

The role of temporary carbon dioxide removal in meeting the Paris Agreement warming targets

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Abstract

Article 6 of the Paris Agreement stipulates the conditions under which parties can make use of internationally transferred mitigation outcomes (ITMOs) – tradeable credits earned from the domestic reduction of GHG emissions – to reduce the cost at which nationally determined contributions (NDCs) are achieved. The specifics of carbon market accounting under Article 6 are still controversial and unsettled, with parties remaining divided on major questions concerning environmental integrity. Given the low cost, potential for co-benefits, and heterogenous global distribution of suitable land, large volumes of nature-based carbon removal could be traded under Article 6. These solutions store captured carbon temporarily, and thus present a challenge to the environmental integrity of Article 6 mechanisms. In order for nature-based solutions to meet the high standards for integrity described by the Paris Agreement, that is, to ensure the stated or implied mitigation impact of temporary carbon storage is realized, methodological advances are necessary. This thesis addresses three. Firstly, it establishes a carbon dioxide removal deployment estimate and compares it to mitigation scenarios in line with the Paris Agreement – an important precondition to assessing progress against climate commitments and the carbon removal need that results. Secondly, it develops an understanding of the temperature implications of temporary carbon removal deployed near net-zero emissions, establishing that, across a range of scenarios, it can be treated directly as a time-fractional permanent removal. Thirdly and finally, it examines possible metrics for informing the exchange of temporary carbon removal with other mitigation outcomes and suggests, to minimize the risk of unintended warming outcomes, the most appropriate role for temporary removal is its exchange with short-lived climate pollutant abatement, where economical to do so. These advances could help define a physically-robust role for nature-based solutions in climate mitigation strategy, which in turn could unlock flows of investment from the Global North into nature-based solutions in the Global South, driving not only positive climate impact, but also protecting and enhancing biodiversity, improving the provision of ecosystem services, and protecting against physical climate risk in some of the most at-risk portions of our planet.

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1. Introduction

1.1 Climate change is a proximate threat

The possibility that human production of greenhouse gasses could influence Earth's climate has been recognized since the mid-1800s, deriving from advances in the study of radiatively-active gasses and the composition of the Earth's atmosphere by Tyndall, Arrhenius, Newton-Foote, and others. [1] Concern about the consequences of a warming planet for human society did not emerge until much later, in the second half of the twentieth century, when changes in the composition of Earth's atmosphere were first detected. [2-3] At this time it was suspected that the socioeconomic consequences of global warming "may well be significant", but it was noted that they "cannot yet be adequately projected". [3] Indeed, initial attempts at quantifying the socioeconomic risks from a changing climate were spectacularly naïve, with, for example, Nordhaus's DICE model calculating the "optimal level of global warming" by fitting an arbitrarily selected quadratic function to the historical relationship between agricultural yield and average temperature in the United States as a proxy for global damages from increasing global average temperature. [4-5] The primary technological restriction to better assessing socioeconomic impacts from climate change was an inability to project regional climate changes with confidence: "at present we cannot simulate accurately the details of regional climate and thus cannot predict the locations and intensities of regional climate changes which [the evidence suggests] will be at least as great as globally averaged changes themselves." [3]

The field of study of socioeconomic impacts has advanced substantially from the final decades of the twentieth century, driven by both continued scientific advances and the building of much faster and more powerful computers, which have allowed scientists to better resolve regional climate changes. As a result of these advances it has become clear that the threat posed by climate change is not long-term, century-level shifts in mean climate parameters, but dramatic changes in frequency and severity of extreme weather events which can occur given even small changes to the location of a distribution mean

in the near-term. [7-9] Human society, from where and how we grow food, to the engineering specifications of our infrastructure, to fundamental assumptions underlying the way we save and allocate capital via the global financial system, is predicated on a generalized assumption of climate stability, and thus can be highly vulnerable to such changes. [10-11]

For example, the viability of the home insurance market depends on a low level of systemic risk to insured assets, which allows providers to distribute and so diversify away the remaining idiosyncratic risk across a portfolio of customers. The increase in frequency and severity of coastal flooding in Florida and wildfire activity in California, given only the present ~1°C increase in global average temperatures, has already caused some of the largest providers of home insurance to cease operations in those states. [12] In short, the level of systemic risk to residential property has begun to exceed the socioeconomic "threshold" for insurance market viability in some geographies. Given property tax is the primary form of revenue for the State of Florida, the second-order impacts of passing this threshold could be substantial. [12-13] Modelling of regional climate change suggests that minimal additional warming will be necessary to pass similar physical "thresholds" in more important socioeconomic systems including, for example, the introduction of summer temperatures that depart from the human thermal niche, producing physiologically non-survivable heatwaves (without the protection of climate control) for the first time in human history. [14-16] This could call into question the near-term habitability of some of the hottest and most densely populated parts of the planet today. Furthermore, the more of these "thresholds" that are crossed, the greater the possibility of catastrophic second-order effects occurring, including food and water shortages, widespread migration, and armed conflict. [17-20]

Therefore, it is important that we limit further increase in global average temperature to a level which preserves the suitability of the planet's surface for human civilization. While no conclusive evidence exists to justify a specific warming level as "safe", the 2015 Paris Agreement, to which 195 of the 196 members of the United Nations Framework

Convention on Climate Change (UNFCCC) are party, has enshrined "well-below 2°C" as the goal of global climate policy [21], and some preliminary evidence exists to suggest this represents a suitable upper limit to warming that could be tolerated without introducing truly existential risks. [22] One of the primary focuses of academic inquiry related to climate change over the past several decades has therefore been understanding and quantifying precisely the conditions necessary to achieve specific climate targets, and designing and implementing a management framework which can be applied by state and non-state actors towards this goal.

1.2 Existing frameworks for managing climate change are incomplete

Initial attempts at designing a climate change management framework centered around setting a stabilization target for atmospheric CO_2 concentrations. [23] The problem with this approach is Earth's temperature is very slow to equilibrate to a sustained change in its radiative forcing due to the presence of large ice-sheets and a substantial ocean of liquid water on its surface, and thus maintaining a constant atmospheric CO_2 concentration implies continued warming for hundreds to thousands of years into the future. [24] Estimating the eventual warming that would result from a sustained change in atmospheric composition is made difficult by the simple fact that the properties of the climate system we can observe today are insufficient to constrain very high eventual levels of warming. This is true because the relationship between Earth's feedback factor (a measure of how much energy is radiated to space per degree warming) and climate sensitivity is asymptotic, with temperature approaching infinity as feedback gain approaches unity. [25] Indeed, it took forty years to narrow the best estimate of the Earth's Equilibrium Climate Sensitivity (ECS - the eventual level of temperature increase resulting from a constant doubling of atmospheric CO_2) from 1.5-4.5°C [3] to 2.6-3.9°C with >66% probability, with the proviso that the high end of this range should be "regarded cautiously" [26].

In the early 2000s, it was recognized that a more relevant question for climate policy is not "can we estimate the eventual warming from constant atmospheric CO_2

concentrations", but "what would need to be true in order to stop warming today?". [27] Because of the multi-century atmospheric lifespan of CO_2 in the atmosphere [28], near-zero emissions of CO_2 are the necessary condition for stabilizing global temperatures [29]: once the net addition of carbon to the atmosphere is zero, natural sinks are free to absorb excess carbon from it, reducing atmospheric CO_2 concentrations and thus radiative forcing. Given the ocean is the primary sink for both excess carbon and heat, the rate of decline in CO_2 forcing is roughly equal to the increase in temperature from ocean equilibration to past forcing, producing constant surface temperatures. As a direct corollary, if zero CO_2 emissions are required to halt warming, there is some discrete quantity of cumulative emissions which can be emitted before any arbitrary warming target is reached; an associated "carbon budget". [30]

The usefulness of the carbon budget concept as a policy framework is aided by the fact that the relationship between carbon dioxide emissions and transient (e.g. instantaneous) warming is approximately linear. [30] As such, the discrete quantity of cumulative emissions available for a given warming target can be divided fungibly between different actors and across time. The principle issue with the carbon budget framework is the substantial sensitivity of carbon budgets to changes in non-CO_2 forcing, particularly in scenarios where the warming target is ambitious and thus the remaining carbon budget is small. CO_2 emissions presently represents about +2.16 w/m^2 or about 56% of total anthropogenic greenhouse gas-driven forcing of the climate system, with the next largest component being well-mixed, short-lived climate pollutants or SLCPs (such as methane and the halogenated gasses, at +1.16 w/m^2 or 30%). [31]

Changes in the concentration of atmospheric aerosols contributes an estimated -1.1 w/m^2 to the global anthropogenic climate forcing. [31] It is anticipated that the emission of aerosols will decline as CO_2 emissions approach zero, causing additional warming. In fact, if aerosol cooling was eliminated today while holding all other present-day forcing constant, we already would have exceeded the carbon budget for 1.5°C warming, and

would be near to exhausting the 2°C budget. [32] That any carbon budget remains for the Paris Agreement warming targets relies on the assumption that the forcing from SLCPs will be reduced over time, counterbalancing the warming from decreasing aerosol forcing and thus leaving space for additional carbon emissions. [33-35] However, understanding exactly how SLCP emissions contribute to the size of the remaining carbon budget is not straight-forward, because unlike carbon dioxide, warming from SLCPs varies as a function of not cumulative emissions, but the rate of their emission, subject to their own atmospheric decay dynamics and climate-carbon feedbacks. [36]

One approach to measuring the contribution of SLCPs to remaining carbon budgets is to employ climate models to calculate the evolution of future non-CO_2 forcing according to a given scenario, and diagnose the remaining carbon budget as a residual term. [37] Another more common approach is to assess the relationship between CO_2 and non-CO_2 forcing across a range of scenarios, and thus in diagnosing the carbon budget assume non-CO_2 forcing will vary in some constant proportion to future CO_2 emissions. [35] Both of these approaches have faced criticism in that they restrict the degrees of freedom available to real-world mitigation strategy, given non-CO_2 forcing cannot diverge from scenario assumptions without an ambiguous impact on the remaining carbon budget. [38] Jekins et al. (2018) provides a solution: generalizing the carbon budget framework by converting changes in non-CO_2 forcing into forcing-equivalent CO_2 emissions (CO_2-fe), defined as the CO_2 emissions pathway that would give the same radiative forcing impact as SLCP changes over time. [38] Under such a system equivalent changes in any forcing are fungible, facilitating the simple analysis of trade-offs between different mitigation actions or calculating individual actor's multi-forcing contributions to global warming.

However, calculating CO_2-fe emissions for various forcing species is not straightforward without access to an Earth-system model. Existing metrics for comparing the climate value of different greenhouse gases – the integrated-radiative-forcing based Global

Warming Potential (GWP) metric, or the point-in-time temperature-based Global Warming Potential (GTP) metric – fail to capture accurate forcing over time for SLCPs, as they implicitly treat such gasses as long-lived, accumulating forcings. [36] A framework for improving the ability of the GWP metric to approximate forcing-equivalency between greenhouse gasses, known as GWP*, achieves this aim by comparing one-off pulses of cumulative emissions to discrete, sustained changes in rate of emission of SLCPs. [39] While this framework allows the approximation of CO_2-fe emissions using a simple equation, it faces valid criticism of its ability to capture the behavior of highly noisy emissions data, accurately inform marginal mitigation decisions, and therefore integrate into existing policy frameworks. [40] This said, the ability (or inability) of various metrics to accurately incorporate SLCPs into the carbon budget framework is, to a first order, irrelevant when considering the Paris Agreement warming targets, given (as discussed above) short-lived forcing needs to be reduced to the limits of what is possible in order for a material present-day carbon budget to exist at all. [35] As such, there are presently calls for individual actors to report short-lived forcing separately from CO_2 emissions, instead of trying to equate the two under a carbon budget framework. [41]

1.3 Carbon dioxide removal will be required to deliver Paris Agreement

The best estimate of the remaining <2°C carbon budget is ~1000 $GtCO_2$, or roughly 25 years of present-day emissions, assuming non-CO_2 forcing is reduced to the limits of what is presently assessed as possible. [35] A synthesis of integrated assessment modelling efforts conducted as part of the 6th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) concluded with high confidence that available mitigation pathways which limit warming to below 2C with >67% probability all involve some level of carbon dioxide removal (CDR) to compensate for residual GHG emission remaining after 'substantial direct emissions reductions in all sectors and regions'. [42] The stated range of required CDR deployment across surveyed scenarios is between 490-900 cumulative $GtCO_2$ by 2100. [42] While a profusion of CDR methods have been proposed [43], present-day deployment is small, on the order of 20%

of a gigaton per year, or about 0.5% of annual emissions, [44] and further scaling faces a number of technological, economic, and policy challenges. [45] In addition to these scaling challenges, it is also critical that we understand how to incorporate CDR into mitigation accounting, or specifically, what effect CDR has on the remaining global carbon budget, and whether it can and should be integrated directly into the global carbon budget framework, or measured independently like methane and other SLCPs.

In the context of net-positive ongoing emissions, one ton of CDR exhibits an exactly inverse impact on global average temperature to that of emitting one ton CO_2, and so CDR can be directly integrated into the carbon budget framework. [46] This is because, as discussed, the relationship between cumulative CO_2 emissions and transient temperature (known as the Transient Climate Response to Cumulative Emissions, or TCRE) is roughly linear. If some CDR occurs after having reached zero-emissions, however, this relationship no longer holds true: the climate system exhibits thermal and biogeochemical hysteresis, meaning each ton of removal exhibits a fractional inverse relationship to an equivalent volume of CO_2 emissions.

The mechanics underlying this hysteretic behavior have been examined preliminarily at both the aggregate feedback [47-48] as well as individual mechanism [49] level, using highly idealized instantaneous removals [50-51], and more complex pathways of atmospheric CO2 reduction. [52-55] Using experiments conducted with five Earth System Models (ESMs), Asaadi et al. (2024) demonstrated that this hysteretic behavior can be traced to changes in the sensitivity of both ocean and land sinks to changes in atmospheric CO2 and global average temperature, quantified by the sink-specific carbon-concentration feedback metrics β_i and climate-carbon feedback metrics γ_i respectively, which lead to increases in both parameters under periods of net-negative emissions. [47] Furthermore, these changes are shown to result not from region-specific dynamics, but from changes in the global behavior of the carbon cycle, with the ocean sink showing more substantial and persistent hysteresis in response to legacy warming compared to the land sink. [47] Experiments investigating this behavior using simplified

Earth-System Models of Intermediate Complexity (EMICs) have suggested that ocean hysteresis is driven by meridional overturning circulation decreasing more in response to temperature increase than in response to temperature decline under negative emissions, thanks to the thermal inertia of the ocean, and the buffer capacity of CO2 in seawater decreasing non-linearly with CO2 partial pressures (pCO2) at the sea surface, resulting in a larger air–sea CO2 flux under negative emissions than positive emissions. [49] In the biosphere, net-primary productivity (NPP) follows changes in atmospheric CO2 concentrations, and therefore declines in direct response to net-negative emissions, while soil respiration scales with global average temperatures and therefore exhibits a lagged response, resulting in net carbon loss from the land sink. [49] Permafrost release has also shown to be material to the changing climate-carbon feedback under scenarios where CDR is used to recover from a substantive release of GHGs. [47]

Given this hysteretic behavior, following global achievement of net-zero emissions, new or updated metrics will be needed to quantify the mitigation value of a ton of permanent CDR relative to a ton of emissions. Exactly what this fraction is, and how it differs based on emissions scenario remains uncertain, and will be informed by continued work under ongoing modelling projects like CDRMIP. [56]

1.4 Temporary carbon removal could play a role in mitigation strategy

CDR with temporary storage (tCDR) comprises the bulk of present-day CDR deployment, as well as the most available and cost-efficient set of approaches to CDR, via an umbrella of biomass-growing solutions referred to as nature-based solutions. [43-45] Arguments have been made that tCDR has no climate value because any cooling it induces will be reversed [57], or that tCDR has limited possible scale because the storage capacity of the biosphere is small relative to the volume of carbon already introduced to the atmosphere [58], however it has been demonstrated that at-scale afforestation and reforestation, across the regions of the tropics with sufficient quantities of fit-for-purpose land, could store on the order of hundreds of gigatons over the course of the

century [43, 58-59], and that this sort of intervention, applied in addition to all other available mitigation levers, including permanent engineered removals, would be sufficient to meaningfully reduce peak warming in an ambitious mitigation scenario. [60] Additionally, nature-based solutions are the only CDR approach which provide a host of co-benefits, including biodiversity enhancement [61], widely-used industrial feedstock in the form of harvested wood products [62], and even physical risk adaptation capabilities including costal flood risk and erosion management [63]. As such, while tCDR is clearly not the optimal mitigation lever for addressing a problem caused primarily by the accumulative of long-lived gasses in the atmosphere, finding a physically-justifiable role for temporary carbon removal in mitigation strategy could be a worthwhile endeavour, a supposition further reinforced if you consider as tCDR nominally permanent carbon storage methods for which a sufficiently long-term policy mechanism does not exist to ensure monitoring and management over decadal timescales. [45, 64]

Finding a physically-justified role for tCDR in mitigation strategy will require additional work to understand the Earth-system dynamics behind its climate impact. While tCDR deployed during a transient climate state of ongoing emissions will have an equivalent impact to delaying an emission (thanks to the aforementioned dynamics underlying the linearity between cumulative emissions and temperature), limited initial studies on the dynamics of tCDR suggest removing CO_2 from the atmosphere temporarily post-net-zero could cause short term cooling but long term warming relative to the counterfactual in which that removal had never occurred. [50, 65] The proposed mechanism for this warming effect is as follows: initial removal causes a decline in atmospheric CO_2, which in turn induces the global carbon cycle to re-equilibrate, producing a "rebound" in atmospheric CO_2 following removal. When stored carbon is then re-introduced to the atmosphere, CO_2 concentrations peak above starting conditions before declining on the order of about three centuries. [50, 65] If these results are robust to investigation with a fully-dynamic Earth system model and range of carbon cycle parameterisations, climate states, and scenarios, this long-term warming

effect will need to be incorporated into a determination of the usefulness of tCDR deployment for, for example, the purposes of 'shaving' peak warming.

Furthermore, in addition to our incomplete understanding of the Earth-system dynamics behind tCDR, the metrics used today to measure the climate value of tCDR are highly problematic. The most commonly cited approach to measuring the value of tCDR is "ton-year accounting", which takes an integrated-radiative-forcing approach to equating tCDR and CDR by comparing, in effect, the integral of the cumulative removal pathways over some arbitrary time period. [67-68] Another more contemporary approach conceptualizes tCDR as delayed emissions which can be equated to CDR by applying a time-preference to avoided damages. [65, 69] Both of these approaches implicitly assume that the forcing effect of tCDR accumulates over time [70] and so can be summarized via fractional equation with long-lived climate pollutants, while it has been amply demonstrated that the forcing effect of tCDR scales with rate of deployment, not cumulative deployment, as it does with methane and other SLCPs. [71] As such, the most commonly used valuation metrics for tCDR deployment today lead to ambiguous measurement of warming outcomes. [70] A systematic review of the validity of other commonly used equation metrics across different exchange scenarios is needed, as is an investigation of plausible alternative measurement approaches.

1.5 Article 6 of the Paris Agreement & organization of this thesis

Article 6 of the Paris Agreement stipulates the conditions under which parties to the agreement can make use of internationally transferred mitigation outcomes (ITMOs), or carbon credits earned from the domestic reduction of GHG emission and traded to others with the aim of improving the economic efficiency with which nationally determined contributions (NDCs) are met. According to industry analysis, the effective use of trading carbon credits could reduce the cost of implementing NDCs by up to half between now and 2030. [72] However, the specifics of carbon market function and accounting under Article 6 are still controversial and unsettled, with parties remaining divided on major questions concerning environmental integrity. [73] Given the low cost,

co-benefits, and heterogenous global distribution of available land discussed above, large volumes of tCDR could be traded under Article 6 if an appropriately physically-justified role for nature-based solutions can be found. In order for tCDR to meet the high standards for environmental integrity described in Article 6.2 [73], that is, to ensure that tCDR counted towards NDC progress actually causes the stated or implied temperature impact, the methodological advances described above are necessary. This thesis addresses each of them, organized across three distinct research papers as follows:

Quantifying global carbon dioxide removal establishes a robust framework for defining which activities should be counted as CDR and at what point in time, in order to avoid double counting between temporary and permanent CDR methods which share feedstocks. It then applies this framework to quantify a deployment baseline for all global CDR activity, both CDR and tCDR, in recognition that establishing a robust estimate of deployment is a precondition to assess progress against climate goals and commitments. This paper demonstrates that existing deployment of reported CDR is small, on the order of 0.2 $GtCO_2$, that the bulk of this deployment (>99%) is comprised of nature based solutions, and that this deployment rate must scale exponentially going forward in order for the world to meet the Paris Agreement warming targets.

On the dynamics of temporary carbon dioxide removal applies both an Earth-system Model of Intermediate Complexity (EMIC) and an emulated perturbed parameter ensemble to build an understanding of the climate system response to tCDR under different climate states and deployment scenarios. These results inform the physical requirements any valuation or exchange metric must account for in equating CDR projects with different storage lifetimes. This paper demonstrates that temperature overshoot due to re-release of temporarily-stored carbon in a near- or post-net-zero climate state is insignificant across a reasonable set of scenarios and therefore that tCDR can be conceptualized directly as a time-fractional permanent removal.

Temporary carbon dioxide removal and short-lived climate pollutant emissions could be effectively exchanged as International Traded Mitigation Outcomes examines the potential role of temporary carbon dioxide removal (tCDR) generated by nature-based solutions within the framework of Internationally Traded Mitigation Outcomes (ITMOs). This paper demonstrates that tCDR could be used to offset one-off pulses of methane or other SLCPs under a "do-no-harm" principle using Global Warming Potential (GWP) metrics. Additionally, it explores the possibility of chaining tCDR into sustained deployments approximating permanent removal, while acknowledging the associated socio-political challenges. Finally, a novel method for incorporating nature-based solutions into carbon markets is proposed, using Linear Warming Equivalent (LWE) units of tCDR to directly offset methane emissions. This approach could address hard-to-abate SLCP pollution while promoting biosphere restoration as a "peak shaving" approach when nearing the point of net-zero emissions.

This thesis then closes with a conclusory chapter summarizing the key findings of the research presented within, and discussing the implications of these findings for future research and global climate policy. It demonstrates that if the advances developed herein are incorporated into existing accounting frameworks, it could help unlock significant flows of investment from the Global North into nature-based solutions in the Global South, which not only will drive positive climate impact, but also assist in protecting and enhancing biodiversity, improving the provision of ecosystem services, and protecting against physical climate risk in some of the most at-risk portions of our planet. The conclusory chapter is followed by supplementary materials, co-author declarations stipulating to the author's role in each respective research project, acknowledgements, and finally the references used herein.

2. Quantifying global carbon dioxide deployment

This paper establishes a robust framework for defining which activities should be counted as CDR and at what point in time, in order to avoid double counting between temporary and permanent CDR methods which share feedstocks. It then applies this framework to quantify a deployment baseline for all global CDR activity, both CDR and tCDR, in recognition that establishing a robust estimate of deployment is a precondition to assess progress against climate goals and commitments. This paper demonstrates that existing deployment of reported CDR is small, on the order of 0.2 $GtCO_2$, that the bulk of this deployment (>99%) is comprised of nature based solutions, and that this deployment rate must scale exponentially going forward in order for the world to meet the Paris Agreement warming targets.

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Quantifying global carbon dioxide removal deployment

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Abstract

Despite the importance of carbon dioxide removal (CDR) in most climate change mitigation scenarios that limit warming to well below 2°C, the study of CDR is still a nascent field with basic questions to be resolved. Crucially, it is not known how much CDR is currently deployed at a global scale, nor how that compares to mitigation scenario estimates. Here, we address this problem by developing an estimate of global current CDR activity. We draw on national greenhouse gas inventory data combined with CDR registries and commercial databases to estimate that global anthropogenic activity presently generates ~1985 $MtCO_2yr^{-1}$ of atmospheric removals, of which ~210 $MtCO_2yr^{-1}$ are from reported CDR projects. Almost all removals are from land-use, land-use change and forestry (LULUCF) activity. Non-land-management CDR projects such as bioenergy with carbon capture and storage (BECCS), direct air capture with carbon capture and storage (DACCS) and biochar remove only about 2 $MtCO_2yr^{-1}$. We compare this estimate with Shared Socioeconomic Pathways (SSPs) projections of CDR deployed in "well-below 2°C" mitigation pathways. In so doing we demonstrate current CDR deployment would need to grow exponentially to keep the world aligned with most "well-below 2°C" scenarios, which see CDR deployment growing between 75 and 100% per year between 2020 and 2030, adding ~300-2500 $MtCO_2$ in total CDR capacity. To conclude we discuss uncertainties related to our estimates, and suggest priorities for the future collection and management of CDR data, particularly related to the role of the land sink in generating CDR.

Introduction

The recent 6th assessment report by the Intergovernmental Panel on Climate Change (IPCC) highlights Carbon Dioxide Removal (CDR) as a fundamental component of any mitigation strategy aimed at limiting global warming to well below 2°C [42]. In particular, it identifies three specific roles for CDR: First, to accelerate near-term mitigation, second, to achieve net-zero emissions by compensating for hard-to-abate residual emissions; and third to generate net negative emissions for reducing anthropogenic forcing. [74] The amount of CDR observed in mitigation scenarios consistent with the goals of the Paris Agreement varies considerably, from a few hundred gigatons of CO_2 to greater than a thousand across the 21st century. [42, 74]

A wide range of different CDR methods (also referred to as negative emission technologies or negative emission practices) has been proposed. Commonly-cited are afforestation/reforestation, the production of biochar, soil carbon sequestration, bioenergy with carbon capture and storage (BECCS), direct air carbon capture and storage (DACCS), enhanced weathering, ocean fertilisation, and ocean liming, [75], but there has also been a recent proliferation of other novel methods introduced in the literature. [76-80] There further exists a wider discussion on greenhouse gas removals (GGR) [81] that also covers methods to remove methane [82] nitrous oxide [83] or other GHGs [84], however the methods considered most scalable are focussed on carbon dioxide, which is our focus here.

The study of CDR is still a nascent field [43, 45, 75] and is therefore still grappling with fundamental issues. First, which methods qualify as CDR and which do not is unclear or contested [75, 85]. Secondly, no consistent approach has been developed to integrate CDR into emissions accounting activities [75, 86-87]. Thirdly, no estimate exists of how much CDR is currently deployed. Fourthly, and finally, it is not known how current deployment compares with modelled mitigation scenarios, many of which treat CDR as a largely monolithic intervention (e.g. BECCS) inversely equivalent to the emission of

carbon dioxide [88] despite uncertainty surrounding the permanence of nature-based CDR and climate impact of more permanent engineered approaches. [87, 89-92]

Resolving these challenges is important to achieving the goals of the Paris Agreement, as establishing a robust estimate of CDR deployment is a precondition to assess progress against climate goals and commitments. Here, we introduce an accounting framework for CDR approaches. We apply this framework to develop a present-day deployment estimate, and, finally, compare this estimate with CDR observed in mitigation scenarios to draw conclusions about necessary future action.

Defining Carbon Dioxide Removal

Though there is no universally-used definition of CDR, IPCC AR6 provides a good starting point [92]:

CDR refers to anthropogenic activities removing CO_2 from the atmosphere and durably storing it in geological, terrestrial, or ocean reservoirs, or in products. It includes existing and potential anthropogenic enhancement of biological, geochemical, or chemical CO_2 sinks, but excludes natural CO_2 uptake not directly caused by human activities.

There are other commonly cited approaches that introduce important considerations not included in the IPCC definition. For example, Tanzer and Ramirez (2019) [85], set out four criteria for a technique to qualify as CDR, including that the lifecycle emissions of a project be net-negative. However, this definition also imputes motive ("intended to be permanent"), which is hard to assess externally and leaves open the inclusion of highly-impermanent removal as long as it was intended to be permanent. While some non-zero level of permanence is widely accepted to be a defining quality of CDR, there is no agreed minimum storage lifetime, given temporary storage may have value in delaying peak warming, thus buying time for further technological advancement, or in substituting for

more expensive permanent storage via long-term management [89-90, 71]. For this reason, and because most available CDR data is measured in gross terms, not net of lifecycle emissions, here we use the IPCC AR6 definition.

In addition to the issues of lifecycle emissions and storage duration, however, there is another complication faced when defining CDR. Many CDR methods involving biomass-based capture require multiple years to complete the process of capturing carbon from the atmosphere and transferring said carbon to its final storage reservoir. Over the full lifetime of a CDR process multiple removals, emissions, and transfers between storage pools can occur. (See Figure 1). Therefore, it is not clear in which year the CDR activity should be accounted for, as carbon captured in one year may be transferred to a new storage reservoir in a future time period, altering the permanence and therefore value of said removals.

