissions. However, global emissions from fossil and land use changes are projected to reach 41.6$GtCO_2$ in 2024, representing an increase in 2% over the 2023 level of 40.6 $GtCO_2$. This increase has been largely driven by large fire emissions (Friedlingstein et al., 2024).

2.3.8. **Land-use change emissions**. The magnitude and trend of CO_2 emissions from land-use change remain highly uncertain (**Figure 6**). Using bookkeeping methods, it is estimated that CO_2 emissions from land use, land-use change and forestry (LULUCF) have decreased slightly by 0.1 Gt C per decade over the past three decades, as a result of total deforestation emissions remaining relatively stable while forest regrowth has increased steadily. Using DGVM methods, the average has increased over the 1970 – 2022 period, as the DGVM methods include the loss of additional sink capacity, which grows with time. Global CO_2 emissions LULUCF are expected to increase slightly in 2024 relative to 2023.

2.3.9. **Brazil, Indonesia and the Democratic Republic of Congo are the highest land-use emitting countries**, both cumulatively over 1959 – 2023 and on average between 2014 – 2023. These three countries contributed 60% of the global net land-use emissions (between 2014 - 2023), mostly from land conversion for agricultural expansion (Friedlingstein et al., 2024).

2.3.10. **Terrestrial and ocean sinks.** In absolute terms, both land and ocean carbon sinks continue to increase in line with increasing anthropogenic emissions since 1850 (**Figure 6**). The land and ocean CO_2 sinks continue to take-up around half of the CO_2 emitted to the atmosphere. Since the pre-industrial era, the ocean has removed 25% on average of total anthropogenic emissions, while the land has removed 32% of total anthropogenic emissions. The increase in global terrestrial CO_2 sink is due to the CO_2 fertilisation effect and increased nitrogen deposition stimulating plant photosynthesis, particularly in tropical forest regions.

2.3.11. The **land CO_2 sink** was 11.7±3.3 $GtCO_2\,yr^{-1}$ for the decade 2014 - 2023. The land sink in 2023 was estimated at 8.4±3.7 $GtCO_2\,yr^{-1}$, 41% below the 2022 La Niña associated sink of 14.3±3.7 $GtCO_2yr^{-1}$. This reduced land sink relative to the longer-term average and the 2022 estimate can be attributed to El Niño conditions. For example, a decline in the land sink has been observed in regions such as Amazonia due to El Niño associated severe droughts and increased tree mortality (Friedlingstein et al., 2024).

2.3.12. The **ocean CO_2 sink** was 2.9±0.4 Gt Cyr^{-1} during the period 2014 - 2023, with an estimate of 2.9±0.4 GtC yr^{-1} for 2024 (Friedlingstein et al., 2024).

2.3.13. Climate change has reduced the ability of the ocean sink to take up CO_2 by 5.9% (0.17±0.05 Gt C yr^{-1}), while the land-sink has weakened by 27% (0.87±0.56 GtC yr^{-1}) over the 2014 - 2023 period (Friedlingstein et al., 2024).

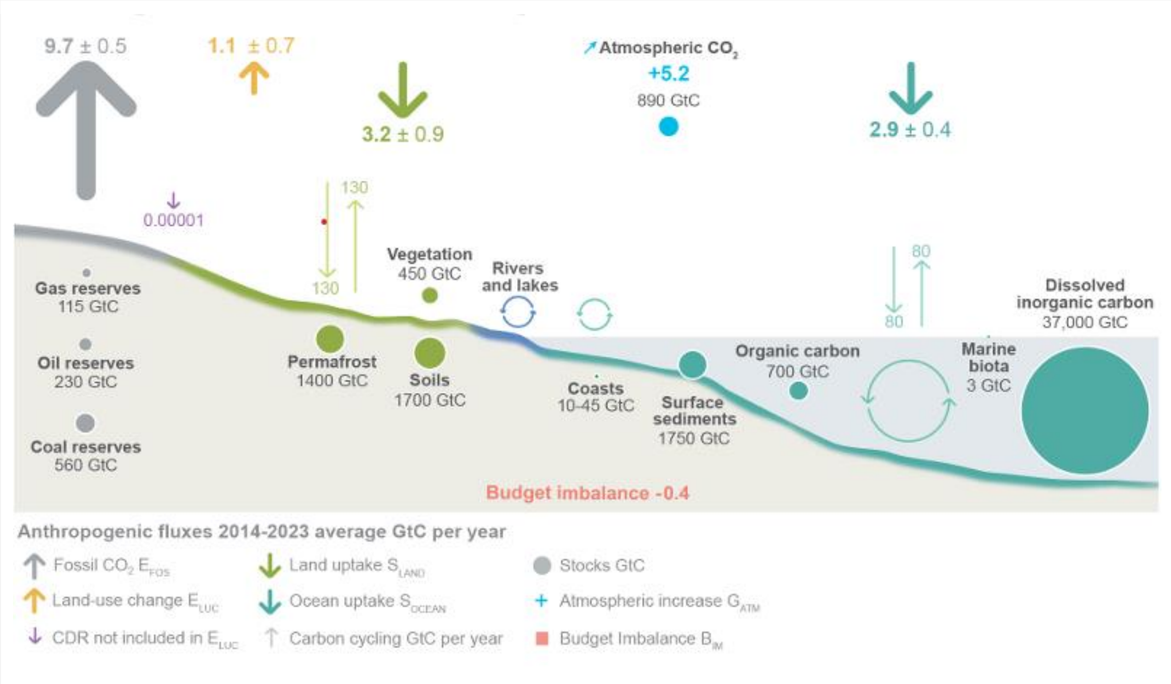


Figure 5. Schematic representation of the overall perturbation of the global carbon cycle caused by anthropogenic activities, averaged globally for the decade 2014–2023. The carbon budget imbalance — the difference between the estimated total emissions and the estimated changes in the atmosphere, ocean and terrestrial sinks — is a measure of imperfect data and incomplete understanding of the contemporary carbon cycle. The CDR estimate is for the year 2023 only. Source: Global Carbon Budget 2024 (Friedlingstein et al., 2024).

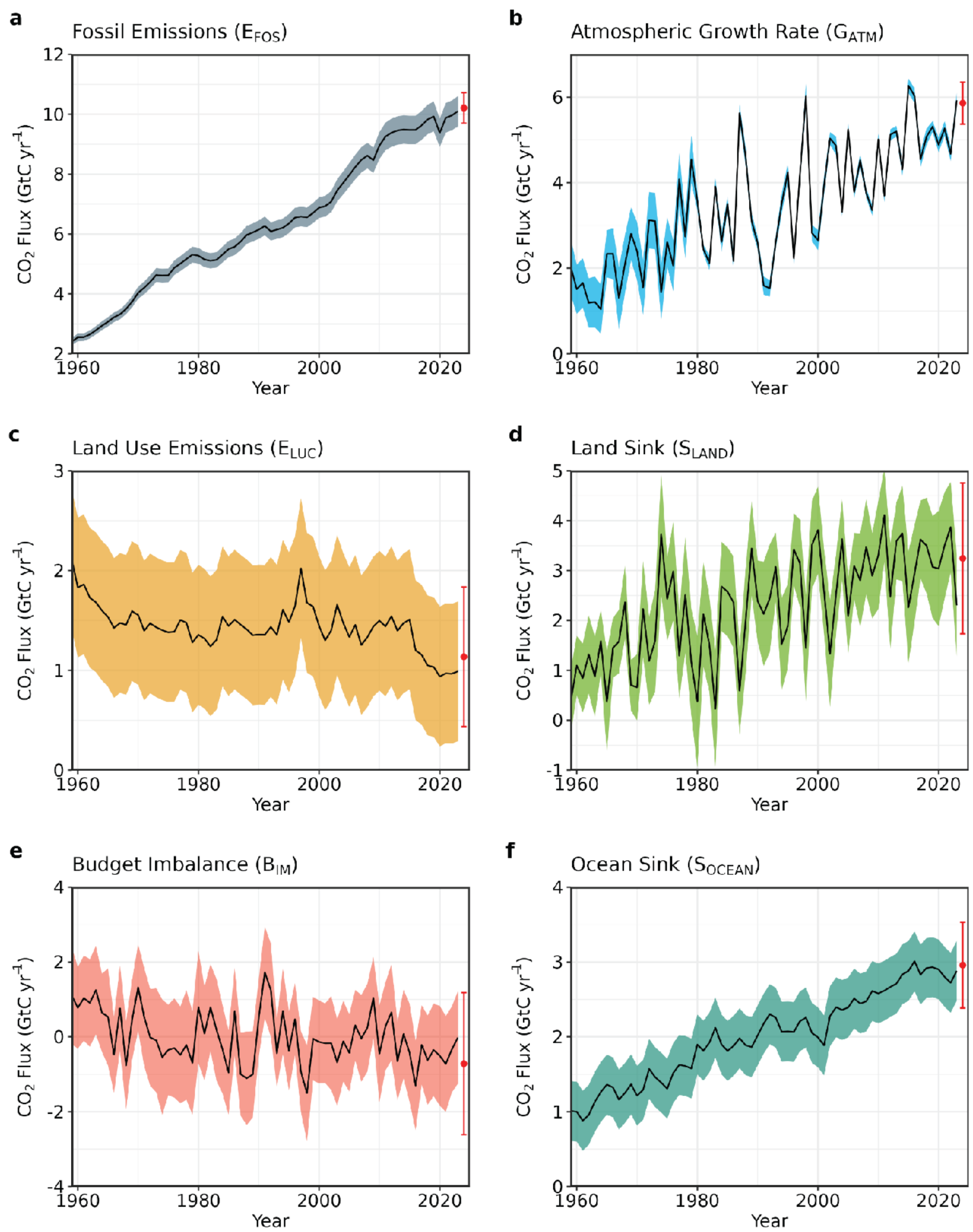


Figure 6. Components of the global carbon budget and their uncertainties as a function of time; presented individually for (a) fossil CO_2 and cement carbonation emissions (E_{FOS}), (b) the growth rate of atmospheric CO_2 concentration (G_{ATM}), (c) emissions from land-use change (E_{LUC}), (d) the land CO_2 sink (S_{LAND}), (e) the budget imbalance that is not accounted for by the other terms, and (f) the ocean CO_2 sink (S_{OCEAN}). Positive values of S_{LAND} and S_{OCEAN} represent a flux from the atmosphere to land or the ocean. All data are in gigatonnes of carbon per year (Gt C yr-1) with the uncertainty bounds representing ±1 standard deviation in shaded colour. Source: Global Carbon Budget, Friedlingstein et al. 2023.

Methane (CH_4)

Addressing methane emissions is high on the international climate policy agenda. Methane is the second most important anthropogenic GHG in terms of climate forcing after carbon dioxide. Although methane has a relatively short atmospheric lifetime of around 9 - 12 years, it has a strong radiative forcing effect (IPCC AR6 WGI, 2021; Prather et al., 2012; Saunois et al., 2024). Methane currently contributes ~0.5 [0.3 - 0.8]°C to warming relative to pre-industrial temperatures (1850 - 1900) (IPCC, 2023b). The short-lifetime of methane means that a stabilisation or reduction in methane emissions will likely result in a stabilisation or reduction in its atmospheric concentration over decadal timescales (Shindell et al., 2012). However, even if the pledged reduction in CH_4 emissions of 30% is achieved by 2030, there is still the risk of overshooting 1.5°C, especially if CO_2 and other GHG emissions continue to increase at current rates. Emissions of methane also contribute to complex chemical processes in the atmosphere which lead to increased concentrations of other species including tropospheric ozone (Saunois et al., 2024)

The Global Methane Pledge (GMP) was launched in 2021 at COP26. Participants joining the Pledge agreed to take voluntary actions to contribute to a collective effort to reduce global methane emissions by at least 30% from 2020 levels by 2030 (GMP, 2024). At least 158 countries have signed the pledge, representing just over 50% of global anthropogenic methane emissions (GMP, 2024). Meeting this pledge would likely reduce methane emissions to a level consistent with a 1.5°C pathway while delivering significant benefits for human and ecosystem health, food security and economic development. As methane is a precursor to air pollutants such as ozone, methane emission reductions are also required under the Convention on Long Range Transport of Air Pollution (CLRTAP). The importance of reducing methane emissions was also identified in the outcome from the first Global Stocktake (GST) under the Paris Agreement in 2023.

The following section provides a summary of the state of CH_4 emissions, and atmospheric concentrations. It has been primarily informed by the pre-print of the 2024 Global Methane Budget (GMB) which was published in 2024 (Saunois et al., 2024). Here, the terms 'atmospheric concentration' are used to refer to the atmospheric mixing ratio of CH_4, expressed as dry mole fractions in parts per billion (ppb). Methane emissions are reported in terms of fluxes and are expressed in teragrams of CH_4 per year (Tg CH_4 yr^{-1}). Emissions estimates are reported in both top-down (TD) and bottom-up approaches (BU) as per the methodology of the GMB. Top-down estimates are based on in-situ and satellite atmospheric concentration observations. Bottom-up approaches are based on data from process-based models and inventories of anthropogenic emissions including from demographic and socioeconomic activity data. Methane is emitted through biogenic, thermogenic and pyrogenic processes and can be from anthropogenic or of natural origin.[4] Where relevant, this section adopts the same sectoral partitioning of anthropogenic emissions as the GMB (for example, agriculture and waste, fossil fuel production and use, biomass and biofuel burning).

2.3.14. **Atmospheric concentrations are 2.6 times higher than its pre-industrial concentration in 1750** (Saunois et al., 2024) (**Figure 7**). The average surface dry air mole fraction of atmospheric methane reached 1942 ppb in October 2024 (Lan et al., 2024).

2.3.15. **Atmospheric methane concentrations have risen faster over the past five-year period than in any previous five-year period since 1983** (Lan et al., 2024). The reason for the recent increase in the rate of concentrations is uncertain. Global methane concentrations rose by 15 ppb, 18 ppb, 13 ppb and 10 ppb respectively in the years 2020 to 2023 (Jackson et al., 2024). Large reductions in

[4] See glossary for definitions of biogenic, thermogenic or pyrogenic.

anthropogenic methane emissions are therefore required to meet the GMP to reduce global methane emissions by 30% from 2020 levels by 2030.

2.3.16. **Direct anthropogenic methane emissions in 2020 (the last year of complete globally available data[5]) reached 372 [345 - 409] and 392 [368 - 409] Tg CH_4 yr^{-1} for BU and TD estimates, respectively[6]** (**Figure 8**) (Jackson et al., 2024).

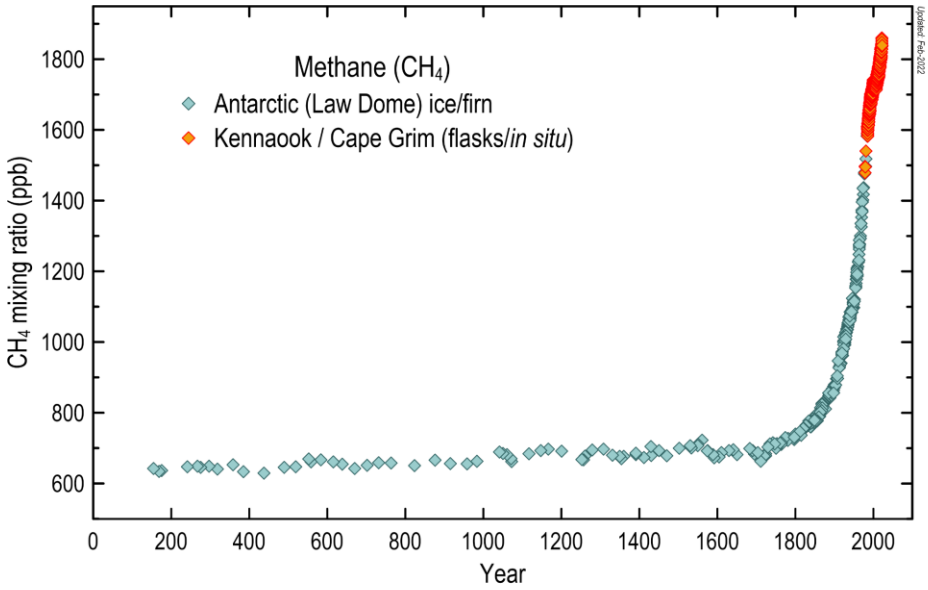


Figure 7. Atmospheric methane concentrations (ppb) over the last 2000 years. Source: Global Carbon Project 2024.

[5] The last year of full global top-down and bottom-up methane emission datasets are available is 2020. Although top-down satellite observations can be available within days to weeks; the surface and atmospheric concentration observations that inform bottom-up approaches may face lag-times of three to five years due to the time it takes to collect and analyse atmospheric in-situ observations and undertake data quality checks (Saunois et al., 2024).

[6] Brackets indicate the uncertainty range.

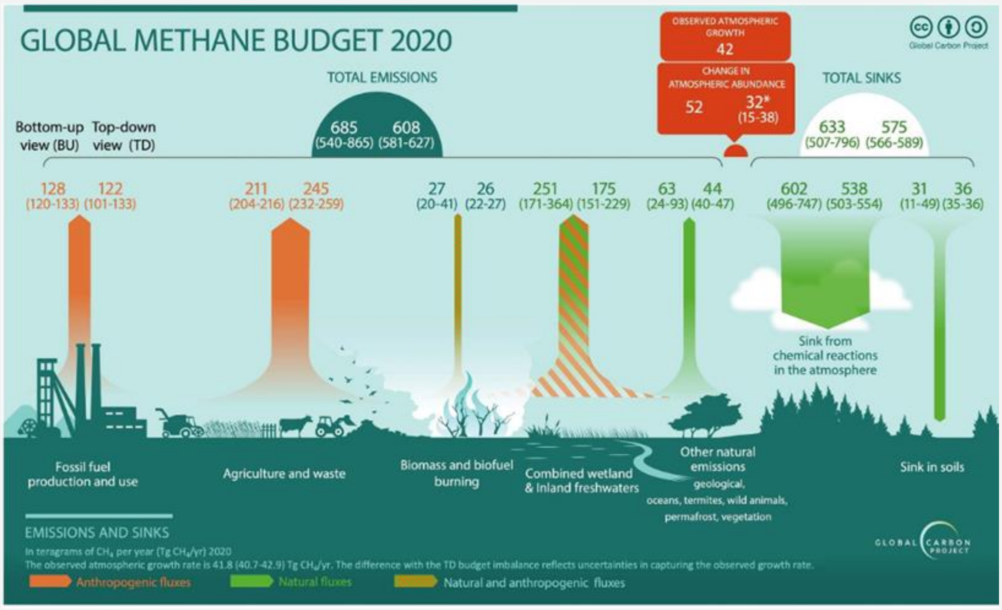


Figure 8. The global methane budget (Tg CH_4 yr^{-1}) for the year 2020, based on top-down and bottom-down methods for natural sources and sinks (green), anthropogenic sources (orange), and mixed natural and anthropogenic sources (hatched orange-green). Source: Jackson et al., 2024.

2.3.17. **Anthropogenic sources are now responsible for at least two-thirds of methane emissions** (Jackson et al., 2024). This includes both direct anthropogenic emissions (which constitute ~65% of global emissions, based on TD estimates) from fossil fuels, agriculture and waste and anthropogenic biomass burning, and indirect anthropogenic emissions such as those from dams and reservoirs (Jackson et al., 2024).

2.3.18. The percentage of methane emissions attributed to both direct and indirect anthropogenic sources is higher than previously estimated by BU estimates partly due to the reallocation of some inland freshwater and wetland emissions (which were previously fully categorised as 'natural'), to indirect anthropogenic sources. For example, emissions from human-built reservoirs, or those which occur in freshwater sources as a result of anthropogenically driven factors including eutrophication or CO_2 induced warming, are now classified as indirect anthropogenic emissions. Due to the realisation that these sources are influenced by anthropogenic activities, 50% of inland water emissions (56 of 112 Tg yr^{-1}), and ~19% of wetland emissions (30 out of ~160 Tg yr^{-1}) have now been reallocated to indirect anthropogenic emissions (Jackson et al., 2024).

