Annex: Scientific Evidence

What do Remaining Carbon Budgets tell us about when humanity needs to stop emitting carbon?

- According to Friedlingstein et al. (2023), the remaining carbon budget for a 50% chance of limiting warming to 1.5°C is 275 gigatonnes of CO2 – which will be blown within 7 years (~2030) at current rates (~40 Gt CO2 per year)[4]
- For a 50% chance of 1.7°C (or "well-below 2°C), the remaining carbon budget is 625 Gt of CO2, equivalent to 15 years at current rates (~2040)[5]
- According to Forster et al (2023) for a 67% chance of limiting warming to 1.7°C, the carbon budget (700 Gt CO2) will be blown in 17 years, or in 2040[6]
- According to Forster et al (2023), for an 83% chance of 2°C, the remaining carbon budget is 900 Gt CO2, which will be blown in 2046 at current rates of emission[7]

What is the evidence that Carbon Capture and Storage (CCS) cannot play a significant role in the energy transition?

The deployment of CCS has fallen well short of projections.[1]

- Globally, ~70% of the projects proposed to be operational by 2020 have failed to arise mainly due to cost blowouts, low readiness levels in capture technology, and a lack of investment.[2]
- The Intergovernmental Panel on Climate Change (IPCC) projects subsurface carbon storage of up to 30 btpa by 2050. Even if CCS grows at a rate of 10% – more than it has in the last 20 years – it would still only reach 1 btpa of storage and 5-6 btpa is the upper limit of feasibility. [3]
- A major study by the Institute for Energy Economics and Financial Analysis (IEEFA) of CCS projects – that together account for over half of global capacity – found that almost every project had either failed or significantly underperformed, typically at the implementation stage.[4]

Other issues:

- Of the few CCS projects in existence, 80% of capacity is earmarked for enhanced oil recovery – perpetuating the use of fossil fuels instead of incentivising long-term storage of carbon underground. [5]
- The International Energy Agency (IEA) estimates that to achieve 1.5°C under today's policy settings, the amount of electricity needed to power fossil fuel CCS by 2050 would exceed the entire world's electricity demand today.[6] In 2023, the IEA asked the fossil fuel industry to "let go of the illusion that implausibly large amounts of carbon capture are the solution" and commit to real decarbonisation.[7]
- To detect leakage and apportion liability for any leakage from underground stores, reservoirs will need to be monitored at public expense, in all likelihood, for centuries to thousands of years.[8]

Is CCS a danger to human health?

- In 2020 a CO_2 pipeline explosion in a small town in the USA left residents unconscious in their cars and shaking on the ground, unable to breathe.[9]
- Leakage of CO_2 from underground into groundwater can also lead to contamination of drinking water with heavy metals.[10]
- CCS can trigger earthquakes, increasing the risk of CO_2 leaking.[11] In fact, a scientific paper in 2012 cited seismicity as the reason why CCS is "a risky, and likely unsuccessful, strategy for significantly reducing greenhouse gas emissions." [12]
- Due to these well-understood threats, onshore CCS is heavily restricted in several countries including Germany, the Netherlands, Sweden, Belgium and Finland.[13] Queensland banned CCS in the Great Artesian Basin this year.[14]

Natural carbon sinks have been growing as emissions rise

- The ocean and land collectively absorb ~55% of global CO_2 emissions from human activities.[15] This means that atmospheric CO2 is increasing about half as fast as it would be in the absence of carbon sinks.[16] The ocean takes up around 25% of human carbon while the land takes up ~30%.[17] Land ecosystems alone store almost 4x the current atmospheric CO_2 content.[18] Soil is a significant carbon store – Australia's soil holds 30 billion tonnes of carbon in its upper 20 cm.[19] The ocean stores around 60x the current atmospheric CO_2 content – the vast majority in the deep ocean.[8]
- As atmospheric CO_2 has risen, ocean uptake has also risen. CO_2 dissolves into seawater at the ocean surface.[20] The ocean sink is concentrated, with 70% of the sink focused on 40% of the ocean's area.[21] On land, the "CO_2 fertilisation effect" has led to increased growth of plants and forests while climate change has lengthened growing seasons in temperate regions.[22]

But carbon sinks are starting to weaken due to climate change

Land sink

Between 2012 and 2021, the rate at which the land absorbed CO_2 was 17% lower than expected, indicating a weakening of the land sink.[23],[24] The land sink is forecast to become a net source of carbon by the end of the century, under a high emissions scenario, due to increasing fires in the northern hemisphere, drought, loss of soil moisture, insect outbreaks and thawing permafrost.[25],[26] There's also the possibility that the CO_2 fertilization effect is limited beyond a certain threshold.