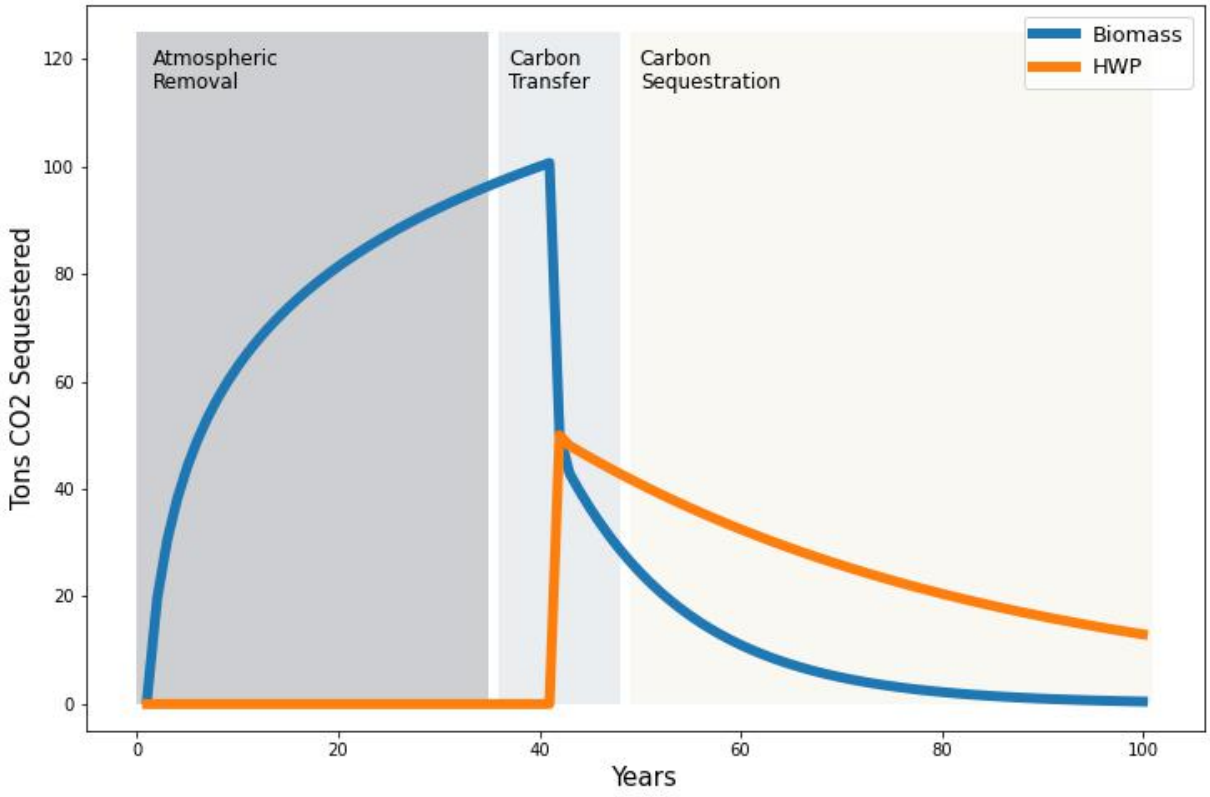


Figure 1. *An illustrative sequestration pathway for the production of Harvested Wood Products (HWPs). During the Atmospheric Removal phase, carbon is sequestered incrementally and at a declining rate through biomass growth in forests [93]. During the Carbon Transfer phase, a portion of stored carbon is transferred from forest biomass to HWPs, with the remainder deposited as deadwood [94]. During the sequestration phase, both the deadwood and HWP decay to the atmosphere, though at different rates [95].*

This challenge could be overcome by accounting for cumulative future or past CDR activity in one year. However, accounting for future removals in the present year exposes accounting processes to the risk of overestimation, should, for example, the lifetime of a planted tree be less than expected. Accounting for total lifetime (past) removals in one year (e.g. the year of HWP production) exposes accounting processes to the risk of double counting should, for example, trees previously accounted for as standing forest later be harvested to produce HWP. In light of these challenges, accounting approaches should follow a 'reality principle': reporting emissions and removals when and where they actually occur [87]. To capture the full scope of CDR activity, however, such "reality principle" based approaches must then include separate quantifications of fluxes of carbon from the atmosphere and between non-atmospheric reservoirs, as both have important but different climate value. This can be done by accounting for CDR through a stock-and-flow framework used, for example, in the UNFCCC accounting guidelines for HWPs [96], and in doing so subdividing CDR into two subsidiary groups of activities, which we will define here. The first of the two activities we will term atmospheric removals and define as follows:

Anthropogenic activity that removes CO_2 from the atmosphere and durably transfers it to a non-atmospheric carbon reservoir in a given year.

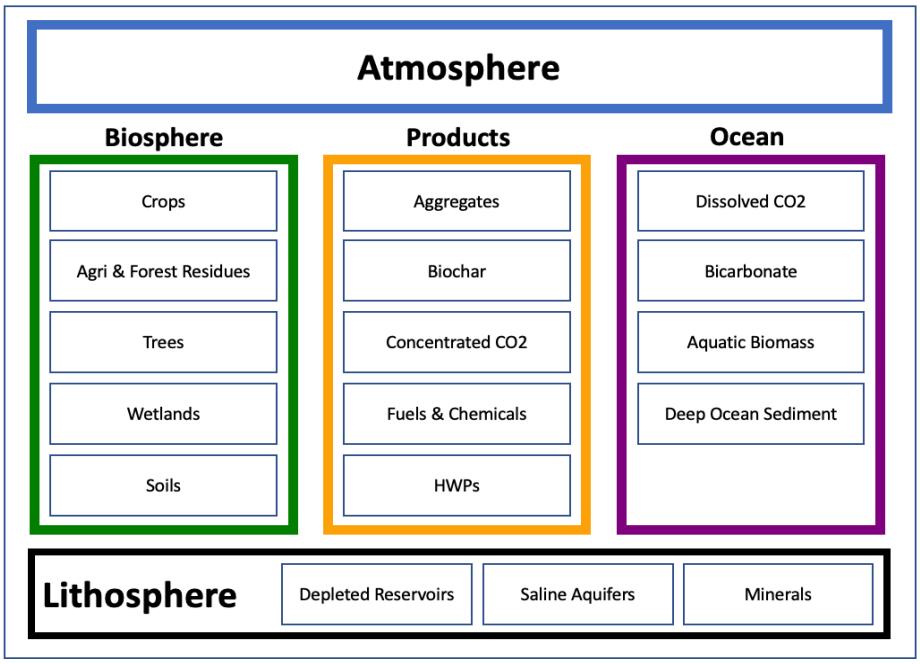
We stipulate the durable storage of removed carbon to avoid classifying projects that conduct capture but not storage as CDR: for example a proof-of-concept CDR plant with no storage capability. The second activity we will term carbon transfers, and define as:

Anthropogenic activity that moves carbon previously captured from the atmosphere from one non-atmospheric reservoir to another in a given year, with the effect of increasing time to re-emission.

Understanding the volume and nature of these two activities, together with information about the permanence of carbon stored in different carbon sinks, should provide sufficient information for an interested stakeholder to account for the full climate value of CDR activity that occurs in a given year.

Mapping Carbon Dioxide Removal Pathways

There have been several prior attempts to develop a framework to organize CDR data for ease of accounting [75, 97-99]. Collectively, these approaches have several drawbacks, including: (a) few link carbon removal directly to the stocks and flows of carbon within and between the reservoirs of the global carbon cycle (an important characteristic to accurately measure CDR deployment, as discussed), (b) those that do link removal to stocks and flows of carbon do not distinguish between intermediate conversion processes, and finally, (c) few include industrial / commercial products as a storage option, despite its inclusion in the definition of CDR by the IPCC. Here we expand on existing frameworks to address these issues. We build on Smith et al. [98] and Hepburn et al. [99], defining the principle carbon reservoirs as the atmosphere, land, ocean, lithosphere, and products. We further divide these reservoirs into subsidiary carbon pools with differing characteristics including permanence (Figure 2).



Reservoir	*Carbon Pool*	*Permanence*
Biosphere	*Crops*	*< Years*
	Agri & Forest Res.	*< Years to Decades*
	Trees	*Years to Centuries*
	Wetlands	*Years to Centuries*
	Soils	*< Years to Decades*
Products	*Aggregates*	*Centuries to Millenia*
	Biochar	*Years to Centuries*
	Concentrated CO_2	*< Years*
	Fuels & Chemical	*< Years*
	HWPs	*Decades to Centuries*
Ocean	*Dissolved CO_2*	*< Years to Centuries*
	Bicarbonate	*< Years to Centuries*
	Aquatic Biomass	*< Years*
	Deep Ocean	*Centuries*
Lithosphere	*Depleted Reser.*	*> Millenia*
	Saline Aquifers	*> Millenia*
	Minerals	*> Millenia*

Figure 2. *A stock-and-flow framework for categorizing carbon dioxide removal approaches. We define the principle carbon reservoirs as the atmosphere, land, ocean, lithosphere, and products. We further delineate these reservoirs into carbon pools with different storage characteristics, detailed in the table below. Storage lifetimes taken from [43, 74, 100].*

Individual CDR techniques can be represented as fluxes between pools – transferring carbon captured from the atmosphere through various intermediate stages before reaching the final storage reservoir. Given CDR techniques can be represented as pathways through various carbon pools, the characteristics of a CDR technique can then be systematically formalized by aggregating the characteristics of said carbon pools (or, in the case of permanence, the final carbon reservoir(s)) and the processes used to transfer carbon between them. Atmospheric removals can be visualized as all activities which cause a flow out of the atmosphere and into durable storage in a given year, while carbon transfers can be visualized as all activities that cause movement of previously captured carbon between non-atmospheric carbon pools. Most importantly, tracking CDR deployment using such a framework will facilitate easier integration of CDR data into other emission accounting and stock-take activities, including the global carbon budget (GCB) estimation and national greenhouse gas inventories (NGHGIs), which are based on similar stock-and-flow conceptualizations.

Methods

We now apply the CDR definitions and framework developed above to estimate and evaluate current global CDR deployment. The data infrastructure is not yet in place to monitor CDR deployment on a global scale. As such, our deployment estimate must be calculated through the combination of many different data sources. We organized our search for appropriate data around the recognition that human management of land and forests for non-CDR reasons is the single largest source of CDR given the scope of

this activity compared to the nascent state of carbon capture technology. As such, an estimate of total deployment was reached by combining gross estimates of the flow of carbon into the global managed land sink with a survey of individual CDR projects.

Estimating total CDR from registered CDR projects

Having set the boundaries of our analysis, we first gather the necessary data. To estimate total CDR generated from registered CDR projects (that is – projects specifically developed for the purpose of generating CDR, and recorded in a registry or carbon purchase database), data on project-level CDR volumes were aggregated from across twenty unique registries and databases (Table 1). A thorough double-counting check was performed using datapoints including project name, location, project size / sequestration rate, and sponsoring institution. Given some projects split their total sequestration volume across multiple registries, or accumulate future removals into a single cumulative value, this double-counting check necessitated line-by-line project-level verification using web searches of publicly available information. This process resulted in the creation of a database with 603 unique projects, including both nature-based and non-nature-based approaches.

Database Name	**Date Accessed**	**Ref**
Berkeley Goldman School Voluntary Offsets Registry Database	*31/07/22*	[101]
Verra Standard Registry Database	*31/07/22*	[102]
Gold Standard Project Registry	*31/07/22*	[103]
American Carbon Registry Database	*31/07/22*	[104]
Carbon Action Reserve Database	*31/07/22*	[105]
Stripe CDR Purchase Database	*31/07/22*	[106]
Microsoft CDR Purchase Database	*31/07/22*	[107]
Carbon(plan) CDR Database	*31/07/22*	[108]
Thirdway CDR Project Database	*31/07/22*	[109]

Global Carbon Capture and Storage Institute Database	*31/07/22*	[110]
MIT's Carbon Capture & Sequestration Technologies Database	*31/07/22*	[111]
ID-RECCO Project Database	*31/07/22*	[112]
CIFORs GCS-REDD+ database	*31/07/22*	[113]
Forestry Trends Ecosystem Markets Database	*31/07/22*	[114]
UN FCCC's Clean Development Mechanism project database	*31/07/22*	[115]
Innovation for Cool Earth Forum (ICEF) BiCRS Roadmap 2021	*31/07/22*	[78]
Marginal Carbon CDR Purchase Database	*31/07/22*	[116]
European Biochar Initiative Report	*31/07/22*	[117]
North American Biochar Initiative Report	*31/07/22*	[118]
China Bamboo Association Annual Report	*31/07/22*	[119]

Table 1. List of the twenty unique registry databases and access dates used to compile an estimate of current global CDR deployment.

Once the project-level database was compiled the next step was to derive annual sequestration estimates for projects missing data. This was done following three separate protocols. First, for reforestation/afforestation projects, which make up 486 of the 603 projects, project size data was standardized as total hectares reforested. Hectares reforested were then converted into annually sequestered carbon using empirically derived logarithmic, geography-specific sequestration curves that measure carbon sequestration rates based on forest location and age. [93] Second, for soil-sequestration-related projects, total project hectares were combined with literature estimates of sequestration rates per hectare. [120] Thirdly, all remaining projects had publicly available annual sequestration data available in their registries or web-pages, which was employed. As a final step, each project was assigned a CDR pathway describing its movement of carbon between pools and reservoirs, and whether that pathway classifies as an atmospheric removal or carbon transfer. The total annual sequestration rate for each unique pathway was then summed and recorded.

Estimating total anthropogenic CDR

As discussed above, estimating total anthropogenic CDR necessitated combining data on registered CDR projects with estimates of CDR generated via land use, land-use change and forestry (LULUCF) [121]. It is challenging to quantify CO_2-LULUCF fluxes [121-128]. The most recent IPCC assessment gives a relative uncertainty estimates of ±70% for the annual, net anthropogenic CO_2 emissions flux from LULUCF and highlights that *"net anthropogenic CO_2 emissions from land use, land-use change and forestry (CO_2-LULUCF) are subject to large uncertainties and high annual variability, with low confidence even in the direction of the long-term trend."* [126]

There are at least two established approaches to estimate anthropogenic CO_2 fluxes from LULUCF: the first is biosphere bookkeeping models as originally proposed by Houghton (2003) [128]. The second is data from national greenhouse gas inventories (NGHGIs) submitted to the UNFCCC, which contain country-level self-reported data on the impact of human activity on specific carbon sinks and sources. Both quantification approaches differ in the way they define what constitutes an "anthropogenic" CO_2 flux. Bookkeeping models separate natural from anthropogenic drivers, i.e. effects of changes in environmental conditions from effects of land-use change and land management. By contrast, the NGHGI approach separates fluxes based on areas, with all those occurring on managed land being declared anthropogenic [121-123, 125]. These conceptual differences give rise to an enormous divergence between CO_2 LULUCF estimates from bookkeeping models and NGHGIs. The mean projection of bookkeeping models suggests managed land results in a net source of ~3.2±2.3 $GtCO_2$ per year, while NGHGI data suggests a net sink of ~1.6±0.5 $GtCO_2$ [121, 124].

In an ideal world we would quantify land-based CDR as the gross flux into the biosphere resulting from human management activities alone. This is not possible using the generally more accurate NGHGI data, which estimates only net fluxes such as total net flux, net flux from forested land, net flux from deforestation, and so on. Therefore, for our deployment estimate we approximate the desired gross flux by applying

adjustments to an aggregated and standardized NGHGI database developed by Grassi et al (2022) [124]. Firstly, we began with the total net LULUCF flux. We then removed all non-forest-management flux estimates, including the impact of deforestation and peat fires. To address missing indirect-effect variability from the NGHGI data [124-125], we applied annual mean variance estimates generated through historical runs of the OSCAR model to the measured mean NGHGI flux. [121] Finally, we subtracted OSCAR's estimated total indirect effect fluxes from the adjusted NGHGI data to leave us with an approximation of the isolated direct impact of human activity in the forest sink. (Figure 3).

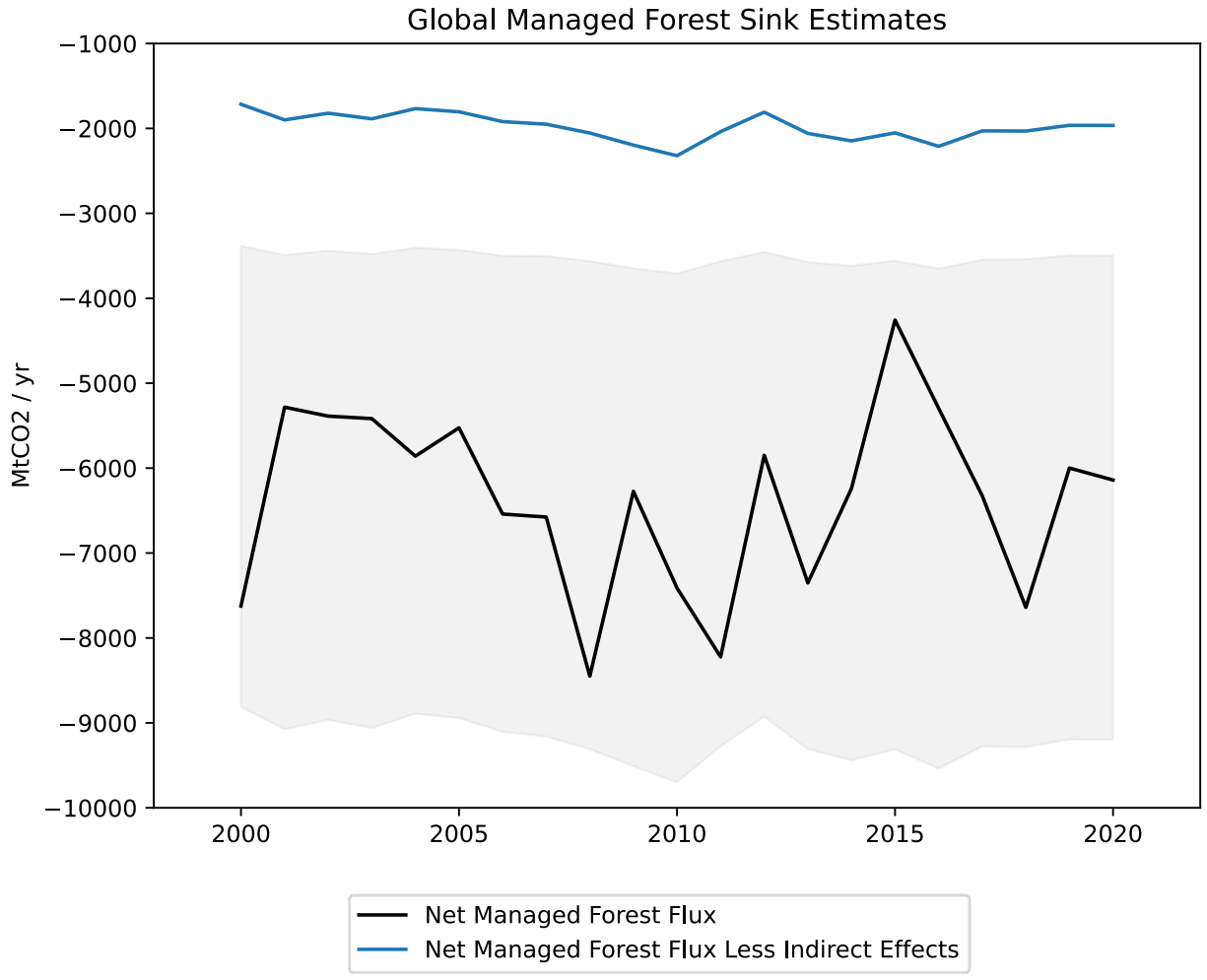


Figure 3. *NGHGI annual net managed forest flux, adjusted to include indirect effect variability (Black). NGHGI annual net managed forest flux, less indirect effects (Blue), the estimate of managed land sequestration we use here. Shaded grey area indicates range of uncertainty on NGHGI estimates.*

Because annual crops and forest residues (deadwood) are considered in equilibrium with the atmosphere under the UNFCCC reporting guidelines, CDR methods that use annual crops and forest residues as methods of capture (e.g. BECCs and Biochar) are not double-counted in the land sink quantification and so were not removed from our estimate. [96] Finally, because HWPs present an important source of carbon transfers out of the biosphere and into products, we needed to separately quantify the total production of HWPs at a global scale. For this, data was taken directly from the FAOSTAT Forest Product Statistics database, and converted from units of production into tons of CO_2 following the methodology in the UNFCCC Guidelines for National Greenhouse Gas Inventories. [96]

Comparing deployment to target-consistent scenarios

In order to compare our real-world CDR deployment estimate to different possible mitigation scenarios, we use the Shared Socioeconomic Pathways. [129] Specifically, we investigate how our deployment estimate compares to various levels of climate ambition under SSP1, a sustainability-focused development pathway, SSP2, a middle-of-the-road development pathway, and SSP5, a fossil-fuel led development scenario. These scenarios split CDR deployment into two variables: total engineered carbon capture, and the net flux resulting from land use, land use change and forestry (LULUCF).

There are two problems with this approach. Firstly, all engineered CDR projects are assumed to be atmospheric removals, not carbon transfers. Because the volume of deployed carbon transfers other than harvested wood products is currently zero (e.g. BECCS using lumber), this does not present a problem for our analysis, but it could in the future. Secondly, the necessary variables do not exist to replicate our NGHGI gross-sink

estimate using SSP data: while the SSP LULUCF estimates are already net of indirect effects, it is not possible to ensure the list of included and excluded land fluxes are apples-to-apples. This is a critical problem that will need to be addressed in future work.

Results

We estimate that, in 2022, human society globally is generating 1985 $MtCO_2yr^{-1}$ of atmospheric removals, and an additional 222.9 $MtCO_2yr^{-1}$ of carbon transfers between non-atmospheric reservoirs. Of the 1985 $MtCO_2$ yr^{-1} of atmospheric removals, 1982.7 (>99.9%) are generated through land use management practices – mainly forest management. (Figure 4) An estimated 207.5 $MtCO_2yr^{-1}$ of these removals (10.4%) are accounted for via registered land sink enhancement CDR projects, meaning the vast bulk of CDR is not reported as part of a specific CDR project. The remaining 2.3 $MtCO_2yr^{-1}$ removals are generated outside LULUCF-related CDR and are divided as follows: 1.82 $MtCO_2$ yr^{-1} of BECCs with geological storage, 0.5 $MtCO_2$ yr^{-1} from Biochar production, and 0.01 $MtCO_2$ yr^{-1} of other approaches, including DACCs, mineralization, aquatic biomass growth, and others. All 222.9 $MtCO_2yr^{-1}$ of carbon transfers are generated through the production of harvested wood products, specifically Sawnwood and Wood Panels. Other categories of HWP are excluded from carbon transfers as they have half-lives less than those of the trees they are made of, and as such represent not CDR activity but an acceleration of emissions from forest carbon stock.

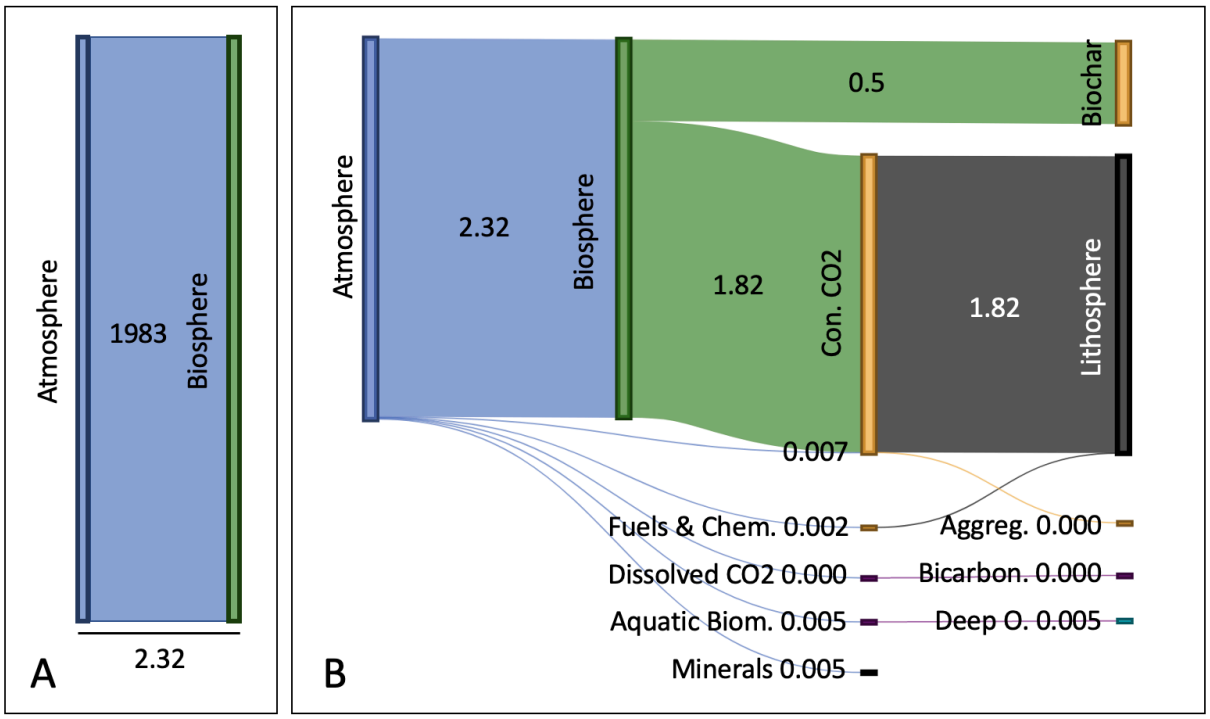


Figure 4. *(A) A to-scale carbon stock-and-flux diagram of total Atmospheric Removals currently generated by global management of the land sink and deployment of CDR projects, measured in $MtCO_2yr^{-1}$. (B) A zoom in on the 2.3 $MtCO_2yr^{-1}$ of Atmospheric Removals generated by deployment of CDR projects.*

There are a number of CDR projects currently in development that will become operational over the course of this decade. As such, it is possible to develop a baseline estimate of future CDR deployment by assuming no new projects are initiated, and all in-development projects are completed. Under this assumption, non-land-management atmospheric removals will grow from 2.3 $MtCO_2$/yr in 2022 to 11.75 $MtCO_2$/yr by end-of-year 2024, driven almost entirely by the completion of the Summit Carbon Solutions BECCs project, which involves bringing online 30 coupled Ethanol-production / BECCs plants and associated geological storage. By 2030, the remaining in development projects will be completed, bringing the total engineered atmospheric removal volume to 22.76 $MtCO_2$/yr, accounting for several large developments including two Drax BECCS plants, and one of Carbon Engineering's two in-development Mt-capacity DACCS

plants. By 2030 the annual volume of non-land-management atmospheric removals other than BECCS and DACCS will remain well below 1 $MtCO_2yr^{-1}$ in volume. Given this deployment trajectory, by 2025 "engineered" CDR activity will have sequestered a cumulative 31.49 $MtCO_2$, of which 29.48 $MtCO_2$ will be via lithospheric storage. By 2030, the total cumulative value will approach 124.93 $MtCO_2$.

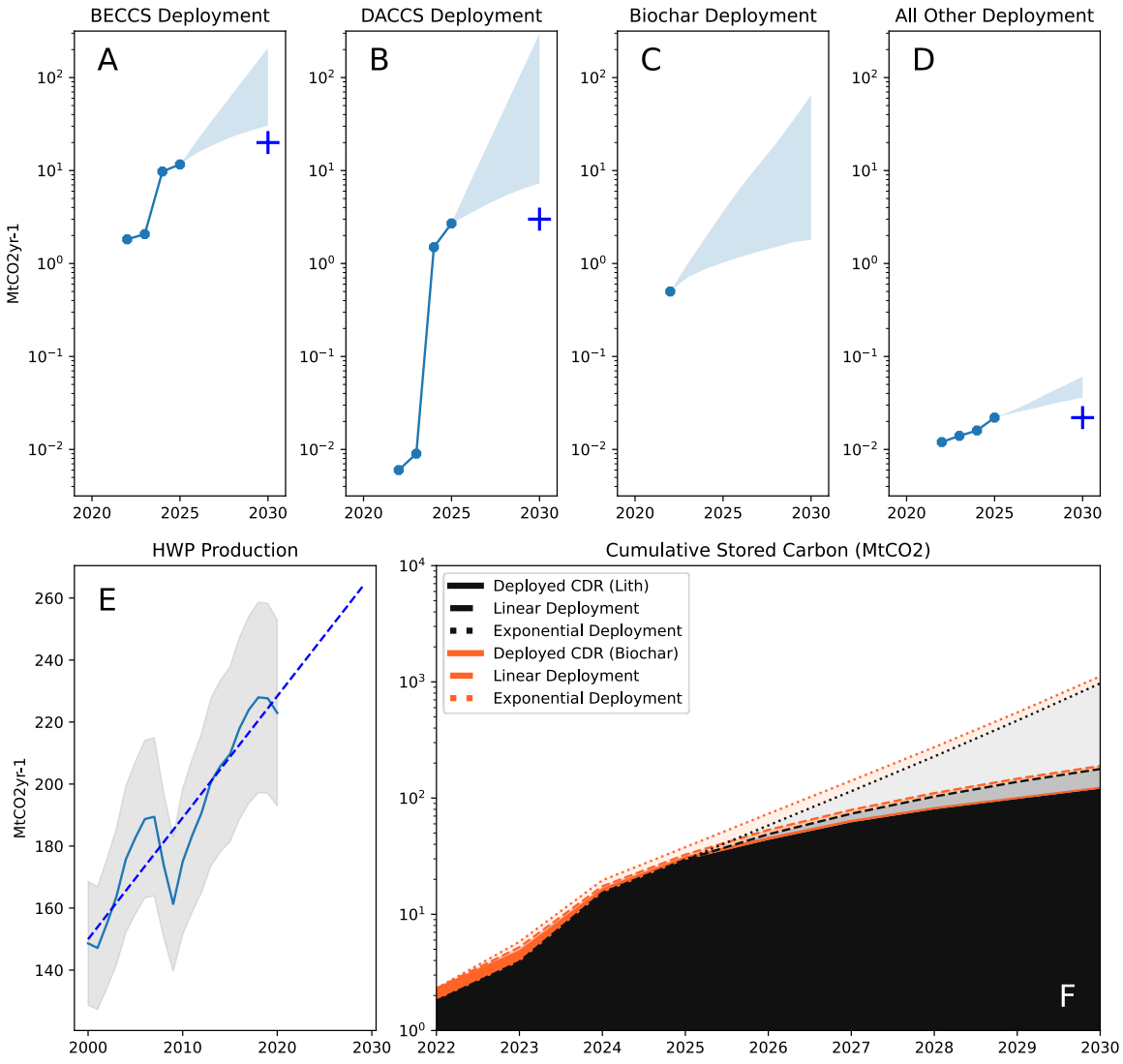


Figure 5. *(A-D) Deployment of various forms of engineered atmospheric removals, measured in $MtCO_2yr^{-1}$. Light blue projection indicates a lower (linear) and upper (exponential) fit to 2020-2025 deployment data. The dark blue crosses indicate 2030 deployment if only currently in-development projects are completed. (E) Harvested*

Wood Product production, measured in $MtCO_2yr^{-1}$. (G) Cumulative atmospheric removals by final storage reservoir, given observed deployment, continued linear deployment, and continued exponential deployment. Measured in $MtCO_2$.