2.3.19. Freshwater sources and wetland emissions show contrasting trends between the periods of 2000 to 2002 and 2018 to 2020, depending on the approach. Land surface models tend to infer an increase of around 10 Tg yr^{-1} over the last two decades contrary to atmospheric methane constrained models. This illustrates that uncertainties in methane emissions remain high for natural sources of methane (Jackson et al., 2024).

2.3.20. **Anthropogenic methane emissions rose substantially across all major sectors.** The greatest absolute increase in emissions was observed for the Agriculture and Waste sectorial partitioning, which rose by 33 Tg CH_4 yr^{-1} (for both bottom-up, BU, and top-down, TD, estimates respectively) in the 2018 - 2020 period relative to the 2000 - 2002 period (Jackson et al., 2024). Within this sector and time period, emissions from enteric fermentation and manure from cows (and other domestic ruminants) rose by ~16 Tg CH_4 yr^{-1} (for both BU and TD estimates). Similarly, emissions from landfills rose ~15 Tg CH_4 yr^{-1} (for both BU and TD estimates). Emissions from rice cultivation rose by 3 Tg CH_4 yr^{-1} (BU) to 4 Tg CH_4 yr^{-1} (TD). In comparison, emissions from fossil fuel production and use rose by 27 Tg CH_4 yr^{-1} (TD) or 18 Tg CH_4 yr^{-1} (BU). Consequently, the scale of methane emissions from fossil fuel extraction and use are comparable to emissions from cows and other domestic ruminants globally. Agriculture (including enteric fermentation and manure, and rice cultivation) and waste (including landfills) emissions remain approximately twice those from fossil fuel sources (Jackson et al., 2024).

2.3.21. China, South Asia, and South-East Asia were the top three methane emitting regions over the past decade (2010 - 2019)(Saunois et al., 2024). A range of sectors contributed. Coal mining was the largest contributing sector in China; responsible for 38% of anthropogenic emissions (21 of 57 Tg CH_4 yr^{-1}). Enteric fermentation and manure contributed ~46% of anthropic emissions from South Asia (20 of 44 Tg CH_4 yr^{-1}). Rice cultivation was the largest contributing sector in South-East Asia, producing ~30% of anthropic emissions (9 of 32 Tg CH_4 yr^{-1}) (Saunois et al., 2024). Decreasing methane emissions were observed in Europe and potentially Australasia (Jackson et al., 2024, 2020). In Europe, this decrease may be linked to the implementation of the EU Landfill Directive (1999) which diverts biodegradable waste from landfills to source separation, recycling and energy recovery (Saunois et al., 2024).

2.3.22. Emission estimates from recent years (2020 - 2023) from TD analysis of satellite data indicates tropical regions have contributed the most to recent emission increases, particularly the Congo (partly due to wetland emissions), and parts of southeast Asia (rice cultivation) and southern Brazil (due to emissions from livestock management and manure) (Jackson et al., 2024; Lin et al., 2024).

2.3.23. Although the amount of methane removed by the atmospheric sinks is increasing proportionally to the rising atmospheric methane concentrations, the imbalance between global sources and sinks is still growing (Jackson et al., 2024; Lan et al., 2024).

2.3.24. **In order to support actions under the Paris Agreement and GMP there is an urgent need to improve analysis and estimates of methane emissions including in national reporting of emissions and through the use of advanced observation systems.** Integrated analysis and information provision i.e., space based and remote measurements, with in-situ data, and improved emission inventories can assist governments, sub-national actors e.g. cities, and major international energy companies in addressing emissions.

2.3.25. **Estimates of methane sources and sinks will benefit from new approaches and analysis tools.** For example, more complete and rapid methane emission estimates will be achievable through the incorporation of new satellites optimised for methane detection, including MethaneSAT, and CarbonMapper (Duren et al., 2019). This will help improve regional methane emission estimates and can support national GHG inventory development processes. Top-down estimates would benefit from finer resolution capabilities and from the incorporation of additional tracers such as ethane and methane isotopes such as $^{13}CH_4$, which are present in emissions from fossil fuel exploration or industrial processes but tend to be absent in biological methane sources such as wetlands, landfills and livestock. New approaches to address large scale methane emissions are outlined in Section 3.2.

Nitrous Oxide (N_2O)

Nitrous oxide (N_2O) is a long-lived and potent GHG with an average atmospheric lifetime of 117 years. On a molecular level it has a greater warming capacity than either carbon dioxide or methane.[7] It currently contributes ~0.1 [0.0 - 0.2]°C to warming relative to pre-industrial temperatures (1850 - 1900) (IPCC, 2023b). In addition to being considered the third most important GHG contributing to global warming, its emissions are also the most important emissions of any stratospheric ozone depleting substance.[8] The main source of nitrous oxide emissions is the use of synthetic fertilisers used for food production and other crops. This overview of the trends and abundance of atmospheric N_2O and its emissions is primarily informed by the Global Nitrous Oxide Budget (Tian et al., 2024).

2.3.26. **Global N_2O atmospheric concentrations have increased by nearly 25%, from the pre-industrial level of 270 ppb to 337.7 ppb in September 2024** (Lan et al., 2024) **(Figure 10).** The rate of N_2O accumulation in the atmosphere has accelerated in the past four decades. Growth rates over the past three years (2020 – 2022) were higher than any previous observed year since 1980. The current concentrations and growth rate of atmospheric N_2O are unprecedented; the tropospheric concentration is higher than at any previous time in the past 800,000 years, while the growth rate of atmospheric N_2O is higher than in any time in the past 20,000 years (Tian et al., 2024). Ice-core data reveals that tropospheric N_2O concentrations had remained relatively constant for the past two millennia prior to the industrial era (Canadell et al., 2023)

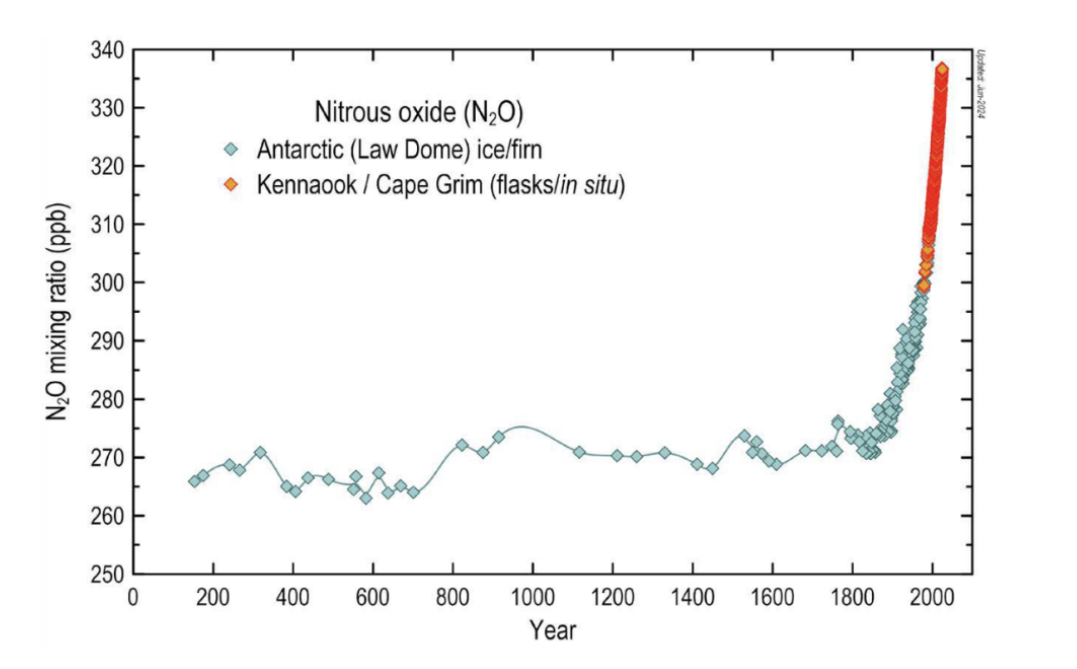


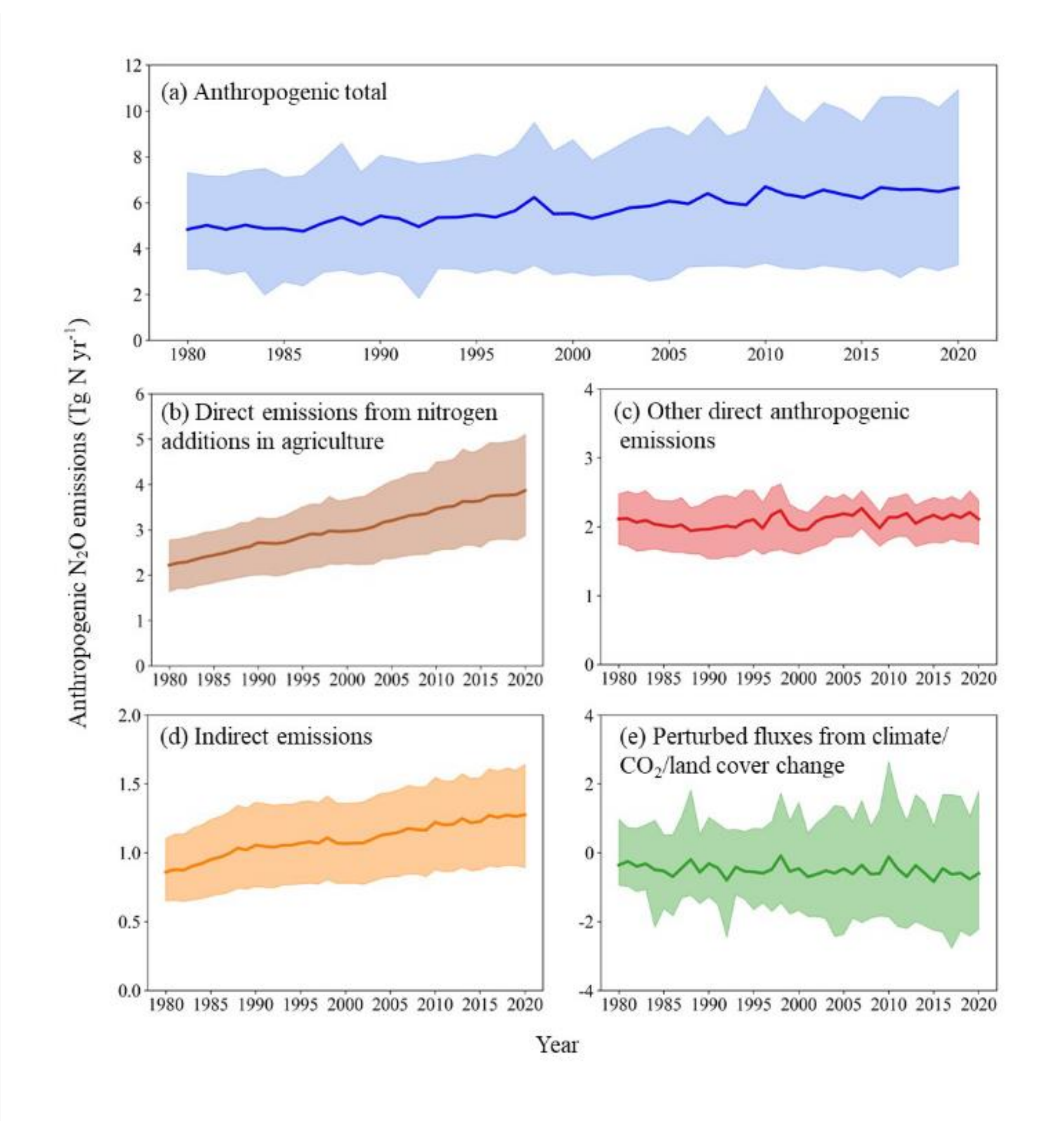
Figure 10. The increase in atmospheric nitrous oxide concentrations for the past 2000 years. Source: Global Carbon Project.

[7] The GWP100 value for N_2O is 273 ± 130 (IPCC AR6 WGI, 2021).

[8] Following effective actions under the Montreal Protocol to reduce and eliminate emissions of highly potent ozone depleting species such as the main Chlorofluorocarbons (CFCs).

2.3.27. **This atmospheric N_2O increase is almost exclusively due to anthropogenic sources; total annual anthropogenic N_2O emissions have increased by 40% over the past four decades**[9] (**Figure 11**). Direct agricultural emissions represent the large majority of anthropogenic emissions (58% or 3.9 Tg N yr^{-1} in 2020). Direct agricultural emissions (such as from the use of synthetic nitrogen fertilisers and animal manure) increased by 77% (from 2.2 to 3.9 Tg N yr^{-1}) between 1980 and 2020. Indirect agricultural N_2O emissions also increased by 44% (from 0.9 to 1.3 Tg N yr^{-1}) over the same period (Tian et al., 2024). Other direct anthropogenic emissions, including those from fossil fuel and industry (which includes emission of N species from transportation), biomass burning and waste and wastewater, did not show a significant trend. Fluxes due to climate perturbations and land cover changes were negative and contributed to a reduction in emissions.

2.3.28. In comparison, global natural land and ocean N_2O (including from inland waters, lightning and atmospheric production) have remained relatively stable, fluctuating between 11.7 and 12.1 Tg yr^{-1} between 1980 and 2020 (Tian et al., 2024).



[9] Using bottom-up accounting methods.

Figure 11. Changes in global anthropogenic N_2O emissions (a) and N_2O emissions from different sectors (b-e) during 1980- 2020. In each panel, the line represents the mean N_2O emissions from different estimates, and the shaded areas show minimum and maximum estimates. Source: Tian et al., 2024.

2.3.29. **Nitrous oxide (N_2O) emissions and atmospheric concentrations are increasing faster than the high-emission 'business as usual' scenarios used in the IPCC Sixth Assessment Report (AR6)**. Observed atmospheric N_2O concentrations in recent years have exceeded even the most pessimistic future GHG scenarios in the Coupled Model Intercomparison Project Phase 6 (CMIP6) used by IPCC AR6 (IPCC AR6 WGI, 2021; Tian et al., 2024)(**Figure 12**) .

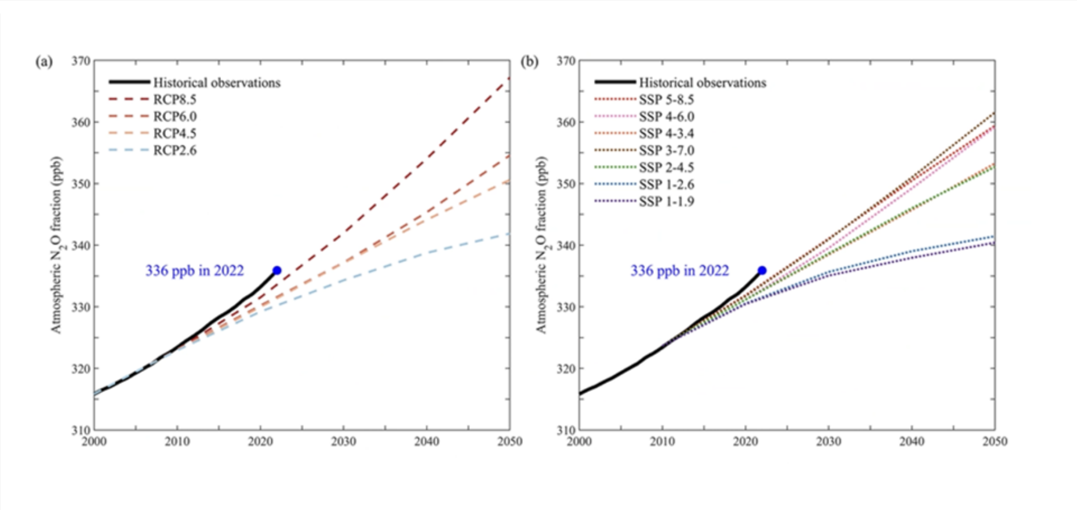


Figure 12. Comparison of the measured global N_2O concentrations and projected concentrations from the (a) four illustrative Representative Concentration Pathways (RCPs) in the IPCC Fifth Assessment Report and (b) the seven illustrative Socioeconomic Pathways (SSPs) used in CMIP6. Source: Global Nitrous Oxide Budget (Tian et al., 2024)

2.3.30. **Urgent reductions in N_2O emissions are required in actions to stabilise the global temperature, and lead to the recovery of the stratospheric ozone.**[10] N_2O has a long atmospheric lifetime, and emissions are projected to rise due to increasing demand for food, energy and increasing waste and industrial processes. Global N_2O emissions are reduced by 22%, 18% and 11% respectively by 2050 in scenarios where the 1.5˚C, 1.7˚C, and 2˚C carbon budgets are met (Rogelj and Lamboll, 2024).[11]

2.3.31. **Trends in N_2O emissions vary regionally, with significant emissions reduction in Europe and Russia but large increases in other regions.** Europe had the largest decline (31% between 2020

[10] Increased stratospheric NO_x from the breakdown of N_2O in the upper atmosphere is implicated in ongoing incremental stratospheric ozone loss (Tian *et al.*, 2024).

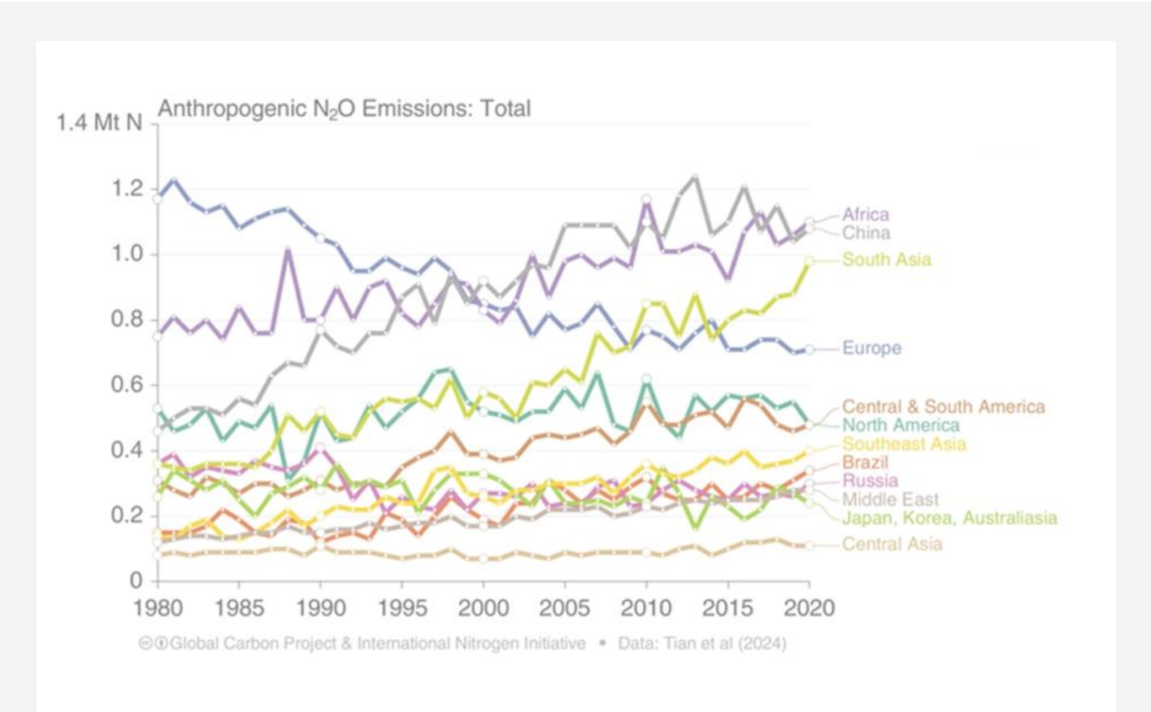
[11] Assuming all GHGs are reduced equally relative to their contribution to global warming, i.e. radiative forcing (Tian *et al.*, 2024).

and 1980) in regional N_2O emissions (**Figure 13**).[12] This decrease is attributed to reduced emissions from industry. Direct and indirect agricultural emissions also likely declined as a result of the European Nitrate Directive and a reduction in fertiliser use following the collapse of the Soviet Union likely contributed to a decline in N_2O emissions in Russia. The decrease in direct agricultural emissions in Europe has plateaued since the early 2000s (Tian et al., 2024).