The IPCC lists the risk of permafrost thaw prior to 2100 as "high" and estimates that it could release 3 to 41 billion tonnes of carbon per 1°C of global warming by 2100. For reference, human society emits around 11 btpa of carbon today.[27] The IPCC currently fails to account for the possibility of abrupt thaw and fire-permafrost interactions.[28]

There is emerging evidence that the land sink may weaken sooner than the IPCC assumes. [29] In 2023 – the first year on record that the world reached an average annual warming of ~1.5°C relative to pre-industrial – the land sink absorbed just 0.44 billion tonnes of carbon, in contrast to its average uptake of 2 btpa between 2010 and 2022. [30] As a result of this weakening of the land sink, the atmospheric CO_2 growth rate was 89% higher in 2023 relative to 2022.[31]

Ocean sink

Between 2012 and 2021, the rate at which the ocean absorbed CO_2 was 4% lower than expected.[32],[33] Research also suggests that without climate change, the mean carbon uptake between 2000 and 2019 would have been 13% higher, while the uptake between 1958 and 2019 would have been 27% higher.[9] The main drivers of weakening in the ocean sink appear to be changes in wind patterns, ocean warming, which reduces the solubility of CO_2 in the water, and acidification.[10]

It is forecast that under a high emissions scenario, growth in ocean uptake of CO_2 could plateau by end of the century and halve by 2300 as the surface layer of the ocean becomes too stratified and acidified to absorb further CO_2.[34],[35] A compounding factor is additional carbon resurfacing from depth, driving further acidification.[36]

Variability and sensitivity

Year-to-year variability in the land sink is about 1 billion tonnes of carbon per year[37] while the ocean carbon sink has varied by about ±20% between 1990 and 2019.[38],[11] This variability makes it impossible to forecast with any confidence how much carbon will be stored in any single year. In addition, carbon sinks are sensitive to CO_2 concentrations in the atmosphere and will absorb less if global emissions fall.[39] Catastrophic carbon sink tipping points and the linkages between them are poorly understood and warrant significant further study.[40]

Figures

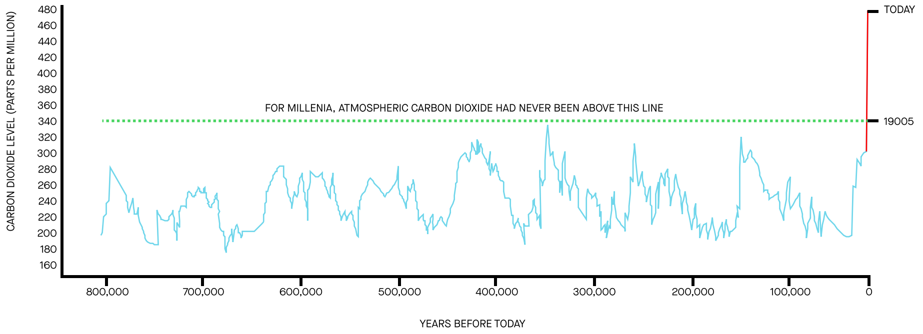


Figure 1. Trends in CO2 emissions over recent history. Adapted from NASA.[41]

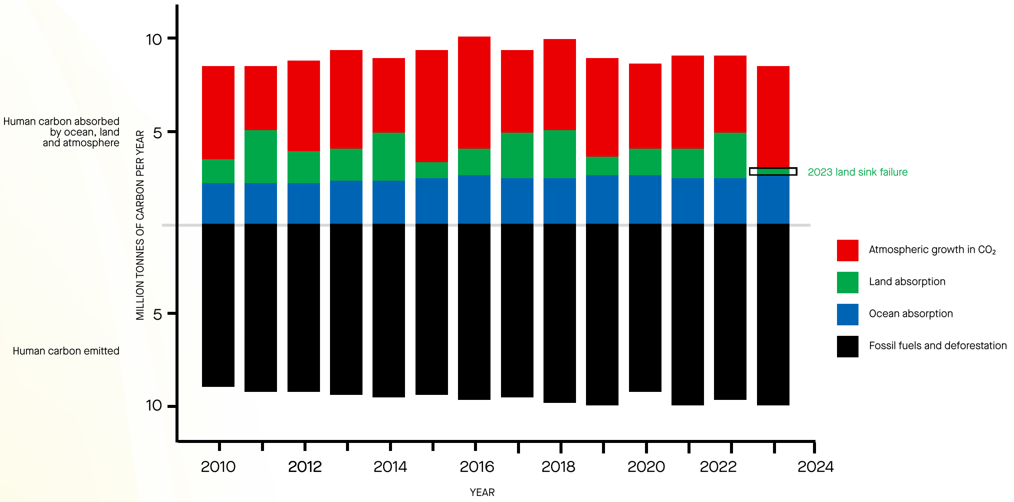


Figure 2. Catastrophic failure of the land sink (green) in 2023 due to fire and drought. Adapted from Ke et al (2024).[42]