To project future CDR deployment, we can also extrapolate current deployment data, given it is unrealistic to assume that there will be no additional project development between now and 2030. To provide a rough range of what might be expected, we fit both linear and exponential functions to the 2020-2025 deployment data for each type of CDR project to serve as plausible upper and lower bounds. Under these assumptions, by 2030 we could see between 30.5 and 208.5 $MtCO_2yr^{-1}$ of BECCs deployment, 7.3 and 297.5 $MtCO_2yr^{-1}$ of DACCs deployment, 1.8 and 65 $MtCO_2yr^{-1}$ of Biochar deployment, and 0.036 and 0.061 $MtCO_2yr^{-1}$ of all other approaches, including enhanced weathering and blue carbon management. (Figure 5). While the exponential extrapolations seem large, it is important to note that despite persistently linear forecasts, solar and wind deployment have exhibited exponential trends for a number of decades [130] and similar dynamics for CDR technologies cannot be ruled out. That said, the farther out a projection is made, the more likely an S-curve or other functional form could provide a better fit, given factors including diminishing marginal returns to economies of scale, decreasing demand, or resource limitations [131]. Because we have 20+ years of data for HWP production which demonstrate a clear linear trend, and lack a plausible theoretical explanation for a future exponential trend, we only conducted linear extrapolation for HWPs, leading to estimates of 260 $MtCO_2yr^{-1}$ HWP production by 2030.

Comparing CDR deployment to scenario estimates

To conclude, we wanted to understand how current CDR deployment compares to deployment assumed under different levels of climate ambition within the SSPs. Here we look at scenario estimates of CDR deployment for RCP1.9, 2.6, 3.4, and 4.5 across SSPs 1, 2, and 5. (Figure 6). Under any SSP restricting warming to 1.9 w/m^2 by end of century, roughly equivalent to a 1.5°C future warming scenario, both linear and exponential extrapolation of current deployment rates result in insufficient CDR

volume by 2030. Given exponential growth, current deployment would result in 550 $MtCO_2$/yr by 2030, while the SSP with the slowest CDR deployment (SSP5-19) sees CDR reaching 650 $MtCO_2$/yr over the same timeframe. Continued exponential growth of current deployment is most closely aligned to the SSPs limiting total end-of-century radiative forcing to below 2.6 w/m^2, (a roughly "well-below" 2°C scenario) while continued linear growth of current deployment is aligned roughly with the lower-end scenarios leading to a radiative forcing of 4.5 w/m^2 (an above 2°C scenario). In short, while there are a wide range of different CDR deployment estimates produced by IAMs running the SSP scenarios, maintaining alignment with a "well-below 2C" scenario would likely require current CDR deployment to grow at least exponentially through to the end-of-the decade, adding a minimum 300 $MtCO_2$ of CDR capacity.

It is important to note that the discussion thus far has been limited to CDR that stores carbon in reservoirs other than the biosphere. Given the size of the biosphere, changes to its carbon stores will inevitably play an important role in most "well-below 2C" mitigation scenarios, reflected by a substantive decrease in net LULUCF emissions across the SSPs that achieve this warming target. As it is not possible to compare present-day deployment estimates to SSP LULUCF emissions (for reasons discussion above), the conclusions that can be drawn about present-day deployment volumes here are limited. That said, given deforestation emissions are a major component of net LULUCF emissions (roughly 4.3 $GtCO_2$/year), a major driver of changes in the scale and direction of LULUCF emissions under different future mitigation pathways is likely to be driven by reductions in deforestation in partnership with a major scale-up of biosphere-based CDR methods.

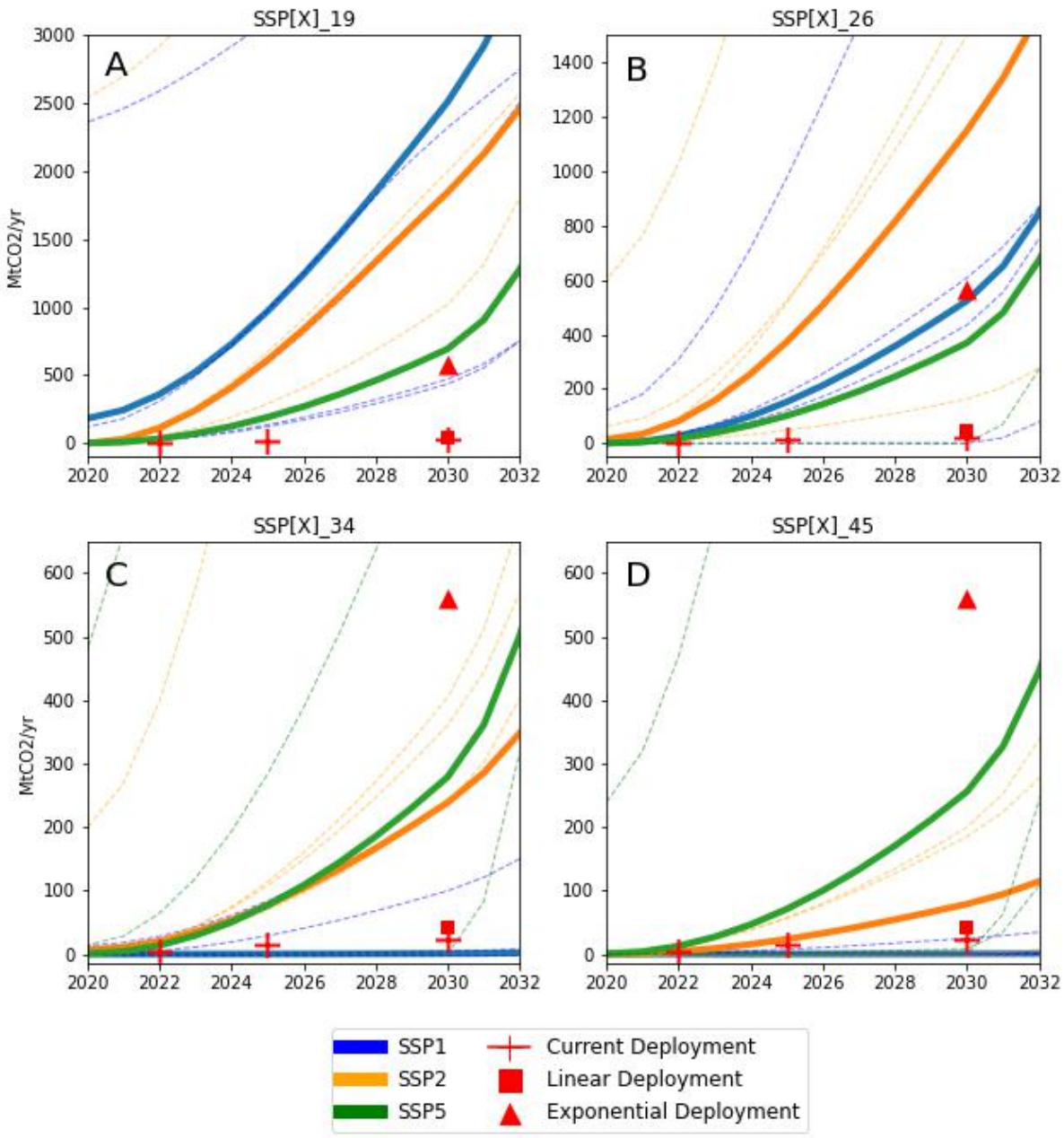


Figure 6. *(A) Total engineered CDR deployment across three SSPs that result in an end-of-century atmospheric forcing of 1.9 w/m^2: SSP1-19, SSP2-19, and SSP5-19. (B) The same for an end-of-century forcing of 2.6 w/m^2. (C) The same for an end-of-century forcing of 3.4 w/m^2. (D) The same for an end-of-century forcing of 4.5 w/m^2. Current deployment of engineered CDR, as well as linear and exponential extrapolation of that data are in red.*

Discussion

Data availability and quality represent the single largest uncertainty in our results. Because there is no central registry for CDR projects, and the database developed here was put together using multiple different sources including project-by-project web searches, the data is undoubtedly incomplete or subject to error. The most substantial gap impacting our estimate of CDR project deployment is the limited geographic coverage of available data. Most databases cover CDR projects deployed in Europe and North America, but have minimal project entries from any other geographies.

Additionally, because, unlike BECCS and DACCS, biochar production takes place over smaller, more diffuse scales, and often not for the express purpose of generating CDR, we have had to depend on industry association reports to estimate production for the three geographies where such associations exist: Europe, the United States, and (partially) China. A second, and substantial, gap that exists is availability of lifecycle emissions data. As previously mentioned, most CDR projects provide annual sequestration volumes, but do not conduct and disclose lifecycle analyses. Finally, there is substantial uncertainty around the accuracy with which NGHGI reporting captures actual carbon fluxes to and from the global land sink. As discussed in detail in Grassi et al (2022), the accuracy of reported data is assessed to be within +/- 35% of the true fluxes for Annex I countries, and within +/- 50% for Non-Annex I countries, due to both ambiguity in the statistical methods used to prepare reports, and the so called "informal harvesting" problem. [120] We suggest, therefore, that one of the most important steps to ensure the sufficient development and deployment of CDR technologies is the development of a data pipeline that gathers, standardizes, and improves information about CDR projects, such that we can understand (a) how much CDR is being generated, and (b) how much more must be deployed to meet targets. The National Greenhouse Gas Inventories (NGHGIs) are one logical place where such infrastructure could be built for CDR projects, and improved for land use management, a topic already being discussed at length elsewhere. [124-127].

Despite these uncertainties, we suggest our results are sufficient to draw three important conclusions: first, that despite the acceleration of interest and finance directed towards CDR development, current deployment will have to grow exponentially to keep the world on track with the assumptions made by 1.5°C and 2°C SSPs. Secondly, they demonstrate that there is a more diverse set of CDR approaches being deployed in the real world compared to model assumptions, and that the bulk of projects deployed in the real world sequester carbon temporarily in the biosphere, highlighting the importance of reconciling temporary CDR use with existing emissions accounting methods. Thirdly, and finally, our results highlight that resolving uncertainties in the measurement of LULUCF fluxes will be essential to determining the sufficiency of CDR deployment efforts going forward. Specifically, both national inventories and IAM-derived mitigation scenarios should provide detailed information regarding the evolution of forest area, subdivided by forest type [132] as well as the gross carbon fluxes (i.e. positive and negative, human-caused and indirect) resulting from the assumed changes in forest area, following a common framework that would enable like-for-like comparison [125]. Only with these advances will it be possible to maintain an accurate stock-take of ongoing CDR activity aimed at achieving a particular climate goal.

3. On the dynamics of temporary carbon dioxide removal

This paper applies both an Earth-system Model of Intermediate Complexity (EMIC) and an emulated perturbed parameter ensemble to build an understanding of the climate system response to tCDR under different climate states and deployment scenarios. These results inform the physical requirements any valuation or exchange metric must account for in equating CDR projects with different storage lifetimes. This paper demonstrates that temperature overshoot due to re-release of temporarily-stored carbon in a post-net-zero climate state is insignificant across a reasonable set of scenarios and therefore that tCDR can be conceptualized directly as a time-fractional permanent removal.

On the dynamics of temporary carbon dioxide removal

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Abstract

Carbon dioxide removal will be required to meet the goals of the Paris Agreement. However, not all carbon removal methods store carbon permanently, and our understanding of the coupled climate-carbon-cycle system's response to temporary carbon dioxide removal is still nascent. Initial investigations suggest temporary carbon dioxide removal can trade short term cooling for long-term warming relative to a counterfactual with no removal. Here we employ an Earth System Model of Intermediate Complexity (EMIC) and an emulated ensemble of Earth System Models (ESMs) to demonstrate that while temporary carbon dioxide removal can result in a cumulative atmospheric CO2 overshoot following re-release of stored carbon (the magnitude of which is determined strongly by the ocean overturning rate). In all cases, the resulting temperature overshoot is small relative to natural climate variability even given hundreds of billions of tons of carbon removal. As such, from an impact measurement perspective, temporary CDR can be approximated as a fractional permanent removal. These findings have important implications for emissions accounting metrics seeking to measure the impact of temporary carbon removals, which will require understanding and incorporating these dynamics.

Main

Given stubbornly high global emission levels and a rapidly dwindling remaining carbon budget, large-scale carbon dioxide removal (CDR) is increasingly cited as a necessary input to achieving the stated goal of the Paris Agreement: limiting the increase in global average temperature to well below 2°C, and pursuing efforts to limit warming to 1.5°C. [42] The IPCC has identified three possible roles for CDR: (a) accelerating near-term mitigation, (b) achieving net-zero emissions by compensating for hard-to-abate residual emissions; and (c) generating net negative emissions for reducing anthropogenic forcing. [74] Across modeled well-below-2°C mitigation pathways, the volume of CDR required to fulfil these roles ranges from several hundred to a thousand gigatons of carbon dioxide (CO_2) before the end of the century. [42] Scaling up such large volumes of CDR presents a myriad of problems (most importantly, "who will pay"?) [70], but methodological challenges also exist.

In particular: the Paris Agreement provides a mechanism for the trade of mitigation outcomes between parties in order to maximize the economic efficiency with which decarbonization is pursued. [73] The trading of different mitigation outcomes requires metrics to equate their climate impact. While the climate impact of permanently removing a ton of CO2 from the atmosphere during a period of ongoing emissions is demonstrably 1:1 (thanks to the well-established linear relationship between cumulative emissions and warming [30]) this relationship breaks down in a climate state of net-negative emissions, with each increasing ton of removals exhibiting a smaller impact on atmospheric CO2 concentration. [47-55] Thus, new equivalency metrics will be needed to facilitate the trade of CDR deployed towards achieving net negative emissions.

Nature-based solutions, which are both the most cost-effective CDR methods and make up the majority of deployed CDR solutions today, do not permanently store the CO_2 they remove from the atmosphere. [44] One of the most commonly cited roles for tCDR in mitigation strategy is "peak shaving", that is, reducing peak warming by deploying large

volumes of temporary storage around the point at which net-zero emissions are achieved, and then compensating for the re-release of that carbon over the long-term with more expensive technical methods. [60] Importantly, the dynamics underlying the Earth-system response to tCDR deployed around and after achieving net-zero are more complex than that of permanent CDR, and are not well understood. Preliminary work suggested such deployment could cause long term warming relative to the counterfactual scenario in which said tCDR never occurred, in contrast to the temporary cooling and neutral long-term impact that results from deployment during ongoing emissions. [57, 65] The proposed mechanism for this temperature overshoot effect is as follows: initial removal causes a decline in atmospheric CO_2, which in turn induces the global carbon cycle to re-equilibrate, producing a "rebound" in atmospheric CO_2 following removal. When stored carbon is then re-introduced to the atmosphere, CO_2 concentrations peak above starting conditions before declining on the order of about three centuries. [57, 65]

There is good reason to believe that the impact of temporary CDR is state-dependant. In its simplest form, temporary CDR can be broken down into a removal of CO_2 from the atmosphere followed at a later point by an equivalently sized emission. It is known that the Transient Climate Response to Emissions (TCRE) is path-invariant but volume and state dependant (it decreases with increasing cumulative emissions and background atmospheric CO_2 concentrations, and increases in transient climate states with declining atmospheric CO_2). [49, 133] The Transient Climate Response to Removals (TCRR) has also been shown to exhibit volume and state-dependence [49] – the greater the perturbation to the climate system the more the climate system 'resists' CDR through outgassing from the ocean and land, while the more saturated the climate system is with carbon, (a) the less outgassing occurs and (b) the less cooling impact a given ton of removals has due to the band saturation effect. [46-49, 55] Furthermore, it is known that asymmetries in the climate response to emissions and removals result in the TCRR being larger than the TCRE across multiple climate states, and that this

asymmetry itself is not state invariant but increases with background atmospheric CO_2 concentration. [49]

Here, we employ the University of Victoria Earth System Model (UVic ESCM v.2.10), an Earth-system model of intermediate complexity, to investigate the dynamics underlying the climate response to temporary CDR under different states. We also employ a 10,000-member perturbed parameter ensemble of emulated Earth-System Models (ESMs) from the sixth Coupled Model Intercomparison Project (CMIP6), using the FaIR v2.0.0 simple climate model, to investigate the sensitivity of our results to varying Earth system parameters. In doing so, we demonstrate that tCDR deployed to generate net-negative emissions can cause a cumulative atmospheric carbon overshoot upon re-release of stored carbon, the magnitude of which is determined primarily by the strength of ocean turnover rates. This overshoot increases with removal size and storage lifetime, and decreases with background atmospheric CO_2 concentration and non-instantaneous deployment pathways. Finally, we demonstrate that the magnitude of temperature overshoot resulting from tCDR deployment is small relative to natural climate variability across all scenarios, given even hundreds of GtC of removals, and as such from an impact-measurement perspective tCDR can be approximated as a fractional permanent removal with respect to time.

Temporary CDR in an equilibrium climate

We first examined the impact of different CDR sizes and storage lifetimes in an equilibrium climate state. Instantaneous removals of 100, 300, and 500 GtC were applied to a pre-industrial equilibrium climate and stored for periods between 20 and 60 years before being re-released to the atmosphere. No forcing other than CO_2 was applied. (Figure 1) We also investigated the impact of changing background equilibrium state, applying the same removals to a 2x-pre-industrial- CO_2 equilibrium. (Sup. Figure 1). While a 100 GtC removal is much larger than any given one-off CDR project that could be applied in reality, this is the minimum removal size necessary to extract a statistically significant signal from natural variability simulated by the UVic ESCM. We expect the

dynamics demonstrated by a 100 GtC removal to scale proportionally down to smaller quantities, which would be relevant for the measurement of individual removal credits. The simulations produced by UVic ESCM and the emulated CMIP6 ensemble agree on the broad dynamics of the climate response to temporary CDR. The initial carbon removal causes an instantaneous drop in atmospheric CO_2 , and then a rebound as the reduced partial pressure of CO_2 in the atmospheric causes a release of stored carbon from the ocean and biosphere in an re-equilibration process. This rebound is driven in the near-term by the slow decline in soil respiration rates on land (which scale with temperature) relative to the immediate decline in NPP (which scales with atmospheric CO_2), and in the long-term by the release of carbon from the ocean's mixed layer given the negative CO_2 gradient at the sea-surface. [49] As a direct result of this process, when the carbon removal is re-introduced to the active carbon cycle at the end of storage, atmospheric CO_2 and temperature peak above starting conditions for multiple centuries.

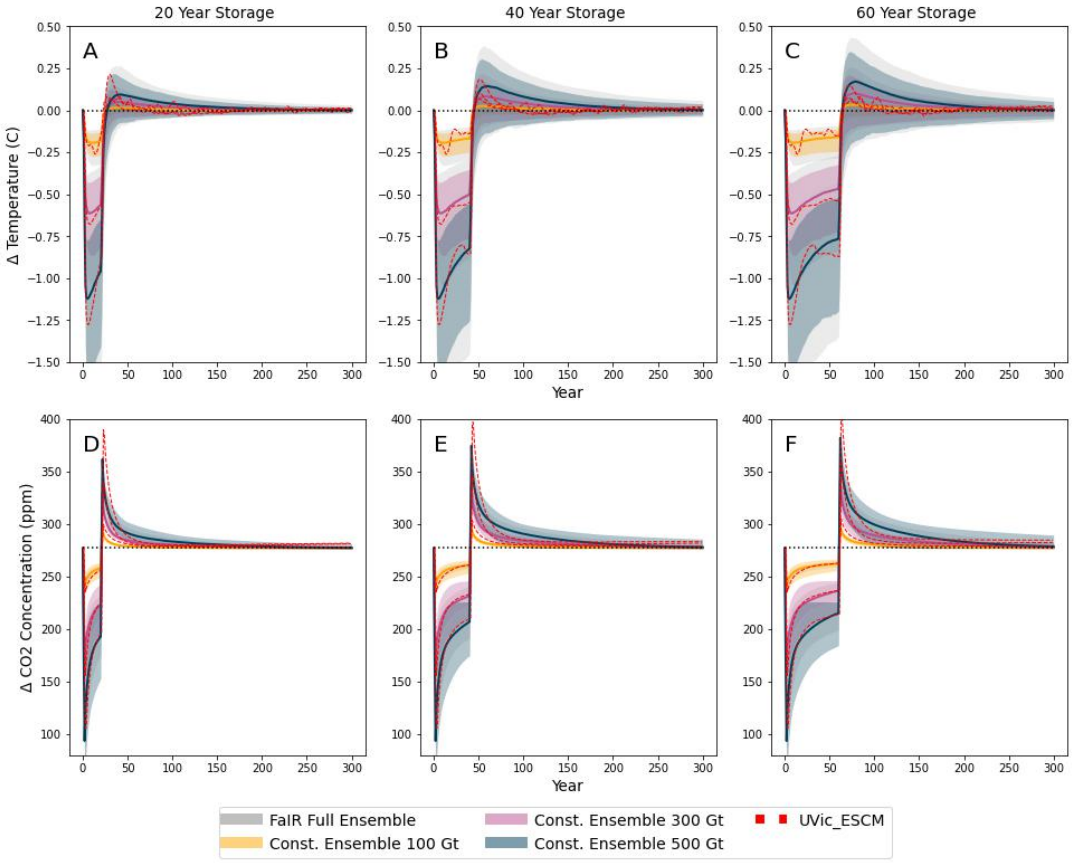


Fig. 1: Global average temperature and atmospheric CO_2 concentration response to temporary CDR in an equilibrium climate. A-C, *global average temperature response to temporary CDR with storage lifetimes of 20, 40, and 60 years respectively. Mean emulated CMIP6 ensemble results plotted as lines, with the observationally-constrained results shaded and full ensemble results shaded in gray . UVic ESCM results in red.* ***D-F,*** *atmospheric CO_2 concentration response to temporary CDR, coloring the same.*

When measuring the magnitude of atmospheric CO2 overshoot resulting from tCDR, we use a cumulative ton-year metric, integrating the overshoot in atmospheric carbon content over time relative to starting conditions. This metric captures both the duration and magnitude of overshoot, which are used in many valuation methods [65], and also reduces uncertainty introduced by the instantaneous release of stored carbon, which may produce uninformative transient concentration peaks. When examining cumulative overshoot across both the emulated and modelled equilibrium experiments, three important observations stand out. (Figure 2) Firstly, and trivially, the larger the removal, the larger the cumulative overshoot, given greater outgassing from carbon sinks and the well-established increasing airborne fraction with increasing emission pulse size. [135] For example, for a 40-year tCDR, increasing removal size from 100 GtC to 500 GtC increases the mean cumulative overshoot 6x from ~1 to 6 TtC-years. Secondly, as storage lifetime increases, the cumulative overshoot also increases, by virtue of allowing the global carbon sinks more time to outgas stored carbon during equilibration with the atmosphere, and thus a resulting in a higher background atmospheric concentration to which re-released removals are exposed. For a 300 GtC tCDR, increasing storage lifetime from 20 to 60 years doubles mean cumulative overshoot from ~2 to 4 TtC-years. Of these two effects, increasing removal size has a dominant effect in the long run, given the maximum magnitude of carbon cycle rebound approaches an asymptote with increasing storage lifetime as the climate system approaches re-equilibration. Thirdly, and finally, when considering the full emulated ensemble of Earth-system models, the larger the tCDR the more sensitive the cumulative overshoot is to variance in key climate system parameters. For example, the ensemble

interquartile range of cumulative overshoot for a 100 GtC removal stored for 20 years is ~100 GtC-years, while for a 500 GtC removal the range is 10x larger, at 1 TtC-years. This is relevant insofar as in order for tCDR to be a policy-relevant intervention it must be deployed at scale, however the more tCDR we deploy the less certain we can be about the resulting impact on the climate system.

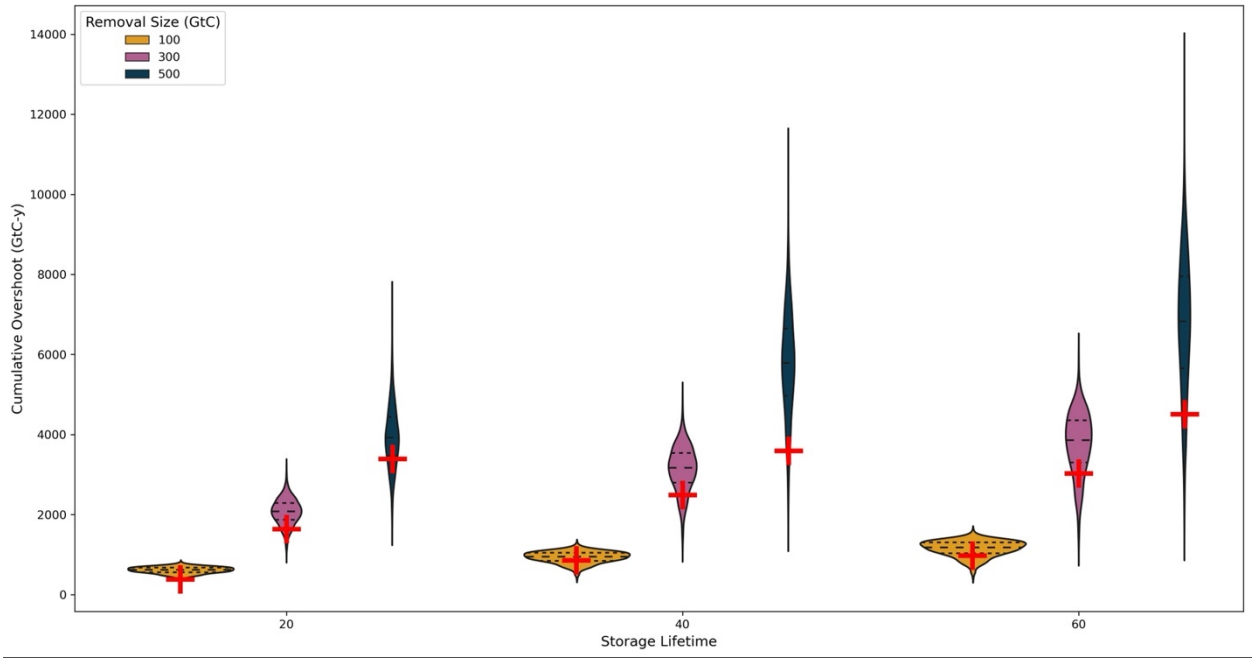


Fig. 2: Cumulative overshoot resulting from tCDR experiments. *The cumulative overshoot, measured in tC-years following the re-release of 100, 300, and 500 GtC stored for 20, 40, and 60 years, respectively. The vertical range of a given plot represents the range of projections across the emulated perturbed parameter ensemble of Earth-system models, while the horizontal width of a plot represents the probability density of that value within the ensemble. UVic ESCM results plotted as individual markers.*

In order to decompose which aspects of the Earth system are most responsible for the large spread in cumulative overshoot values across experiments, we conducted a global sensitivity analysis of the influence of our observationally-constrained 10,000-member

sample of the simplified CMIP6 ESM parameter space. Of the 21 tunable parameters in the FaIR model, 9 take standard values, and 12 are tuned, of which one parameter (f2) takes a universal value of 0, leaving an investigable parameter set of 11. [136-137] The qualitative analogues of these parameters is as follows:

Table 1. Tuned climate system parameters of the FaIR v2.0 model

Parameter	**Qualitative Analogue**
d_i	Response timescale of the ith thermal box
q_i	Equilibrium response of the ith thermal box
$r0$	Strength of pre-industrial carbon uptake from atmosphere
rC	Sensitivity of carbon uptake from atmosphere to cumulative uptake of carbon since model initialization
rT	Sensitivity of carbon uptake from atmosphere to temperature change since model initialization
$f1$	Logarithmic concentration-forcing coefficient
$f2$	Square-root concentration-forcing coefficient

To investigate the influence of these 11 parameters we applied the Sobol method of variance-based sensitivity analysis, which allowed us to (a) measure sensitivity of cumulative overshoot to the entire input space, (b) capture any non-linear responses, and (c) measure the effect of interactions between parameters. For each parameter, the Sobol method calculates the first-order sensitivity, defined as:

$$S_i = \frac{Var(E(Y|X_i))}{Var(Y)} \quad (1)$$

where S is the first-order sensitivity of parameter i, $Var\left(E(Y|X_i)\right)$ is the variance in the cumulative overshoot only considering variation in parameter i, and $Var(Y)$ is total variance in cumulative overshoot. The first-order index measures the main effect contribution of parameter i to variance in cumulative overshoot. The Sobol method also

calculates the total-effect index, which measures the contribution of a given parameter to variance in cumulative overshoot including all interactions of any order with any other parameter, where $Var(E_{Xi}(Y|X_{\sim i})$ is the variance of cumulative overshoot with respect to all variables except parameter i:

$$S_{Ti} = 1 - \frac{Var(E_{Xi}(Y|X_{\sim i}))}{Var(Y)} \quad (2)$$

The results of this analysis are shown in Figure 3. Universally, across all experiments, the variance in cumulative overshoot can be described via a combination of variance in three ($0.4 < \sum S_i < 0.6$), and strong high-order interactions resulting from four ($\sum S_{iT} > 1$), of the 11 parameters: r0 (the pre-industrial sensitivity of the carbon cycle), rT(the sensitivity of the carbon cycle to changes in temperature), and d2-d3 (the equilibrium response of the second and third thermal boxes, which can be qualitatively equated to medium-to-long term response of the ocean temperature to change in forcing). Intuitively, this suggests a potential hypothesis: the cumulative overshoot could be decomposed into the initial sensitivity of the carbon cycle (which determines the height of the initial overshoot upon re-release), and the duration of the overshoot, determined by long-term carbon absorption into the ocean, which is causally linked with the long-term temperature response of the ocean, a phenomenon explored in depth by the ZECMIP experiment, in which the UVic ESCM model participated and the results of which the emulated ensemble used herein replicates well. [138] (See Methods)