2.3.32. The global increase in N_2O emissions has been driven by emissions from Asia, followed by Africa and Central and South America. Emerging economies had the largest increases in N_2O emissions from 1980 to 2020; the rate of increase over this period was 82% from China and 92% from South Asia. This is largely due to increases in the application of synthetic nitrogen fertilisers and animal manure in agriculture (Tian et al., 2024).

2.3.33. **Improved reporting and monitoring of N_2O emissions can identify major sources and aid the management of emissions.** The establishment of a global terrestrial and ocean N_2O monitoring network to better resolve spatiotemporal patterns and quantify N_2O fluxes from the earth's surface to the atmosphere would be beneficial in reducing uncertainties in estimates and can support reporting under the Paris Agreement and UNFCCC. Such information can also inform the global stocktake (GST) process. As part of the transparency framework under the Paris Agreement, Parties will provide information on emissions in the Biennial Transparency Reports (BTRs).

2.3.34. **There is a need to address scientific uncertainties which can assist in more effective management of food production, crop management, and associated fertiliser use**. Large uncertainties exist in the estimates of soil N_2O from tropical regions in the Amazon and Congo basins, in South-east Asia and in regions with high fertiliser application such as China and northern India. Additionally, N_2O emissions from Mediterranean agriculture have likely been overestimated. N_2O fluxes from atmospheric CO_2, and mature forest conversion and biomass burning would also benefit from further data.



[12] Amongst the 18 countries analysed by the Global N_2O budget.

Figure 13. Emissions trends across nations and regions included in the Global Nitrous Oxide Budget (Tian et al., 2024)

Key insights:

- **Carbon Dioxide Emissions.** Carbon dioxide is the most important GHG contributing to global warming. Global CO_2 emissions continue to grow, although at a slower rate than in recent decades. This high rate of global CO_2 emissions increases the challenge of reaching net zero CO_2 emissions by mid-century.
- **Methane Emissions.** Methane is the second most important anthropogenic GHG in terms of climate forcing after carbon dioxide. Globally, atmospheric methane concentrations continue to increase. However, effective actions to reduce emissions including those adopted under the Global Methane Pledge can play an important and relatively rapid role in limiting warming to the Paris Agreement Temperature Goal. However, even if the pledged reduction in CH_4 emissions of 30% are achieved by 2030, there is still the risk of overshooting 1.5°C, especially if CO_2 and other GHG emissions continue to increase at current rates. Some methane emissions reduction progress is occuring; decreasing emissions have been observed in Europe.
- **Nitrous Oxide Emissions.** Nitrous oxide (N_2O) emissions is the third most important GHG contributing to global warming, and its emissions are the leading contributor to stratospheric ozone depletion. Although nitrous oxide emissions have been reduced in Europe, global N_2O emissions are increasing at an unprecedented rate, and faster than the high-emission 'business as usual' scenarios used in the IPCC Sixth Assessment Report. Actions to address emissions of N_2O produced by extensive use of fertilisers have benefits for climate change, protection of the stratospheric ozone layer, and water quality. Enhanced management of land and reduced reliance on synthetic fertilisers is cost effective in many, although not all, agricultural systems. Improved methods of monitoring N_2O will aid management.

2.4 The Paris Agreement and the global stocktake process

2.4.1. **The Paris Agreement temperature goal provides a framework for climate policy on the emissions reductions pathways and the carbon budget ranges needed to limit warming to well below 2°C and pursuing efforts to limit warming to 1.5°C.** The Paris Agreement has near-global participation; it has been signed by all of the 198 parties of the UNFCCC, and ratified by almost all signatories. Implementation of the Paris Agreement is through the five year Global Stocktake (GST) process in which Parties assess the progress and level of combined commitments expressed in their Nationally Determined Distributions (NDCs). These are supported by the information provided under the Enhanced Transparency Framework, under which Parties are required to submit biennial transparency reports (BTR) every two years starting from December 2024. The BTRs include updates on National Greenhouse Gas Inventory reports, progress towards NDCs, capacity building needs and levels of financial development.

2.4.2. The Long-term Global Goal (LTGG) under the Paris Agreement was adopted in 2015. It mirrors the Paris Agreement temperature goal (see glossary). The LTGG was adopted following the first Periodic Review, and was informed scientifically by the information provided by the IPCC in its 5th Assessment Report (AR5). The second Periodic Review of the LTGG and progress in its implementation was completed at COP27 in 2022. The second review served to confirm that the LTGG is a climatological goal that is assessed over decades, rather than an annual or short-term global average temperature which is subject to interannual variability.

2.4.3. The Paris Agreement temperature goal remains open to interpretation. For the policy community, many World Leaders have stressed the need to limit global warming to 1.5°C by the end of this century. Recent UNFCCC COP meetings have focused on 'keeping 1.5°C alive', 'within reach' or as the 'North Star' to guide ambition. This direction was informed by the *IPCC Special Report on Global Warming of 1.5* °C (SR1.5) and the IPCC AR6, which articulated a robust difference between climate-related risks associated with global warming of 1.5˚C and present day conditions, and between global warming of 1.5 ˚C and 2˚C. These indicated that crossing the 1.5°C threshold risks more severe climate change impacts, including more frequent and severe droughts, heatwaves and rainfall while the risks of large scale global impacts are increased.

2.4.4. Issues being explored within the scientific community include: (1) if the temperature goal refers to peak or stabilisation temperature; (2) what timeframe warming must be stabilised over; (3) and the definition by which warming should be tracked. These considerations have resulted in exploration of issues such as temperature overshoot and return, and ongoing analysis of temperature data, trends and projections.

2.4.5. Overall, statements of ambition since the adoption of the Paris Agreement have emphasised limiting warming to 1.5˚C rather than focus on 'well below 2 ˚C'. This is also expressed in statements relating to a goal of net zero. The timing within which net zero CO_2 is to be achieved has been more clearly and ambitiously specified in COP decisions over time, from achieving a balance 'in the second half of this century' (adoption of the Paris Agreement, decision 1/CP.21 in 2015) to achieving net zero 'around mid-century' (Glasgow Climate Pact, decision 1/CMA.3 in 2021), and further to 'by or around mid-century' (outcome of First Global Stocktake, decision 1/CMA.5 in 2023).

2.4.6. **The first global stocktake held in 2023 at COP28/CMA5 found that some progress has been made in stated ambition in NDCs; however, the current levels of ambition and implementation are insufficient.** The GST outlined several future actions required to achieve the Temperature Goal, including the need for a just, orderly and equitable transition away from fossil fuels, the tripling of renewable energy capacity, and the doubling of energy efficiency. The next global stocktake will take place in 2028, ahead of which Parties are expected to update their NDC. Guidance from the GST is that the next round of NDCs should be informed by or linked with LTSs.

Key insight: The Paris Agreement architecture serves as a framework to drive climate policies in line with the long term global goal (a climatological goal assessed over decades to limit warming 'well below' 2°C while pursuing efforts to limit the increase to 1.5 °C) and determine progress towards this goal through the Global Stocktake and Enhanced Transparency Framework processes. The 2023 Global Stocktake (GST) (COP28/CMA5) found that while some progress has been made, current ambition and implementation levels are insufficient to meet the Paris Agreement goals. The GST called for a just, orderly and equitable transition away from fossil fuels, the tripling of renewable energy capacity, and the doubling of energy efficiency.

Key questions for CNF2026:

- Can observations support statements on effectiveness of emissions reductions at a European level? They are contained in some NIRs but need a more open publication?
- Can we determine the vitality of the ocean and terrestrial carbon sinks and factors determining this via observation systems?
- Can the drivers of atmospheric methane levels be better determined?
- How have changes in aerosol composition changed the radiative forcing and how will this evolve?

2.5 Global emissions pathways characteristics for 1.5˚C and 2˚C

2.5.1. **Emissions pathways that limit warming (with a >50% probability) below 1.5°C achieve net zero CO_2 emissions by around 2050.** Pathways that limit warming to 2°C (with a >67% probability) reach net zero CO_2 emissions around 2070 (IPCC, 2023a). Stabilising GMST on multi-decadal timescales requires reaching and sustaining 'net zero' global anthropogenic CO_2 emissions, and declining net non-CO_2 radiative forcing (IPCC, 2018). Further, limiting warming to a specific temperature in line with the Paris Agreement imposes a budget for the remaining amount of CO_2 that can be emitted before these cumulative emissions need to have ceased (see section on remaining carbon budget below).

2.5.2. **Pathways that limit warming to 1.5˚C include clear CO_2 emissions reductions by 2030 of around 45% relative to emissions in 2010** (IPCC, 2018). Global warming is largely driven by cumulative CO_2 emissions (i.e. historic, current and future emissions of additional CO_2), and the shape of the pathway to net zero CO_2 strongly affects the scale of committed warming.

2.5.3. **Delays in reducing CO_2 emissions increase risks for breaching the Temperature goal or reliance on large-scale carbon removal burden and associated costs and risks.** The analysis provided in the IPCC AR6 indicated that limiting warming to 1.5°C required CO_2 emissions to halve by 2030 relative to 2015 levels (IPCC, 2023a). Since 2015, global CO_2 emissions have risen continuously until 2023 (apart from a negligible decrease in 2020 due to the COVID pandemic). Hence emissions reductions of 42% relative to 2019 levels are now required by 2030 (UNEP, 2024).

2.5.4. **Pathways that limit warming to 1.5˚C include deep reductions in non-CO_2 GHGs.** Peak warming is a function of the cumulative CO_2 emissions and the level of warming by non-CO_2 GHGs such as methane and nitrous oxide at the time of net zero (IPCC AR6 WGI, 2021). Rapid and deep reductions in methane emissions would reduce its warming contribution over a relatively short period of time i.e. years or decades. Reductions in nitrous oxide emissions would reduce its contribution to global warming and the scale of CDR required to balance this warming.

2.5.5. **The reduction in the cooling effects of aerosols must be considered in analysis of action to limit global warming.** Aerosols are microscopic particulate matter (PM) in the atmosphere, which are typically invisible (see glossary). They have an overall cooling effect which masks a portion of warming by GHGs. Aerosols which arise from the combustion of fossil fuels, in particular sulphate and nitrate aerosols have declined or are projected to decline due to policies and actions on air pollution and transition from use of fossil fuel. In high ambition scenarios, the decline of aerosol cooling contributes to observed increases in warming (IPCC, 2023a).

2.5.6. **Current atmospheric GHG levels and scale of emissions means that most modelled pathways include overshoot and temporarily exceed the 1.5˚C limit before returning to 1.5˚C by 2100.** Overshoot trajectories have increased climate risks, and result in higher impacts and associated challenges compared to pathways that limit warming to 1.5˚C with no overshoot (IPCC AR6 WGII, 2022a).

2.5.7. **All pathways that limit warming to 1.5˚C with limited or no overshoot require carbon dioxide removal (CDR) to reach and sustain a significant level of global net-negative CO_2 emissions** (**Figure 14**). The timely establishment of sustained and robust (i.e. permanent) CDR is necessary to limit warming to 1.5°C. CDR must be additional to (and does not replace) required emissions reductions. Further, essentially all pathways that limit warming to 2 °C were shown to also require global net-negative emissions, though this is required later and in smaller amounts in 1.5 °C pathways (IPCC AR6 WGII, 2022a).

2.5.8. GHG emissions peaking may occur later in some developing economies. The societal and systems transformations for pathways to 1.5˚C or 2˚C need to be climate resilience pathways that achieve ambitious climate mitigation in a just-manner and involve a diversity of interest groups and stakeholders and support longer-term sustainable development goals. Social justice and equity are core aspects of climate resilient pathways. Mitigation pathways need to include climate action in national and sub-national authorities, civil society, Indigenous people, and local communities (IPCC AR6 WGII, 2022b).

Key insight: Pathways that limit warming to 1.5˚C include clear CO_2 emissions reductions by 2030 and deep reductions in non-CO_2 GHGs. Most modelled pathways include overshoot and temporarily exceed the 1.5˚C limit before 2100. All pathways that limit warming to 1.5°C with minimal or no overshoot require carbon dioxide removal (CDR) to achieve and maintain substantial global net-negative emissions.

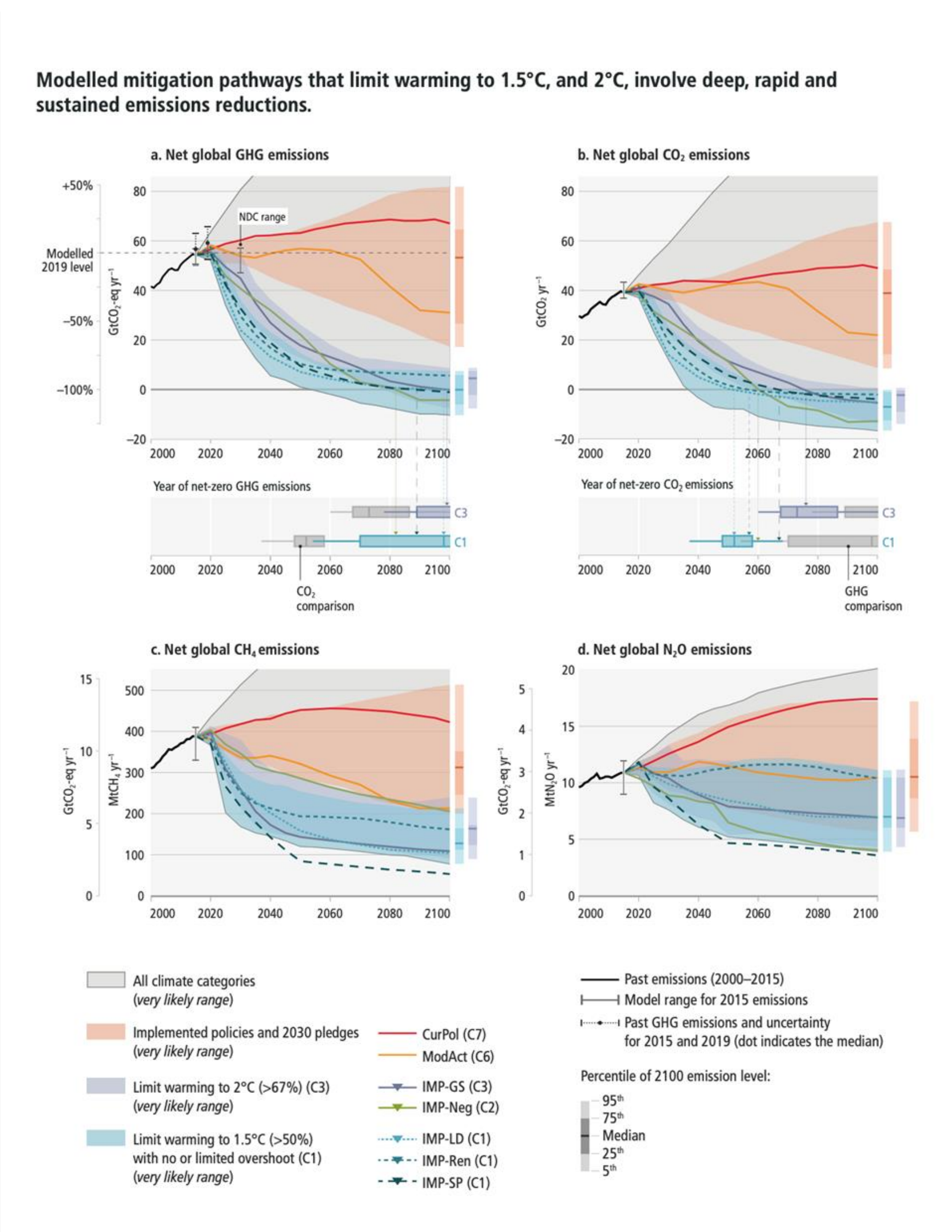


Figure 14: Illustrative Mitigation Pathways and net zero CO_2 and GHG emissions pathways. Source: AR6 WGIII Figure SPM.5 (IPCC AR6 WGIII, 2022).

The remaining carbon budget

2.5.9. **The remaining carbon budget (RCB) to limit warming to 1.5 °C without CDR is becoming untenably small.** The RCB for a 50% likelihood of limiting global warming to 1.5˚C has halved between 2020 and 2024. The RCB was assessed to be 500 $GtCO_2$ in 2020 by AR6 WGI. An IPCC-consistent update (using the same IPCC methodology but updated data from WGIII) by Forster et al., (2024) revised the RCB for 2020 down to 400GtC. The same update assessed the RCB in 2024 to be 200 Gt CO_2 (see Table 1 below; Forster et al., 2024). For 1.7 and 2˚C, the remaining carbon budget has reduced to 625 $GtCO_2$ and 1150 Gt CO_2 respectively.

2.5.10. **If emissions continue at current levels, the 1.5˚C budget (the amount of CO_2 that can still be emitted for a 50% chance of staying below 1.5C of warming) would be exhausted in 7 years** (Forster et al., 2024). This estimate is based on the current emissions level and the remaining carbon budget. It is corroborated by a 1.5°C crossing time based on extrapolating the current level and rate of human-induced warming. For 1.7 and 2˚C, the RCB implies a timeline of 15 and 28 years from the beginning of 2024 before the budget is exhausted, unless net emissions are significantly reduced in this period (Forster et al., 2024).

2.5.11. **Carbon budget estimates assume projected reductions in non-CO_2 emissions in line with pathways that achieve net zero.** The remaining CO_2 budget includes the non-CO_2 GHGs and the role of pollutants indirectly as a result of how they are projected to evolve in Integrated Assessment Models (IAMs); it already assumes stringent reductions between 2020 and 2050 in methane (median ~50% reduction) and nitrous oxide (median ~20% reduction). This means, for example, that reducing methane emissions would not increase the remaining carbon budget. Rather, the remaining carbon budget would be smaller if methane and nitrous oxide emissions reductions are not achieved (Forster et al., 2024).

2.5.12. **Estimates of reduced aerosol cooling are included in the calculation of the remaining carbon budget calculation.** The reduction in the budget is a function of both continued emissions (164 $GtCO_2$ was emitted between 2020 and the end of 2023) and improved methods, including the incorporation of knowledge on how non-CO_2 emissions such as sulfate aerosols contribute to future warming (Forster et al., 2024). As carbon emissions decline, linked aerosol emissions will also decline; since aerosols cool the planet, these reductions result in an additional relative warming effect. Policies and measures to address air quality have also reduced regional aerosol levels, for example in Europe and North America, and the North Atlantic region.

2.5.13. Uncertainties in the size of remaining carbon budgets means the carbon budget provides an approximation rather than a precise estimate of how fast decarbonization needs to occur. Uncertainties in the climate response and non-CO_2 emissions across the scenarios in the AR6 scenario database mean the estimated RCB values can be higher or lower by 200 $GtCO_{2,}$ depending on the level of non-CO_2 mitigation (Forster et al., 2024). Communication of a single number estimate of years remaining within the budget should therefore be couched within the understanding that small changes in the scenarios and estimates used to calculate the carbon budget can result in different budget outcomes. Deep reductions in non-CO_2 emissions is therefore central to achieving the goals of the Paris Agreement. As the budget for 1.5˚C becomes smaller, geophysical and other uncertainties will have a relatively higher presence.[13]

[13] Note these figures differ from those in the annual Global Carbon Budget, which in 2024 used an average between AR6 WGI estimates and Forster *et al.*, (2024) estimates.

Table 1. *Updated estimates of the remaining carbon budget for 1.5, 1.7 and 2.0 °C, across five levels of likelihood, considering only uncertainty in TCRE. Estimates start from AR6 WGI estimates (first row), updated with the latest MAGICC emulator and scenario information from AR6 WGIII (second row) and an update of the anthropogenic historical warming, which is estimated for the 2014–2023 period (third row). Estimates are expressed relative to the start of either the year 2020 or the year 2024. The probability only includes the uncertainty in how the Earth immediately responds to carbon emissions, not long-term committed warming or uncertainty in other emissions. All values are rounded to the nearest 50 Gt CO_2. Bold numbers refer to the full remaining carbon budget estimate containing all terms.* Source: Forster et al., 2024.