Figures

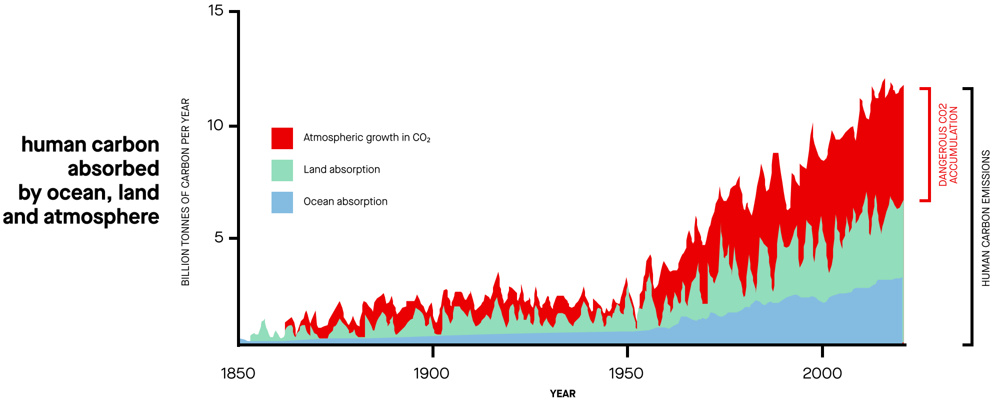


Figure 3. The role of the ocean and land in absorbing human carbon emissions. Adapted from Friedlingstein et al (2023).[43]

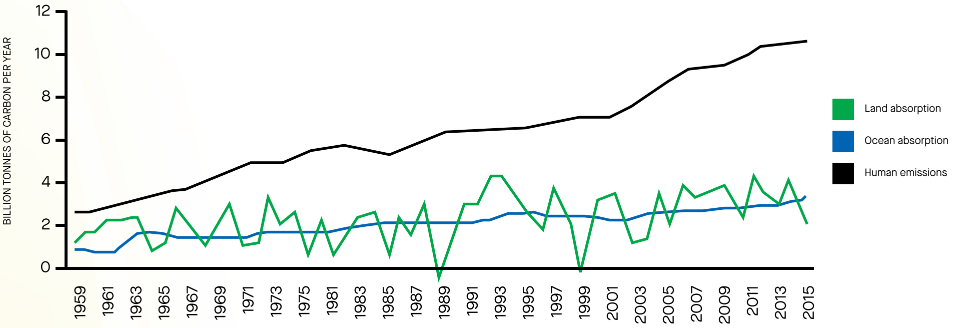


Figure 4. Rising CO2 emissions set against a backdrop of limited carbon sink uptake. Adapted from Redlin and Gries (2021).[44]

Figures

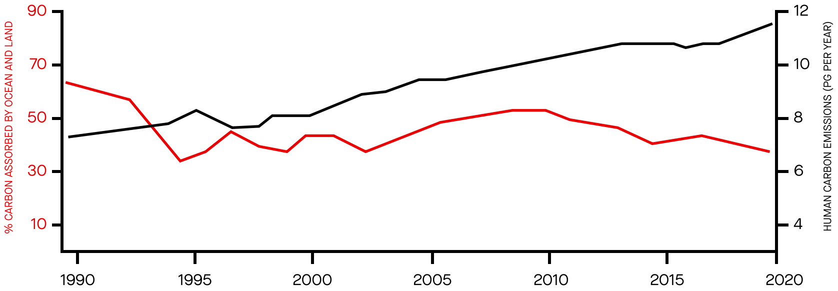
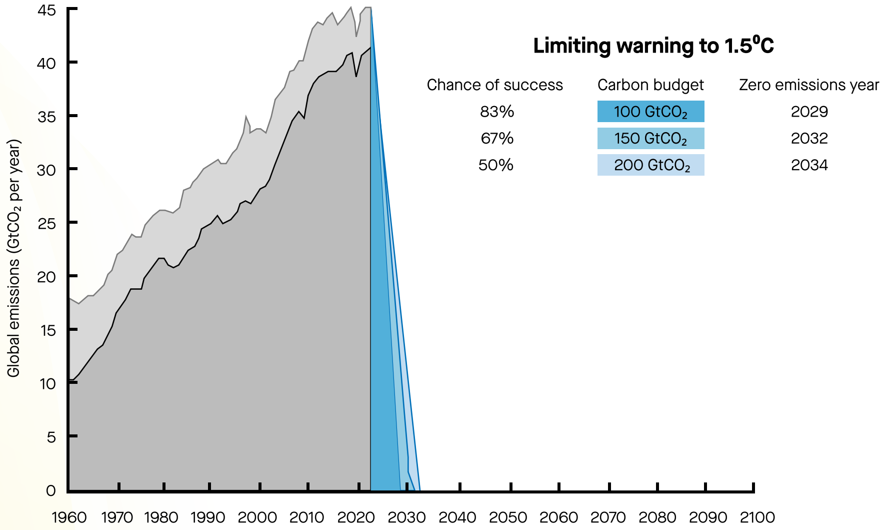


Figure 5. The trend in the global carbon sink since the 1990s. Adapted from the IPCC.[45]



Limiting warning to 1.5°C

Chance of success	Carbon budget	Zero emissions year
83%	100 $GtCO_2$	2029
67%	150 $GtCO_2$	2032
50%	200 $GtCO_2$	2034

Figure 6. Carbon budget remaining for 1.5C, adapted by Professor Nerilie Abram.

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