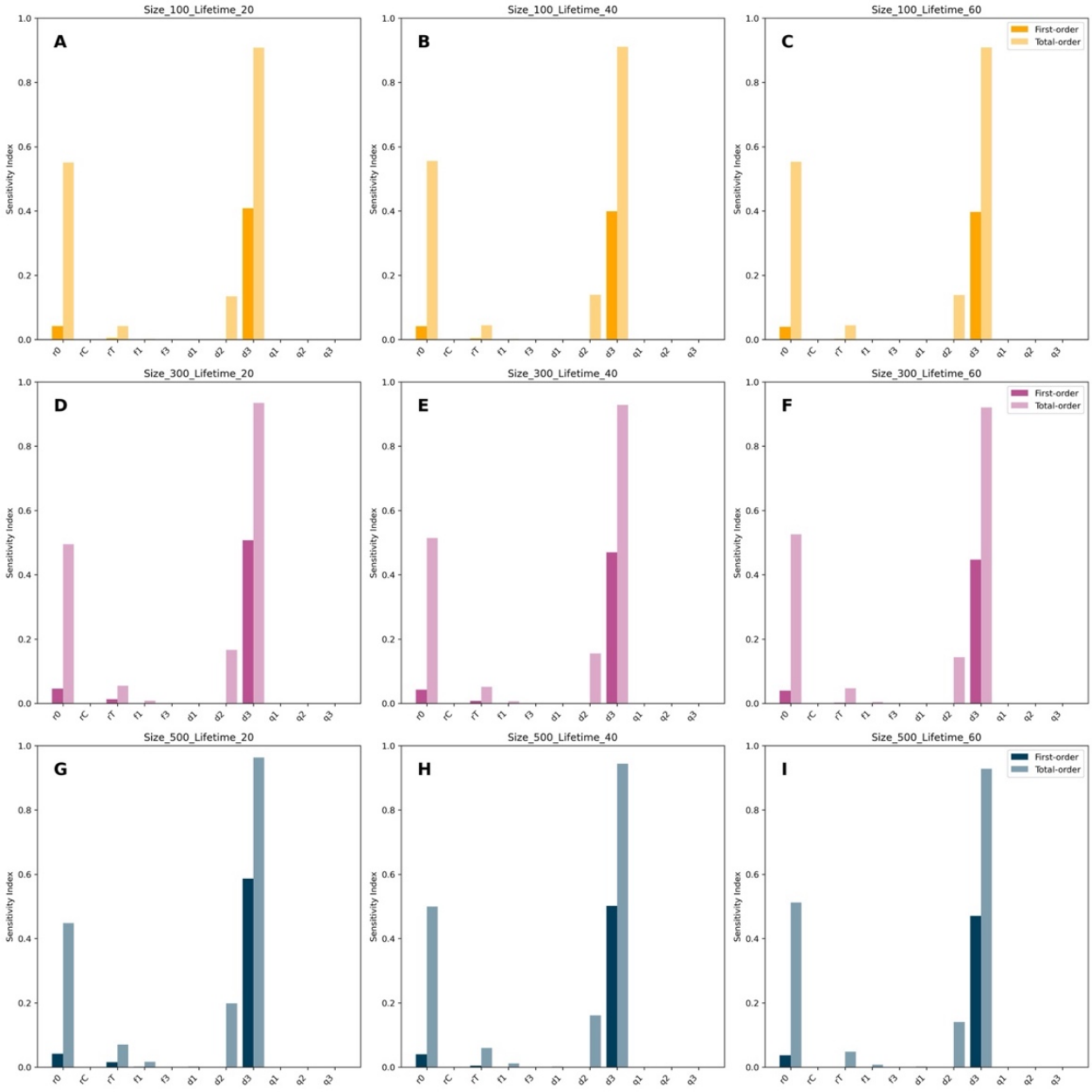


Fig. 3: Global sensitivity analysis of FaIR model parameters impact on cumulative overshoot across tCDR experiments. ***A-C,*** *first-order and total-effect Sobol indices measuring the influence of FaIR model parameters on cumulative overshoot across 100 GtC experiments.* ***D-F,*** *the same, for 300 GtC experiments.* ***G-I,*** *the same, for 500 GtC experiments.*

In order to test this hypothesis, we used the FaIR v2.0 model to diagnose the r0, rT, and d3 parameters of the UVic ESCM model, as well as the 5 CMIP6 ESMs which participated

in CDRMIP: CNRM-ESM2-1, CanESM5, MIROC-ES2-L, NorESM2-LM, and UKESM-0-LL. [47, 56] (Figure 4) The results are suggestive. UVic has a mean d3 response, representing a deep ocean thermal response on par with the mean of the CMIP6 ensemble. This implies an average rate of long-term carbon storage by the deep ocean, given carbon and heat invasion of the deep ocean are governed by the same mechanisms, a postulate further confirmed by examining the similar long-term ocean uptake response of UVic relative to five CMIP6 ESMs under the 1pctC02 experiments, and the ZECMIP experiments. (See Methods). Despite an average long-term ocean response, the UVic ESCM exhibits a low cumulative overshoot relative to the mean emulated ensemble across scenarios. What leads to the difference in behavior is a high r0 parameter (which determines the rate of fast sink response to initial emission in the atmosphere), and therefore the cumulative emissions area beneath the near-term impulse response function.

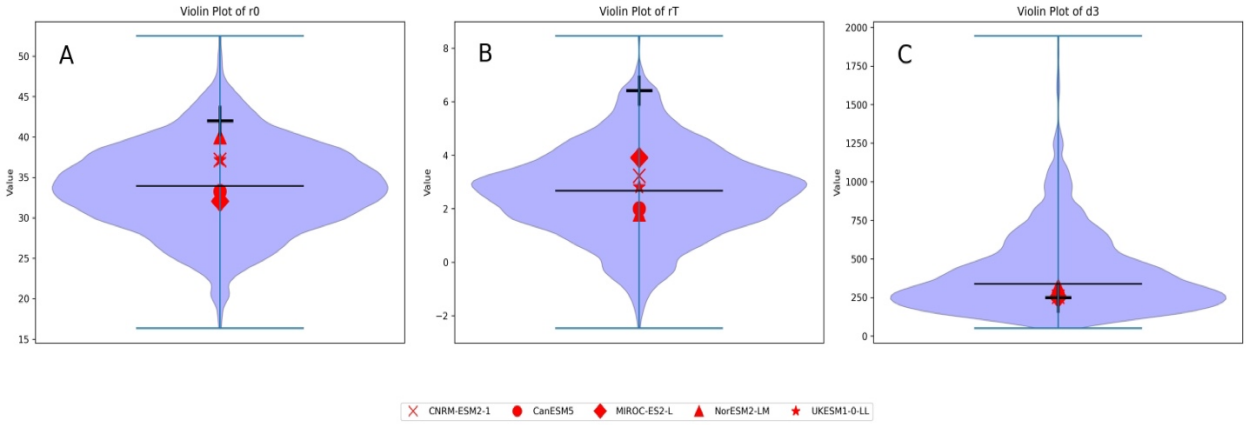


Fig. 4: Distribution plot of diagnosed parameters for the emulated and observationally-constrained CMIP6 ensemble, as well as the UVic ESCM and five individual ESMs. A, *the ensemble distribution of r0 (initial carbon-cycle sensitivity) values, UVic ESCM plotted as a cross.* ***D-F,*** *the same, for rT (climate-carbon feedback).* ***G-I,*** *the same, for d3 (equilibration timescale for the third thermal box).*

To further investigate the dynamics behind the UVic ESCM carbon-cycle uptake strength, we made use of its explicit quantification of fluxes of carbon between various

land and ocean sinks, starting with the atmospheric rebound following removal. Given a 500 GtC tCDR with a storage lifetime of 60 years (the experiment with the largest perturbation) at t=60 atmospheric carbon content is ~135 PgC lower than starting conditions. This represents a cumulative removal fraction, evaluated over storage lifetime s, of 0.27. The land sink outgasses ~190 PgC of carbon, and the ocean ~175 PgC, contributing 52 and 48% of the rebound respectively. (Figure 4). When comparing the net change in carbon content of the surface ocean relative to the ocean as a whole, the loss of carbon from the surface ocean to the atmosphere outpaces the replacement of carbon from upwelling by a cumulative sum of about 35 PgC, representing 20% of the ocean outgassing. (Figure 5) Geographically, the distribution of carbon loss and gain across the ocean surface follows well-established patterns, with (a) tropical regions showing more pronounced release due to higher temperatures and faster exchange rates with the atmosphere, (b) polar regions exhibiting slower response times and, in the most extreme latitudes, continued deep water formation, and (c) equatorial upwelling zones showing more muted release patterns compared to less productive areas. The nature and magnitude of this response are in line with previous studies which have conducted similar experiments [49-52], and the mechanics behind this rebound are well understood (as described at length in the introduction). As such, this portion of the experimental results are not novel, but instead confirmatory that the employed model is producing the correct order of magnitude of response and dynamics to carbon removal.

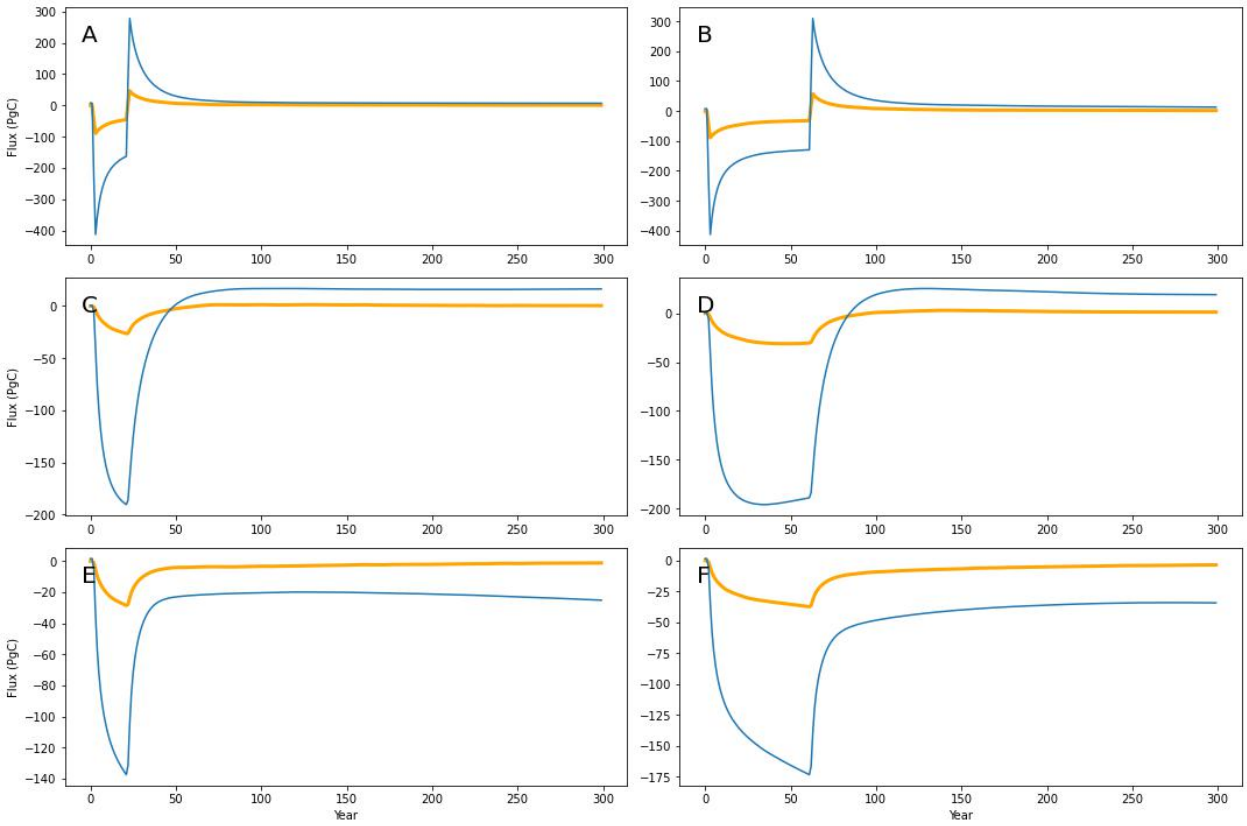


Fig. 5: Changes in carbon pool content in response to various tCDR experiments. A-B, *change in the atmospheric carbon pool across 100 (blue) and 500 (orange) GtC tCDR experiments with storage lifetimes ranging from 20-60 years.* ***C-D,*** *the same, for the land sink.* ***E-F.*** *the same, for the ocean.*

Following the re-release of stored carbon, the climate system returns to starting atmospheric CO2 concentrations on the order of two to three centuries after re-release. However, the return to equilibrium is not driven by a direct reversal of removal dynamics. Over the following two centuries the ocean regains 125 PgC of carbon (about 70% of the outgassed volume), the land surface regains ~240 PgC (126% of the outgassed volume). (Figure 4) This occurs because stronger hysteresis exists in the behavior of the ocean sink than the land sink. Specifically, non-linearities in the temperature and biogeochemical response of the surface ocean sink result in the saturation of the sink before it is able to re-absorb the carbon outgassed during removal. Meridional overturning circulation decreases more in response to temperature increase upon re-

emission than it increases in response to temperature decline on removal, and the buffer capacity of CO2 in seawater decreases non-linearly with CO2 partial pressures (pCO2) at the sea surface, resulting in a larger air–sea CO2 flux upon removal than upon re-emission. (Sup. Fig. 2) In the biosphere, net-primary productivity (NPP) scales immediately with changes in atmospheric CO2 concentrations, and therefore strengthens, while soil respiration scales with global average temperatures and as such lags the increase in NPP. This differential leads to short-term uptake of atmospheric carbon by the biosphere relative to surface ocean following tCDR re-release.

When we examine the flows of carbon within the ocean layers, not only does the entire ocean uptake less than was outgassed, but proportionally more of that carbon ends up in the surface ocean, which ends up regaining not 70% but 110% of lost carbon after 300 years, demonstrating a differential display of hysteresis across ocean depth layers. (Figure 6) This is interesting given (a) the UVic ESCM exhibits a roughly average land surface response to atmospheric emissions relative to the CMIP6 ensemble ESMs (see Methods), and a roughly average deep-ocean response, but an aggressive near-term surface ocean uptake. It is possible that this behavior is the result of the insufficiently resolved interaction between the dynamic ocean and slab atmosphere components of the model, which are incapable of capturing the impact of pattern effects and changing wind forcing on ocean circulation, which in turn are predicted to influence the rate of ocean mixing under changing climate forcing. [139]

In ESMs with weaker short-term ocean responses, we may see a more gradual immediate decline in atmospheric CO2 (and larger cumulative overshoot) following re-release of stored carbon, or (in models with more aggressive land-surface responses), a greater transfer of stored carbon between the ocean and land surface. It is important to note that the UVic ESCM version used in this study lacks a representation of the terrestrial nitrogen cycle and its interaction with the carbon cycle. This omission results in greater land carbon gain under increasing CO2 and more carbon loss with climate change compared to ESMs with nitrogen cycles. Under decreasing CO2, the model likely overestimates land carbon gain from climate changes alone, as it doesn't account for

reduced nitrogen mineralization at lower temperatures. The impact on carbon change due to CO2 concentration alone is less certain, as nitrogen limitation could further constrain CO2 fertilization effects, potentially offset by enhanced photosynthesis from lower carbon-nitrogen ratios. [48] Further investigation with a subset of the CDRMIP ESMs will be important not only to verify the general dynamics behind tCDR, but also to determine whether the magnitude of cumulative overshoot following tCDR scales more closely with surface-ocean response, as suggested by UVic, or deep-ocean response, as suggested by the emulated FaIR ensemble.

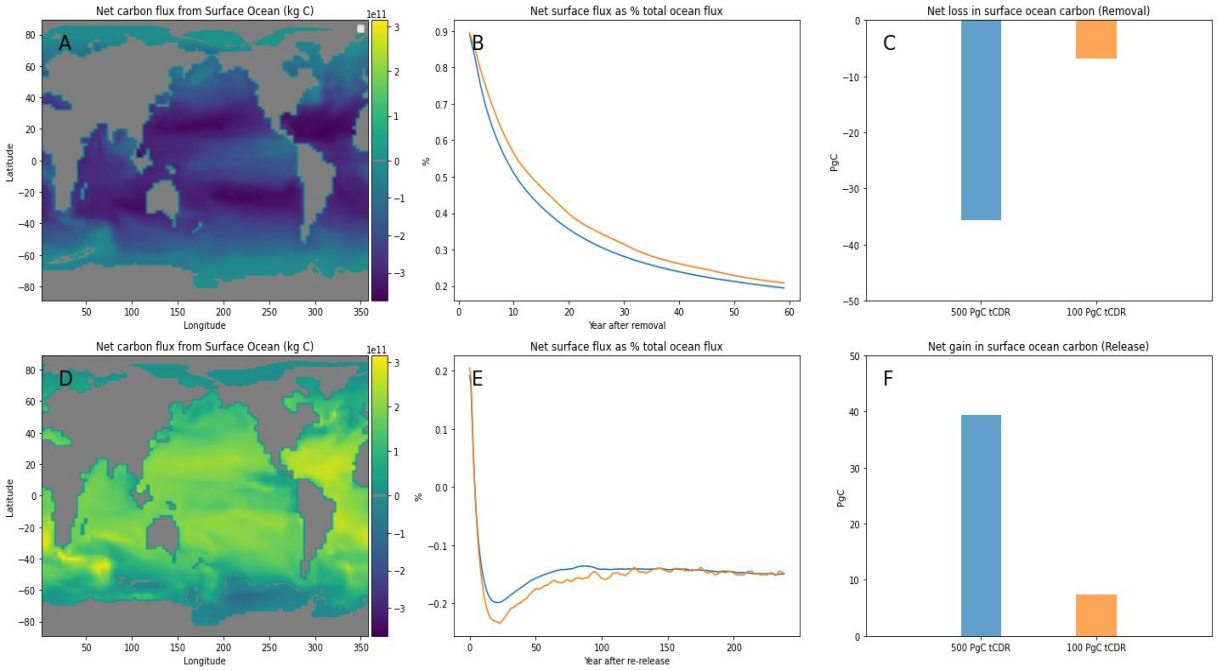


Fig. 6: Surface ocean response to 100 and 500 GtC tCDR experiments. A,D, *geographic pattern of net surface ocean response through the removal (A) and re-release (B) portion of a 500 GtC, 60-year tCDR experiment.* ***B,E,*** *net surface flux as a percentage of total ocean flux throughout the duration of both a 100 and 500 GtC 60-year tCDR experiment during (B) the removal and (E) re-release phase. This metric demonstrates the extent to which (B) carbon is released from the surface ocean without replacement from the deep ocean following release, and (E) the extent to which carbon is returned to the deep ocean over the long term following re-release.* ***C,F,*** *the cumulative difference in surface ocean carbon content after removal (C) and after re-release (F).*

State dependence of temporary CDR

In an equilibrium climate state there is no underlying temperature or biogeochemical effect impacting the coupled carbon-climate system response to removals. Given one of the primary proposed uses of tCDR is "peak shaving", that is, reducing or delaying peak warming via deployment around the point at which net-zero emissions is reached, understanding how the established dynamics of tCDR change when applied to a climate system which has been perturbed from equilibrium by a high volume of GHG emissions is policy-relevant. To investigate the mechanics behind temporary CDR in a transient climate state, we employed both the UVic ESCM model and our emulated ESM ensemble to introduce a trillion tonnes of cumulative emissions to a pre-industrial equilibrium climate starting at 1 GtC per year and increasing at 1% per year. Upon reaching a trillion tonnes of cumulative emissions, we halted emissions and applied removals of 100, 300, and 500 GtC with differing storage lifetimes. (Figure 7) While temporary CDR applied to a transient state of increasing emissions exhibits the same shape of temperature impact as temporary CDR applied to an equilibrium state, it is clear that the magnitude of the effect changes, e.g. is state-dependent. (Figure 8) For example, the mean cumulative overshoot across storage lifetimes for a 100 GtC tCDR in an equilibrium climate is ~2.3 TtC-years, while the mean cumulative overshoot in a transient climate declines to 1.5 TtC-years. This occurs due to changes in the ocean and land sinks which reduces their ability to both (a) re-equilibrate with the atmosphere via outgassing given a removal, and (b) absorb the re-emitted carbon after re-release.

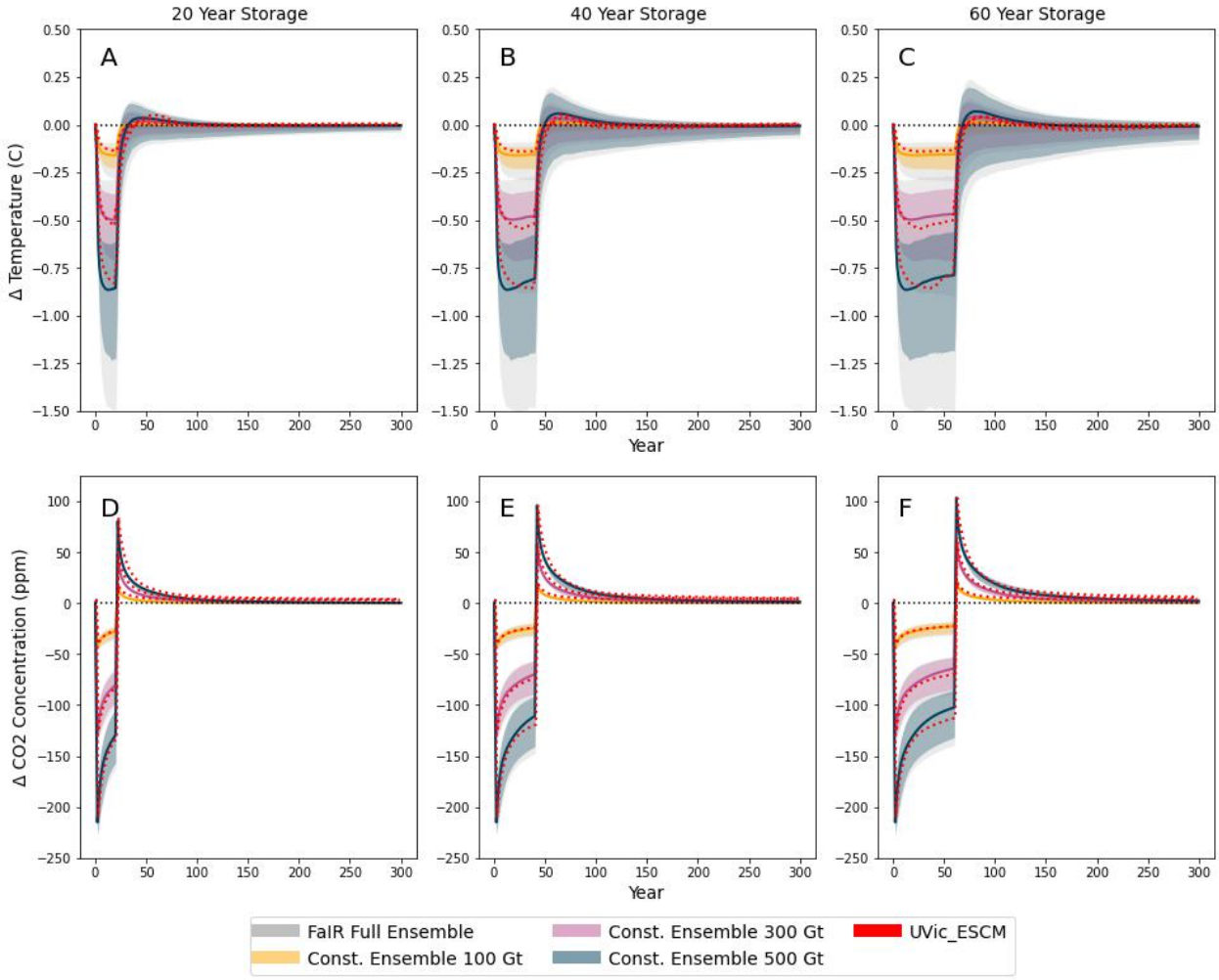


Fig. 7: Global average temperature and atmospheric CO_2 concentration response to temporary CDR in a transient climate state. A-C, *global average temperature response to temporary CDR with storage lifetimes of 20, 40, and 60 years respectively. Mean emulated CMIP6 ensemble results plotted as lines, with the observationally-constrained results shaded and full ensemble results shaded in gray . UVic ESCM results in red.* ***D-F,*** *atmospheric CO_2 concentration response to temporary CDR, coloring the same.*

Specifically, warming of the surface ocean reduces its ability to carry (and therefore discharge and uptake) dissolved carbon, as well as its rate of exchange (and therefore carbon transfer) with the deep ocean through the weakening of key currents driven by temperature differential between the equator and high and low latitudes. [47] In the biosphere, the declining impact of CO2 fertilization (e.g. CO2 concentrations are above

optimal for plants, so reducing them doesn't reduce growth and hence carbon storage to the same extent as in equilibrium) reduces the magnitude of carbon loss from soils, particularly in the Northern latitudes, due to smaller NPP reductions (carbon in) relative to changes in soil carbon respiration rates (carbon out). [49] For example, given a 500 GtC removal with a storage lifetime of 60 years, the cumulative removal fraction over storage lifetime increases to 0.41, ocean rebound reduces to 86 GtC (42%), and the land surface rebound to 118 (58%) relative to an equilibrium climate. It is also interesting to note that the differential between cumulative overshoot projected by UVic and the emulated ensemble closes in a perturbed climate state. This seems to be attributable to a decline in near-term carbon cycle sensitivity to the re-release of stored carbon in UVic, with less of the carbon being taken up by the fast carbon sinks and more persisting over the long term to be absorbed by the deep ocean. This observation is in line with the difference between UVic and ESM projections of the climate response to CDRMIP (see Methods) where fast carbon sink response is much larger for UVic than the CMIP6 ESMs under initial phases of emissions, but in-line with the ensemble during the initial phases of carbon removal.

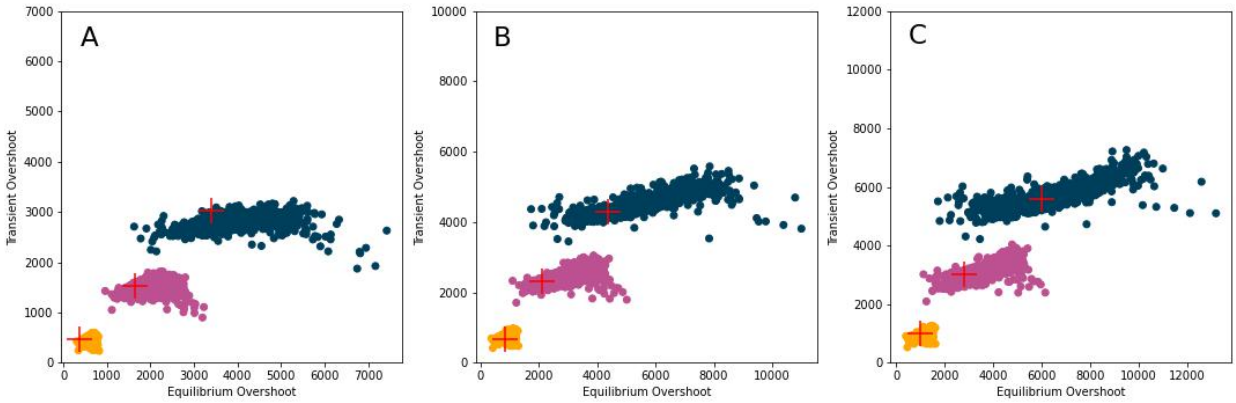


Fig. 8: Cumulative carbon overshoot resulting from tCDR compared across equilibrium and transient climate states in GtC-years. A, *cumulative overshoot from different pulses of tCDR stored for 20 years across two climate states* ***B,*** *the same, for 60 year experiments.* ***C,*** *the same, for 60-year experiments. UVic ESCM results plotted as red crosses.*

Finally, it is important to consider why the emulated results and UVic ESCM results continue to correspond closely, despite (a) known non-linear feedback behavior in scenarios where atmospheric CO2 concentrations are lowered after a period of prolonged emissions, and (b) the linear FaIR model parametrization of climate-carbon and concentration-carbon feedbacks. Is this a coincidence, or is there a mechanical explanation? In FaIR, changes to the strength of carbon sinks are captured through the exponential form of Millar et al (2017)'s [140] linear iIRF100 parameterization, referred to as α. This parameter strengthens or weakens the flux of carbon between the atmosphere and four idealized carbon sinks as a function of equilibrium carbon-cycle sensitivity (r0), the carbon-concentration feedback (rC), and the carbon-climate feedback (rT). As part of the tuning process, the α parameter was fit for UVic and the five ESCMs which participated in CDRMIP using data which captures both fully coupled and biogeochemically coupled carbon sink behavior under both increasing and declining atmospheric CO2 concentrations. [47, 56] Using prescribed atmospheric CO2 changes and the gas cycle equations, the necessary values of α were solved for each model numerically and subsequently converted to iIRF100 values (average airborne fraction over 100 years). (Figure 9).