Remaining carbon budget case/update	Base year	Estimated remaining carbon budgets from the beginning of base year (Gt CO_2)				
Likelihood of limiting global warming to temperature limit		17 %	33 %	50 %	67 %	83 %
1.5 °C from AR6 WG1	2020	900	650	500	400	300
+ AR6 emulators and scenarios	2020	750	500	400	300	200
+ Updated warming estimate	**2024**	**450**	**300**	**200**	**150**	**100**
1.7 °C from AR6 WG1	2020	1450	1050	850	700	550
+ AR6 emulators and scenarios	2020	1300	950	750	600	500
+ Updated warming estimate	**2024**	**1000**	**700**	**550**	**450**	**350**
2 °C from AR6 WG1	2020	2300	1700	1350	1150	900
+ AR6 emulators and scenarios	2020	2200	1650	1300	1100	900
+ Updated warming estimate	**2024**	**1900**	**1400**	**1100**	**900**	**750**

Key insight: The remaining carbon budget (RCB) to limit warming to 1.5°C without CDR is becoming untenably small. The remaining carbon budget for a 50% likelihood of limiting global warming to 1.5˚C has halved from 2020 to 2024 and is estimated at 200 $GtCO_2$. This budget could be depleted in seven years if emissions continue unchanged. However, this carbon budget provides an approximation rather than a precise timeline due to uncertainties in climate response and non-CO_2 emissions scenarios.

2.6 Land ecosystems and their roles in climate change

Land ecosystems play a fundamental role in regulating and stabilising the world's climate. They constitute a major carbon store (in soils and biomass), and are both a source and sink of GHGs. In 2023, terrestrial sinks were estimated to take up approximately 30% of anthropogenic CO_2 emissions, mainly in forests (see Section 2.3.11) (Friedlingstein et al., 2024). The AFOLU sector (mostly the Forestry, and Other Land Use (FOLU) subsector) is estimated to be able to provide 20 - 30% of the global GHG emissions mitigation needed for 1.5°C or 2°C pathways towards 2050 (Forster and Storelvmo, 2021; Grassi et al., 2023; IPCC AR6 WGII, 2022a). Most modelled global GHG emissions pathways that limit warming to 1.5°C and 2°C rely on large-scale land-based carbon removals (IPCC, 2023a, 2018). Land-based mitigation methods include carbon sequestration in agriculture, ecosystem restoration, afforestation and reforestation, reduced conversion of forests and improved sustainable forest management. However, while the FOLU sector offers considerable near-term mitigation potential, it does not compensate for delayed emissions reductions in other sectors.

Although land-based mitigation is increasingly recognised as an important component in achieving the Paris Agreement temperature goal, the scale and feasibility of land based removals has been questioned, including in the IPCC Special Report on Land (IPCC, 2019). In addition, understanding and managing the current and future role of terrestrial ecosystems in regulating emissions remains hindered by uncertainty and inconsistencies in the estimation approaches utilised across a range of scientific communities (IPCC, 2024). This includes the modelling, remote observation and monitoring scientific communities, at global and national scales (e.g. in national GHG inventories). Land systems are complex given the multiple biological entities they host and the interactions among them and with the physical environment. The land sink responds to both anthropogenic and natural drivers of land-use change, regrowth and deforestation, making the distinction between anthropogenic and natural fluxes challenging. In addition, realising the estimated technical mitigation potential of the land sink requires navigating complex social, cultural, economic and political constraints. Building confidence in land-based mitigation GHG emission estimates is needed. Some aspects of these challenges are addressed here based on presentations and contributions made by Maria José Sanz, Giacomo Grassi, Peter Iversen, Adrian Leip, Myles Allen and others during and following the 2024 Climate Neutrality Forum. Mitigation options associated with agriculture and food systems were not discussed in-depth at the CNF2024 and as such are not within the scope of this report.

Challenges in monitoring and assessing terrestrial mitigation

2.6.1. **Although global model projections indicate large potentials for increasing the land sink through afforestation and forest management, many of these models do not account for potential climate feedbacks, uncertainties in estimates, implementation barriers including land competition for other uses including timber, bioenergy production and food** (IPCC AR6 WGII, 2022a). Reliance of mitigation efforts on land sinks must be taken with caution, and scenarios considering the possibility of land negative feedbacks seriously considered. Land fluxes are dominated by highly dynamic biological processes including interannual variabilities such as the El Niño oscillation, which are not always well understood, and are potentially vulnerable to climate change. Predictions of terrestrial carbon sinks often also omit the variation of forest carbon uptake that occurs with forest age. The forest carbon sink potential is related to net-primary productivity which is highest when forests are young and decreases as forests mature (Tang et al., 2014). Soil organic carbon, which forms the largest terrestrial reservoir of organic carbon, remains largely unquantified (Georgiou et al., 2022).

2.6.2. Reliance on forests and land-use sinks for climate mitigation is also problematic due to **uncertainty over the duration of storage**. Natural disasters (drought, wildfires, insect infestations) which are expected to increase with climate change, can destroy standing forests and ecosystems and effectively negate decades of carbon sequestration instantly.

2.6.3. **Increasing temperatures are weakening many land carbon sinks.** Regions exposed to extreme heat in 2023 contributed a gross carbon loss of 6.34 $GtCO_2$ yr^{-1}, indicating that record temperature anomalies had a strong negative impact on the capacity of terrestrial ecosystems to mitigate climate change (Ke et al., 2024). In 2022, Central Europe switched from a sink of carbon to a source due to the summer heatwave (and associated drought and wildfire) causing widespread losses (van der Woude et al., 2023). Globally, over the 2013–2022 period, climate change reduced the land sink by 2.50 ± 2.27 $GtCO_2$ yr^{-1} (Friedlingstein et al., 2023). The future global balance of climate response and CO_2 response may depend on the geographic extent of drought and heat stress.

Discrepancies in land-based GHG emissions and removals

2.6.1. **Monitoring and assessing the status of the land sector as a source or sink is difficult due to the complexity of estimating land based GHG emissions and removals, specifically the anthropogenic component of these.** There are substantial differences in estimates of the scale of the land sink from different global models — i.e. bookkeeping models, dynamic global vegetation models, integrated assessment models (IAMs) — and analysis provided in National GHG Inventories (NGHGIs). This discrepancy is estimated to differ by around 7 Gt CO_2 per year or ~15% of global CO_2 emissions. This is a source of confusion for policymakers, practitioners, and between scientific communities (IPCC, 2024).

2.6.2. **Differences in estimates of the global net LULUCF CO_2 flux reflect different analysis approaches that are not readily reconciled.** The approach and system boundary used to define anthropogenic emissions in NGHGIs is different to that used in global models (**Figure 15**). Bookkeeping models only consider direct human-induced fluxes such as deforestation, shifting cultivation, wood harvest, and regrowth after harvest or abandonment of agricultural lands as anthropogenic. NGHGIs use the IPCC Managed Land Proxy (MLP) definition for anthropogenic sinks which constitutes a broader definition than used by global models. NGHGIs therefore consider a greater area of managed land than the models, and within that area, include most of the land sink caused by indirect human-induced environmental change (such as CO_2 fertilisation in response to increased CO_2 atmospheric concentration) as anthropogenic, which global models consider to be natural (Grassi et al., 2023).

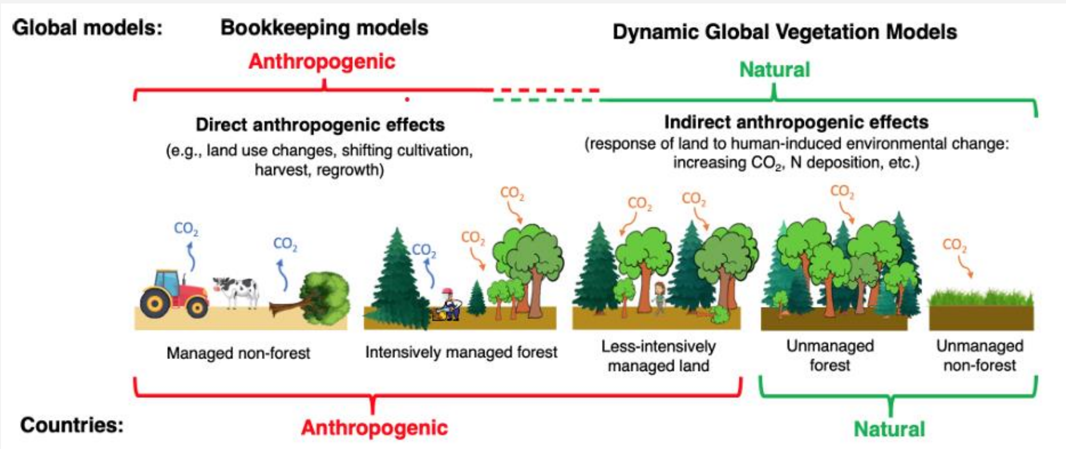


Figure 15: **Conceptual illustration of the different approaches for estimating the anthropogenic and natural land CO_2 fluxes by global models used in the Global Carbon Budget (bookkeeping models and dynamic global vegetation models, DGVMs) and by countries' national GHG inventories (NGHGIs).** Note that the figure is a simplification: DGVMs can also estimate the anthropogenic flux, but here only the natural fluxes are shown; not all NGHGIs include all indirect effects in managed land; other differences between BMs and NGHGIs exist that are not included in this figure, e.g. on the representation of forest management and forest demography. Source (figure, caption text): Grassi et al., 2023.

Implications for net zero CO_2 and the Paris Agreement temperature goal

2.6.3. **All scenarios that meet the goals of the Paris Agreement achieve Geological Net Zero (GNZ), meaning a balance between any remaining production of CO_2 from fossil sources and storage of CO_2 in geological-timescale sinks, around the time of halting global warming** (**Figure 16**) (Allen et al., 2024)**.** In most scenarios that meet the Paris Agreement goals, GNZ is achieved within a few years of achieving global net zero from all emissions. Emissions and removals from land-use affect the timing of net zero by at most a few years (Allen et al., 2024; Jenkins et al., 2023). Progress to GNZ can be tracked easily by monitoring the fraction of CO_2 produced from any continued use of fossil fuels or cement production that is either captured at source or recaptured from the atmosphere and committed to geological-timescale storage. This geologically stored fraction (currently 0.1% globally – Smith et al., 2024) needs, by definition, to reach 100% to deliver GNZ.

2.6.4. **Reducing the amount of CO_2 produced, by replacing fossil fuels with low or zero-carbon alternatives, remains by far the largest single component of mitigation strategies under all Paris-compliant scenarios.** Transitioning away from fossil fuels prevents the generation of some two to three trillion tonnes of CO_2 by 2100 in 1.5°C compatible scenarios. Increasing the amount committed to geological storage disposes of a further trillion tonnes on average. The transition from net deforestation to restoring carbon to the biosphere saves a further 250-500 million tonnes by 2100 (Jenkins et al., 2023).

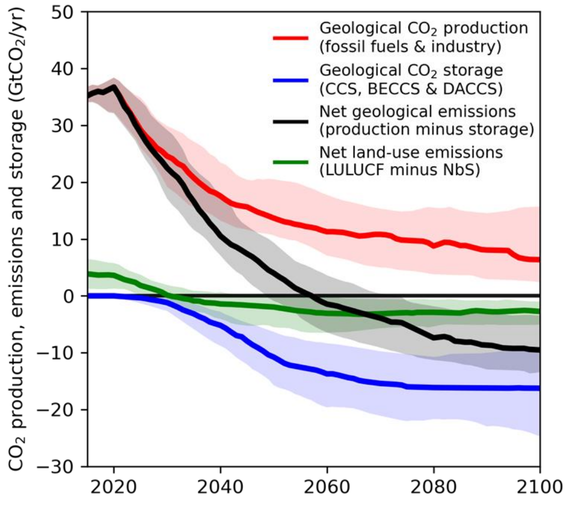


Figure 16. 1.5°C compatible scenario produced from the IPCC's AR6 scenario database depicting the relative contributions from reduced CO_2 production (red), geological storage (blue), and reducing deforestation and nature-based solutions (green). Billions of tonnes of CO_2 are expected to be produced annually out to 2100, albeit at a significantly reduced rate relative to the present, through continued use of fossil fuels for hard-to-abate sectors such as aviation and processes like cement production for which there is no economic alternative (indicated by the red line). A substantial upscaling in geological storage will therefore be required (blue) to reach geological net zero while the transition from net deforestation to restoring carbon to the biosphere through nature-based solutions (green) also plays an important, albeit smaller, role. The figure shows the median and interquartile range of all technology-neutral 1.5°C-compatible scenarios. Source: Jenkins et al., 2023.

2.6.5. **Mismatched land-based removals definitions and methods mean assessments undertaken for processes such as the Global Stocktake may provide an inaccurate indication of progress towards the achievement of climate goals** (**Figure 17**). Nationally Determined Contributions (NDCs) and pledges related to land are based on data in National GHG Inventories, while progress towards global goals are benchmarked by global models within the IPCC Assessments. Comparing both can lead to misleading conclusions. A metaphor for this confusion is that of a car driver (policy maker) who is provided a navigation system (global models, indicating the required route to achieve an end goal) in miles, while the car dashboard (national GHG inventories, indicating progress along the route) is provided in kilometers (IPCC, 2024). The importance of obtaining accurate estimates of land based emissions and sinks increases as climate change intensifies.

2.6.6. **Reconciling the differing estimates of the land sink will likely reduce the estimates of the remaining carbon budget provided by global models.** One approach to bridge this gap is to operationally translate the estimates of carbon flux from global models into National GHG Inventories (IPCC, 2024). This translation adds the CO_2 sink considered natural by models (DVGM) to the anthropogenic flux from bookkeeping models (**Figure 18**). The implication of doing this is that the remaining carbon budget as defined by global models is reduced (IPCC, 2024) and, crucially, net collective emissions would need to be reduced below zero to halt warming (Allen et al., 2024).

2.6.7. **Scientific inconsistencies in the interpretation of 'removals' for use in National GHG Inventories imply that reaching net zero CO_2 emissions globally based on the current rules would not necessarily halt warming** (See **Figure 19**). The original scientific concept of global net zero,[14] and that which was included in the IPCC Scientific Assessments, explicitly excludes 'natural CO_2 uptake not directly caused by human activities', or passive removal.[15] For net zero to halt global warming, anthropogenic CO_2 emissions must be fully balanced by active anthropogenic CO_2 removals. However, the use of the MLP for anthropogenic emissions in GHG reporting implicitly allows some indirect or passive uptake to be classed as an anthropogenic removal, if it takes place on 'managed land'. For example, most countries define all of their forests as 'managed' for the purposes of UNFCCC reporting. Currently, 6.5 billion tonnes of CO_2 per year (or 60% of terrestrial uptake) are classified as CO_2

[14] See the following cohort of 2009 papers: Solomon, S., Plattner, G.-K., Knutti, R. & Friedlingstein, P. *Irreversible climate change due to carbon-dioxide emissions*. PNAS 106, 1704–1709 (2009); Meinshausen, M. et al. *Greenhouse-gas emission targets for limiting global warming to 2°C*. Nature 458, 1158–1162 (2009); Allen, M. R. et al. *Warming caused by cumulative carbon emissions towards the trillionth tonne*. Nature 458, 1163–1166 (2009).Matthews, H. D., Gillett, N. P., Stott, P. A. & Zickfeld, K. *The proportionality of global warming to 649 cumulative carbon emissions*. Nature 459, 829–832 (2009).Zickfeld, K., Eby, M., Matthews, H. D. & Weaver, A. J. *Setting cumulative emissions targets to reduce the risk of dangerous climate change*. PNAS 106, 16129–16134 (2009); Gregory, J. M., Jones, C. D., Cadule, P. & Friedlingstein, P. *Quantifying Carbon Cycle Feedbacks*. Journal of Climate 22, 5232–5250 (2009).

[15] See glossary for definition of 'passive removals'.

removals in national inventories - a substantial fraction of which results from passive uptake in standing forests (Allen et al., 2024; Friedlingstein et al., 2024).

2.6.8. **Increasing the area of land classified as 'managed' may result in a greater gap between model estimations and GHG inventory reported land base CO_2 emissions and removals.** As global pressure to reduce net-emissions increases, nations may consider the need to enhance the use of land sinks and choose to reclassify more land as 'managed', resulting in the potential inclusion of more passive uptake in their estimations and reports against their NDCs. This does not contribute to enhanced ambition to limit global warming and risks undermining the Paris Agreement (Allen et al., 2024). A sense of precaution is required when land sinks are invoked in mitigation efforts.

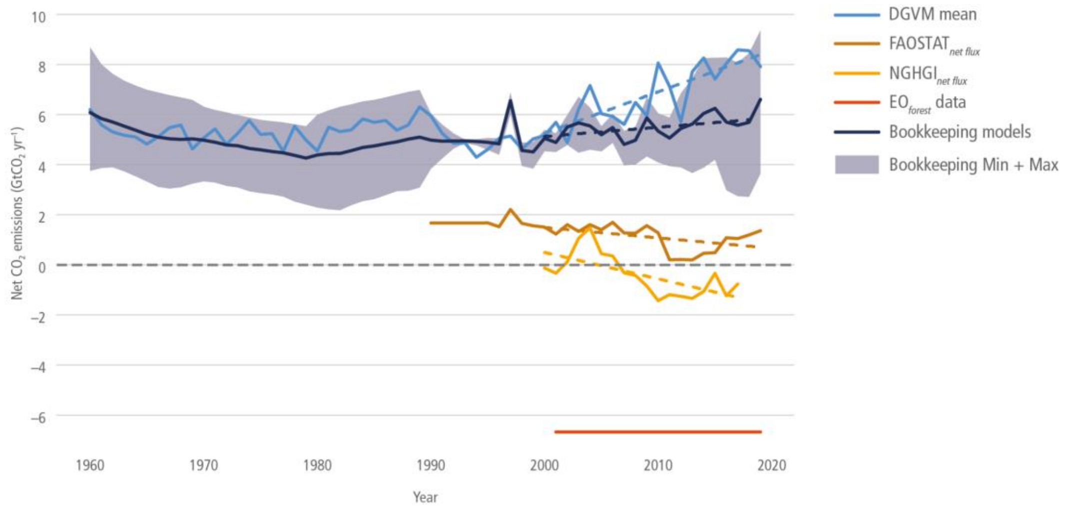


Figure 17. Global net LULUCF CO_2 flux, estimated using different methods: (i) Global models from the Global Carbon Budget (Friedlingstein et al. 2020): Dynamic Global Vegetation Models (DGVMs) and Bookkeeping models; (ii) Earth Observation data (forest-related fluxes only, Harris et al. 2021); and (iii) country-based data: National GHG Inventories (NGHGI, Grassi et al. 2021) and FAOSTAT (Tubiello et al. 2020). Source: IPCC AR6 WGIII (2022).