What we see as a result is a roughly linear increase in iIRF100 under increasing cumulative emissions – a trend to which the feedback parameters of the FaIR model are fit. However, as cumulative emissions begin to reduce under carbon dioxide removal, the iIRF100 values exhibit hysteresis (e.g. dependency on prior conditions), continuing to increase (albeit at a slower rate) in response to legacy ocean warming, before declining at an accelerated rate relative to the increasing emissions phase of the experiment. This behavior is driven by increasing rT(γ) and rC(β) feedbacks under periods of extended negative emissions. CMIP6 models with higher climate-carbon (rT) and carbon-concentration (rC) feedbacks tend to exhibit larger hysteresis under at-scale carbon dioxide removal, driven by changes in global processes, not specific regions. [47] This hysteretic behavior is indicative of greater system 'resistance' to initial declining atmospheric CO2, in that the more CO2 removed the more sensitive sinks

become. With respect to the experiments contained herein, these results help explain the consistency between UVic and the linearly constrained FaIR model – a linear approximation of the iIRF100 is sufficient enough to approximate the climate system response for the first ~500 GtC of removals across most of the Earth-system models, with model hysteresis not becoming material until higher sums of removals- as such, the core insights here (that tCDR under a transient climate implies smaller cumulative overshoot due to sink saturation) should be considered robust.

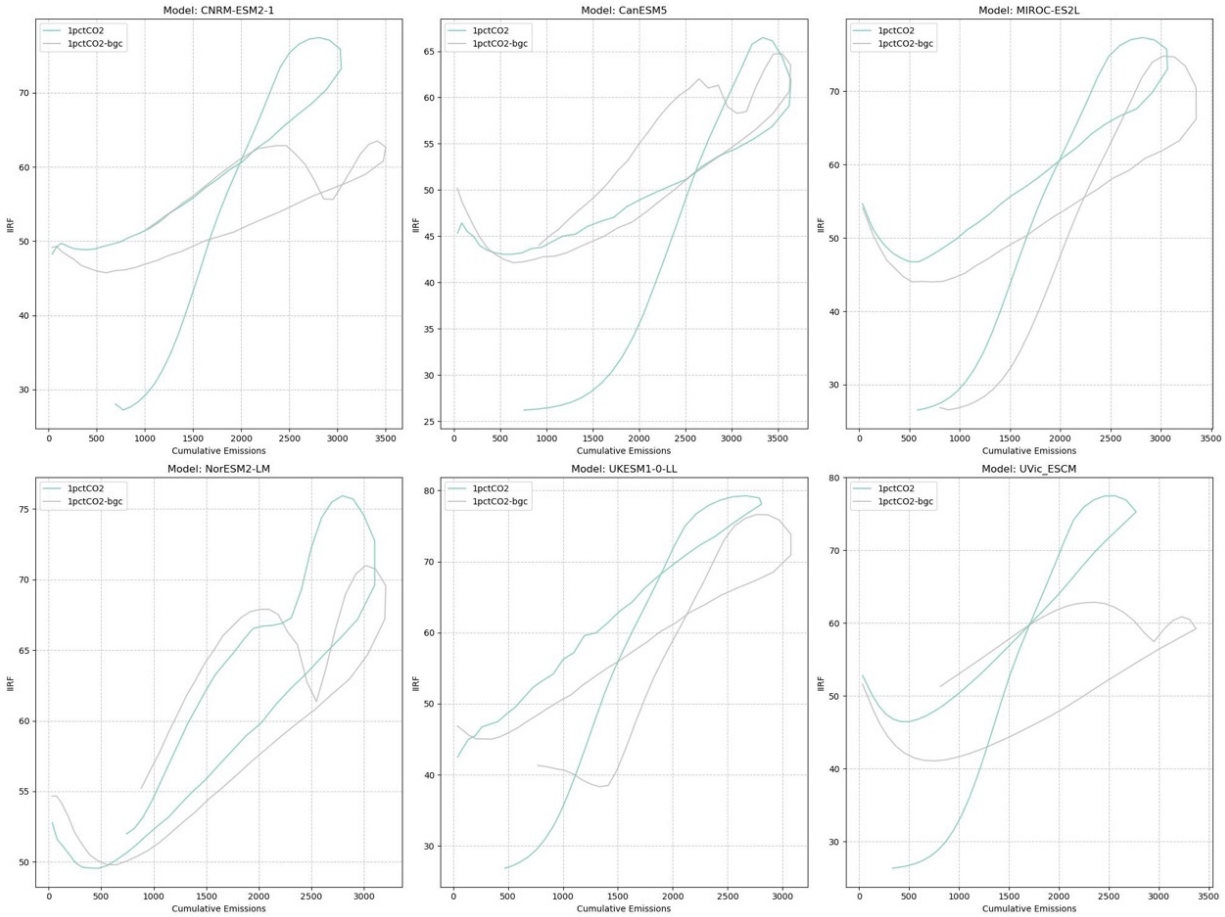


Fig. 9: Diagnosed iIRF100 for a set of ESMs under fully-coupled and biogeochemically coupled runs of the CDRMIP experimental protocol. *iIRF100 values diagnosed using the FaIR v2.0 carbon cycle parameterisation. Model names indicated above each exhibit, fully coupled runs in blue, biogeochemically coupled runs in gray.*

Comparing the behavior of the UVic ESCM iIRF100 under CDRMIP experimental protocols to that of five CMIP6 ESMS provides another source of confidence that the model is sufficient for the preliminary investigations conducted here, given the magnitude and slope of the iIRF100 in response to changing cumulative emissions corresponds well to the other models. That said, this comparison also raises two interesting observations. Firstly, the UVic ESCM's iIRF100 is particularly sensitive to increasing temperature (e.g. there is a large difference in iIRF100 between the fully coupled and biogeochemically coupled runs across the full experimental protocol, relative to the average of the other CMIP ESMs). This corresponds with the parameterisation of the UVic ESCM's climate-carbon feedback (rT), which is near the upper end of the distribution of values for both the CMIP6 ESMS evaluated here and the emulated ensemble used within. More importantly, however, it also suggests a more nuanced hypothesis behind the difference in equilibrium and perturbed near-term carbon sink response: the iIRF100 exhibits a near-term dip in response to changing cumulative emissions, while the FaIR parameterization of this behavior is linear [136], thus the quasi-dynamic UVic Model and emulated ensemble are using divergent models of iIRF100 behavior in the equilibrium simulation, but identical in the perturbed simulation.

Peak warming from temporary CDR

We have seen that the cumulative atmospheric carbon overshoot from temporary CDR increases with storage lifetime and total removals, and declines with an increasingly perturbed climate state. We have furthermore seen that the magnitude of cumulative overshoot is determined primarily by the interaction of the surface ocean and biosphere, and that all else held equal, large volumes of tCDR may transfer carbon from the former to the latter due to different magnitude asymmetries in the two sinks. To conclude, it is important to consider how cumulative carbon overshoot translates into peak warming, in order to be able to make a conclusive statement about the policy relevance of this overshoot phenomenon. Across our experiments, generating a

temperature overshoot exceeding 0.1°C requires at least 500 GtC of tCDR with >50% probability, an absolutely enormous volume of CDR which is almost eight times the estimated global capacity for carbon storage by nature-based solutions. [51-52] This said, these are highly idealized experiments, and the full temperature impact of tCDR is likely also dependent on the rate of storage and release.

As such, we replicated our pre-industrial equilibrium experiment with the emulated CMIP6 ensemble, using six different temporary CDR archetypes: (A) instantaneous capture and storage with some storage lifetime S, (B) linear capture over S years, storage of S years, and instantaneous release, (C) instantaneous capture, storage of S years, and linear release over S years, (D) continuous linear capture and release over project lifetime S , (E) continuous linear capture over lifetime S and instantaneous release, and finally (F) instantaneous capture and linear release over lifetime S. These six archetypes allow us to investigate the isolated impact on temperature overshoot of spreading both removals and re-release over time, as well as the impact of more realistic nature-based carbon capture projects which do not have a storage period but instead are gradually capturing and / or releasing carbon throughout the entire life of the project. It is clear that spreading a given removal or release over several decades does not meaningfully affect the temperature impact of tCDR intervention (Fig 4. A-C), but that temporary CDR loses path invariance when removal or release is spread over the lifetime of the project in such a way as to reduce the "rebound" process. (Fig. 4. D-F)

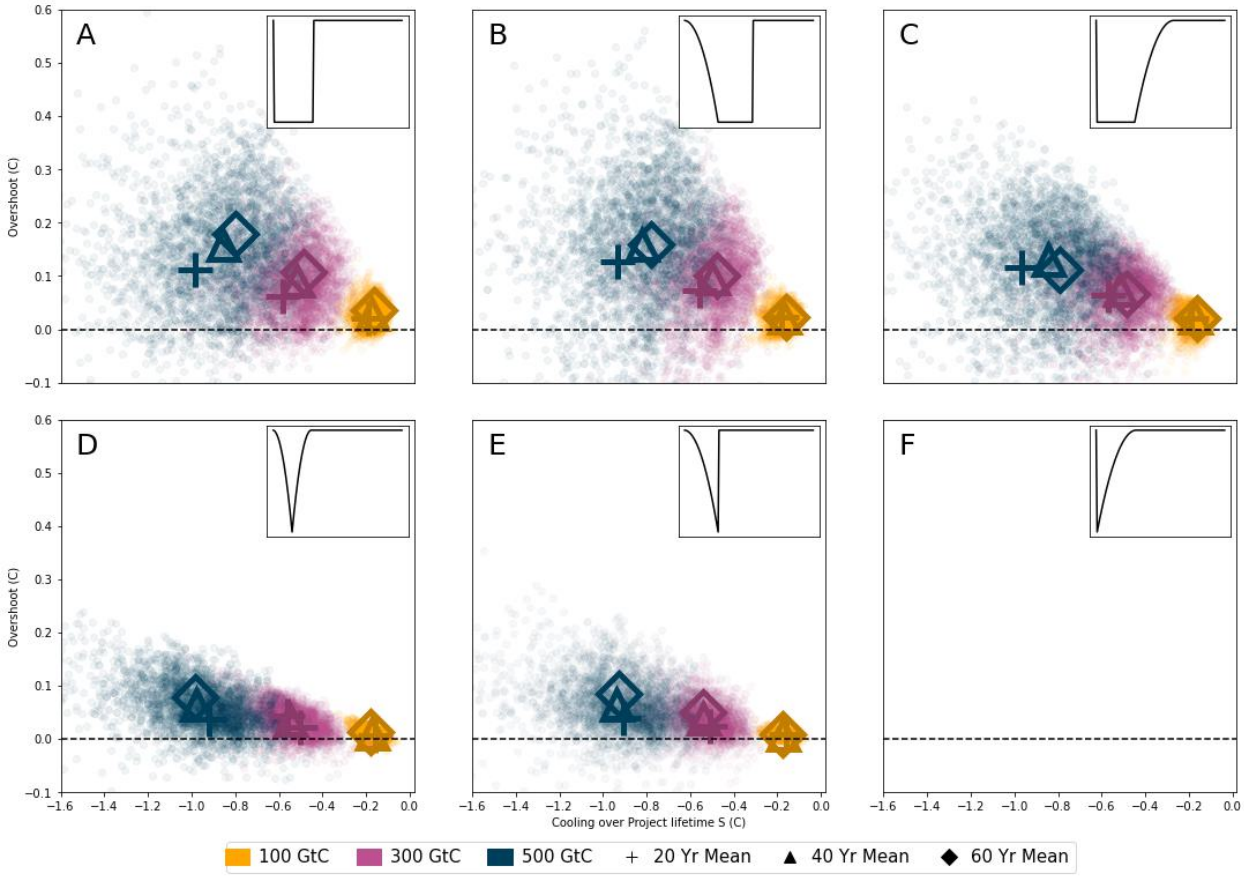


Fig 10. Temperature overshoot and cooling evaluated over project lifetime (S) for six temporary CDR archetypes. A-F, (A) *temporary CDR pulses applied to a pre-industrial equilibrium climate state, following an instantaneous capture and release archetype. Cumulative emissions inset,* ***(B)*** *the same, following a linear capture and instantaneous release archetype,* ***(C)*** *instantaneous capture and linear release,* ***(D)*** *linear capture and release over project lifetime ,* ***(E)*** *linear capture over lifetime , and instantaneous release,* ***(F)*** *instantaneous capture and linear release over lifetime. Results here not shown given there is no meaningful way to calculate TCRR with an instantaneous start to removal re-release.*

For example, given 100 GtC stored and re-released instantaneously after 20 years in an equilibrium climate, we have established there is an overshoot of 0.02°C, or roughly 11% of the cooling achieved during storage. This percentage is near-constant as a function of increasing cumulative removals, but increases logarithmically with storage lifetime at

about 0.1 percentage points per 1% increase in storage life. If the stored carbon is instead captured and released linearly over the same project lifetime, instead of instantaneously, (Fig 4. D), the cooling achieved remains approximately the same, but the resulting overshoot converges to near-zero. Furthermore, the effect of increasing storage lifetime declines to 0.03 percentage points per 1% increase. Thus, we can say that in addition to tCDR-driven temperature overshoot being below the threshold of detection for realistic deployment volumes, across the most likely range of scenarios (e.g. increasing background CO_2 concentrations and the spreading of large volumes of deployment over time) the state and path dependence of the C-CC response to tCDR will act to reduce it further. Given that 0.1°C is within the bounds of natural variability both observed and simulated to occur in the Earth System [141-142], we can state that when considering tCDR the cumulative overshoot phenomenon raised by [57, 65] can be safely ignored, to a first order, and tCDR projects deployed post-net-zero can still be conceptualized directly as time-fractional CDR.

Discussion

Here we have confirmed that tCDR deployed in an equilibrium or post-net-zero climate state causes atmospheric carbon content to overshoot starting conditions upon re-release of stored carbon. The cumulative overshoot size is climate state, atmospheric CO_2 concentration, removal size, storage lifetime, and deployment pathway-dependant. However, we have also shown that across all experiments the magnitude of the resulting temperature overshoot is below the threshold for detection given natural variability of the climate system, except for unrealistically large instantaneous removals (on the order of 500 GtC), and moreover that most state-dependencies act to further reduce overshoot magnitude (e.g. increasing background CO_2 concentration or spreading removals over time). As such, tCDR can be thought of as directly approximating a time fraction of a permanent removal, an insight which is directly applicable to any valuation method.

Our findings are subject to several uncertainties resulting from the choice of the modelling tools used. To begin, we employed only a Earth-system Model of Intermediate Complexity (EMIC), the UVic ESCM v2.10, which has several shortcomings. For example, it is known that the land response to changes in atmospheric CO_2 and global average temperature are strongly model dependant, and thus we would expect the carbon cycle response underlying our results to differ across models. [135] This is particularly true given the sensitivity of land sink behavior to changes in precipitation and temperature patterns, which the UVic ESCM's slab atmosphere cannot replicate. [143] The UVic ESCM is also restricted to a single climate sensitivity value which, although it is close to the mean value across other EMICs / ESMs, has been shown to exhibit simplified behavior relative to expectations for the actual Earth System. [144] In an attempt to compensate for the shortcomings of using only one dynamic model, we also employed FaIR v2.0.0, a simple climate model, to emulate an ensemble of CMIP6 ESMs to test the sensitivity of our results to different carbon cycle and thermal response parameterizations.

The usefulness of this choice is limited by the fidelity of the training data available for the emulation process. The ensemble employed here was trained using data from the fully and biogeochemically-coupled 1 percent-CO_2 runs from the C4MIP experiments, as well as the available CDRMIP data. [56] Importantly, FaIR v2.0.0 is not able to capture the rapidly decreasing initial airborne fraction exhibited by the CMIP6 ESMs in response to near-term emissions in these runs, and so tuning to long-term behavior was prioritized using data starting at year 60. [136]. Using other experimental data or additional model terms which better capture the full range of carbon-cycle behavior of more complex ESMs, particular with respect to suspected asymmetries in the climate response to removals vice emissions [47, 49], could improve the results of our sensitivity analysis, though given the high degree of agreement between the mean emulated ensemble response and the UVic ESCM response across investigated scenarios, we expect the magnitude of this potential improvement to be small. (See Methods) Future work will also need to investigate whether or not our results change if the carbon removed from the atmosphere as part of a temporary CDR is stored in the biosphere, as opposed to

being stored in an idealized geological reservoir, as done here. The storage of carbon in the biosphere would necessitate prescribing land use changes (such as, for example, afforestation or reforestation) which could have non-trivial albedo impacts [145], and could also act to alter the behavior of the land sink throughout the re-release and equilibration processes. For example, preliminary work has shown that albedo effects from large scale reforestation could half the climate impact of the removals it generates [60].

All of this said, we expect the findings presented to be generally robust to these improvements, and note they are directly relevant to efforts to find metrics that equate the climate impact of CDR with differing storage lifetimes. Given the ease of scalability, low cost, and disparate geographic distribution of nature-based solutions, it is possible that forms of tCDR could be traded between nations under Article 6 of the Paris Agreement. We show that ensuring tCDR meets the high standards for environmental integrity required for Internationally Transferred Mitigation Outcomes (ITMOS) can be done without need to reference the possibility of substantial temperature overshoot resulting from its deployment.

Materials and Methods

Model Description

To investigate the dynamics behind the C-CC response to temporary CDR, we employed the University of Victoria's Earth System Climate Model (UVic ESCM) version 2.10 [146], an intermediate-complexity global climate model with a spatial resolution of 3.6° longitude and 1.8° latitude. This model explicitly resolves a three-dimensional general circulation ocean model with 19 vertical layers [146], which is coupled to an energy-moisture-balance slab atmosphere model with dynamical feedbacks [146], a dynamic-thermodynamic sea-ice model [146], a dynamic vegetation model [147], and an interactive land and ocean carbon cycle [148] that includes ocean sediments [149] and permafrost carbon [150].The primary limitation of this model is its non-dynamic

atmosphere, which does not represent atmospheric circulation or cloud distributions. Instead, these are prescribed from observations [146]. The UVic ESCM has been employed extensively to investigate questions including the magnitude of climate-carbon cycle feedbacks and the carbon-cycle dynamics of both temporary and permanent negative emissions. [49, 52-55] It has also been included in numerous model intercomparison projects, including the sixth phase of the Coupled Model Intercomparison Project (CMIP6), or more specifically C4MIP, the intercomparison of Earth system models of intermediate complexity (EMICs), and the Carbon Dioxide Removal and Zero Emissions Commitment model intercomparison projects (CDR-MIP and ZECMIP). [56, 138] The model's standard climate sensitivity is 3.4 °C when doubling the pre-industrial atmospheric CO_2 concentration, placing it near the middle of the range of responses of other Earth systems models of both full and intermediate complexity. [144]

Given (a) that the UVic ESCM makes use of a slab atmosphere model, and (b) changes in the flux of carbon between the atmosphere and ocean and land sinks under climate forcing are subject to substantive influence from the dynamic behavior of the atmosphere (e.g. thru regional temperature and precipitation patterns, or wind-driven surface ocean circulation [135]), it is important to verify that the UVIC ESCM outputs plausible temperature and carbon sink behavior compared to fully dynamic Earth system models across a range of experimental conditions relevant to this paper's point of inquiry. To verify the sufficiency of the UVIC ESCM as a preliminary tool for investigating the climate response to temporary CDR, we compared it's surface temperature, ocean-, and land-carbon response to 5 CMIP6 ESMs under the CDRMIP and ZECMIP experiments. These experiments investigate the climate response to at-scale carbon dioxide removal following a large emissions perturbation, as well as the long-term equilibration response to the cessation of positive emissions, which are the two fundamental components of a temporary carbon dioxide intervention. The UVIC ESCM produces a consistent middle-of-the-range temperature and land sink response to both the CDRMIP and ZECMIP protocol, and a surface ocean sink response which is higher

than the five examined ESMs, but within the 75th percentile of the full CMIP6 ensemble, and an average long-term ocean response. For these reasons, we believe UVIC ESCM to be a sufficient tool for the purposes of this paper, with the understood caveat that ocean uptake trends towards the higher end of plausible responses.

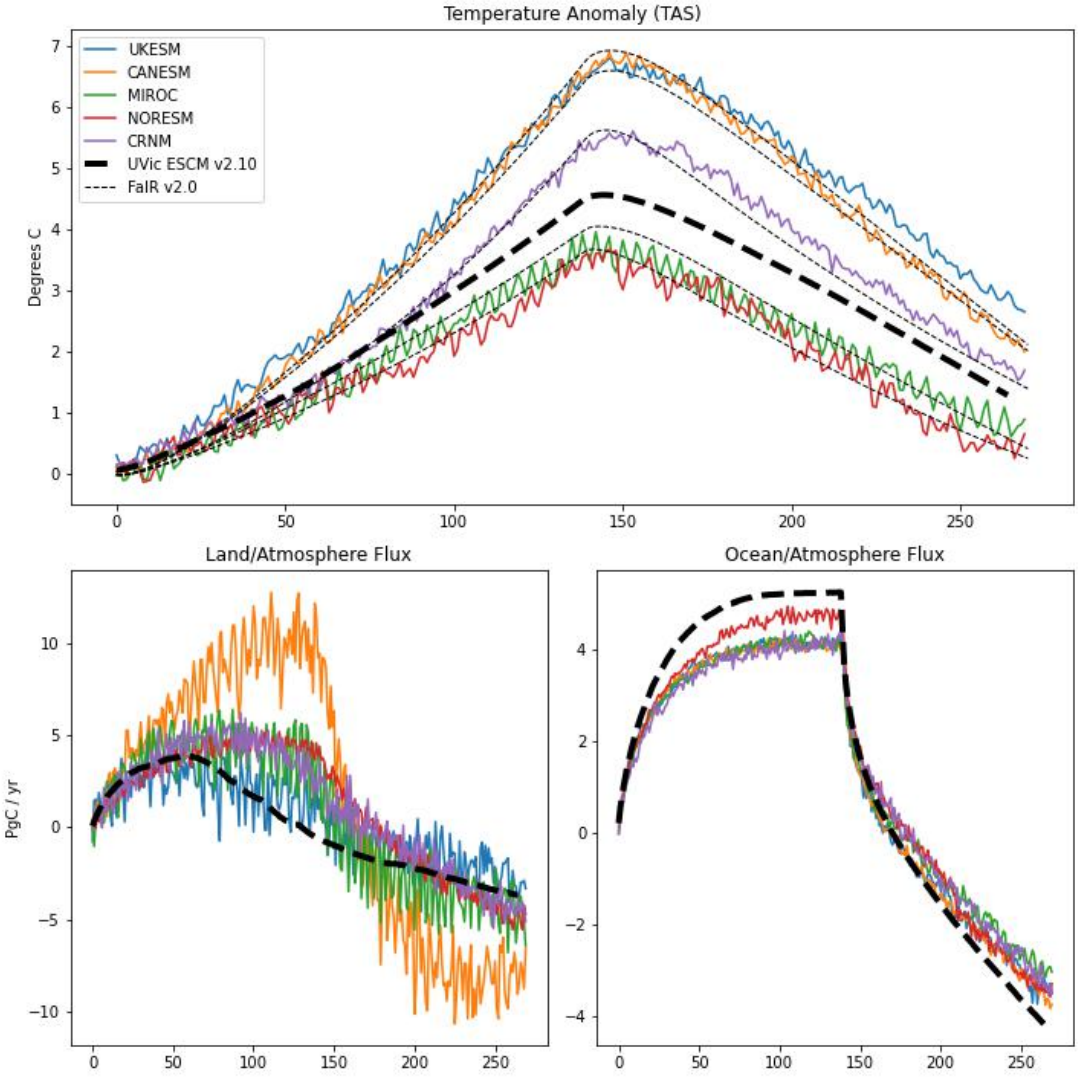


Fig 11. Climate system response to the CDRMIP experimental protocol. A-C. A, *average surface air temperature response across a set of CMIP6 ESMs, UVic ESCM v2.10, and FaIR V2.10 emulations of these models.* ***B,*** *the same, for land/atmosphere carbon flux,* ***C,*** *the same, for ocean/atmosphere carbon flux.*

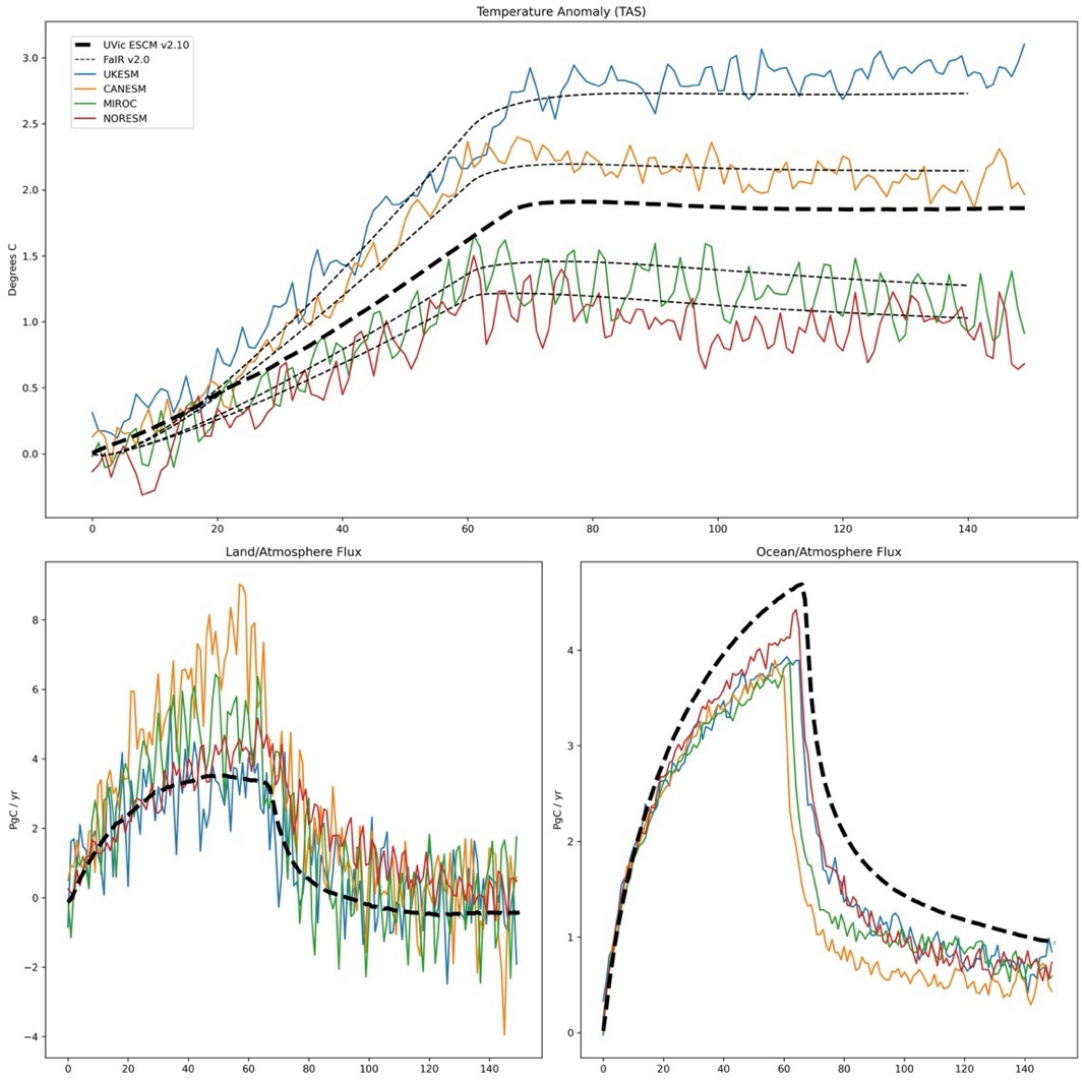


Fig 12. Climate system response to the ZECMIP experimental protocol. A-C, A, *average surface air temperature response across a set of CMIP6 ESMs, UVic ESCM v2.10, and FaIR V2.10 emulations of these models,* ***B,*** *the same, for land/atmosphere carbon flux,* ***C,*** *the same, for ocean/atmosphere carbon flux. Note that CNRM-CM5 participated in CDRMIP but not ZECMIP, and so is not featured here.*

To perform a perturbed parameter analysis investigating the extent to which the climate response to temporary CDR depends on climate system parameters which could hold a wide range of plausible values, we employed the Finite Amplitude Impulse Response

(FaIR) simple climate model version 2.0.0. [136] This simple model is comprised of a set of six equations, five of which correspond to the IPCC's Fifth Assessment Report standard impulse response function, and to which one additional equation has been added to represent state-dependent non-linearities in greenhouse gas cycle response times found in both observations and more complex Earth System models. [136] The three benefits of employing this model are (a) its computational inexpensiveness, (b) its' ability to accurately emulate the behavior of a wide range of more complex climate models, and (c) its' relatively simple parameterization of the key components of the climate system. In order to test the fitness of this model, we first tuned FaIR 2.0.0's carbon cycle and thermal response parameters to emulate the behavior of UVIC ESCM and the 5 CMIP6 ESMs investigated above, using data from the 4pctCO2, 1pctCO2, and CDRMIP experiments. While FaIR is not able to explicitly resolve the flow of carbon from the land and ocean, the resulting emulations replicated the surface temperature response to both experiments across all models. It is important to note that while FaIR v2.0 does an adequate job of replicating the climate response to the CDRMIP experiment, this is because changes to atmospheric CO2 are prescribed. The influence of diagnosed changes to carbon cycle feedbacks (which FaIR cannot capture without being trained separately on the increasing and decreasing components of the CDRMIP experiment) are discussed in the results above. To provide a wider parameter ensemble with which to do a sensitivity analysis, we emulated an ensemble of 28 CMIP6 ESMs for which sufficient data was available, and then constructed a 10,000 member perturbed parameter ensemble by sampling randomly from the carbon cycle / climate system parameter space defined by these emulations. [136] This ensemble was constrained using observed levels and rates of warming obtained by applying the Global Warming Index methodology [151] to six available observational data products, and averaging the resulting distributions. [152-158]

Experimental Design

Our experiments were divided into three sets. First, for our equilibrium climate state experiments, we removed 100, 300, and 500 GtC from the atmosphere instantaneously

and stored it out of the active carbon cycle prior to re-emitting it to the atmosphere following storage lifetimes of 20, 40, and 60 years. For these experiments the model spin-up protocol ensured equilibria, and thus model drift was negligible and did not need to be accounted for. The dynamics behind the tCDR response was investigated thru the decomposition of atmospheric CO2 response into carbon sink behavior via UVic ESCM v2.10's explicit representation of both the ocean and land surface. Furthermore, Sobol sensitivity indices were calculated for eleven of FaIR's parameters spanning the carbon-cycle feedbacks, temperature response, and effective radiative forcing response, in order to determine the first- and total-order effect of each parameter on cumulative carbon overshoot. To investigate the importance of storage and release rates on the climate system response to temporary CDR, the emulated FaIR ensemble was used to apply 100, 300, and 500 GtC pulses with 20, 40, and 60 year storage periods to an equilibrium climate under six different capture / release archetypes: (A) instantaneous capture and storage with some storage lifetime S, (B) linear capture, storage, and instantaneous release, (C) instantaneous capture, storage, and linear release, (D) continuous linear capture and release over project lifetime , (E) continuous linear capture over lifetime and instantaneous release, and finally (F) instantaneous capture and linear release over lifetime.