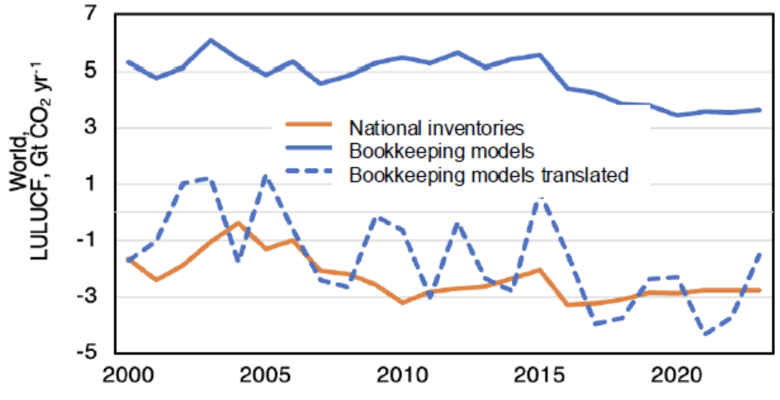
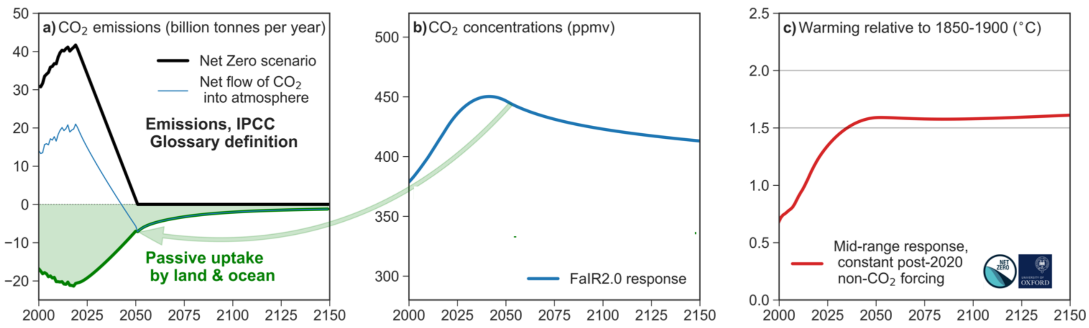
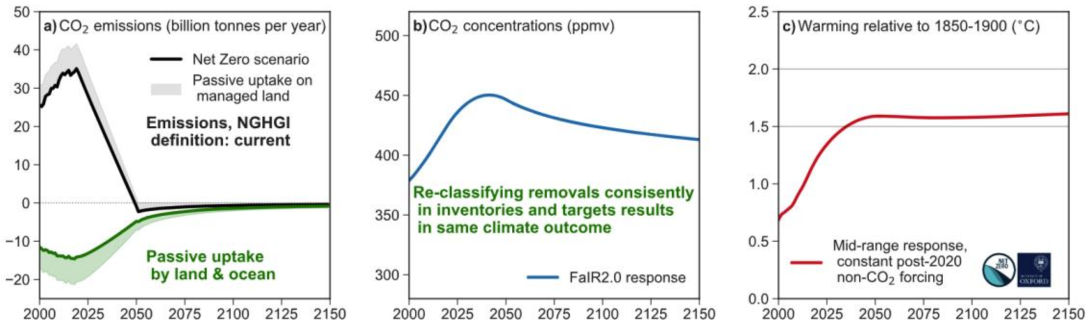


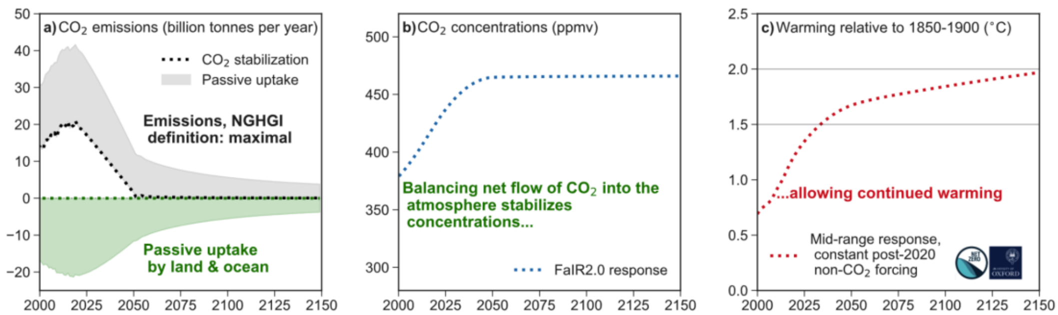
Figure 18: Comparison of LULUCF fluxes from National Inventory and bookkeeping models, and the operational translation of the BM results into the inventory approach. Source: Grassi 2023.



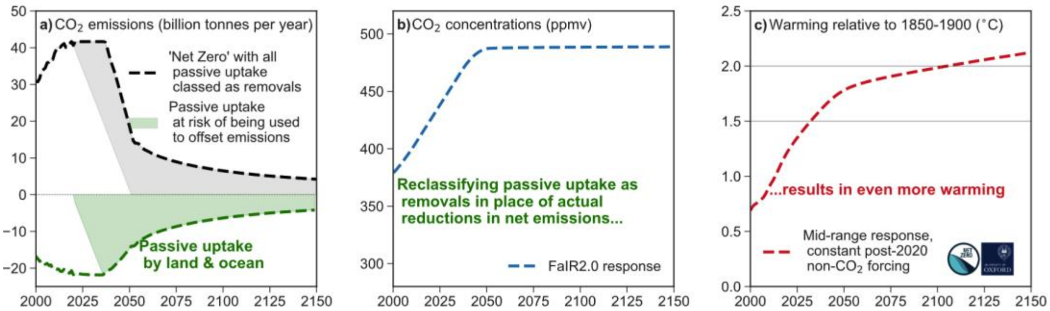
(A) The definition of net zero according to the 2009 net zero papers[9] and subsequent IPCC Assessment Reports employs a narrow definition of removals that *excludes* passive uptake, meaning the response of the natural carbon cycle to past emissions. *Removals* only include consequences of human action that are additional to that response. The green shaded area represents the passive uptake from past emissions (currently ~20 billion tonnes per year). This declines as emissions are reduced but not to zero. As a result, CO_2 concentrations peak before 2050 and decline after mid-century, falling at about 0.3% per year as they are taken up by the oceans and biosphere. Global temperatures stabilise.



(B) Under the classification of anthropogenic and passive removals operationally used in current NGHGIs, whereby some passive uptake is included as removals, nominal emissions would need to drop to below zero to halt warming. The grey shading indicates the component of the passive sink that takes place on 'managed land' and is currently regarded as a removal within NGHGIs. Here emissions have been reallocated from the passive sink to the active removal. If climate targets are revisited and amended we can achieve the same climate outcome, but net zero no longer achieves the temperature goal of the Paris Agreement to halt warming. The more passive sinks that are allocated as removals, the greater the adjustment to negative emissions required.



(C) If climate targets are not amended, and all passive uptake is included with removals as per the broader NGHGI definition, achieving net zero emissions only stabilises atmospheric CO_2 concentrations, so temperatures will continue to warm. Including passive sinks in the definition of net zero without revisiting climate targets risks failing to deliver on the Paris Agreement.



(D) Under a hypothetical 'extreme offsetting' scenario whereby all passive uptake on land and oceans is re-classified as anthropogenic removals and used to offset ongoing emissions to avoid actual emission reductions or active removals, temperatures continue to increase beyond 2.0°C even thought nominal emissions appear to follow a 'net zero by 2050' trajectory. This scenario is currently potentially allowable under current approaches to emissions accounting, highlighting, in an extreme case, the impact of ambiguity in the definition of CO_2 removals.

Figure 19. Ambiguity in the definition of carbon dioxide removals from land could undermine the goals of the Paris Agreement. Source: Allen et al., 2024.

2.6.9. **Greater collaboration between carbon monitoring and modelling communities — i.e. the global carbon models (bookkeeping, DVGMs, and IAMs), Earth Observation (EO), National GHG Inventories (NGHGIs) — is needed in order to develop a common approach to include anthropogenic land use estimates and ensure greater comparability between future IPCC products and national GHG data.** A greater understanding of the origin and magnitude of the gap in land use emissions estimated between communities that support the IPCC and National GHG Inventories will help better elucidate its implications for the remaining carbon budget and net zero goal. More comparable estimates of land based removals across communities would allow the next IPCC Assessment Reports and the next Global Stocktake under the Paris Agreement to better assess the role of land use with more precision, consistency and confidence. The 1st Biennial Transparency Reports (BTR) provides an opportunity to provide greater transparency on the implementation of the managed land proxy, particularly in developing countries.

2.6.10. Opportunities to strengthen collaboration between modelling and monitoring communities may include: (*i*) regular dialogues to advance mutual understanding, improve data sharing and interoperability, and develop joint protocols for translation; (*ii*) engaging experts from various communities in smaller groups at regional and national levels (for example under Global Carbon Project/ RECCAP processes); (*iii*) determining a deeper understanding of the underlying rules governing the Paris Agreement and the IPCC methodological guidelines for global models, and the key concepts relevant for Article 2 and 4 of the Paris Agreement, particularly the *remaining carbon budget* and *net zero* (IPCC, 2024).

2.6.11. Global models could be improved through: (*i*) enhanced accessibility to methods and data; (*ii*) improved representation of forest demographics; (*iii*) improved integration of Earth observation data; (*iv*) better documentation of CO_2 fertilization effects; (*v*) improved consistency between anthropogenic and natural components; (*vi*) disaggregation of results consistently with national inventories; and (*vii*) use of more detailed country-specific information (IPCC, 2024).

2.6.12. The transparency of national GHG reporting and target-setting would be significantly enhanced by disaggregated reporting of carbon sinks, differentiating as far as possible between CO_2 uptake to permanent geological-timescale storage, CO_2 uptake through active land-based interventions that are additional to passive uptake, and passive CO_2 uptake resulting from historical emissions. This would allow clear monitoring of progress to Geological Net Zero.

2.6.13. Methods within the Earth Observation community could be improved by: (*i*) cross-comparisons of EO data and improving the transparency and accessibility of data; (*ii*) standardizing land-use and cover classes; (*iii*) enhancing time-series consistency; (*iv*) better monitoring of forest disturbances and regrowth rates (*v*) improved estimation of carbon stocks and stock changes; (*vi*) better validation with ground-based data; and (*vii*) enhanced guidance and capacity building on how EO data can be integrated into inventories using IPCC methods (IPCC, 2024).

2.6.14. **Policy approaches should account for the other ecosystem functions and services that the biosphere provides in addition to its mitigation potential.** Achieving other sustainable development outcomes on land can result in emissions reductions from land-use, such as through reduced consumption of ruminant products and food waste, biodiversity protection (Frank et al., 2021). These approaches can also contribute to more resilient land systems and enhance their capacity to adapt to climate change and mitigate its impacts.

Key insights:

- Terrestrial ecosystems are vital for stabilising the global climate and are integral to mitigation pathways for 1.5°C or 2°C. However, although the AFOLU sector offers substantial mitigation potential, the biosphere sink is vulnerable to being weakened by climate impacts like extreme heat and wildfires.
- Land-based GHG accounting would benefit from clearer definitions and consistent methodologies across modelling and National GHG Inventory communities, including but not limited to better methods of distinguishing active anthropogenic interventions from passive natural uptake. The current gap between land use emissions estimated between the global modelling and National GHG Inventory communities (~7 $GtCO_2$ yr^{-1}) has implications for the remaining carbon budget and net zero and undermines achieving the temperature goal of the Paris Agreement.
- Greater collaboration is needed between carbon monitoring and modelling communities. Greater *transparency* of methods and data, *translation* of outcomes between global models and National GHG inventory communities, and *communication of the implications* of these discrepancies is needed to ensure effective climate policies and progress toward stabilising global temperatures.
- Achieving Geological Net Zero (GNZ) is needed to stop global warming and meet the Paris Agreement temperature goal. This requires a balance between any remaining production of CO_2 from fossil sources and storage of CO_2 in geological-timescale sinks. While reducing CO_2 emissions remains the primary mitigation strategy, geological storage must scale up significantly if GNZ is to be achieved. Distinguishing geological storage from land-based interventions and passive uptake will be crucial for tracking progress towards GNZ.

3 The emerging roles of observation systems in policy and action

Monitoring changes in GHG fluxes with spatially and temporally comprehensive and precise data is critical for adequately managing anthropogenic climate change. The Paris Agreement identifies the need for an effective response to climate change based on the best available scientific knowledge. However, uncertainty on the size, nature and stability of carbon sinks as well as the speed of release of heat stored in the ocean hinders an adequate policy response. Observation systems enable improved understanding of GHG fluxes, which can result in better-informed policy and improve the accuracy of future climate change projections (Scholes et al., 2009). The following section synthesises key insights on the emerging roles of observation systems in facilitating policymakers to address GHG emissions. It has been informed by discussions at the CNF2024 and material provided by Werner Kutch and Bram Maasakkers.

3.1 *In-situ* carbon and GHG observations for policy action

3.1.1. **A coordinated, global system of *in-situ* observations would provide decision-makers with timely and reliable policy-relevant information.** Current efforts to obtain carbon observations are fragmented. Coordinated observations would require greater cooperation between GHG observing organisations, increased interoperability between data and information systems, and integration among terrestrial, ocean and atmospheric networks. Observation systems such as the Integrated Carbon Observation System (ICOS) contribute European-wide measurements across the atmosphere, ecosystems and ocean on the carbon-cycle, GHG fluxes and atmospheric concentrations.

3.1.2. **Standardised high-precision observation data would improve science-based monitoring, reporting and verification methods for national inventories, the establishment of long-term observations for CDR certificates, and improved understanding and quantification of climate-carbon feedbacks.** It can be also beneficial for calibrating remote-sensing data, the validation of climate models and the calculation of emission factors (Kutsch et al., 2018). For example, limited *in-situ* data on carbon fluxes presents a major obstacle in determining how much CO_2 from fossil fuels burning remains in the atmosphere rather than be sequestered by oceans and terrestrial ecosystems (Heiskanen et al., 2022).

3.1.3. Monitoring the carbon cycle presents challenges due to the different spatio-temporal scales. A long-time series of observations is needed to enable the interpretation of extreme events and the detection of system changes. In addition, while it is beneficial if the spatial coverage of such observation systems is global, this can be challenging in regions with frequent and high cloud coverage such as the tropics.

3.2 Detecting and quantifying methane "super-emitters" from space

Detecting and quantifying methane leaks are an important component of reducing emissions. The odourless, and invisible nature of methane gas makes it difficult to identify the limited number of methane 'super-emitters' in the oil, gas, coal and waste sectors that are responsible for a disproportionate fraction of methane emissions. However, a rapidly expanding set of space-based or satellite instruments are improving the ability of scientists to find, pinpoint, and understand these large leaks. These satellite instruments encompass so-called flux mappers that provide daily global coverage with 'city-scale' resolution (~7 km) and high-resolution instruments that can "zoom in" to detect and quantify emissions at 'facility level' (20-500 m).

3.2.1. **The identification of high-emission regions allows for targeted mitigation strategies, such as industrial emissions regulations, and land-use management improvements.**

3.2.2. The TROPOspheric Monitoring Instrument (TROPOMI) satellite instrument aboard ESA's Sentinel-5P satellite is currently playing a key role in mapping methane fluxes as it detects methane plumes across the world, with daily global coverage. The detection of these plumes is now part of the Copernicus Atmosphere Monitoring Service. In most cases, the 7 x 5.5 km^2 resolution observations do not allow pinpointing individual facilities responsible for those observed emissions.

3.2.3. Advances in analysis techniques have improved the ability to extract methane signals from instruments (such as Earth images) which were not initially designed for that purpose. This has allowed a significant expansion of the coverage of the largest methane emissions, that are partly transient in nature and difficult to capture if follow-up observations have to be scheduled in the future. Initially, this process has mainly focused on the oil and gas industry, where the synergistic use of these satellites has allowed the uncovering of large leaks from production as well as midstream facilities.

3.2.4. **Several countries including the US and European Union have launched frameworks to use the detection of these large emissions in their regulations.** The Methane Alert and Response System (MARS) from UNEP's International Methane Emissions Observatory (IMEO) uses the satellite data to notify responsible governments and companies of their large methane emissions.

3.2.5. Several successful mitigation cases have been shown, but so far the response rate for the notifications has been low (1%). High-resolution observations of waste disposal sites are more recent as emissions are more difficult to detect because of their more diffuse nature, making most of the repurposed Earth imagers unsuitable. Satellite observations can be used to improve baseline emission estimates, pinpoint where the emissions occur (for example at the active surfaces of landfills and sometimes at gas extraction infrastructure), and track emission reduction efforts.

3.2.6. **Comparison of high-resolution satellite estimates with traditional emission estimation modeling approaches have shown large differences, emphasizing the importance of facility-level information to best estimate emissions.** A dialogue between the modeling and observation communities is required on how to best incorporate the new satellite observations into the modeling frameworks to realize consistency. Global initiatives such as the Lowering Organic Waste Methane (LOW-Methane) have brought together data, policy, and financial partners to support waste methane emission reductions in the Global South in support of the Global Methane Pledge. LOW-Methane is aimed at reducing global annual waste methane emissions by one million metric tons by 2030 and unlocking 10 billion dollars in funding to support these reductions.

3.2.7. **Recently launched instruments designed to observe methane at the facility level (e.g., Carbon Mapper) and intermediate resolutions (e.g., MethaneSAT), as well as several additional flux mappers (e.g., GOSAT-GW, Sentinel-5) will provide additional insights into emissions around the world.** Combined with the existing data sources and their evolving analysis, these observation systems will give us an unprecedented view of methane emissions around the world in the upcoming years.

4 The energy transition: current trends and policy pathways for climate neutrality

Since the global energy system represents the largest source of CO_2 emissions, its decarbonisation is critical for achieving climate neutrality (IPCC AR6 WGIII, 2022). Energy system mitigation measures could account for 74% of total global mitigation for net zero GHG emissions (UNFCCC GST, 2024). The first global stocktake (GST) under the Paris Agreement emphasised the need for a just, orderly and equitable transition away from fossil fuels and an upscaling of renewable energy sources to achieve net zero CO_2 by 2050 (UNFCCC GST, 2024). The GST also recognised that insufficient progress has been made in addressing and reducing greenhouse gas emissions. At COP28, nearly 200 countries pledged to triple renewable energy power (corresponding to at least 11 TW of installed renewable energy) and double the global average annual energy efficiency (from 2% to 4%) by 2030 to meet the objective of limiting warming to 1.5˚C (IRENA, 2024). However, achieving this goal hinges on successful policy implementation. The forthcoming round of updated NDCs expected in early 2025 will provide an opportunity for nations to articulate increased ambition towards implementing this goal.

The following section provides the latest trends in energy system decarbonisation and renewable energy development, and presents information on the effectiveness of different policy instruments. It has been informed by the presentations and discussions held at CNF2024, the work of the International Energy Agency (IEA), International Renewable Energy Agency (IRENA), the Joint Research Center Global Energy and Climate Outlook (Keramidas et al., 2023), other relevant literature.

4.1 Recent emissions trends and renewable power capacity development

4.1.1. **Global total energy sector emissions continue to rise, but at a decreasing rate**. **Global energy GHG emissions are projected to peak in the current decade.** In 2023, global energy sector emissions increased by 1.1% relative to those in 2022, reaching a record high of 37.4 Gt CO_2[16] (IEA, 2024b). This rate was close to the 1.3% annual increase seen in 2022, despite overall energy demand rising. Notably, the emissions growth rate in 2023 was substantially below the 3% global growth in GDP. This structural slowdown in energy emissions growth has largely been attributed to the expansion of solar PV, wind, nuclear power, heat pumps and electric cars.

4.1.2. **Energy emissions in advanced economies[17] fell by 4.5% in 2023 to a 50 year low** (IEA, 2024b). Nearly two-thirds of this decline is due to a reduction in emissions from electricity due to a rise in renewable power generation capacity, which contributed 43% of total power capacity in 2023, mostly in advanced economies (IRENA, 2024). Coal use in advanced economies fell to a historic low of 17% in advanced economies (IRENA, 2024). However, coal demand in emerging markets and developing countries remains the biggest driver in global emissions growth (IEA, 2024b).

4.1.3. **At the sectoral level, transport experienced the most significant growth in emissions** (Figure 21a). The power sector made the second largest contribution to emissions, and exhibited a high regional disparity due to the decline in advanced economies and increase in industrial development in emerging and developing economies. The only sector to experience a reduction

[16] This estimate includes CO_2 emissions from energy combustion, industrial processes and flaring.
[17] The IEA definition of advanced economies includes all OECD member nations as well as Bulgaria, Croatia, Cyprus, Malta and Romania.

in emissions was the buildings sector, due to a reduction in cooling and heating demand due to milder temperatures in 2023 (IEA, 2024b).

4.1.4. **The pledge to triple renewable energy by 2030 represents a feasible target; however, despite record growth in renewable capacity additions in 2023, current policy ambition remains insufficient** (IRENA, 2024). Some analyses indicate that the implementation of current legislated energy sector low-emissions policies is projected to result in a 2.6°C temperature rise by 2100 (Keramidas et al., 2023). Current investment in oil and gas remains twice the level needed to meet the 2030 goal. Scenario analysis by IRENA estimated that investment in renewable power, grids, and energy efficiency needs to increase from USD 1.29 trillion in 2023 to 4.5 trillion annually from 2024 to 2023 if the renewable energy and energy efficiency goals are to be met (IRENA, 2024).

4.1.5. **To meet the 2030 renewable energy capacity and efficiency targets, renewable energy technology adoption needs to be accelerated in a broader range of countries, including those with emerging and developing power systems and electricity markets.** Of the nearly 473 GW of new renewable power capacity installed globally in 2023 (86% of all additional power capacity installed in 2023), approximately 85% was contributed by China, the European Union and the United States (IRENA, 2024). Nations with mature renewable energy markets can help promote growth in other regions through providing financial assistance, peer-to-peer knowledge and communication of the enabling environment parameters that encourage deployment (IRENA, 2024).

4.2 Transitioning to climate-neutral energy systems

4.2.1. **Although approaches to undertake the energy transition will differ between sectors and nations, a central tenet of all climate-neutral energy transitions is a reduction in fossil fuel use and the decarbonisation of the power supply through the large-scale deployment of renewable energy technologies such as wind and solar.** The widespread electrification of end-use energy demand such as transport, space heating and cooking plays an important role in both reducing emissions and increasing energy efficiency and security. Other energy sources such as low-emission fuels (biofuels, hydrogen and hydrogen derived fuels such as ammonia), will likely supplement the energy transition where renewable energy supply is intermittent or direct electrification is more difficult or expensive, such as heavy industry or long-distance transport (IEA, 2024c).

4.2.2. **The energy transition requires a systems approach.** The energy transition will require greater energy system integration across regions and across components of the energy system. Historically many policies have been designed, and research and innovation implemented to address specific, compartmentalised challenges. However, this approach fails to recognise and integrate interdependencies in sectors and hinder holistic thinking and collaboration (Kisielewicz et al., 2024).

4.2.3. **A systems approach enables the identification of synergies or linkages between sectors or societal 'needs'; including shelter (built environment), energy, mobility (transport), food, water and social interaction and participation (wellbeing and equity).** For example there are interconnections in urban planning, transportation, and energy which will be important for climate-neutral living. An energy transition towards renewable energy will also reduce air pollution, leading to health benefits; smog air pollution contributes to the premature deaths of seven million people annually (WHO, n.d.).

4.2.4. **Digital infrastructure can enable an acceleration of the energy transition, but more transparency and research is needed to determine its impact on sustainability.** The soaring use and development of artificial intelligence presents both an opportunity in the energy transition as AI tools help improve efficiency; and a challenge as the large-scale computational needs of AI such as large-language models are associated with an increase in emissions from the energy sector (Kisielewicz et al., 2024).

4.2.5. Given the uncertainty and dynamism of the energy innovation landscape, nations and sectors will need to adapt to changing demand or avoid path dependencies in future investments that hinder adoption of new technologies if or when they reach maturity - such as geothermal energy, battery technologies, or nuclear fission (Robinson and Tennican, 2024). It is not certain which of the current emerging technologies will reach their potential.

4.2.6. **Equity should be a guiding principle of the energy transition.** Ensuring the transition's benefits and burdens are distributed across different populations and generations is critical in addressing the complex balance between social equity and climate mitigation. Transitioning away from fossil fuels towards a low-carbon energy system inevitably creates both winners and losers. The historical dependence on fossil fuels for modern economic development means a rapid decline in parts of the fossil fuel extraction sector may result in job losses. A just transition requires safeguarding the interests of workers in affected industries and addressing health and wellbeing issues. Energy projects must respect human rights across supply chains, from mining critical minerals, fair labour practices, gender equity and local community engagement. Procedural justice should be incorporated in the implementation of energy policies to ensure inclusivity, transparency and stakeholder participation in decision making and take account of human health and wellbeing. This includes both urban and metropolitan populations, local and marginalised communities.

4.2.7. **Policies and mechanisms that account for the risk of stranded assets are needed if the energy transition is to be accelerated**. Stranded asset risk affects the willingness of energy system participants to shift away from fossil fuels. This is particularly the case in emerging and developing countries with young coal-fired plants. Market changes, such as changes in economic conditions, technology innovation, regulation, and financing conditions can create shifts that result in a reallocation of resources and the retraining of people.

4.2.8. **Further research and consultation is needed to better understand the impacts of the energy transition**, and how communities will be most affected, such that inclusive policies can genuinely support vulnerable populations through the transition. International collaboration to share best practices and lessons can help establish standard frameworks and processes for energy transformation.

4.4 Policy pathways to accelerate decarbonisation

Navigating the path to a low-emission energy system can be assisted by knowledge about which climate policies have worked, where and why. Stechemesser et al (2024) considered 1500 climate policies implemented between 1998 and 2022 across 41 countries from six continents. Of these 69 successful policy interventions were identified, which had total emission reductions between 0.6 billion and 1.8 billion metric tonnes CO_2*. The analysis was conducted utilising the OECD global policy database, in which policies are disaggregated by relevant economic sectors. The following section provides a summary of the insights provided by the study.*

4.4.1. **Decision-making for the energy transition would be aided by models informed by a wider range of data.** Policy response mechanisms are better when they can be segregated by sector or region. **Alongside technological advancements in energy, public acceptance of changes in the energy system is needed to support a willingness to adapt behaviours.** Acceptance of additional upfront investment costs in certain sectors is also required for a successful transition (Stechemesser et al., 2024).

4.4.2. **A carbon tax is the only effective stand-alone policy. A well-designed policy mix can result in greater emissions reductions than individual policies implemented alone** (Figure. 20A). However, the combination of policy instruments that are complementary differs between sectors and nations. Taxation was the only policy instrument that resulted in near equal or larger emissions reductions when it was implemented as a standalone policy (compared to in a policy mix) across all sectors (Stechemesser et al., 2024).

4.4.3. **For transport sectors in developed economies, most emissions reductions were achieved from pricing instruments** implemented alone; 20% of all successful detected interventions were associated with pricing mechanisms (Figure 20B). **Subsidies** in developed economies represented the most complementary instrument in the transport sector (Stechemesser et al., 2024).

4.4.4. **In developing economies, regulation has resulted in the most emissions reductions.** This was found both when implemented alone, and in combination with subsidies and pricing (Stechemesser et al., 2024).

4.4.5. **For the electricity sector** in developing economies, **subsidies** implemented as stand-alone interventions were the most commonly effective, representing 66.7% of detected successful interventions. However, in developed economies, **regulation** was the most effective stand-alone policy (33%). Pricing was a key policy intervention in the electricity sector in developed economies, and was present in 50% of all successful policy mixes (Stechemesser et al., 2024).

4.4.6. **For industry, pricing** is a key instrument, and is most effective in developed economies when implemented individually. Pricing instruments were also found to be complementary in 50% of successful policy mixes in developing economies. **Subsidies** were found to be complementary in both developed and developing economies. The success of these types of interventions likely reflects the fact the industrial sector is dominated by profit maximising firms (Stechemesser et al., 2024).

4.4.7. **For buildings,** a broad set of instruments exhibit similar effectiveness across nations; however, **subsidies marginally dominate in developed economies** as does the use of **regulations in developing economies**. These results may reflect the fact that the building sector includes a large section of private consumers which are subject to behavioural factors (Stechemesser et al., 2024).

Key insights: Achieving climate neutrality requires a just, orderly and equitable transition away from fossil fuels, the large-scale deployment of renewable energy technologies, improved energy efficiency and security, and the widespread electrification of final energy demand. Global energy sector emissions continue to rise but at a decreasing rate due to the growth in solar PV, wind, nuclear power, heat pumps and electric cars. Current levels of ambition in NDCs, long-term strategies and existing national policies are insufficient to achieve the pledge to triple renewable energy by 2030.

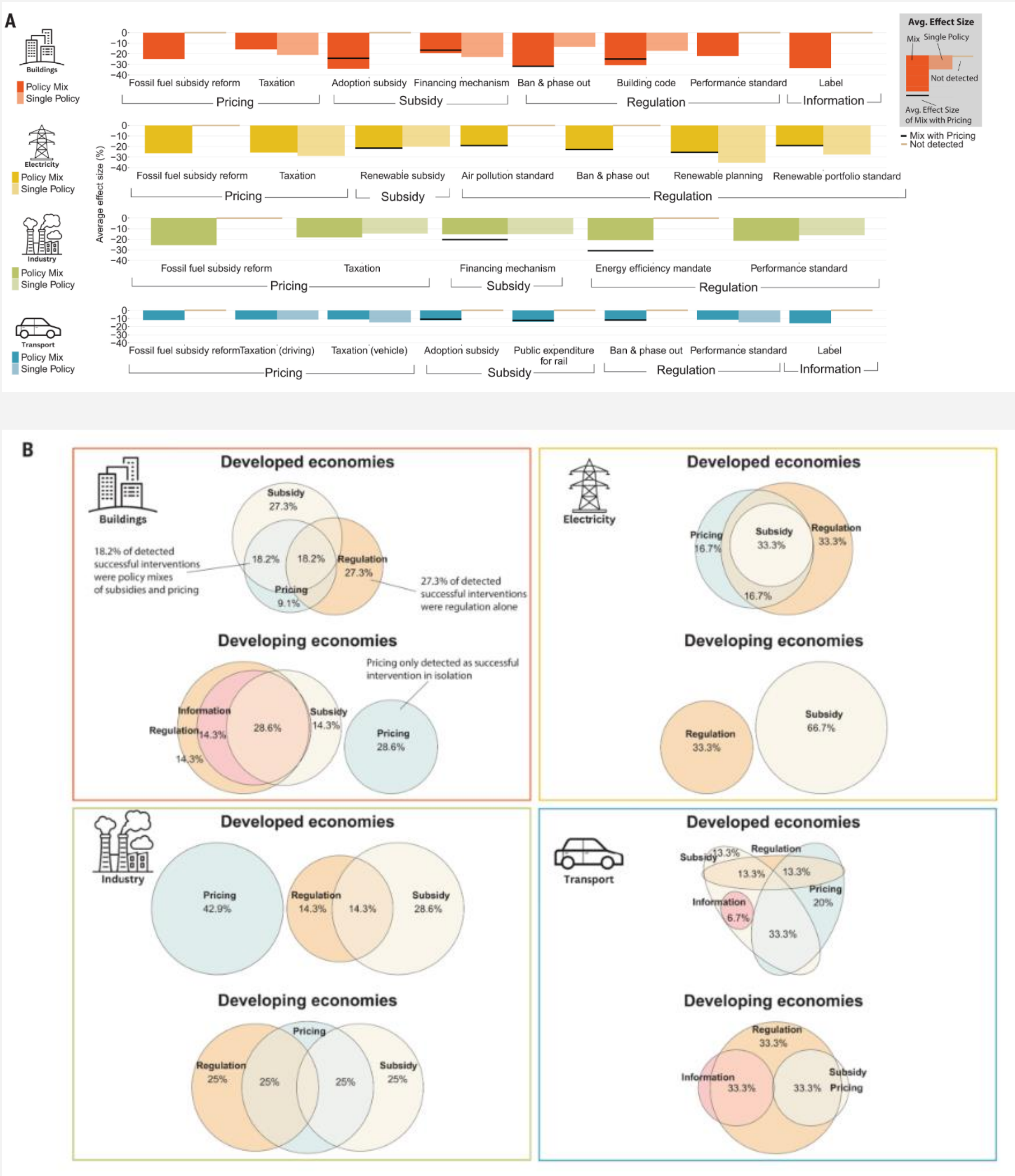


Figure 20. The effectiveness of policy instruments implemented individually and as a mix, across different sectors. (A) Average effect sizes in terms of observed emissions breaks in which a policy instrument appears individually, and those in which the policy instrument appears in a mix. For non-price based policies, the black thick line also indicates the average effect size of a mix with a given policy instrument and pricing (through taxation or reduced fossil fuel subsidies); (B) the combinations of policy types that were found to be effective in each sector for developed and developing economies. The percentage indicates the share of successful interventions in this sector were the result of a specific policy type or a combination of policy types. Source: Stechemesser et al., 2024.

5 Carbon Dioxide Removal (CDR)

The IPCC Sixth Assessment Report (AR6) states that carbon dioxide removal (CDR) entails 'human activities capturing CO_2 from the atmosphere and storing it durably in geological, land or ocean reservoirs, or in products. This includes human enhancement of natural removal processes but excludes natural uptake not caused directly by human activities.' Whereas emission reduction seeks to limit the amount of CO_2 newly released to the atmosphere, CDR involves taking CO_2 out of the atmosphere that is already there. This definition includes three key conditions: (i) that captured CO_2 must come from the atmosphere (not fossil fuels); (ii) that the subsequent storage must be durable (so that CO_2 is not reintroduced into the atmosphere); and (iii) the removal must result from human intervention and be additional to the Earth's natural processes.

*CDR encapsulates a variety of methods, which differ in terms of readiness, durability (the timescale on which carbon is stored) and sequestration potential. There are a variety of categorisations for CDR methods; a common differentiation is made between 'conventional CDR' and 'novel CDR'. Conventional CDR includes CDR methods that are well-established and already deployed at scale, including land-use, land-use change and forestry activities (afforestation and reforestation, soil carbon sequestration, in croplands and farmlands, peatland and coastal wetland restoration). Novel CDR methods include bioenergy with carbon capture and storage (BECCSs), direct air carbon capture and storage (DACCSs), enhanced rock weathering, biochar, mineral products and ocean alkalinity enhancement (**Figure 21**).*

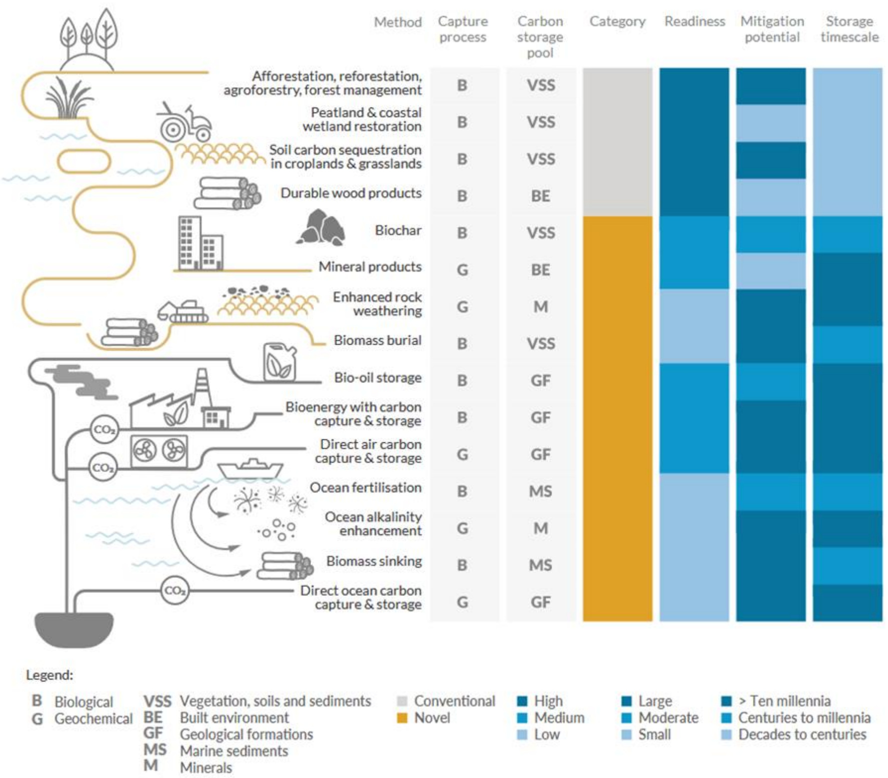


Figure 21. A summary of the variety of CDR methods available, characterised by capture process, carbon storage pool, technology readiness, mitigation potential and storage timescale. CDR methods can also be broadly grouped into "conventional" and "novel" types. Source: Smith *et al.* (2024).

The following section has been informed by the 2nd State of CDR Report (Smith et al., 2024), the 3rd International Conference on Negative Emissions Conference that took place 18 – 21 June in Oxford, and other key literature. It aims to elucidate the current state of CDR deployment and point towards policy interventions which may accelerate the upscaling of CDR in a sustainable, economic and equitable manner.

As methods for the removal of GHGs (other than CO_2) such as methane or nitrous oxide are in a much earlier stage of development, this section will focus on CDR rather than GGR.

5.1 Role of CDR in future mitigation scenarios

5.1.1. **Alongside rapid, deep and widespread emissions reductions, carbon dioxide removal (CDR) will be necessary to achieve the Paris Agreement temperature goal.** CDR is a key element in modelled scenarios that limit warming to 1.5˚C or well below 2˚C.

5.1.2. **CDR is not a substitute for immediate and deep emissions reductions, but rather has a complementary role along a mitigation timeline.** In the near term, CDR can be used to reduce net CO_2 or GHG emissions. In the medium term, it can be used to counterbalance residual emissions in hard-to-abate sectors including in industry and aviation, and agriculture. In the long term, CDR may play a role in achieving net-negative emissions (if removals exceed emissions) or potentially reverse some temperature overshoot if global temperatures exceed acceptable levels. These roles may exist in parallel: some countries may aim to have reached net-negative emissions at the time of global net zero, enabling developing economies a longer timeframe to achieve net zero. Successful climate policy needs to include both CDR scaling and implementation, as well as enhanced emissions reductions which reduce future dependence on CDR methods.

5.1.3. The scale and timing of CDR deployment that will be required, and the choice of CDR methods implemented depends on: (*i*) the level of gross emissions reductions achieved; (*ii*), the peak temperature reached as a result of cumulative emissions, and; (*iii*) how sustainability and equity concerns are managed.

5.1.4. Where CDR projects will be implemented, and who will pay for their deployment, remains uncertain. Future mitigation scenarios that assume CDR will be deployed at a very large scale present greater risks; CDR approaches have limits to the speed and size of deployment, and may result in high impacts to ecosystems, land use and productive sectors including agriculture.

5.1.5. The 2nd *State of CDR Report* assessed that 190 Gt CO_2 is cumulatively deployed by the time of net zero in scenarios that limits warming to 1.5˚C or less with limited overshoot. Scenarios that limit warming to 2˚C deploy 330 Gt CO_2 cumulatively by the time of net zero (Smith et al., 2024).

5.1.6. **Less CDR (and more emissions reductions) is deployed in more sustainable and Paris-consistent mitigation scenarios.** Smith e*t al.* (2024) also assessed a more 'sustainable' and Paris-consistent subset of CDR scenarios to better assess the scenarios that are consistent with limiting warming and meeting other sustainability outcomes. **The 25-75% range for the more sustainable scenarios corresponds to projected CDR deployment of 7 to 9 GtCO_2 per year by 2050, or 170 Gt CO_2 cumulatively by 2050** (**Figure 22**). The sustainability criteria evaluated for these scenarios included the following; (*i*) the halting of deforestation and conversion of ecosystems and protection of biodiversity and ecosystem services (SDG 15); (*ii*) reducing the population at risk of hunger; (*iii*) limiting the increase of global energy demand while enhancing equitable access to energy (SDGs 7, 12); limiting reliance on energy from biomass to reduce land and water resource needs (SDGs 7, 15); and keeping temperature rise well below 2˚C, and striving to limit it to 1.5 ˚C (SDG13).