To replicate these experiments in a perturbed climate state, we introduced a trillion tonnes of carbon to a pre-industrial equilibrium climate (starting at 1 GtC and increasing at 1 percent per year for 200 years). In year 200 we stopped emissions and applied 100, 300, and 500 GtC removals with the same storage lifetimes. The impact of these removals was then isolated by subtracting the results of a baseline run with no removal. To investigate the extent to which the FaIR emulations of these experiments could be biased by non-linearities in carbon-cycle feedbacks established in the literature [47, 49], carbon cycle feedbacks under declining atmospheric CO2 were diagnosed from FaIR model emulations of the 5 CDRMIP ESMs, as well as UVic ESCM.

4. Temporary carbon dioxide removal and short-lived climate pollutant emissions could be effectively exchanged as International Traded Mitigation Outcomes

This paper examines the potential role of temporary carbon dioxide removal (tCDR) generated by nature-based solutions within the framework of Internationally Traded Mitigation Outcomes (ITMOs). This paper demonstrates that tCDR could be used to offset one-off pulses of methane or other SLCPs under a "do-no-harm" principle using Global Warming Potential (GWP) metrics. Additionally, it explores the possibility of chaining tCDR into sustained deployments approximating permanent removal, while acknowledging the associated socio-political challenges. Finally, a novel method for incorporating nature-based solutions into carbon markets is proposed, using Linear Warming Equivalent (LWE) units of tCDR to directly offset methane emissions. This approach could address hard-to-abate SLCP pollution while promoting biosphere restoration as a “peak shaving” approach when nearing the point of net-zero emissions.

Temporary carbon dioxide removal and short-lived climate pollutant emissions could be effectively exchanged as International Traded Mitigation Outcomes

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Abstract

The transfer of mitigation outcomes between parties allows for markets to determine the most cost-efficient way to achieve an arbitrary warming target. Exchanging mitigation actions which affect greenhouse gasses of different atmospheric lifetimes can lead to ambiguous warming outcomes, and thus appropriate metrics are needed to equate the two. Prior work has suggested the use of both "do-no-harm" and "warming-equivalent" principles to select exchange metrics which address this problem. However, the first approach disincentivizes exchange in mitigation actions due to necessarily punitive exchange rates, while the second requires socio-politically challenging multi-decade or -century obligations as a prerequisite for exchange. Here, we demonstrate that temporary carbon dioxide removal generated by nature-based solutions could play a limited role offsetting one-off pulses of methane or other SLCP under a "do-no-harm" principle using GWP100 or GWP20, or play a role in offsetting a wider range of climate pollutants through chaining removals together into sustained deployments which approximate permanent removal, though this option faces material socio-political challenges. Finally, novel method for incorporating nature-based solutions into carbon markets is proposed, operationalizing Linear Warming Equivalent (LWE) units of tCDR to directly offset methane emissions. This approach could address hard-to-abate SLCP pollution while promoting biosphere restoration as a "peak shaving" approach when nearing the point of net-zero emissions.

Main

By virtue of the heterogenous nature of global economic activity, different economic actors have different greenhouse gas mitigation options available to them, and different capacity to pay for those options. Therefore, a given mitigation target can be achieved most efficaciously by allowing for the exchange of mitigation actions between actors over time such that the lowest-cost global decarbonization pathway can be discovered by the market. [159] For this reason, the Paris Agreement provides for the exchange of mitigation actions between parties to the agreement through Internationally Traded Mitigation Outcomes (ITMOs) under Article 6.2 [160] At COP24 in Katowicze it was agreed that all parties to the Paris Agreement will report emissions and removals of greenhouse gasses separately, in units of CO2-e100 using the GWP100 equivalency metric. This is helpful insofar as it can provide clarity with respect to the contribution of mitigation efforts to warming: the contribution of aggregate long-lived greenhouse gas emissions can be derived by multiplying cumulative emissions in CO2-e100 by the constant TCRE parameter (Transient Climate Response to Emissions), while the contribution of aggregate short-lived emissions can be determined by the aggregate rate of emission in CO2-e100 multiplied by the AGWP100 (Absolute Global Warming Potential) of CO2. [161] On the other hand, however, this resolution also introduced a substantial concern related to the environmental integrity of ITMOs, which is: the ambiguous warming outcomes which result from trading nominally "equivalent" volumes of long- and short-lived mitigation actions reported under the CO2-e100 metric. [39, 162]

Achieving the Paris Agreement target of limiting warming to well-below 2°C depends on restricting additional cumulative CO_2 emissions to within on the order of 1000 $GtCO_2$, a budget which itself only exists under the assumption that the aggregate forcing from SLCP emission will be substantially reduced over the same time. [163] Without this reduction in SLCPs, we have already consumed the 1.5C carbon budget and nearly all of the 2°C budget. [33-35] Substantial mitigation of both long- and short-lived pollutants are therefore required, and their exchange at scale via carbon markets therefore is likely.

Prior work has demonstrated that, for a given decarbonization pathway, the choice of exchange metric between long- and short-lived mitigation actions has substantial influence not only on the volume of exchange between the two, but also the final level of warming which occurs, and the level of cost with which that warming level is achieved. [164-166] Careful selection of the metrics used under Article 6.4 are necessary.

This is especially true given increased recent focus on the possible role of nature-based carbon solutions in mitigation strategy. [60-63, 86] Nature-based solutions can capture and store of atmospheric carbon through the protection, restoration, or improved management of the biosphere. [60] Policymakers and industry leaders are excited by the potential of nature-based solutions because of their available scale, low cost, and potential to generate measurable co-benefits including enhancing biodiversity, air and water quality, and cultural services [61], providing physical climate risk abatement [63], and generating economically valuable feedstock for industry. [62] However, nature-based solutions are vulnerable to both human and natural-based disturbance through wildfires, droughts, insect outbreaks, and changing land-use priorities, and thus store carbon only temporarily, acting as a short-lived mitigation lever like methane. [167] Given their relative abundance attractive economic qualities, it is likely that policymakers will want to exchange temporary carbon removal credits generated from nature-based solutions under the Article 6 mechanism if permitted. Indeed, the vast majority of reported CDR activity today is already generated from nature-based solutions, which also makes up the propensity of carbon credits sold over voluntary compliance markets. [44]

Prior work [159] demonstrated one way to avoid unintentional warming from the trade of short- and long-lived mitigation outcomes: widen the scope of metrics used when exchanging long- and short-lived mitigation outcomes under a “do no harm” principle. Under such a system, two parties exchanging mitigation outcomes would select from a list of commonly used equation metrics that which produces no additional warming. While employing such a system is possible, it can also imply punitive exchange rates

with, for example, a CO2-methane pulse abatement ratio of 81:1, and an inverse of 4:1 for methane-CO2 abatement. Since these multiples are larger than the present cost differential in abatement of long- versus short-lived pollutants [164], such an exchange scheme is likely to disincentivize multi-gas exchange under ITMOs, which reduces the degrees of freedom available for parties to achieve their NDCs. A second option which has been put forward [38-39, 159] is the use of warming equivalency or warming equivalency approximations to exchange the mitigation of short- and long-lived gasses. While such an approach addresses the risk of ambiguous warming contributions of an exchange of long- and short-lived gases, it requires equating the abatement of a pulse of a long-lived gas to a sustained reduction in the emissions of a short-lived gas, which implies long-term obligations unlikely to be politically feasible for one of the two parties to the ITMO. [159] Furthermore, such a system can introduce substantial variability in emissions accounting which complicate tracking of progress and ease of exchange [40].

Given these realities, while economically suboptimal, it seems the best use of ITMOs is encouraging the trade of mitigation options under a two-basket system, in which the mitigation of long-lived and short-lived gasses are exchanged only with themselves. This said, however, to date these proposals have not considered how temporary carbon dioxide removal should be integrated into the trade of mitigation outcomes. Here, we demonstrate that when temporary CDR (tCDR) generated from nature-based solutions is incorporated into mitigation outcome trading under a "do no harm" principle, it faces the same challenges as the exchange of other short- and long-lived mitigation outcomes. Specifically, we demonstrate that individual tCDR could be used to offset one-off pulses of methane or other SLCPs when using either GWP100 or GWP20, but that this implies very large exchange rates. tCDR could also play a role in offsetting a wider range of climate pollutants through chaining removals together into sustained deployments which approximate permanent removal, but similar socio-political challenges exist here as with methane abatement. To conclude we propose a new method for incorporating nature-based solutions into carbon markets which could provide a more effective physical justification for scaling up individual land-use projects

to offset hard-to-abate short-lived forcings as we collective approach net-zero emissions and therefore peak warming.

Incorporating tCDR into the transfer of mitigation outcomes under a "do no harm" principle

There are two commonly used approaches to measuring the mitigation value of tCDR. The first is an integrated-forcing-style approach, comparing the cumulative change in some climate-system metric to determine a constant fractional relationship between tCDR and another mitigation action over an arbitrary time period. Ton-year accounting which compares tCDR and CDR based on the integral of cumulative removals over a 100-year period, is the most commonly cited example. [66-68] The second approach conceptualizes tCDR as a postponed emission, the value of which can then be determined by comparing avoided damages to those resulting from a different mitigation scenario via the application of a time preference. The Social Value of Offsets (SVO) is the most commonly cited example of this second approach. [65,69] Both of these approaches produce 'equivalency factors' which are used to equate discrete tons of tCDR with other discrete mitigation actions.

For the purposes of this analysis, we have used the GWP100, GWP20, and GTP100 approaches to calculate 'equivalency' between a given ton of tCDR (in this case, with a decay rate which completely re-releases stored carbon over a 20-year lifetime) and the emission of a ton of CO2 (producing CO2-e removals) or methane (producing CH4-e removals). We then employ the Finite Amplitude Impulse Response (FaIR) simple climate model version 2.0.0 [136] to compare the temperature impact of an offset or ITMO exchanging tCDR for these mitigation outcomes using nominally "equivalent" emissions. (Figure 1). This choice was made given the common use of these metrics by the IPCC / UNFCCC, the similarity of exhibited behavior between equivalent emissions (or removals) calculated under GXP frameworks and under ton-year or SVO metrics, and, most importantly for the benefit of their definitional properties in our accounting proposal in the following section.

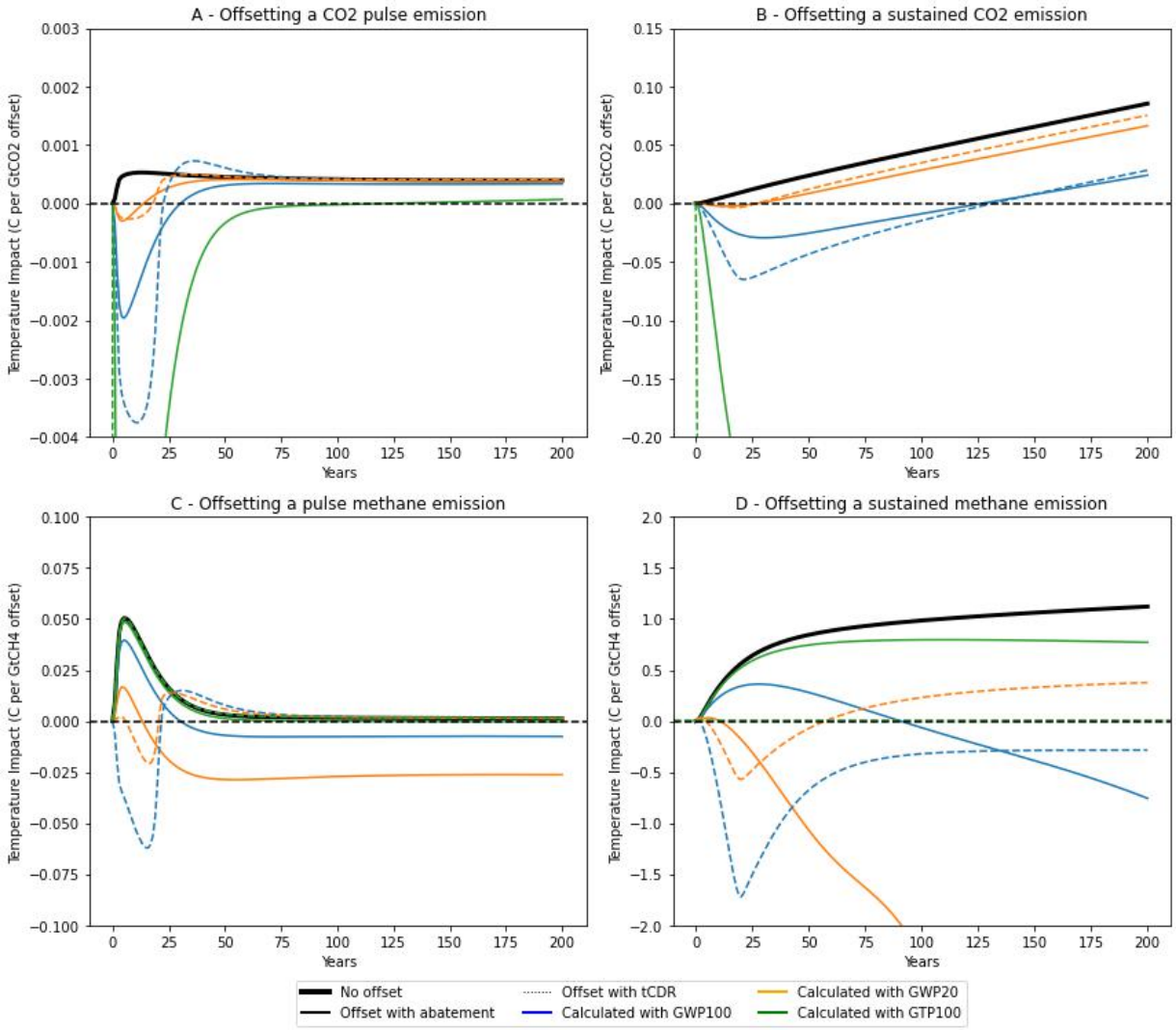


Fig. 1: Global average temperature response to offsetting the emission of carbon dioxide or methane with carbon dioxide removal, methane abatement, and temporary carbon dioxide removal. A,B, *temperature impact of offsetting a Gt pulse, or sustained emission, of carbon dioxide with equivalent abatement of methane (solid lines) or temporary carbon dioxide removal (dashed lines) all calculated with GWP100 (blue), GWP20 (orange), and GTP100 (green).* ***C,D,*** *the same, but offsetting a Gt pulse or sustained emission of methane with equivalent abatement of CO2 or carbon dioxide removal. Note for these exhibits, the GWP-equivalency is calculated directly between methane and tCDR, so the result is CH4-e emissions, not CO2-e emissions for tCDR.*

The GWP framework has long come under criticism for failing to produce warming equivalency over time when comparing long- and short-lived climate pollutants. [162] This is demonstrated in Figure 1A, in that when offsetting a ton of CO_2 with GWPH equivalent abatement of methane, the impact on global average temperature is near-term cooling, and long term warming, which introduces the risk of moral-hazard in the near-term, and failing to meet temperature goals in the long-term. This phenomenon emerges because methane is a short-lived climate pollutant with an atmospheric lifetime of approximately two decades, while CO2 persists in the atmosphere on the order of centuries. The GWP framework is agnostic of the time distribution of forcing, and so implicitly assumes the atmospheric lifetime of the two gasses is identical. [162] The same issue emerges with tCDR – whether ton-year accounting, SVO, or the GWPH framework, any system of exchange that treats tCDR as fractionally equivalent to the permanent abatement or removal of CO2 from the atmosphere will underestimate both the near-term cooling and long-term warming that results, by scaling near-term forcing up in proportion to the differential in long-term forcing between the two interventions.

Under a "do-no-harm" principle, permanent reductions in CO_2 could be offset with equivalent emissions of methane when equated under the GTP100 metric, given, by construction, this metric equates emissions such that they give the same temperature impact after 100 years. Thus, using GTP100 underestimates near-term cooling, but accurately captures the long-term temperature impact. The problem with this approach is that it necessarily equates 1 ton of CO2 abatement to 4 tons of CH4 abatement, which would quickly become cost-prohibitive given the relative scale of CO2 and CH4 emissions and highly non-linear marginal abatement cost curves of short-lived pollutants. [159] Because tCDR returns the climate system to initial conditions on the order of a century, the GTP100 of tCDR is 0, meaning there is no meaningful amount of tCDR which can be used to offset CO2 emissions under the GTP100 framework. As such, under a "do-no-harm" principle, tCDR should not be exchangeable with CO2 abatement or permanent removal under any fractional metric.

When considering offsetting the sustained emission of CO_2, the difficulty in equating short- and long-lived pollutants again becomes obvious. Sustained emissions in CO_2 results in a perpetually increasing forcing scaling linearly with cumulative emissions, while sustained emissions of methane asymptotes quickly to a constant forcing over time, as the rate of decay and re-introduction of methane to and from the atmosphere reach equilibrium. For this reason, offsetting any sustained emission of CO_2 with a "equivalent" sustained abatement of methane will result in long-term warming. [159] Furthermore, because of the enormous aforementioned GTP100 exchange between a pulse of CH_4 and a pulse of CO_2, using the GTP100 metric to equate offsets between sustained emission of the two gasses results in an unfeasible blow-up in the quantity of methane abatement necessary.

When considering tCDR, the reader will note that the sustained abatement of GWP-"equivalent" methane, or deployment of GWP-"equivalent" tCDR, produces nearly the same temperature behavior over time. This occurs for two reasons. First, as a short-lived climate forcing, sustained tCDR (or methane abatement) approximates the climate impact of a permanent GHG removal once the rate of new removals (abatement) is balanced by the cumulative re-release of stored carbon (atmospheric decay). For the sustained deployment of some volume α of a short-lived climate removal with an arbitrary half-life *h,* the equivalent permanent abatement *E(x)* (the sum at which the resulting impact asymptotes) can be calculated by the sum of the respective infinite geometric series. Furthermore, it follows that the AGTP(s) (Absolute Global Temperature Potential for a sustained emission) can therefore be given by:

$$E(x) = \frac{\alpha}{1-e^{\frac{-\ln(2)}{h}}} \tag{1}$$

$$AGTP_s(tCDR) = TCRE \cdot \frac{\alpha}{1-e^{\frac{-\ln(2)}{h}}} \tag{2}$$

If we scale the deployment volume by GWPH:

$$AGTP_s(tCDR) = TCRE \cdot \frac{\alpha * GWPH}{1 - e^{\frac{-\ln(2)}{h}}} \quad (3)$$

But we also know from [162] that:

$$GWPH = \frac{AGTPs(tCDR)}{AGTPs(CO2)} \quad (4)$$

Then by result:

$$\frac{TCRE \cdot \frac{\alpha * GWPH}{1 - e^{\frac{-\ln(2)}{h}}}}{AGTPs(CO2)} = GWPH \quad (5)$$

And so:

$$TCRE \cdot \frac{\alpha}{1 - e^{\frac{-\ln(2)}{h}}} = AGTPs(CO2) \quad (6)$$

In short, by scaling both tCDR and methane abatement by GWPH, we get a sustained removal with the equivalent forcing, over H years, of a sustained removal of one ton of CO2. If we replicate the same process with any arbitrary short-lived pollutant, we end up with the same equivalency, and thus we should expect to see forcing between sustained tCDR and methane abatement line up roughly H years after constant forcing is achieved, which is what we observe.

Given this behavior, neither sustained methane abatement nor sustained tCDR deployment can be used to offset sustained CO2 emissions under a "do-no-harm" principle. This said, however, given the inverse proposal that a sustained step-change in the rate of emissions of a cumulative pollutant is approximately equivalent to a linear change rate of a short-lived pollutant, increasing deployment of tCDR [71] or methane abatement [39] could be used to offset sustained emissions of long-lived gasses like

CO2. In this case, the required rate of deployment scaling could be calculated simply as a 1/H annual increase in sustained CO2-e removals. The problem with these approaches is the same as with the proposal that sustained short-lived abatement be used to offset one-off abatement of long-lived pollutants: they (a) require indefinite obligation to maintain abatement or deployment, or deployment rate, which is socio-politically infeasible, and (b) they introduce substantial variability into emissions management by virtue of implicitly projecting each small change in emissions rate to last for the next century. [40] Thus in practice, under a "do-no-harm" principle, CO2 emissions should only be offset on a one-off basis by either: permanent C2O abatement, permanent CO2 removal, or GTP100-equivalent methane abatement.

When offsetting methane emissions via carbon abatement or removal, several new possibilities occur. Firstly, while warming outcomes remain ambiguous, one-off pulses of CO2 can be used to offset one-off pulses of methane under a "do-no-harm" principle when using a short-time-horizon GWP metric like GWP20 which captures the large disparity in radiative efficiency of the two gasses. [159] Secondly, CH_4-e tCDR pulses calculated under either of the GWP frameworks produce net-cooling, with near-zero temperature change in the long-run. The production of net-cooling can be ascribed to the difference in radiative forcing profile over time, with the tCDR pulse ceasing to have a radiative impact in year 21, while methane continues to exhibit declining (though marginal) radiative impact for a full 100 years. When sustained carbon removal is applied to offset sustained methane emissions, permanent removal can be used under a "do-no-harm" principle when calculated using GWP20 (for the same reason as when offsetting a pulse of methane), while CH_4-e tCDR could be used when calculated using GWP100, or CO_2-e tCDR under any GWPH metric, as discussed above. Thus, under a "do-no-harm" principle, methane emissions can be offset on a one-off or sustained basis using GWP20 for permanent CO2 abatement or removal, and GWP100 for CH_4-e temporary removals.

Incorporating tCDR into the transfer of mitigation outcomes under a "warming equivalence" principle

As discussed above, most warming-equivalent proposals for exchanging the mitigation of short-and-long lived gasses face operationalization problems ranging from needing a climate model to calculate equivalency [38], to requiring multi-decade to century management commitments [39], to magnifying noise in emissions datasets in unmanageable ways. [40] This said, however, the short-lived climate impact of both methane and nature-based solutions provides another possibility, which is that linear warming equivalent (LWE) carbon removals for a pulse of methane could be calculated and used to inform a directly equivalent and less punitive exchange metric between the two. Described in reference [159], LWE emissions for a 1 ton pulse emission of CH_4 can be calculated by estimating the radiative forcing profile resulting from a CH_4 pulse through the multiplication of emissions with it's AGFP matrix $F_A \cdot e_A$, and then feeding the result through the inverted AGFP matrix for CO2: $e_b = {F_b}^{-1} \cdot F_A \cdot e_A$. For reasons which will become clear in a moment, we have here calculated the LWE-equivalent emissions for 1 $GtCO_2e100$ of methane. This process produces a LWE-equivalent removal of ~4.5 tons CO2 per ton CO_2e100-CH_4, with a half-life of 14 years. (Figure 2).

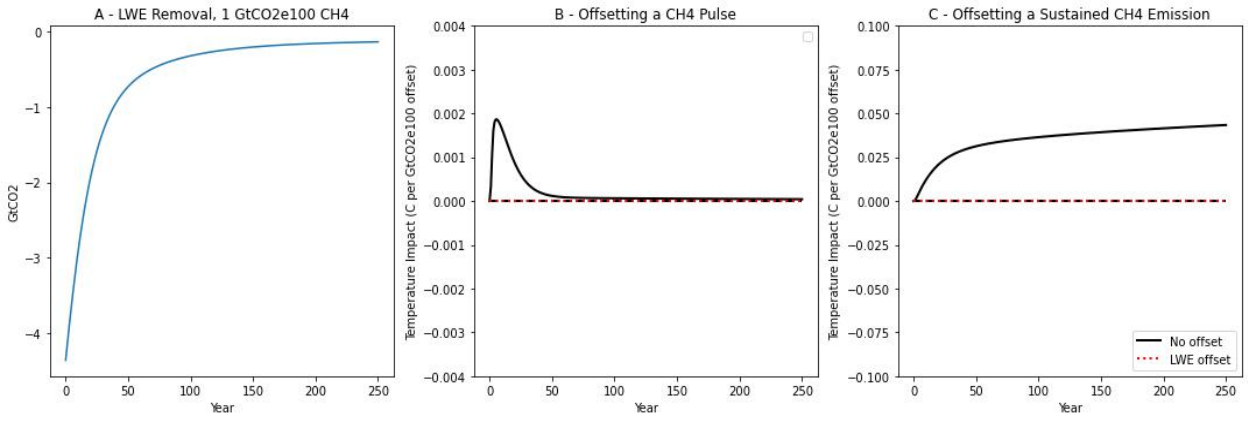


Fig. 2: Global average temperature response to offsetting the emission of a pulse, or sustained pulse, of methane with linear warming equivalent (LWE) CO_2 emissions. A, cumulative LWE emissions for a 1 $GtCO_2e100$ pulse of CH4 (blue). B, the temperature

impact of offsetting a pulse emission of methane with LWE emissions. ***C****, the same, but offsetting a sustained emission.*

While it is unlikely that there will be many (or any) nature-based carbon capture projects that exhibit a cumulative emissions profile identical to that of the LWE emissions of an abated methane pulse, this is not necessary in order for LWE emissions to be applicable to the trade of ITMOs through carbon markets. Much like collateralized securities in financial markets, providers of nature-based solutions could, in a given year, create a synthetic offset through the packaging of discrete quantities of carbon removals with different expected lifespans from a diverse range of owned biomass enhancement / protection / management projects such that the aggregate magnitude and behavior of the offset matches that of the LWE-requirements. (E.g. 4.5 tons with a collective half-life not less than 14 years). Under such a system, emitters with hard-to-abate sources of methane could finance nature-based solutions projects through the purchase of LWE-equivalent offsets, which would have an unambiguous and equal marginal impact on the climate system over time.

Furthermore, purchasers of such offsets could also continue to accurately measure the climate impact of their aggregate emissions using the GWP100 equivalency metric prescribed by the UNFCC:

$$\Delta T = TCRE \cdot E_L \, \Delta \, t + TCRF \cdot A_{100}(\Delta \, E_s + \, \rho E_s \, \Delta \, t) \tag{7}$$

Where E_L is cumulative long-lived emissions (reported in CO2e-100), the TCRF is the transient "fast" climate response to warming, A_{100} the AGWP of CO2, $\Delta \, E_s$ the change in short-lived emissions (reported also in CO2e-100), and $\rho E_s \, \Delta \, t$ a scaling term to account for the long-term equilibration of the climate to past levels of short-term forcing. [161] Under such a system, purchased LWE-equivalent offsets could be approximately incorporated as reductions to the E_s term, given they are already denominated in CO2e-100 tons of CH_4. Alternatively, more accurately, and consistent with the logic described

above, purchased offsets could also be incorporated as a separate cumulative emissions term via the changing rate of deployment:

$$\Delta T(tCDR) = AGTP_s(tCDR) \cdot \Delta R(t) \quad (8)$$

Where $\Delta R(t)$ is the change in rate of purchase of offsets over time period t. With equation (2) and the magnitude and half-life from the LWE calculation this gives us:

$$\Delta T(tCDR) = TCRE \cdot \frac{4.5}{1e^{\left(\frac{-\ln(2)}{14}\right)}} \cdot \Delta R(t) \quad (9)$$

Conclusion

Here, we have demonstrated that tCDR generated by nature-based solutions could play a limited role as ITMOs under future global carbon markets given the use of standardized metrics of exchange selected under a "do-no-harm" principle. Specifically, we have demonstrated that individual temporary removal could be used to offset one-off pulses of methane or other SLCPs when using any GWPH with a sufficiently large timeframe to capture the bulk of the offset pollutant's radiative forcing. tCDR could also play a role in offsetting a wider range of climate pollutants through chaining removals together into sustained deployments which approximate permanent removal, but there are socio-political challenges associated with implementing such offsets. Finally, we have proposed a new method for incorporating nature-based solutions into carbon markets which could help unlock a more physically-justified role for scaling up individual land-use projects as part of individual actor mitigation strategy.