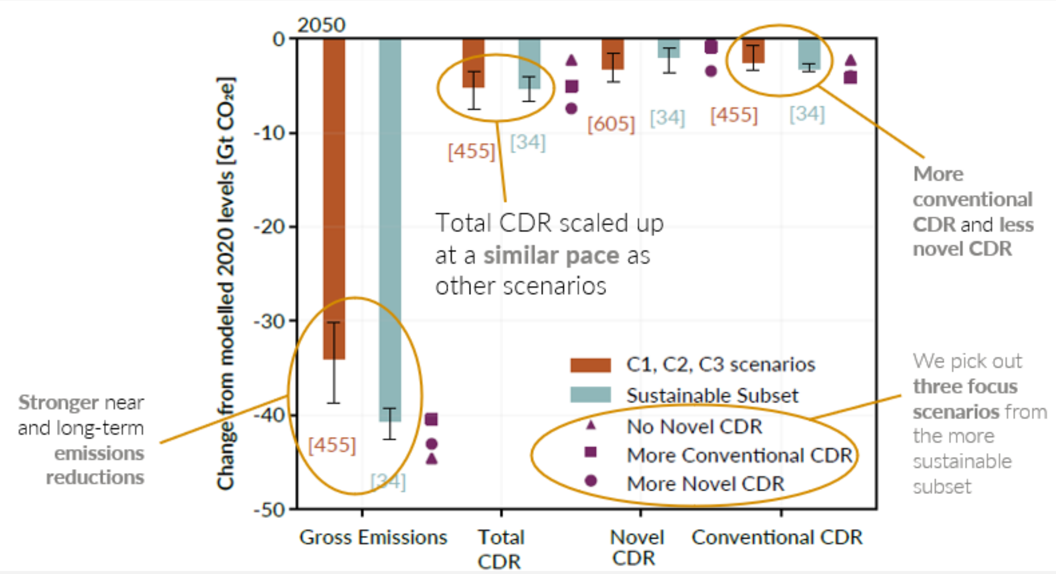


Figure 22. The more sustainable scenarios feature stronger gross emission reductions, more conventional carbon dioxide removal (CDR) (with potentially strong co-benefits), and less novel CDR (with potentially greater risks) by 2050. Gross emission reductions include all greenhouse gases (GHGs). Source: Smith *et al.*, 2024.

5.1.7. **Sustainability should be foregrounded in CDR policy and implementation.** The technical mitigation potential and the economic potential of CDR methods should be considered in the context of the sustainability risk. A sustainable CDR budget should incorporate consideration of the (*i*) ecological and biophysical risks; (*ii*) social feasibility constraints; (*iii*) competing land use demands such as food production and the bioeconomy; (*iv*) human rights and sustainable development priorities such as food security and respecting land tenure; (*v*) address concerns regarding the permanence of non-geological storage; and (*vi*) scrutinize bioenergy accounting rules and capture rate assumptions (Deprez et al., 2024).

5.1.8. Deprez et al., 2024 undertook an assessment of the sustainability limits of CDR methods and found that the sustainability risks of BECCS and 'nature-based' CDR occur at levels of deployment well below the mean levels of technical potential identified by the WGIII IPCC AR6. Of the scenarios included in the IPCC AR6 database, 60 and 29% of 1.5°C pathways with high overshoot exceed the estimated high BECCS and AR risk thresholds, respectively, in 2050. For 1.5°C pathways with limited overshoot, 70% and 39% will exceed high risk thresholds in 2050. These thresholds indicate the limit between acceptable and unacceptable sustainability impacts. Exceeding these thresholds will likely result in high risks to biodiversity, water availability, biogeochemical cycles and competition for food production.

5.1.9. Deprez et al., (2024) estimated that the low risk levels for 'nature-based' CDR (including ecosystem restoration and limited land-use change) to be 2.6 $GtCO_2$ per year (including 1.3 $GtCO_2$ from reforestation), while the upper bounds of medium risk is 5.1 $GtCO_2$ per year (including 3.8 $GtCO_2$ from reforestation) (**Figure. 23**). For BECCs, the upper bounds of medium risk occur at 1.3 $GtCO_2$ per year for low conversion and capture efficiencies and 2.8 $GtCO_2$ per year for BECCS with a medium capture rate.

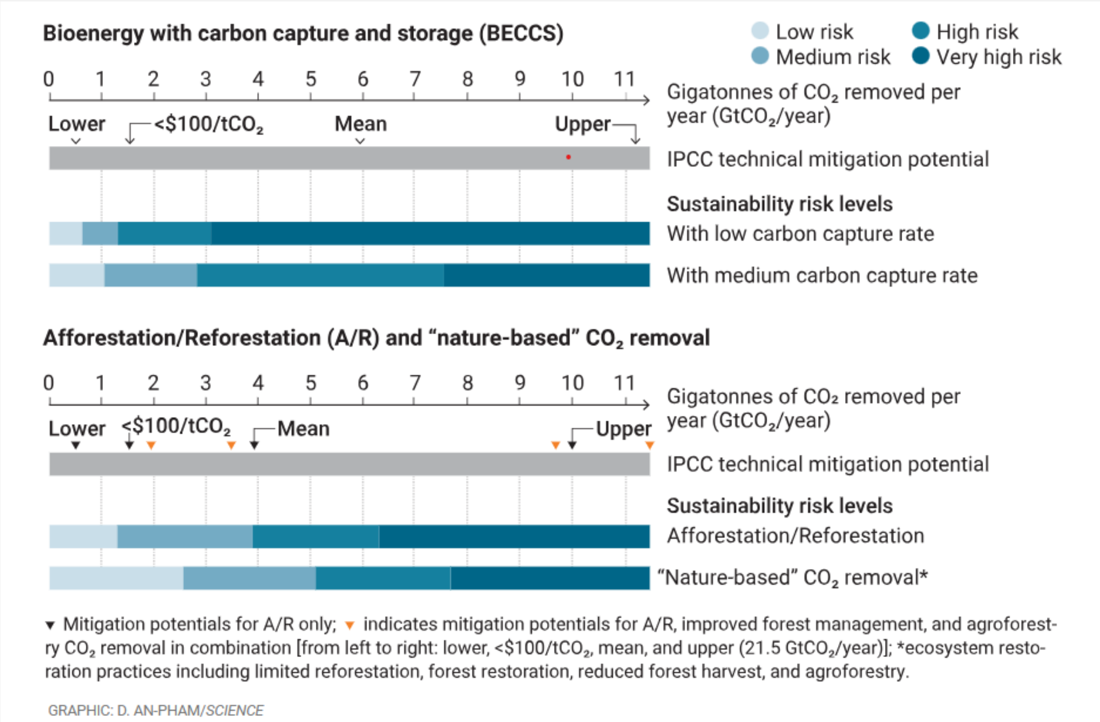


Figure 23: The sustainability limits to land-based CDR as assessed by Deprez et al., (2024). The technical mitigation potential reported by the Intergovernmental Panel on Climate Change (IPCC) and economic potential (<$100 per tonne of CO_2 (tCO_2)) must be contextualised within the associated sustainability risk. Source: Deprez et al., 2024.

5.1.10. **Many of the modelled mitigation scenarios for CDR remain heavily reliant on conventional CDR methods.** For many of the modelled scenarios assessed by the IPCC AR6, BECCS is the only novel CDR option. Newer scenarios such as those presented in Smith *et al.* (2024) include a broader portfolio of CDR options that increasingly also include DACCS, enhanced rock weathering and other methods such as biochar.

5.1.11. **Carbon emissions and removals should balance over multi-decadal timescales** (Fankhauser et state al., 2022). The carbon storage capacity of the biosphere is limited, and shorter-lived than geological storage. Land-based CDR (such as afforestation and soil sequestration) is vulnerable to climate impacts, biogeochemical cycles, and human activities leading to the potential re-release of CO_2. A durable net zero in which global temperatures are stabilised sustainably requires that emissions from fossil fuels and industrial processes are balanced by sinks from air capture and geological storage. Similarly, emissions from land-use change should balance sinks from land-use change. The like-for-like method ensures that emissions from the long-term cycle are not accounted for by offsets that have shorter timeframes, resulting in re-emission on longer timescales (Fankhauser et al., 2022).

Key insights: Alongside rapid, deep and widespread emissions reductions, near-term upscaling of carbon dioxide removal (CDR) will be necessary to achieve the Paris Agreement temperature goal. CDR is not a substitute for immediate and deep emissions reductions, but rather has a complementary role along a mitigation timeline.

Sustainability should be foregrounded in CDR policy and implementation. Sustainable CDR deployment must balance technical and economic potential with ecological, social, and equity considerations. Excessive reliance on land-based or high-risk methods like BECCS may harm biodiversity, water availability, and food security.

5.2 Current state of CDR implementation and deployment

5.2.1. **Around 2 $GtCO_2$ per year of CDR is already taking place, almost entirely from conventional CDR methods including land use, land-use change and forestry (LULUCF) activities such as afforestation and reforestation. Novel CDR methods currently contribute only 1.3 million tons (0.0013 Gt) of CO_2 removal per year (<0.1% of total CDR).** Current novel CDR methods include biochar (which currently provides 0.79 $MtCO_2$ per year of CDR), BECCS (0.5 $MtCO_2$ per year), DACCS (0.004 $MtCO_2$ per year) and enhanced rock weathering (ERW, providing 0.03 $MtCO_2$ per year).

5.2.2. **An emerging diversity of conventional and novel methods are being developed (Figure 24).**

5.2.3. **In the period since 2020, conventional forestry CDR has received the highest investor attention in terms of the percentage of deals (38%), followed by DACCS (23%) and biochar (14%).** The number of investment deals for enhanced rock weathering and soil carbon sequestration have grown twofold and fourfold respectively since 2020; however, they remain a small share of total deals.

5.2.4. **In the last year, novel forms of CDR have gained increasing attention from investors.** As well as the high number of deals, DACCs and biochar have also received the most total funding, at $808 million and $234 million respectively. In comparison, investment in forestry CDR has declined since 2020; the number of credits issued for conventional CDR fell from approximately 20.4 million to 13.3 million in 2023.

5.2.5. Growth in CDR start-ups has increased in the past decade, although with a dip in 2023, with investment into CDR projects accounting for 1.1% of investment in climate tech start-ups. However, patents in CDR have declined since 2010 after an initial period of growth.

5.2.6. **Currently, there is a gap between the levels of CDR proposed in countries' NDCs and long-term strategies, and that which is needed to meet the Paris temperature goal**. Further investment and development of CDR is required to close this gap. The 2nd *State of CDR Report* assessed the CDR gap for 1.5˚C aligned scenarios to be 0.9 – 2.8 $GtCO_2$ per year in 2030 and 0.4 – 5.4 $GtCO_2$ per year in 2050. As these scenarios assume significant emissions reductions are already underway (while in reality global emissions continue to rise), the actual future CDR gap is likely to be higher.

5.2.7. Conventional CDR methods are included in Nationally Determined Contributions (NDCs) but novel CDR is largely absent from pledges in international negotiations. Many governments have included conventional CDR methods such as forestry measures in their NDCs. While a few countries refer to BECCs, DACCS and enhanced rock weathering in long-term emissions strategies, very few countries are integrating a broad spectrum of CDR methods into their emissions reduction plans.

5.2.8. **Delay in reducing emissions will lead to an increasing mitigation burden to meet climate goals.** For a scenario with 1.5˚C of warming and no novel CDR deployment, an additional mitigation burden of between 0.7 and 1.5 $GtGO_2$ per year through emissions reductions and CDR is already required to compensate for emissions reductions missed between 2020 and 2022, relative to the scenario pathway (**Figure 24**). Bridging the gap would involve even more rapid emissions reductions later, and/or additional CDR.

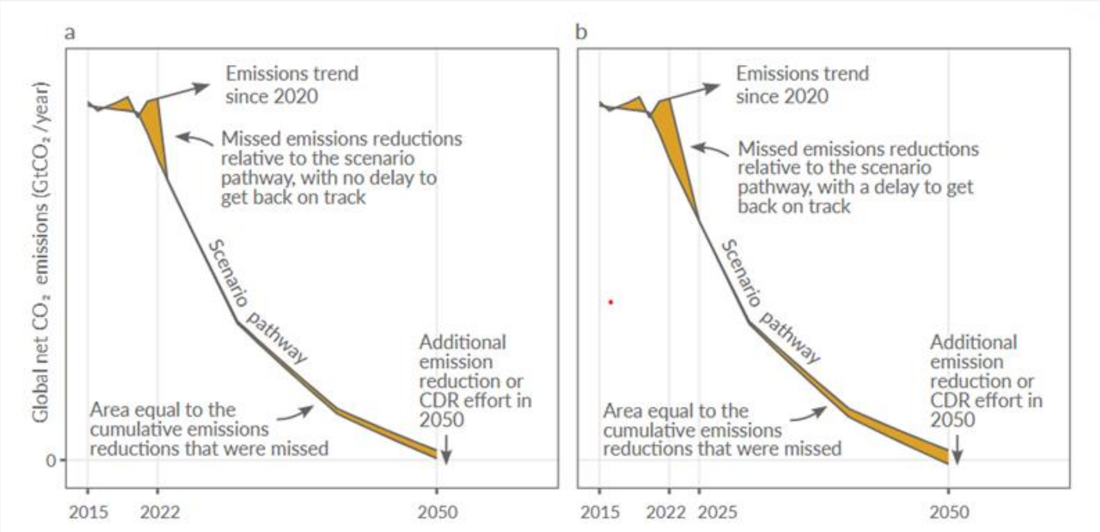


Figure 24: An illustration of potential calculations to quantify the additional mitigation burden where emissions reductions are not carried out at enough speed, resulting in additional CDR being required. Panel (a) has no delay to getting back on track to scenario pathways, while panel (b) has a delay. Source: Smith *et al.* (2024).

5.2.9. More progress is occurring outside of the UNFCCC process. Australia, Canada, the EU, Japan, Norway, the UK and the US have government funding programmes to encourage CDR demonstration projects. Governance frameworks for CDR such as the European Union's Carbon Removal Certification Framework may provide a mechanism to ensure high-quality standards are followed for certifying CDR (initially with a focus on DACCS and BECCS) and for integrating removals into existing climate policy (Smith *et al.*, 2024). Some counties are also moving towards integrating CDR into planned and existing carbon credit schemes. For example, India may include both removals and reductions in a future carbon credit trading scheme which has both compliance and voluntary components.

5.2.10. **The voluntary carbon market (VCM) has been an important, if insufficient, mechanism for channelling finance, establishing norms and practices, and accelerating the deployment of CDR.** The VCM provides a niche market facilitating early adopters of CDR, has provided a forum to facilitate innovation and experimentation, and develop methods for measuring, reporting and verifying CDR projects. Currently, conventional CDR in the VCM dominates novel CDR. However, the VCM will likely not facilitate sufficient finance for CDR at the scales required in the longer term. Most of the credit on the VCM are for avoided emissions (~8%) or emissions reductions (80%) rather than CDR. CDR requires more capital investment and higher financing than credits for avoided or reduced emissions.

5.2.11. After an initial rapid development, growth in the VCM has slowed due to criticisms on the transparency and effectiveness of credits due to inadequate baseline methodologies undermining claims of additionality, and consequent overestimation of projects emissions reductions and incorrect issuance of credits. This is particularly the case for projects involving afforestation and reforestation. Some projects registered through the VCM have also received criticism for displacing Indigenous and local communities.

Key insight: Some CDR deployment is occurring, but not enough. Around 2 $GtCO_2$ of carbon dioxide removal (CDR) occurs annually, primarily through forestry and land-use changes. While there is rising investment in novel CDR methods, particularly DACCS and biochar, they currently remain a small share of CDR deployed. A CDR continues to persist between the amount of CDR in IPCC scenarios that meet the Paris temperature goal and the level of CDR in national proposals.

5.3 Policy and governance interventions to accelerate the scale-up of CDR in a sustainable, economic and equitable way

5.3.1. **Upscaling CDR requires an intensification of innovative activity. Commercialisation pathways for novel CDR would benefit from government policies that encourage CDR innovation and demand.** While some countries are starting to develop policies to encourage CDR in the broader policy landscape, commitments to CDR from governments remain vague. Innovation and scaling policies could include initiatives and funding for research and development, deployment incentives, and public or private procurement, and market integration into voluntary and/or compliance markets.

5.3.2. **A diverse portfolio of CDR options deployed at lesser scale presents a more robust strategy for increasing the feasibility and sustainability of CDR upscaling than a single option deployed at large scale**. Although there is a general trend towards diversification, current deployment of CDR methods and modelled mitigation scenarios is concentrated on a few countries and methods.

5.3.3. **Innovation, pilot projects and demonstration projects for CDR technologies help to upscale, de-risk and create an environment that encourages adoption**. Research and development, including proof of concept research, is needed in many countries to diversify the spectrum of novel CDR options, de-risk their development, better inform the technology innovation pipeline, enable an adequate skills base, and ensure connections with international value chains. Improved capacity can also be built in the GHG removal space through teaching, research positions and a focus on improving the foundational science. CDR research is currently dominated by interest in biochar and soil carbon sequestration, with a recent increase in research in DACCs, coastal wetlands restoration and enhanced rock weathering.

5.3.4. **Effective methods of ensuring CDR feasibility and sustainability at scale are required if CDR is to be upscaled to the levels required to achieve the Paris Agreement temperature goal.** All CDR options have some environmental trade-offs as well as some potential benefits; and the specific design, innovation and scaling policies will vary between novel and conventional CDR.

5.3.5. **Improved access to finance (including pre-commercial finance) is needed to support development of a range of CDR methods.** Current public funding for CDR at demonstration and operational stages is patchy, and high capital costs can create barriers for first-of-a-kind projects. Access to finance is a key bottleneck of CDR start-ups that also need workforce capacity to apply for and acquire non-dilutive funding (grants that do not require the company to sell an ownership stake). Such an environment encourages CDR start-ups to learn and observe from larger and more mature competitors, rather than take a risk on a new technology and their own capital.

5.3.6. **International cooperation in CDR approaches is needed to ensure compensation for uneven distribution of CDR potentials across the globe, and account for historical responsibility.**

5.3.7. **Developing best practices for monitoring, reporting, and verification (MRV) methods and standards will help govern the performance of CDR, reduce the risks for investors, drive growth, and improve assessment of the environmental and biodiversity impacts of CDR**. Ensuring that CO_2 has been captured from the atmosphere and stored durably is a foundational requirement for encouraging market trust in CDR methods. Existing non-governmental MRV protocols typically focus on conventional CDR; protocols for novel methods such as DACCs and ocean alkalinity are relatively more recent. Improved MRV could provide a suitable evidence base to encourage private and public sector demand for CDR.

5.3.8. In 2022, the Integrity Council for the Voluntary Carbon Market (ICVCM) released the Core Carbon Principles (CCPs) and the VCMI similarly released the Claims Code of Practice. In the absence of clear rules set out in Article 6.4 of the Paris Agreement, guidelines such as those produced by the ICVCM and VCMI may become the foundation for national CDR regulation. However, the extent to which these guidelines help elucidate a meaningful credit quality signal will be dependent on the extent of the uptake and participation in these frameworks. Costly or complex MRV methods present trade-offs between accuracy and cost, undermining the quality of the MRV undertaken.

5.3.9. **Improved governance of CDR permanence is needed to govern the risks of reversal.** This includes improved liability mechanisms to better manage the risk of reversal where stored CO_2 is released from events such as wildfires, disease and pests, to ensure that the risks associated with managing carbon liabilities in perpetuity are not redistributed.

5.3.10. **Coordination of CDR MRV protocols across jurisdictions (such as the EU and US) helps to ensure inefficiencies are minimised through parallel development.** MRV policy currently differs between jurisdictions; the EU and UK have introduced CDR standards generally, while the US has focused on scaling up-market ready CDR and developing MRV for specific methods.

5.3.11. **There is an urgent need to establish MRV protocols and governance frameworks around marine carbon dioxide removal activities (mCDR) to ensure the environmentally safe and timely delivery of any potential climate mitigation benefit**. Most marine CDR technologies require large areas to have a climate mitigation impact, often in areas beyond national jurisdiction where international laws apply. In scenarios comparing the potential for marine and coastal climate mitigation with projections of excess emissions, find mCDR may be able to contribute significantly in the latter half of the 21st century but the potential is highly uncertain and the risk of adverse consequences, or failure, is high. Economic frameworks and international legislation are not fit for purpose to incentivise or regulate mCDR, although commercial operations by climate-tech startups are already beginning. Governance structures should include all stakeholders in the process.

5.3.12. **Improved guidance on how to incorporate CDR into national proposals under the UNFCCC is critical in the formative stages of upscaling if the gigatonnes of removals are to be achieved in the second half of this century as per emissions mitigation scenarios.** While IPCC guidance on GHG quantification exists for conventional CDR, guidance on novel methods other than BECCs and biochar is lacking. Norms and standards set in the VCM may not map well into national inventory accounting. The forthcoming AR7 IPCC methodology report on CDR Technologies and Carbon Capture Utilisation and Storage (to be completed in 2027) will help outline a method for including novel CDR methods in national inventories, the best practice in the VCM, and a method of including CDR in NDCs. Novel CDR options are in an early stage of development; they are not well integrated into national policy planning.

5.3.13. **Public-private partnerships can accelerate CDR upscaling pipelines by leveraging expertise**. Cutting-edge research often requires up-to-date information, some of which is now produced by businesses. In turn, businesses need transparent validation processes to build trust. Progress could be significantly boosted by partnerships that support access to field sites, enhance modelling capabilities, provide training, and promote collaboration.

5.3.14. **Effective communication of CDR challenges and risks is required to manage the public perception of CDR at national and project levels.** Building trust through clear communication and inclusive engagement is important for widespread adoption of CDR methods. This may include promoting the indirect environmental and social co-benefits of some types of CDR and involving a diversity of stakeholders in consultations.

5.3.15. **Safeguards and links to other policy domains are needed to prevent adverse impacts from large-scale deployment of CDR methods on ecosystem and ocean health, energy security, food security, and human wellbeing.** Inappropriate deployment of certain CDR methods (such as afforestation, reforestation, soil carbon sequestration, BECCs and ocean carbon sequestration) can significantly affect land use, agricultural systems, food security, biodiversity, and ecosystem functions like water quality, as well as the rights of Indigenous and local peoples. Climate and biodiversity governance needs to be harmonised for CDR deployment through methods such as instigating clear bioenergy safeguards, developing political packages to finance the protection of existing forests and ecosystems, and ensuring that the most sustainable CDR options are prioritised (such as promoting restoration of ecosystems rather than monoculture afforestation) (Deprez et al., 2024).

5.3.16. The AR7 assessment of CDR scenarios should explore the sustainability aspects to a greater degree.

5.3.17. **CDR deployment must account for fairness and equity: who will bear the burdens and who will claim the climate benefits from CDR in the future?** Many countries have net zero pledges or ambitions, which implicitly indicates that CDR will be achieved on a territorial basis. However, CDR deployment will likely not be able to be matched equitably by emissions at national scales - small, densely populated and high populated countries often have limited land, while other regions have limited geological storage. Other countries have sufficient CDR potential even after fulfilling domestic emissions liabilities. Many of the early movers, and CDR start-ups are located in the global north. Greater international cooperation is needed to establish the networks and ensure accountability. Geopolitical tension may result as many of the CDR options are not geographically agnostic.

Key insights:

- Upscaling CDR requires intensified innovation and diversification across methods. A diverse portfolio of smaller-scale CDR options offers a more robust, sustainable approach than relying on large-scale deployment of a single method, but current CDR efforts and modeled mitigation scenarios remain concentrated in a few countries and techniques.
- Government policies and support is critical for CDR innovation and commercialization, but current commitments and governance frameworks are vague. Improved guidance, monitoring, reporting, and verification (MRV) standards, as well as liability mechanisms, are needed to ensure permanence, build trust, and support equitable global scaling of CDR.
- Effective deployment of CDR must consider environmental, social, and geopolitical trade-offs, including potential impacts on biodiversity, ecosystems, food security, oceans and equity. Governance structures must harmonize climate and biodiversity policies, ensure safeguards for Indigenous and local communities, and promote fairness in the allocation of climate benefits and burdens.

6 Enabling environments and means of implementation

Achieving climate neutrality will require the development of enabling environments and institutions that facilitate transformative economic, technological and social change. Institutions - formal rules and informal norms - determine the incentive structure for social and economic governance, and shape the political context for decision making such that some interests are promoted while the influence of others are reduced (North, 1991). Key elements of an enabling environment include the choice of policy instruments, legislation, regulation, markets and trade, and finance mechanisms such as subsidies and incentives (IPCC AR6 WGIII, 2022). Fostering progress towards climate neutrality requires identification of the existing barriers as well as the key enablers. It is supported by capacity building, information sharing, the dissemination of best practices, and skill development to ensure that the policies are well-designed and underpinned by equity. Climate neutrality must also occur within a socio-technical landscape that is influenced by local culture, values, and behavioural norms, as well as international politics and geopolitical conflict. The following section provides a high-level overview of some of the key conditions and contexts that support (or hinder) a transition to climate neutrality. The scope of the following section is limited to those elements of enabling environments that were discussed at the What Works Climate Solutions Summit held in Berlin in June 2024, and the discussions held at the 2024CNF.

6.1 Conditions and contexts that enable climate action

Institutional environment and means of implementation

6.1.1. **Greater institutional capacity is required at the local and national level to support climate policy implementation, particularly in low-income or conflict affected countries. Political commitment, clear goals, and inclusive governance processes enable effective climate action**. Government bodies and institutions at a variety of levels are essential for providing an enabling environment for the climate transition by lowering the political, regulatory and macroeconomic or financial risks. Government institutions can mediate the power of interest groups involved in the fossil fuel transition, and encourage the uptake of technologies or processes through rules or standards.

6.1.2. **National climate laws can help mobilise climate action through a range of mechanisms including harnessing state authority and providing increased regulatory certainty.** For example, the *European Climate Law* 2021/1119 establishes a framework for achieving climate neutrality within the European Union.

6.1.3. **Finance is a critical enabling factor for climate resilient development and achieving climate neutrality goals, and current inequities in the distribution of finance and nations' exposure to climate change impacts hinder a just transition.** Both mitigation and adaptation financing need to be upscaled considerably to ensure inclusive and resilient energy, transport, water, food and land-use systems. **Increasing sustainable infrastructure investment in developing economies is currently hindered by over-pricing of loan risk.** Macroeconomic and currency risks and track records can discourage investment.

6.1.4. **Increasing climate investments requires enabling environments that address the structural underinvestment in long-term assets**. Consequently, the short-term bias of economic and financial decision-making needs to be mitigated by trust or agreements between project developers, industry, investors, banks and governments. Sustainable infrastructure investments are often characterised by high uncertainty and long-term benefits while government decision making is often influenced by externalities or swayed by the short-term pressures of election cycles.

6.1.5. **Local governments and cities** play an important role in decarbonisation, as they are unhampered by the politics of international negotiations, and have wide-ranging responsibilities in the provision of infrastructure, and have the ability to integrate mitigation or adaptation into land-use planning. The upcoming IPCC *Special Report on Climate Change and Cities* provides an opportunity to amplify the role of local governments and urban areas in a transition to climate neutrality.

6.1.6. **Voluntary initiatives play an important role in promoting climate neutrality and filling voids in climate action where regulations are absent or still under construction.** For example, in the voluntary carbon market, NGOs, and private sector actors have established voluntary initiatives at a faster rate and with more flexibility than legally binding initiatives. However, this has also led to the co-existence of competing standards and initiatives. Thus while voluntary initiatives are necessary, it has become increasingly clear that regulation – which can make compliance thereto mandatory – will also be needed. Examples of this are the increasing number of jurisdictions that require climate transition plans from listed companies (Hale, 2022).

6.1.7. **Advisory bodies play an important role in guiding the transition, however they are not sufficient to ensure that net zero is reached by mid-century or before.** Government bodies at a variety of levels are essential for providing an enabling environment for the climate transition. Institutions can provide the legal mandate for action, mediate the power of interest groups, and encourage the uptake of technologies or processes through rules or standards (IPCC WGIII). The last few years have seen the rise of voluntary initiatives that aim to provide governance over net zero to ensure that targets are met. While these initiatives are not binding in the same way that legislation is, they can have real-world impacts arising from reputational concerns (Hale, 2022).

Collaboration and coordination

6.1.8. **International cooperation is an enabler of accelerated climate action. Market mechanisms and the associated regulatory environment need to support an efficient energy transition**. Carbon pricing mechanisms need to be further developed whilst taking into account competitiveness concerns, so that governments resist the temptation to resort to protectionist measures such as trade barriers or investment restrictions. As local and regional carbon pricing instruments are being put in place, there is a growing risk of shifting emissions outside the countries that take action to mitigate emissions domestically. Several countries and regions, which have led on carbon pricing, have introduced measures or are planning to do so to mitigate this risk. Hence, rather than complex trade measures like CBAM, one needs to develop effective carbon pricing policies that allow countries to increase cooperation. A consistent and coherent international approach, built on broader principles for effective emission reduction, is key to a global framework that better facilitates cross-border trade, investment, inclusive and economic growth. More opportunities for exchange mean lower production costs, less resource consumption for production as well as technology and knowledge transfer. A common price on carbon emissions can ultimately lead to increased climate ambition.

6.1.9. **Inclusion of a diversity of voices.** Including a diversity of stakeholder perspectives in policy construction and implementation is needed to ensure that policies are appropriate within local contexts while also contributing to global climate goals.

Knowledge capacity and bridging the science - policy interface

6.1.10. **Education and learning networks are critical to promote capacity building and policies for developing sectors such as novel CDR methods or hydrogen energy. Increasing capacity is also needed in countries that currently have limited experience in sustainable infrastructure.** A lack of capacity to implement science or policy effectively stymies climate action progress (Hale 2021).

6.1.11. **The timely and contextualised translation of climate science into policy-relevant forms is critical for enabling the uptake of scientific evidence for policy impact.** Methods of making scientific knowledge legible to a target audience (for example policymakers, regulators, or the public more broadly) can include the use of non-specialist language, the use of storytelling or narratives, and the synthesis of technical or detailed information into visual forms.

6.1.12. **The creation and maintenance of up-to-date systematic summaries of policy relevant research - or 'living evidence' - is needed to ensure policy is informed by the latest scientific understanding** (Berrang-Ford et al., 2020). This addresses an oft cited barrier in evidence-informed policy; the lag between the production of scientific evidence and its delayed or selective dissemination in a form digestible to policy-makers. Our understanding of the causes, implications and potential responses to climate change continues to evolve rapidly. Rigorous evidence synthesis is crucial for effective, efficient and equitable climate action that safeguards both human and planetary health. It is helpful for processes such as the IPCC AR7 and Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) as it provides clarity in complex, fast moving research fields, improves engagement of decision makers, and builds cross-sectoral alignment for coordinated action. The transition to net zero is marked by considerable uncertainty, and as a result models for how to achieve net zero often contain various assumptions. Consequently, governance needs to be flexible but also needs to continually update to reflect the latest knowledge (Hale, 2022).

6.1.13. **Systematic reviews assessing the success of existing policies and governance structures would help elucidate what interventions work under different contexts and why, and identify helpful case studies and best-practices for future implementation**.[18] This includes not just analysis of the effectiveness of individual policies, but also the effectiveness of policies interacting with each other, within a given socio-economic or geographic context. This approach would complement the traditional focus on assessing science and model intercomparisons. A well-functioning evidence pyramid has a robust middle layer of both structured model intercomparisons and systematic reviews of historic policy successes or failures (**Figure 25**). Such evidence syntheses would benefit from building communities of practice and standardised methods. Increasingly, this includes the use of AI and large-language machine learning models to scale evidence synthesis.

6.1.14. **The dynamic nature of living evidence synthesis creates opportunities for greater engagement and network development between the scientific, policy and funding communities.** A dialogue between science and policy provides opportunities for scientists to provide clarification on their

[18] Stechemesser *et al.*, (2024) forms the first global evidence synthesis of climate policies to identify which interventions led to emissions reductions.

research. In turn, scientists may be guided to focus on questions specifically relevant for policy implementation and better scope the forms of data that are needed.

6.1.15. **Ensuring that accurate and digestible science is digitally available can help mitigate against disinformation and bias in the broader politically engaged public.** The proliferation of digital and social media platforms and generative AI has resulted in an increase in the dissemination of convincing but incorrect information which algorithmically exploits existing inherent biases and human behaviour (Raman et al., 2024).

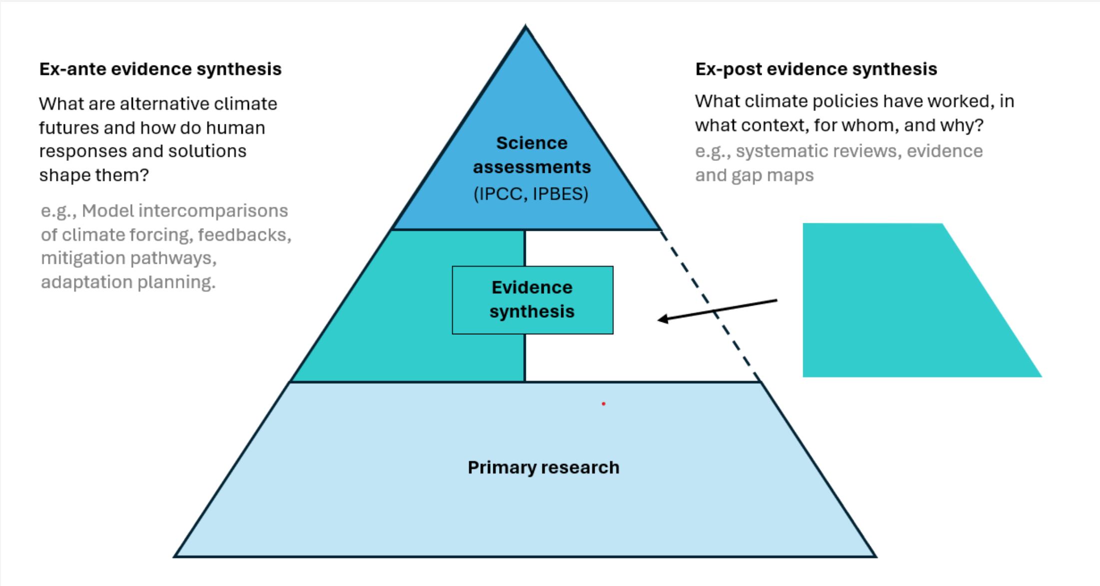


Figure 25. Strengthening the evidence pyramid by including systematic reviews of historic policy successes and failures is needed in climate research and literature to complement the systemic assessment of future scenarios through structured model intercomparisons. Source: Figure adapted from Figure 1 in Berrang-Ford *et al.*, (2020), and presented at the WWCCS (2024).

Systems approaches

6.1.16. **Achieving climate neutrality requires systems thinking and approaches. Although systems thinking is not a new concept, the current institutionalisation of operationalisation of systems approaches is limited.**

6.1.17. Systems approaches can foster more political and social appetite for climate-related policy implementation through highlighting the interdependence of biological, economic, social or health systems and the co-benefits of climate action. This can help overcome political constraints, promote climate neutrality to a wider range of interest groups, and help avoid unintended consequences on other sectors.

Key insights:

- To bridge science and policy, living evidence synthesis and dynamic science-policy dialogues can bridge gaps between scientific research and policymaking, ensuring timely and relevant action.
- Creating enabling environments for climate action requires robust governance, equitable finance mechanisms, capacity building, and market support. Addressing structural barriers, such as underinvestment in long-term climate solutions and inequities in finance distribution, is critical for fostering innovation and scaling transformative solutions.
- While voluntary initiatives and advisory bodies play a role in guiding transitions, binding regulations and clear mandates from governments are essential for achieving net zero goals. Political commitment, inclusive governance, and transparent regulations lower risks and mediate power dynamics to facilitate widespread adoption of sustainable technologies and practices.
- Global collaboration, and regulatory coherence are necessary to mitigate emissions leakage, enhance trade, and promote equitable transitions.
- Policies should emphasize the interconnectedness of economic, social, and environmental systems, leveraging co-benefits such as improved health and biodiversity to garner wider support. Climate action strategies, including CDR governance, should build on existing policy frameworks, recognizing dependencies and ensuring alignment with broader sustainability goals.

The Climate Neutrality Forum 2026

The CNF2024 provided a unique opportunity to consider key elements of the challenge of achieving climate neutrality. The next objective is to explore what developments are on the immediate horizon and where new information can be provided to address knowledge and information gaps. The following section identifies areas that will or have the potential to be ready to be developed for consideration at the next Climate Neutrality Forum in 2026, which will be held just prior to the expected start of the information gathering phase of the 2nd Global Stocktake in 2027.

- **For science and policy:**
    - Expected updates from the Global Carbon Budget for CO_2, CH_4 and nitrous oxide, as well as the Indicators for Climate Change (Forster et al.,).
    - Improved collaboration between global carbon monitoring, earth observation and modelling communities.
- **For removals:**
    - Developments in the upscaling of CDR and the inclusion of sustainability considerations.
    - Characterisation of the role of removals in Europe's climate targets (establishing a separate removal target - what will be included, evaluated or implemented in the ETS or otherwise?).
    - The development of methods of measuring and verifying removals of GHGs other than CO_2. How are other GHGs (other than carbon) included in removals?
    - Mechanisms to improve and understand public perceptions and policy options for the energy transition and CDR.
- Greater focus on cities and the decarbonisation of cities (including the AR7 *Special Report on Climate Change and Cities*).
- Improved understanding of the role of aerosols and short-lived climate forcers (including the AR7 IPCC *Methodology Report on Inventories for Short-lived Climate Forcers*).
- **On systems approaches:**
    - Greater integration of biodiversity and climate concerns and the goals of the Paris Agreement and the Kunming Montreal Global Biodiversity Framework.
    - Developments in new economic thinking including complexity economics.
    - Mechanisms to improve data sharing, capacity building and training.

Others, to be identified by stakeholders in JPI Climate and MAGICA.

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Appendix A

Key insights from the 2021 Climate Neutrality Forum

- **For equity and a just transition**. Climate neutral strategies should explicitly outline their impacts on a wide range of stakeholders and equity considerations outlined. Revenue raising mechanisms such as Border Carbon Adjustment Mechanisms should devote funds to international climate finance to help close international finance gaps. Debt restructuring is also needed as developing countries weather climate catastrophe, increasing financial stress

- **For rapid emissions reductions.** Climate neutral strategies should implement policy instruments that allow society to capitalize on the under-estimated savings potential of clean energy technology with declining cost-curves as well as higher carbon pricing paired with ambitious Carbon Border Adjustment Mechanisms to avoid carbon leakage.

- **For the final 20% hard-to-abate sectors.** Climate neutrality demands more than a shift to low-carbon road transport and renewable electricity generation. This will require public investment and policies to de-risk investment in carbon neutral fuel alternatives and infrastructure, such as, for example Contracts for Differences (CfDs) for shipping hydrogen. Experts warned that policies failing to differentiate between zero carbon versus net zero solutions (such as green and blue hydrogen), may waste public resources by confusing the technology and investment landscape and delaying the transition, and that an over-reliance on blue-hydrogen may lead to carbon lock-in.

- **For nature, land-use and agriculture**. Climate Neutrality demands radical agricultural subsidy reform. The global cost per year of the damage to nature from harmful subsidies is estimated between $4 to $6 trillion (The Dasgupta Review, 2021). Policies are also needed to scale monitoring verification and reporting for soil carbon sequestration. The world's arable soils are estimated to sequester on average 5 billion tonnes CO_2e per (Dunne, 2020). Nature-based solutions must support local communities to ensure integrity (Martin et al. 2021).

- **For greenhouse gas removal (GGR).** Standardization and regulations are key priorities. Climate Neutral strategies must include policies for scaling greenhouse gas removal. The IPCC SR 1.5 assessed that 100 to 1000 billion tonnes of carbon dioxide removal will be needed until 2100 (absent unprecedented development in technology and human behaviour). Policies to scale GGR include investment incentives and public financing, e.g. national Feed-In-Tariffs and a European Removal fund supported by the ETS. Policies are also needed requiring the heaviest emitters to draw down hard-to-abate emissions such as a Carbon Take Back Obligation.

- **For climate finance.** A range of interventions are needed to achieve climate neutrality, green supportive factors, such as "green loan guarantees" and "targeted public private partnerships" to scale decarbonization solutions, as well as "dirty penalizing factors" such as "capital adjustment" (an extension of Basel rules), and "risk adjustments". Experts emphasized that financial institutions must move beyond an era of transparency and climate-risk management and focus more on climate outcomes.