Specifically, we propose LWE units of tCDR could be used to directly offset methane emissions. Under such a proposal, providers of nature-based removals could construct synthetic offsets which combine the annual output of a portfolio of land-sink enhancement projects that together have the appropriate magnitude and half-life to directly offset the radiative forcing of a ton of methane emission. These offsets could be

freely exchanged without imposing ambiguous warming outcomes on the individual action level, and could be seamlessly integrated into the existing CO2e100 GHG reporting structure specified by the UNFCC through either approximating a reduction in the emission of short-lived pollutants, or a new cumulative removals term. Given the known highly non-linear nature of short-lived pollutant marginal abatement cost curves (e.g. there is a material portion of methane emissions which are presently difficult to abate at any cost), adopting this system could help address hard-to-abate SLCP pollution while also providing the co-benefit of moving capital into the restoration of the biosphere, which, as discussed, is an important endeavour for many reasons outside of pure carbon storage. Effective use of such a mechanism will depend on accurate measurement of the LWE of methane and tCDR. This is not as simple as equating net carbon emissions over the lifetime of the methane pulse, as when generated by nature-based solutions tCDR can have (potentially substantial [60]) biophysical effects, including changes to surface albedo, evapotranspiration, or cloud cover driven by avoided deforestation or reforestation efforts. [71] Other factors impacting the atmospheric dynamics of methane would also need to be accounted for – for example, it is known that various changes to human activity, as well as atmospheric conditions, can affect the strength of the atmospheric OH sink, which in turn increases the half-life of a given ton of methane emissions. [168-169]

Finally, it is important to highlight here that SLCP emissions from a given decade only have significant impact on peak temperature under circumstances in which CO_2 emissions are falling, meaning that while immediate action on methane abatement might buy time for adaption by reducing near-term warming, money spent on offsetting near-term methane emissions could be better spent on other mitigation options. [170] Therefore, the importance of this mechanism for integrating tCDR into carbon markets should be considered an approach to managing hard-to-abate residual short-lived forcing as we near net-zero emissions, or, in effect, a proposal for how tCDR can be used as a "peak shaving" mechanism. [60, 71]

5. Conclusion

Human civilization is facing a global poly-crisis: "the causal entanglement of crises in multiple global systems in ways that significantly degrade humanity's prospects". [171] Many facets of this poly-crisis result from the accelerating impact of our economic activity on our planet's interconnected atmosphere, biosphere, and ocean systems, which have now exceeded six of nine boundaries identified as "critical for maintaining the stability and resilience of the Earth system as a whole". [172] These impacts include not only climate change, but reductions in functional and genetic biosphere integrity, the disruption of biogeochemical flows, the depletion of freshwater resources, substantive land system change, and the release of novel entities into our environment. Addressing this poly-crisis will require not only targeted solutions for each individual facet, but also identifying interventions which could positively impact multiple facts at the same time. [171] One such intervention is biosphere enhancement. Enhancing, protecting, or better managing large parts of the biosphere can deliver a wide range of benefits, including enhancing local biodiversity [61], protecting against particular forms of physical climate risks [63], and generating useful and sustainable economic outputs [62]. One of the other by-products of at-scale biosphere enhancement is an increase in the storage of atmosphere carbon in various forms of biomass. [60-61] Predicting the climate impact of this phenomenon is difficult, however, because carbon stored in biomass is, by nature, exposed to the risk of re-release to the atmosphere given various forms of disturbance like fire and pest outbreaks. [167] Given the scale of potential biosphere enhancement available to us, the magnitude of potential benefits across multiple crises that can be derived from it, and the low cost of doing so, a pertinent question to ask is: can we find a physically justifiable role for the temporary carbon storage it generates in the context of global mitigation strategy?

This thesis has attempted to address three of the outstanding methodological barriers for doing so. Firstly, it established a robust framework for defining which activities should be counted as tCDR and at what point in time, in order to avoid double counting between temporary and permanent CDR methods which share feedstocks. It then

applies this framework to quantify the first comprehensive estimate of global carbon dioxide removal (CDR) deployment, addressing a core gap in our ability to track and manage CDR deployment efforts. This effort determined that current anthropogenic activity generates approximately 1985 MtCO2yr-1 of atmospheric removals, with only 210 MtCO2yr-1 coming from reported CDR projects. The vast majority of these removals (>99.9%) stem from land-use, land-use change, and forestry (LULUCF) activities. In contrast, non-land-management CDR projects such as bioenergy with carbon capture and storage (BECCS) and direct air capture with carbon storage (DACCS) account for less than 2 MtCO2yr-1. Comparing these findings with projections from Shared Socioeconomic Pathways (SSPs) for "well-below 2°C" scenarios reveals a significant gap between current deployment and future needs. To align with most climate mitigation pathways, current “engineered” CDR deployment would need to grow exponentially, adding 300-2500 MtCO2 in total CDR capacity by 2030, while necessary contributions from the land-surface remain ambiguous.

Secondly, a detailed analysis of the climate system's response to temporary carbon dioxide removal (tCDR) using both an Earth System Model of Intermediate Complexity and an emulated ensemble of Earth System Models was conducted. This investigation confirms earlier suggestions that tCDR deployed at-scale, around and after the moment of net-zero emissions, could cause an overshoot in cumulative atmospheric carbon content relative to the counterfactual scenario in which that deployment did not take place. This is relevant given one of the primary suggestions for a mitigation role for nature-based temporary carbon storage is “peak-shaving”, or deployment near the moment of net-zero emissions to limit absolute peak warming. Once advance resulting from this work is the identification of the primary drivers behind the cumulative overshoot phenomenon. The ocean overturning rate plays a crucial role, as does the interaction between surface ocean and biosphere carbon sinks. More importantly, however, it demonstrates that for realistic deployment volumes and scenarios the temperature overshoot that results remains below the threshold of detection given natural climate variability. This suggests that, when assessing its climate impact, tCDR

can be approximated directly as a fractional permanent removal, an insight which has significant implications for emissions accounting metrics and policy decisions regarding temporary carbon storage projects, including their potential use in international carbon trading under the Paris Agreement.

Thirdly, and finally, given the recognition that the distribution of eligible land for biosphere enhancement is highly heterogenous (with a pronounced concentration in the tropics), different methods for incorporating nature-based tCDR into the framework of Internationally Traded Mitigation Outcomes (ITMOs) were explored. In doing so, this thesis demonstrated that while Global Warming Potential (GWP) metrics could facilitate the physically-justified use of tCDR to offset one-off pulses of methane or other SLCPs under a "do-no-harm" principle, or the chaining of tCDR into sustained deployments approximating permanent removal, both face substantive operationalization challenges including punitive exchange rates and multi-decade or -century management obligations. Instead, a novel method for incorporating nature-based solutions into carbon markets was proposed, using Linear Warming Equivalent (LWE) units of synthetic offsets drawn from across a portfolio of land enhancement projects to directly offset individual tons of methane emissions. In sum, the collective work up to this point leads to the hypothesis that temporary carbon storage provided by nature-based solutions could provide a small but physically-justified way to address hard-to-abate SLCP pollution as a "peak shaving" approach when nearing the point of net-zero emissions.

To conclude, we will now turn to four directions for important future work from this point of departure. Firstly, as discussed in Paper 1, model-based scientific studies used to determine the requirements of warming target-aligned mitigation pathways account for the role of anthropogenic land-based carbon fluxes very differently from the way countries report them under NGHGIs. The difference between the two is very large, with studies estimating a flux difference in both magnitude (on the order of gigatons) and in sign, which together can be attributed to the inclusion of both direct and indirect effects

on managed land in NGHGI accounting methods, and their exclusion in bookkeeping models. This difference makes it exceptionally difficult to accurately assess whether or not real-world changes in land use align with a given warming target, a pre-requisite for effectively monitoring and managing the deployment of nature-based solutions. [173] A recent study by Gidden et al. (2023) makes a first attempt at reconciling the two by applying a dynamic carbon-cycle model (OSCAR) to adjust the output of mitigation scenario projections to follow NGHGI-accounting definitions. [174] This allows a derivation of required land-based CDR under various mitigation scenarios, with total additional land-based removals estimated at 2.6 GtCO2yr-1 and 0.7 GtCO2yr-1 between 2020 and 2030 in the 1.5°C and 2°C pathways, respectively. [174] Furthermore, three future needed advances are identified: firstly, this study needs to be replicated with a wider and more diverse range of carbon cycle models to investigate uncertainty in the results they present. Secondly, the authors propose that climate targets be explicitly formulated to include gross CO2 emission reductions without LULUCF, net land-based removals, engineered removals, and SLCP abatement, such that contributions can be effectively defined and managed separately. Thirdly and finally, the IAM teams which produce mitigation scenario data should update their processes to provide indirect land flux components consistent with the NGHGI accounting practices.

Given greater clarity on the role of land-sink enhancement in meeting temperature targets, another needed advance is a verification of the tCDR dynamics presented herein with experiments conducted with fully-dynamic Earth System Models (ESMs). As discussed at length in Paper 2, the UVic ESCM model employed herein has two primary drawbacks resulting from it's use of a slab-atmosphere component (which is the primary source of its computational efficiency): an inability to capture changes in atmospheric circulation and therefore regional pattern effects in wind forcing, temperature, and precipitation which are highly relevant for both the land and ocean sink response to a given climate intervention. Given the most important results are those investigating the response of a perturbed climate to tCDR, the experiments conducted herein could be branched directly off of the existing CDRMIP runs, avoiding the computational cost of

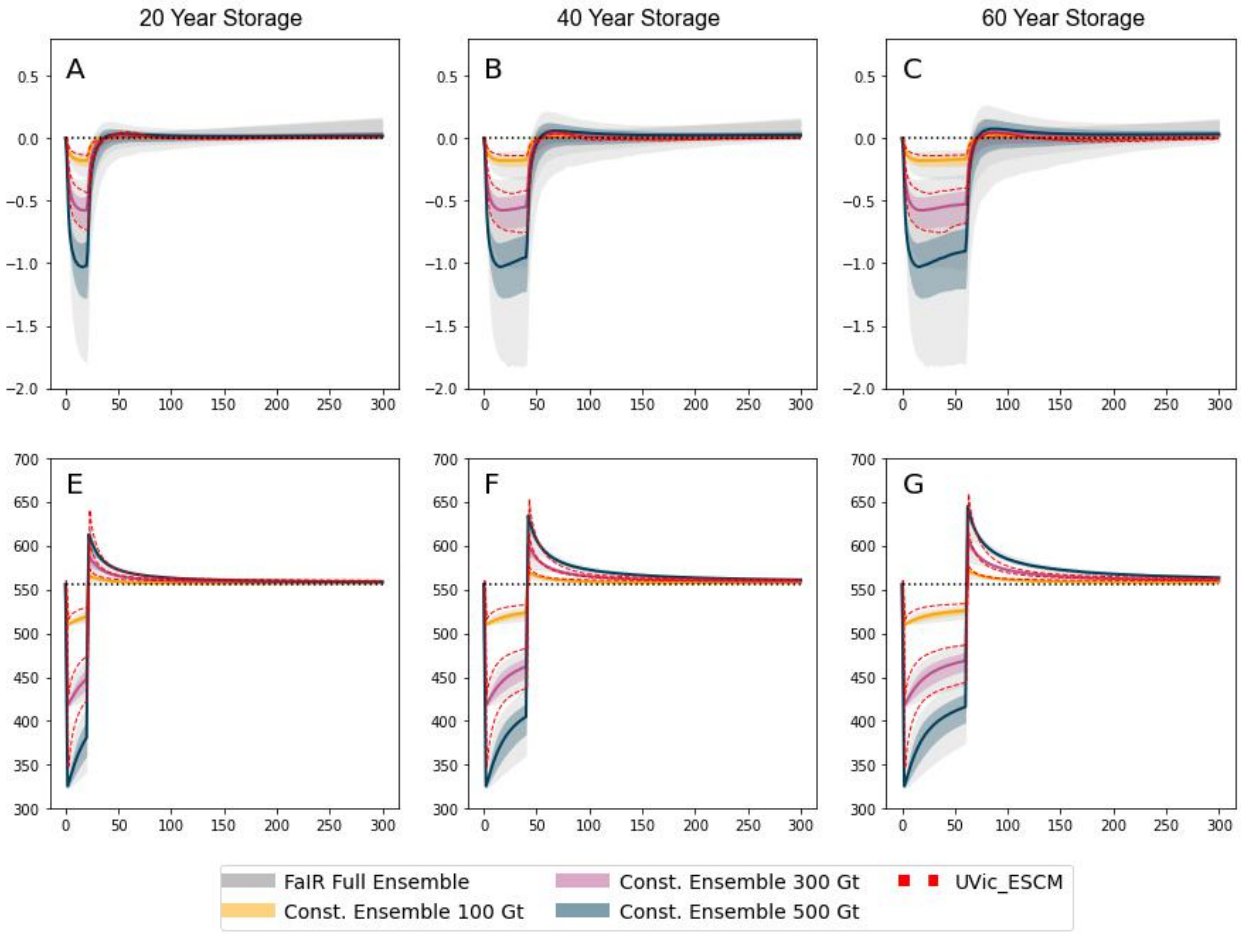
lengthy model spin-up. Initial studies comparing ESM and EMIC behavior across both the ZECMIP and CDRMIP experiments demonstrate some potentially important behavioral differences between simplified and more dynamic models. For example, experiments conducted with ESMs demonstrated that terrestrial uptake of carbon plays a more important role in determining the value of the Zero-Emissions Commitment (ZEC) on decadal timescales compared to investigations conducted with EMICS. [138] Furthermore, the UVic ESCM version used in this study lacks a representation of the terrestrial nitrogen cycle and its interaction with the carbon cycle. This omission results in greater land carbon gain under increasing CO2 and more carbon loss with climate change compared to ESMs with nitrogen cycles. Under decreasing CO2, the model likely overestimates land carbon gain from climate changes alone, as it doesn't account for reduced nitrogen mineralization at lower temperatures. The impact on carbon change due to CO2 concentration alone is less certain, as nitrogen limitation could further constrain CO2 fertilization effects, potentially offset by enhanced photosynthesis from lower carbon-nitrogen ratios. [48]

Whether measuring the global impact of at-scale biosphere enhancement, or quantifying the temperature impact of specific quanta of nature-based tCDR traded via carbon markets, understanding in-depth the full impact of the albedo effects of land-use change is essential. There has been a profusion of recent work in this space. Experiments conducted using two ESMs demonstrated that at-scale forestation increases aerosol scattering and levels of methane and ozone due to increased biogenic volatile compound (BVOC) emissions, in addition to decreasing surface albedo. The net radiative effect from these changes is positive, offsetting 23-31% of the cooling benefit. [175] Further work investigating the climate impact of extant biosphere enhancement projects suggests the majority of on-the-ground afforestation projects are concentrated in climate-positive regions, but still face at least a 20% albedo offset. [176] These efforts recognize that many effects of increasing tree cover impact the global climate in complex ways that are only “weakly characterized at present”. [177] More accurately assessing these impacts will depend on a combination of more extensive

Earth-system experimentation, better tools for forest-atmosphere interaction monitoring, and targeted investigations with more complex land-surface models. [178]

Finally, and perhaps most importantly, the relevance of tCDR's role in mitigation strategy will depend largely on the cost differential between scaling up biosphere enhancement projects and abating the methane sources which exist at the far end of the marginal abatement cost curve. If the cost differential is high and is expected to remain high, there is a good argument to be made that scaling up tCDR to offset hard-to-abate methane or other SLCP emissions is economically and physically useful. If this differential is low, it is unlikely that tCDR has a meaningful role to play, and nature-based solutions will need to contribute to climate mitigation through at-scale and permanent changes in land-use. Extensive recent work on developing long-term non-CO2 abatement costs curves suggests that the maximum economical reduction potential for N20 is higher than previously assessed, while the potential for CH4 is lower, with a projected maximum reduction potential of only 68%. [179] Agricultural emissions remain the bottleneck, comprising almost 80% of remaining non-CO2 emissions once the economically abate-able sources have been reduced. While options for the atmospheric removal or destruction of methane have been proposed via the release of photo-catalysts or enhancement of specific microbial communities [82] these proposals are extremely preliminary. Whether or not such proposals are scalable and could become cost-competitive with nature-based solutions is unclear, but it seems likely that they could become available on the same scale (and with the same volume of co-benefits) as nature-based solutions. Thus, this thesis concludes with the proposition that further academic and institutional investigation be directed towards the operationalization of nature-based carbon offsets as a tool for addressing hard-to-abate SLCP emissions as we approach the point of net-zero emissions. If achieved, this could provide a small but needed mechanism for connecting the mitigation efforts of the joint climate and biodiversity crises, helping to preserve our heritage for future generations.

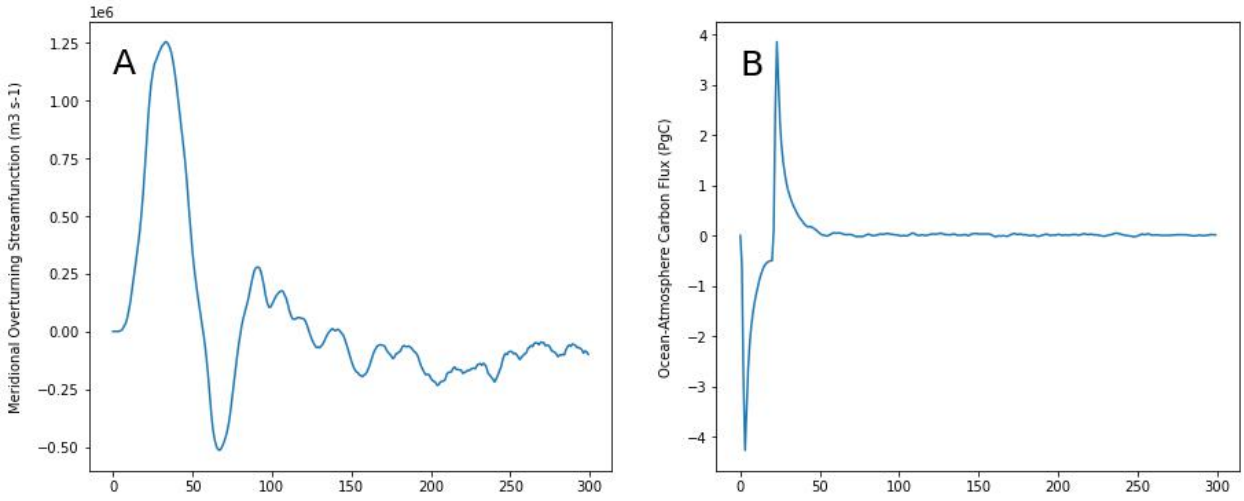
6. Supplementary Materials



Sup. Fig. 1: Global average temperature and atmospheric CO_2 concentration response to temporary CDR in a 2xCO_2 equilibrium climate. A-C, *global average temperature response to temporary CDR with storage lifetimes of 20, 40, and 60 years respectively. Mean emulated CMIP6 ensemble results plotted as lines, with the observationally-constrained results shaded and full ensemble results shaded in gray . UVic ESCM results in red.* ***D-F,*** *atmospheric CO_2 concentration response to temporary CDR, coloring the same.*

In order to produce a 2xCO_2 equilibrium climate state with the UVic ESCM model, the atmospheric CO_2 concentration was prescribed at 2x preindustrial concentrations and

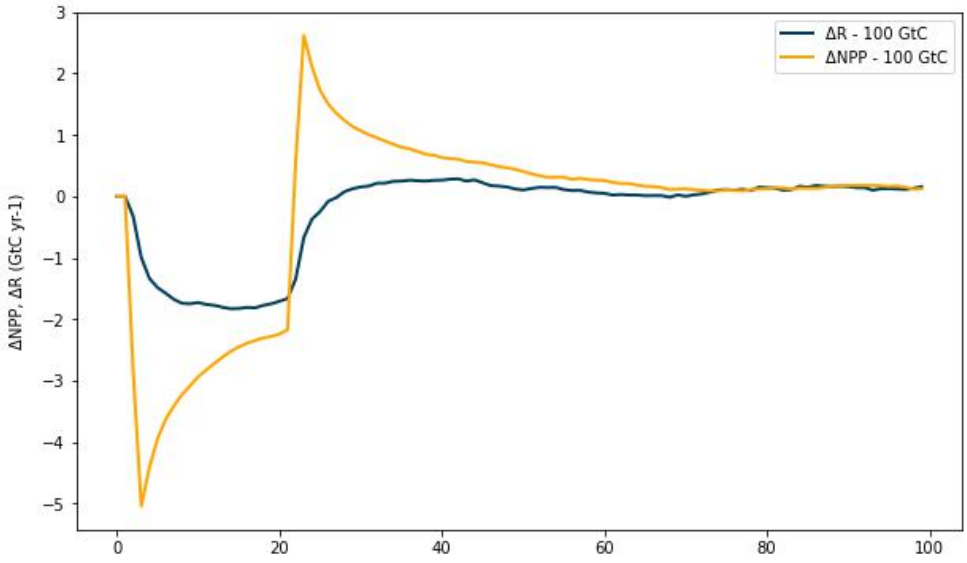
held constant for a period of 10,000 simulated years until the drift in ocean tracers was negligible. To approximate a similar equilibrium state with the FaIR v2.0.0 simple climate model, a 10,000 year simulation was run with atmospheric CO_2 concentrations set at 2x pre-industrial. The resulting emissions were then diagnosed and prepended to the experiment sets. The difference between the magnitude of cooling across results is unsurprising given the FaIR model was tuned using experiments featuring rising emissions in a transient climate state, and thus did not have sufficient information to effectively capture changes to carbon cycle removal dynamics under a new equilibrium state. For this reason when describing the dynamics of the $2xCO_2$ equilibrium tCDR, only UVic ESCM results were used.



Sup. Fig. 2 Meridional Overturning Circulation (MOC) and Ocean-to-Atmosphere Carbon Flux following a 100 GtC removal of 20 years. A, *Meridional overturning streamfunction response to a 100 GtC removal of 20 years in a pre-industrial equilibrium climate, measured in m3 s-1.* ***B,*** *Ocean-to-atmosphere carbon flux response to the same, measured in PgC.*

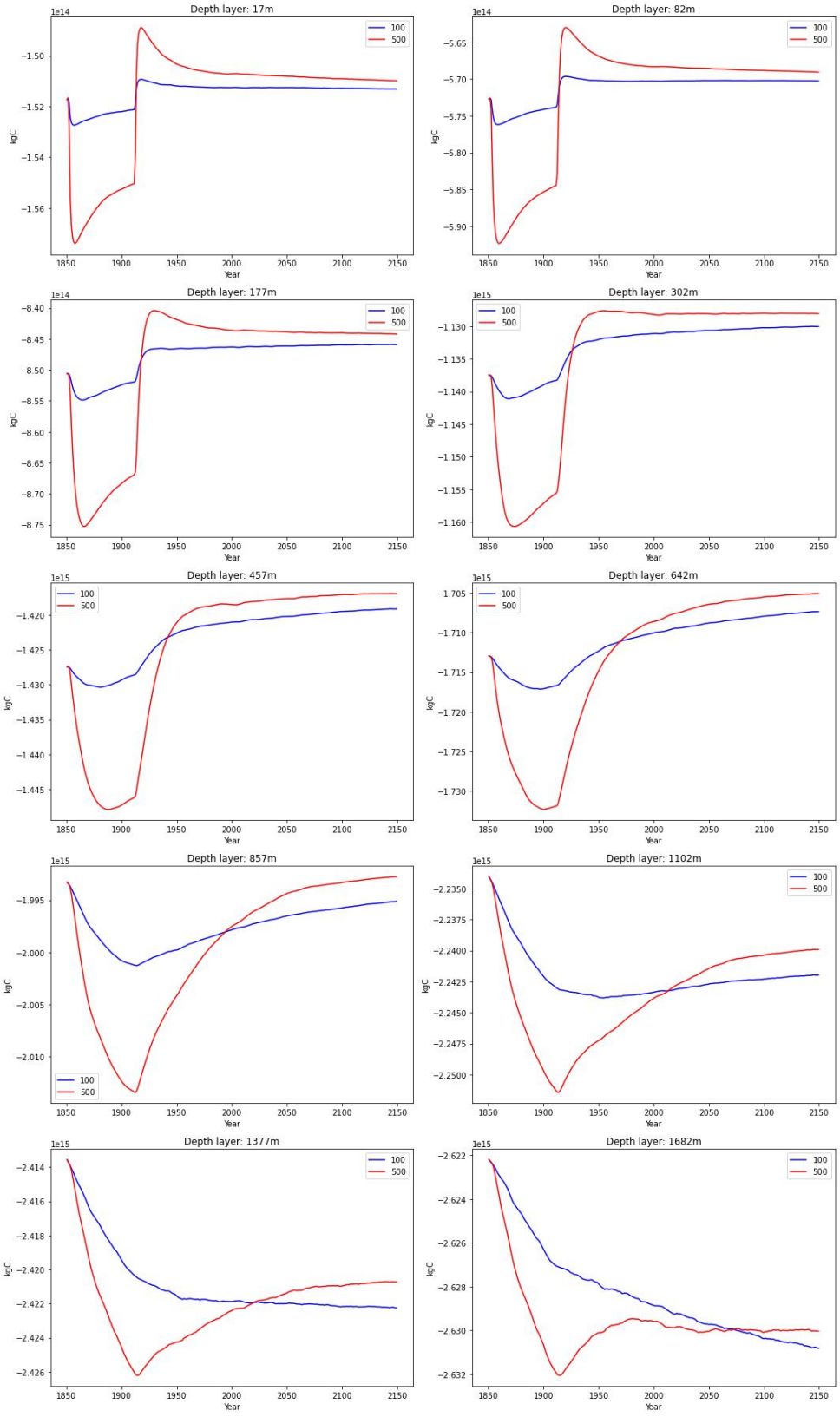
The asymmetric MOC response to tCDR could be model-dependant, as pointed out in the course of CDR experiments conducted by [84], while the asymmetric ocean carbon

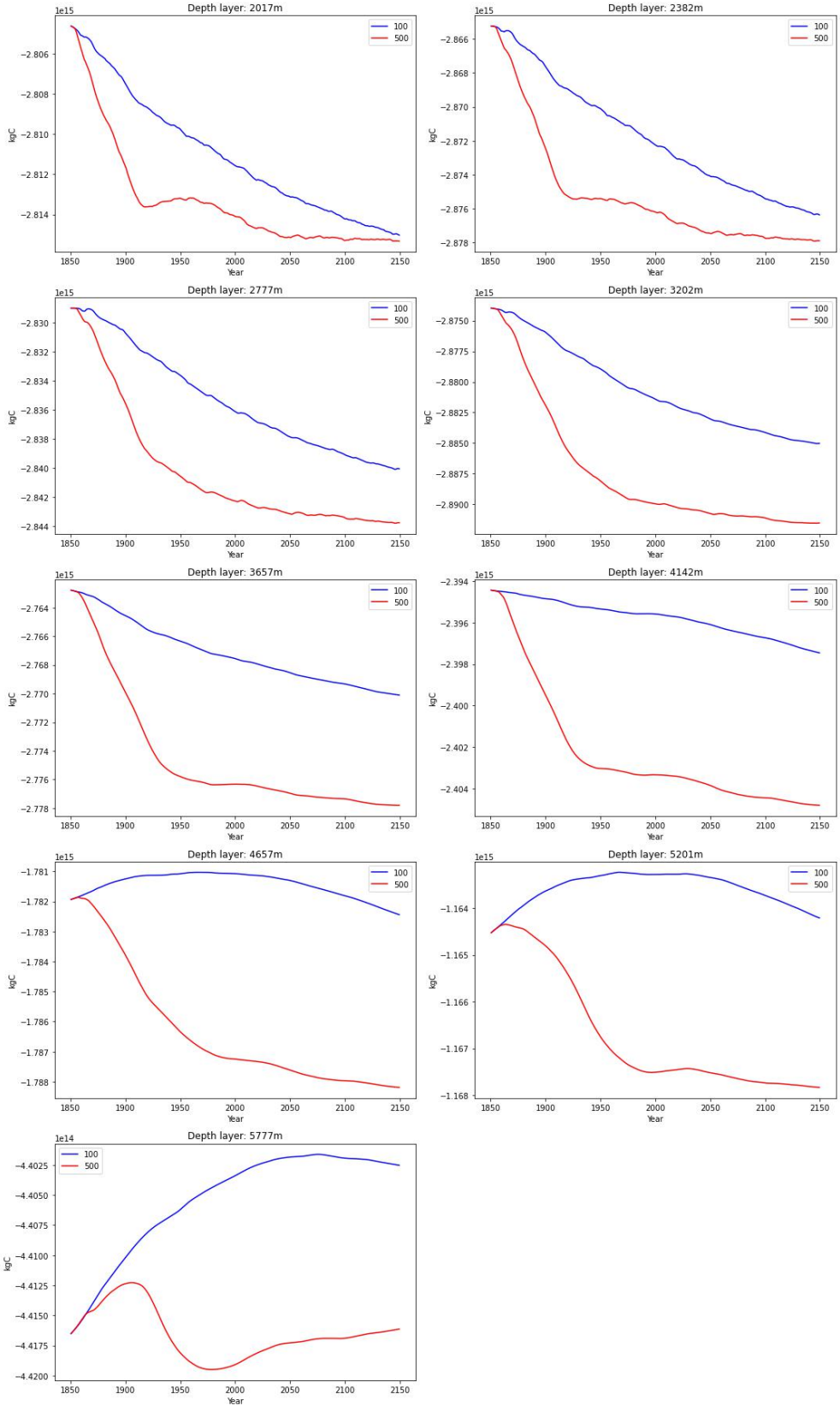
cycle response to changes in pCO_2 is expected to be robust to model choice as it is predicated on the well-known non-linear behavior of the Revelle buffer factor.



Sup. Fig. 3 Biosphere Net Primary Productivity (NPP) and Soil Respiration (R) following a 100 GtC removal of 20 years.

Sup. Fig. 3 Demonstrates the reason that tCDR transfers carbon from the ocean to the biosphere in the long-run, and not from the ocean to the atmosphere. NPP varies as an immediate function of changing atmospheric CO_2 concentrations, while soil respiration lags these changes and exhibits less sensitivity to the tCDR perturbation, varying as a function of global average temperature. As a result, the biosphere loses carbon during the removal portion of the tCDR (as declining NPP outstrips increased carbon retention in soil), but gains carbon following re-release (as increased NPP outstrips decreased carbon retention in soil). This system response exhibits asymmetry because the biosphere equilibration process to removals is interrupted by tCDR re-release, but able to occur in full afterwards, allowing for the transfer of excess ocean carbon into biomass via photosynthesis.


Depth layer: 17m
Depth layer: 82m
Depth layer: 177m
Depth layer: 302m
Depth layer: 457m
Depth layer: 642m
Depth layer: 857m
Depth layer: 1102m
Depth layer: 1377m
Depth layer: 1682m
100
500
kgC
Year


Depth layer: 2017m
Depth layer: 2382m
Depth layer: 2777m
Depth layer: 3202m
Depth layer: 3657m
Depth layer: 4142m
Depth layer: 4657m
Depth layer: 5201m
Depth layer: 5777m
100
500
kgC
Year

Sup. Fig. 4: Ocean-layer response to 100 and 500 GtC tCDR in an equilibrium climate. *Measured in kgC, these plots demonstrate the net flow of carbon between each of the 19 respective ocean layers contained within the MOM ocean model component of the UVic model.*

7. Coauthor declarations

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Title of co-authored article	ON THE DYNAMICS OF TEMPORARY CARBON DIOXIDE REMOVAL

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9. References

1. Wake, B. Climate research Foote note. Nat. Clim. Chang. 10, 888 (2020).
2. Keeling, C.D. The Concentration and Isotopic Abundances of Carbon Dioxide in the Atmosphere. Tellus 12(2), 200-203 (1960).
3. Charney, J.G. et al. Carbon Dioxide and Climate: A Scientific Assessment. Assembly of Mathematical and Physical Sciences: National Research Council. (1979).

4. Nordhaus, W.D. Optimal Greenhouse-Gas Reductions and Tax Policy in the "DICE" Model. The American Economic Review 83(2), 313-317 (1993).
5. Pindyck, R.S. Climate Change Policy: What do the models tell us? Journal of Economic Literature. (2013).
6. Giorgi, F. Thirty years of regional climate modeling: Where are we and where are we going next? Journal of Geophysical Research: Atmospheres 124, 5696–5723. (2019).
7. Hansen, J. et al. Perception of climate change. Proc. Nat. Ac. Sci. 109(37), E2415-E2423 (2012).
8. Stott, P. How climate change affects extreme weather events. Science 352, 1517-1518 (2016).
9. Seneviratne, S.I., et al. Weather and Climate Extreme Events in a Changing Climate. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., et al. (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1513–1766, doi: 10.1017/9781009157896.013. (2021).
10. Feynman, J., Ruzmaikin, A. Climate stability and the development of agricultural societies. Climatic Change 84, 295–311 (2007).
11. Steel, D., DesRoches, T.C., Mintz-Woo, K. Climate change and the threat to civilization. Proc. Nat. Ac. Sci. 42(119) (2022).
12. Botros, A. A looming insurance shock spells trouble for housing markets in Florida and California. Fortune: Housing. (2023). Available at: https://fortune.com/2023/08/18/housing-market-home-insurance-shock-spells-trouble-for-florida-and-california/.
13. McKinsey & Company. Climate Risk & Response: Physical Hazards and Socioeconomic Impacts. McKinsey Global Institute. (2020).
14. Raymond, C., Matthews, T., Horton, R.M. The emergence of heat and humidity too severe for human tolerance. Sci. Adv. 6, eaaw1838 (2020).
15. Vecellio, D.J. et al. Greatly enhanced risk to humans as a consequence of empirically determined lower moist heat stress tolerance. Proc. Nat. Ac. Sci. 120(42) (2023).
16. Powis, C.M. et al. Observational and model evidence together support widespread exposure to non-compensable heat under continued global warming. 9(36) (2023).
17. Kaczan, D.J., Orgill-Meyer, J. The impact of climate change on migration: a synthesis of recent empirical insights. Climatic Change 158, 281–300 (2020).
18. Wheeler, T., von Braun, J. Climate Change Impacts on Global Food Security. Science 341, 508-513 (2013).
19. Koubi, V. Climate Change and Conflict. Annual Review of Political Science. 22(1), 343-360 (2019).
20. Kemp, L. et al. Climate Endgame: Exploring catastrophic climate change scenarios. Proc. Nat. Ac. Sci. 119(34) (2022).

21. United Nations Framework Convention on Climate Change, May 9, 1992, S. Treaty Doc No. 102-38, 1771 U.N.T.S. 107. (2015).
22. Schellnhuber, H., Rahmstorf, S., Winkelmann, R. Why the right climate target was agreed in Paris. Nature Clim Change 6, 649–653 (2016).
23. Houghton, J.T., Jenkins, G.J., Ephraums, J.J. Report prepared for Intergovernmental Panel on Climate Change by Working Group I (eds.). Cambridge University Press, Cambridge, Great Britain, New York, NY, USA and Melbourne, Australia. (1990).
24. Hansen, J. et al. Climate Response Times: Dependence on Climate Sensitivity and Ocean Mixing. Science. 224(4716) (1985).
25. Roe, G.H., Baker, M.B. Why Is Climate Sensitivity So Unpredictable? Science 318, 629-632 (2007).
26. Sherwood, S.C., Webb, M.J., Annan, J.D., Armour, K.C., Forster, P.M., Hargreaves, J.C., et al. An assessment of Earth's climate sensitivity using multiple lines of evidence. Reviews of Geophysics, 58, (2020).
27. Allen, M.R., Frame, D.J. Atmosphere. Call off the quest. Science. 318(5850), 5 (2007).
28. Archer, D. Fate of fossil fuel CO2 in geologic time. J. Geophys. Res., 110, C09S05, (2005).
29. Matthews, H.D., Caldeira, K. Stabilizing climate requires near-zero emissions. Geophys. Res. Lett., 35, (2008).
30. Allen, M., Frame, D., Huntingford, C. et al. Warming caused by cumulative carbon emissions towards the trillionth tonne. Nature 458, 1163–1166 (2009).
31. IPCC, 2021: Chapter 7, Figure 7.6. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Forster, P., et al.]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 923–1054, doi: 10.1017/9781009157896.009.
32. Samset, B.H., Sand, M., Smith, C.J., Bauer, S.E., Forster, P.M., Fuglestvedt, J.S., Osprey, S., Schleussner, C.-F. Climate impacts from a removal of anthropogenic aerosol emissions. Geophysical Research Letters 45, 1020–1029. (2018).
33. Canadell, J.G., et al. Global Carbon and other Biogeochemical Cycles and Feedbacks. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., et al. (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 673–816. (2021).
34. Matthews, H.D., Tokarska, K.B., Nicholls, Z.R.J., et al. Opportunities and challenges in using remaining carbon budgets to guide climate policy. Nat. Geosci. 13, 769–779 (2020).
35. Lamboll, R.D., Nicholls, Z.R.J., Smith, C.J., et al. Assessing the size and uncertainty of remaining carbon budgets. Nat. Clim. Chang. 13, 1360–1367 (2023).

36. Pierrehumbert, R.T. Short-Lived Climate Pollution. Annual Review of Earth and Planetary Sciences 42(1), 341-379 (2014).
37. Millar, R.J., Fuglestvedt, J., Friedlingstein, P., Rogelj, J., Grubb, M.J., Matthews, H.D., et al. Emission budgets and pathways consistent with limiting warming to 1.5°C. Nature Geoscience 10, 741–747 (2017).
38. Jenkins, S., Millar, R.J., Leach, N., Allen, M.R. Framing climate goals in terms of cumulative CO2-forcing-equivalent emissions. Geophysical Research Letters 45, 2795–2804 (2018).
39. Allen, M.R., et al. A new use of Global Warming potentials to compare cumulative and short-lived climate pollutants. Nat. Clim. Change 6, 773–776 (2016).
40. Meinshausen, M., Nicholls, Z. GWP* is a model, not a metric. Environ. Res. Lett. 17, (2022).
41. Allen, M.R., Peters, G.P., Shine, K.P., et al. Indicate separate contributions of long-lived and short-lived greenhouse gases in emission targets. npj Clim Atmos Sci 5, 5 (2022).
42. Riahi, K., R. et al. Mitigation pathways compatible with long-term goals. In IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, NY, USA. doi: 10.1017/9781009157926.005
43. Fuss, S., et al. Negative emissions - Part 2: costs, potentials and side effects. Environ. Res. Lett. 13, 063002 (2018).
44. Powis, C.M., et al. Quantifying global carbon dioxide removal deployment. Environ. Res. Lett. 18, 024022 (2023).
45. Nemet, G.F., et al. Negative emissions - Part 3: innovation and upscaling. Environ. Res. Lett. 13, 063003 (2018).
46. Keller, D.P., Lenton, A., Littleton, E.W., et al. The Effects of Carbon Dioxide Removal on the Carbon Cycle. Curr Clim Change Rep 4, 250–265 (2018).
47. Asaadi, A. et al. Carbon cycle feedbacks in an idealized simulation and a scenario simulation of negative emissions in CMIP6 Earth system models. Biogeosciences. 21, 411–435, (2024).
48. Chimuka, V. R., et al. Quantifying land carbon cycle feedbacks under negative CO2 emissions. Biogeosciences, 20, 2283–2299, (2023).
49. Zickfeld, K., Azevedo, D., Mathesius, S. et al. Asymmetry in the climate–carbon cycle response to positive and negative CO2 emissions. Nat. Clim. Chang. 11, 613–617 (2021).
50. Cao L, Caldeira K. Atmospheric carbon dioxide removal: long-term consequences and commitment. Environ Res Lett. (2010).
51. Boucher O. et al. Reversibility in an earth system model in response to CO 2 concentration changes. Environ Res Lett. (2012).
52. Jones CD, et al. Simulating the earth system response to negative emissions. Environ Res Lett. (2016).

53. Herrington T, Zickfeld K. Path independence of climate and carbon cycle response over a broad range of cumulative carbon emissions. Earth Syst Dyn. (2014).
54. Zickfeld K, MacDougall AH, Matthews HD. On the proportionality between global temperature change and cumulative CO 2 emissions during periods of net negative CO 2 emissions. Environ Res Lett. (2016).
55. Tokarska KB, Zickfeld K. The effectiveness of net negative carbon dioxide emissions in reversing anthropogenic climate change. Environ Res Lett. (2015).
56. Keller, D.P., Lenton, A., Scott, V., Vaughan, N.E., Bauer, N., Ji, D., Jones, C.D., Kravitz, B., Muri, H., Zickfeld, K. The Carbon Dioxide Removal Model Intercomparison Project (CDRMIP): rationale and experimental protocol for CMIP6. Geosci. Model Dev. 11, 1133–1160 (2018).
57. Kirschbaum, M., et al. Temporary Carbon Sequestration Cannot Prevent Climate Change. Mitigation and Adaptation Strategies for Global Change 5-6, 1151-1164 (2006).
58. Walker, W., et al. The global potential for increased storage of carbon on land. Proc. Natl Acad. Sci. 119 (2022).
59. Bastin, J.F., et al. The global tree restoration potential. Science 364, 76–79 (2019).
60. Matthews, H.D., Zickfeld, K., Dickau, M., et al. Temporary nature-based carbon removal can lower peak warming in a well-below 2 °C scenario. Commun Earth Environ 3, 65 (2022).
61. Girardin, C.A.J., et al. Nature-based solutions can help cool the planet – if we act now. Nature 593, 191-194 (2021).
62. Johnston, C.M.T., Radeloff, V.C. Global mitigation potential of carbon stored in harvested wood products. Proc. Nat. Ac. Sci. 116(29) (2019).
63. Chausson, A., Turner, B., Seddon, D., et al. Mapping the effectiveness of Nature-based Solutions for climate change adaptation. Glob Change Biol; 26, 6134–6155. (2020).
64. Honegger, M., et al. Who is paying for Carbon Dioxide Removal? Designing Policy Instruments for Mobilizing Negative Emissions Technologies. Front. Clim. 3 (2021).
65. Groom, B., Venmans, F. The social value of offsets. Nature 619, 768–773 (2023).
66. Moura Costa, P., Wilson, C. An equivalence factor between CO2 avoided emissions and sequestration – description and applications in forestry. Mitigation and Adaptation Strategies for Global Change 5, 51–60 (2000).
67. Fearnside, P.M., et al. Accounting for time in Mitigating Global Warming through land-use change and forestry. Mitigation and Adaptation Strategies for Global Change 5, 239–270 (2000).
68. Korhonen, R. et al. The role of carbon sequestration and the tonne-year approach in fulfilling the objective of climate convention. Environ. Sci. Policy 5, 429–441 (2002).
69. Balmford, A., Keshav, S., Venmans, F., et al. Realizing the social value of impermanent carbon credits. Nat Clim Chang. 13, 1172–1178 (2023).

70. Brander, M. & Broekhoff, D. Methods that equate temporary carbon storage with permanent CO2 emission reductions lead to false claims on temperature alignment. Carbon Management, 14(1) (2023).
71. Matthews, H.D., Zickfeld, K., Koch, A., et al. Accounting for the climate benefit of temporary carbon storage in nature. Nat Commun 14, 5485 (2023).
72. IETA. "The Economic Potential of Article 6 of the Paris Agreement and Implementation Challenges", IETA, University of Maryland and CPLC. Washington, D.C. License: Creative Commons Attribution CC BY 3.0 IGO. (2019).
73. Minas, S. Market making for the planet: the Paris Agreement Article 6 decisions and transnational carbon markets. Transnational Legal Theory, 13(2-3), 287-320 (2022).
74. Babiker, M., G., et al. Cross-sectoral perspectives. In IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Shukla, P.R., Skea, J., Slade, R., Al Khourdajie, A., van Diemen, R., McCollum, D., Pathak, M., Some, S., Vyas, P., Fradera, R., Belkacemi, M., Hasija, A., Lisboa, G., Luz, S., Malley, J., (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA.
75. Minx, J.C., et al. Negative Emissions-Part 1: Research Landscape and Synthesis. Environ. Res. Lett. 13 063001 (2018).
76. Digdaya, I.A., et al. A direct coupled electrochemical system for capture and conversion of CO2 from ocean water. Nat Commun 11, 4412 (2020).
77. Bach, L.T., et al. Testing the climate intervention potential of ocean afforestation using the Great Atlantic Sargassum Belt. Nat Commun 12, 2556 (2021).
78. Sandalow, D., et al. Biomass Carbon Removal and Storage (BiCRS) Roadmap. Innovation for Cool Earth Forum, Japan. (2021).
79. Renforth, P. The negative emission potential of alkaline materials. Nat Commun 10, 1401 (2019).
80. Xi, F., et al. Substantial global carbon uptake by cement carbonation. Nat. Geosci. 9, 880–883 (2016).
81. Lomax, G., et al. Reframing the policy approach to greenhouse gas removal technologies. Energy Policy. 78, 125-136 (2015).
82. Jackson, R.B., et al. Atmospheric methane removal: a research agenda. Phil. Trans. R. Soc. 379, 20200454 (2021).
83. Ming, T., et al. Fighting global warming by greenhouse gas removal: destroying atmospheric nitrous oxide thanks to synergies between two breakthrough technologies. Environ Sci Pollut Res 23, 6119–6138 (2016).

84. De Richter, R.K., et al. Fighting global warming by GHG removal: Destroying CFCs and HCFCs in solar-wind power plant hybrids producing renewable energy with no-intermittency. International Journal of Greenhouse Gas Control. 49, 449-472 (2016).
85. Tanzer, S.E. & Ramírez, A. When are negative emissions negative emissions? Energy Environ. Sci. 12, 1210–1218 (2019).
86. Osaka, S. Framing "nature-based" solutions to climate change. WIREs Clim Change 12, 729 (2021).
87. Brander, M., et al. Carbon accounting for negative emissions technologies. Climate Policy, 21(5), 699-717 (2021).
88. Rickels, W., et al. (Mis)conceptions about modeling of negative emissions technologies. Environ. Res. Lett. 14 104004 (2019).
89. Herzog, H., Caldeira, K. & Reilly, J. An Issue of Permanence: Assessing the Effectiveness of Temporary Carbon Storage. Climatic Change 59, 293–310 (2003).
90. Levasseur, A., et al. Valuing temporary carbon storage. Nature Clim Change 2, 6–8 (2012).
91. Zickfeld, K., et al. Asymmetry in the climate–carbon cycle response to positive and negative CO2 emissions. Nat. Clim. Chang. 11, 613–617 (2021).
92. Pathak, M., R., et al. Technical Summary. In: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Shukla, P.R., Skea, J., Slade, R., Al Khourdajie, A., van Diemen, R., McCollum, D., Pathak, M., Some, S., Vyas, P., Fradera, R., Belkacemi, M., Hasija, A., Lisboa, G., Luz, S., Malley, J., (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA.
93. Doelman, J.C., et al. Afforestation for climate change mitigation: Potentials, risks and trade-offs. Glob Change Biol. 26, 1576– 1591 (2020).
94. Butarbutar, T., Köhl, M. & Neupane, P.R. Harvested wood products and REDD+: looking beyond the forest border. Carbon Balance Manage 11, 4 (2016).
95. Harmon, M.E., Fasth, B.G., Yatskov, M., et al. Release of coarse woody detritus-related carbon: a synthesis across forest biomes. Carbon Balance Manage 15, 1 (2020).
96. IPCC 2006. IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme, [Eggleston H.S., Buendia L., Miwa K., Ngara T. and Tanabe K. (eds)]. IGES, Japan.
97. Morrow, D.R., et al. Principles for Thinking about Carbon Dioxide Removal in Just Climate Policy. One Earth 3 (2020).
98. Smith, P., et al. Biophysical and economic limits to negative CO2 emissions. Nature Clim Change 6, 42–50 (2016).
99. Hepburn, C., et al. The technological and economic prospects for CO2 utilization and removal. Nature 575, 87–97 (2019).

100. Gurwick, N.P., et al. A Systematic Review of Biochar Research, with a Focus on Its Stability in situ and Its Promise as a Climate Mitigation Strategy. PLoS ONE 8(9): e75932. (2013).
101. So, I., Haya, B., Elias, M. Voluntary Registry Offsets Database, Berkeley Carbon Trading Project, University of California, Berkeley. Retrieved from: https://gspp.berkeley.edu/faculty-and-impact/centers/cepp/projects/berkeley-carbon-trading-project/offsets-database (2022).
102. Verra. Verra Registry. Verra, Washington D.C. Retrieved from: https://verra.org/registry-system/ (2022).
103. Gold Standard. Impact Registry. Gold Standard, Geneva, Switzerland. Retrieved from: https://www.goldstandard.org/resources/impact-registry (2022).
104. American Carbon Registry. Public Registry. Winrock International, Little Rock, Arkansas. Retrieved from: https://americancarbonregistry.org/how-it-works/registry-reports (2022).
105. Climate Action Reserve. Public Registry. Climate Action Reserve, Los Angeles, California. Retrieved from: https://thereserve2.apx.com/mymodule/mypage.asp (2022).
106. Stripe. Carbon Removal Portfolio. Stripe, Dublin, Ireland. Retrieved from: https://stripe.com/en-ca/climate (2022).
107. Microsoft. Carbon Dioxide Removal. Microsoft, Redmond, Washington. Retrieved from: https://www.microsoft.com/en-us/corporate-responsibility/sustainability/carbon-removal-program (2022).
108. Chay, F., Cullenward, D., Hamman, J., Freeman, J. "CDR Database" CarbonPlan. Retrieved from: https://carbonplan.org/research/cdr-database (2021).
109. Thirdway. Carbon Capture Projects Map. Thirdway, Washington, D.C. Retrieved from: https://www.thirdway.org/graphic/carbon-capture-projects-map (2022).
110. Global CCS Institute. CO2RE Database. Global CCS Institute, Melbourne, Australia. Retrieved from: https://www.globalccsinstitute.com/co2re/ (2022).
111. MIT. Carbon Capture and Sequestration Project Database. Massachusetts Institute of Technology (MIT), Cambridge, Massachusetts. Retrieved from: https://sequestration.mit.edu/tools/projects/ (2017).
112. ID-RECCO. International Database on REDD+ projects and programmes. Center for International Forestry Research (CIFOR). Retrieved from: https://www.reddprojectsdatabase.org/ (2022).
113. CIFOR. Global Comparative Study on REDD+ Database. Center for International Forestry Research (CIFOR). Retrieved from: https://www2.cifor.org/gcs/redd-map/ (2022).
114. Forest Trends. Mapping Ecosystem Markets Database. Forest Trends, Washington, D.C. Retrieved from: https://www.forest-trends.org/about-our-project-data/ (2022).
115. CDM. Clean Development Mechanism Project Activities Database. Clean Development Mechanism. Retrieved from: https://cdm.unfccc.int/Projects/index.html (2022).

116. Hogland, R. Marginal Carbon List of Known CDR Purchases. Marginal Carbon AB. Retrieved from: https://docs.google.com/spreadsheets/d/1BH_B_Df_7e2l6AH8_8a0aK70nlAJXfCTwfyCgxkL5C8/edit#gid=0 (2022).
117. EBI. European Biochar Market Report 2021-2022. European Biochar Industry Consortium. Retrieved from: https://www.biochar-industry.com/2022/european-biochar-market-report-2021-2022-available-now/ (2022).
118. USBI. US Biochar Market Survey 2018. United States Biochar Initiative. Retrieved from: https://biochar-us.org/news/us-biochar-market-survey (2018).
119. China National Bamboo Research Center. CNBRC Annual Report, 2022. Retrieved from: http://bamboo.caf.ac.cn/ (2022).
120. Zomer, R.J., Bossio, D.A., Sommer, R., et al. Global Sequestration Potential of Increased Organic Carbon in Cropland Soils. Sci Rep 7, 15554 (2017).
121. Friedlingstein, P., et al. Global Carbon Budget 2021. Earth System Science Data, 14, 1917–2005. (2022).
122. Minx, J.C., et al. A comprehensive and synthetic dataset for global, regional, and national greenhouse gas emissions by sector 1970-2018 with an extension to 2019. Earth Sys. Sci. Data. 13, 5213-5252. (2021).
123. Dhakal, S., et al. Emissions Trends and Drivers. In: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Shukla, P.R., Skea, J., Slade, R., Al Khourdajie, A., van Diemen, R., McCollum, D., Pathak, M., Some, S., Vyas, P., Fradera, R., Belkacemi, M., Hasija, A., Lisboa, G., Luz, S., Malley, J., (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA.
124. Grassi, G., et al. Carbon fluxes from land 2000–2020: bringing clarity on countries' reporting. Earth Syst. Sci. Data. Pre-print. (2022).
125. Grassi, G., et al. Reconciling global-model estimates and country reporting of anthropogenic forest CO2 sinks. Nat. Clim. Change, 8, 914–920 (2018).
126. Grassi, G., et al. Critical adjustment of land mitigation pathways for assessing countries' climate progress. Nat. Clim. Change., 11, 425–434 (2021).
127. Gasser, T., et al. Historical CO2 emissions from land use and land cover change and their uncertainty. Biogeosciences 17, 4075-4101 (2020).
128. Houghton, R.A. Revised estimates of the annual net flux of carbon to the atmosphere from changes in land use and land management 1850–2000. Tellus, B. 55, 378–390 (2003).
129. Riahi, K., et al. The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. Global Environmental Change, 42, 153-168. (2017).

130. Way, R., et al. Empirically grounded technology forecasts and the energy transition. Joule. 6, 2056-2082. (2022).
131. Wilson, C. Future capacity growth of energy technology: are scenarios consistent with historical evidence? Climatic Change. 118, 381–395 (2013).
132. Gidden, M., et al. Policy guidance and pitfalls aligning IPCC scenarios to national land emissions inventories. Pre-print. https://doi.org/10.1002/essoar.10512676.2 (2022).
133. Tachiiri, K., et al. Increase of the transient climate response to cumulative carbon emissions with decreasing CO2 concentration scenarios. Environ. Res. Lett. 14 124067 (2019).
134. Tokarska, K.B., and Zickfeld, K. The effectiveness of net negative carbon dioxide emissions in reversing anthropogenic climate change. Environ. Res. Lett. 10, 094013 (2015).
135. Arora, V.K., et al. Carbon–concentration and carbon–climate feedbacks in CMIP6 models, and their comparison to CMIP5 models. Biogeosci. Discuss., 1–124 (2019).
136. Leach, N.J., et al. FaIRv2.0.0: a generalized impulse response model for climate uncertainty and future scenario exploration. Geosci. Model Dev., 14, 3007–3036, (2021).
137. Joos, F., Roth, R., Fuglestvedt, J.S., Peters, G.P., Enting, I.G., von Bloh, W., Brovkin, V., Burke, E.J., Eby, M., Edwards, N.R., Friedrich, T., Frölicher, T.L., Halloran, P.R., Holden, P.B., Jones, C., Kleinen, T., Mackenzie, F.T., Matsumoto, K., Meinshausen, M., Plattner, G.-K., Reisinger, A., Segschneider, J., Shaffer, G., Steinacher, M., Strassmann, K., Tanaka, K., Timmermann, A., Weaver, A.J.: Carbon dioxide and climate impulse response functions for the computation of greenhouse gas metrics: a multi-model analysis. Atmos. Chem. Phys. 13, 2793–2825.
138. MacDougall, A. et al. Is there warming in the pipeline? A multi-model analysis of the Zero Emissions Commitment from CO2, Biogeosciences, 17, 2987–3016, (2020).
139. Heinze, C. et al. The ocean carbon sink – impacts, vulnerabilities and challenges, Earth Syst. Dynam., 6, 327–358 (2015).
140. Millar, R. J., Nicholls, Z. R., Friedlingstein, P., and Allen, M. R.: A modified impulse-response representation of the global near-surface air temperature and atmospheric concentration response to carbon dioxide emissions, Atmos. Chem. Phys., 17, 7213–7228 (2017).
141. Swanson, K.L., et al. Long-term natural variability and 20th century climate change. Proc Nat. Ac. Sci. 106(38), 16120-16123 (2009).
142. Parsons, L.A. Magnitudes and Spatial Patterns of Interdecadal Variability in CMIP6. Geophysical Research Letters. 47(7) (2020)
143. Mengis, N., et al. Evaluation of the University of Victoria Earth System Climate Model version 2.10 (UVic ESCM 2.10). Geosci. Model Dev. 13, 4183–4204 (2020).
144. Eby, M., et al. Historical and idealized climate model experiments: an intercomparison of Earth system models of intermediate complexity. Clim. Past 9, 1111–1140 (2013).

145. Zickfeld, K., MacIsaac, A.J., Canadell, J.G., et al. Net-zero approaches must consider Earth system impacts to achieve climate goals. Nat. Clim. Chang. 13, 1298–1305 (2023). https://doi.org/10.1038/s41558-023-01862-7.
146. Weaver, A.J., et al. The UVic earth system climate model: Model description, climatology, and applications to past, present and future climates. Atmos. Ocean 39, 361–428 (2001).
147. Meissner, K.J., et al. The role of land surface dynamics in glacial inception: a study with the UVic Earth System Model. Clim. Dyn. 21, 515–537 (2003).
148. Matthews, H.D., Weaver, A.J., Meissner, K.J. Terrestrial carbon cycle dynamics under recent and future climate change. J. Clim. 18, 1609–1628 (2005).
149. Eby, M., et al. Lifetime of anthropogenic climate change: millennial time scales of potential CO2 and surface temperature perturbations. J. Climate 22, 2501–2511 (2009).
150. MacDougall, A.H., et al. Significant contribution to climate warming from the permafrost carbon feedback. Nat. Geosci. 5, 719–721 (2012).
151. Jones, C.D., et al. C4MIP – The Coupled Climate–Carbon Cycle Model Intercomparison Project: experimental protocol for CMIP6. Geosci. Model Dev. 9, 2853–2880.
152. Haustein, K., et al. A real-time Global Warming Index. Sci. Rep. 7, 15417, (2017).
153. Lenssen, N.J.L., et al. Improvements in the uncertainty model in the Goddard Institute for Space Studies Surface Temperature (GISTEMP) analysis. J. Geophys. Res.-Atmos., 124, 6307–6326, (2019).
154. Cowtan, K. & Way, R.G. Coverage bias in the HadCRUT4 temperature series and its impact on recent temperature trends. Q. J. Roy. Meteor. Soc., 140, 1935–1944, (2014).
155. Vose, R.S., et al. NOAA's Merged Land–Ocean Surface Temperature Analysis. B. Am. Meteorol. Soc., 93, 1677–1685, (2012).
156. Morice, C.P., et al. Quantifying uncertainties in global and regional temperature change using an ensemble of observational estimates: The HadCRUT4 data set. J. Geophys. Res., 117, D08101, (2012).
157. Morice, C.P., et al. An updated assessment of near-surface temperature change from 1850: the HadCRUT5 dataset. J. Geophys. Res.-Atmos., 126, 3, (2020).
158. Rohde, R.A. and Hausfather, Z. The Berkeley Earth Land/Ocean Temperature Record. Earth Syst. Sci. Data, 12, 3469–3479, (2020).
159. Allen, M.A. et al. Ensuring that offsets and other internationally transferred mitigation outcomes contribute effectively to limiting global warming. Environ. Res. Lett. 16 074009 (2021).
160. Schneider, L. and Theuer, S. L. H. Environmental integrity of international carbon market mechanisms under the Paris Agreement Clim. Policy 19 386–400 (2019).
161. Allen, M.R., Peters, G.P., Shine, K.P. et al. Indicate separate contributions of long-lived and short-lived greenhouse gases in emission targets. npj Clim Atmos Sci 5, 5 (2022).

162. Shine, K.P., Fuglestvedt, J.S., Hailemariam, K., & Stuber, N. Alternatives to the global warming potential for comparing climate impacts of emissions of greenhouse gases. Climatic Change, 68(3), 281–302, (2005).
163. Lamboll, R.D., Nicholls, Z.R.J., Smith, C.J. et al. Assessing the size and uncertainty of remaining carbon budgets. Nat. Clim. Chang. 13, 1360–1367 (2023).
164. Huntingford, C. et al. The implications of carbon dioxide and methane exchange for the heavy mitigation RCP2.6 scenario under two metrics. Environmental Science & Policy. 77-87 (2015).
165. Reisinger, A., Havlik, P., Riahi, K. et al. Implications of alternative metrics for global mitigation costs and greenhouse gas emissions from agriculture. Climatic Change 117, 677–690 (2013)
166. Smith, S.J., Karas, J., Edmonds, J. et al. Sensitivity of multi-gas climate policy to emission metrics. Climatic Change 117, 663–675 (2013).
167. Anderegg, W. R. L. et al. Climate-driven risks to the climate mitigation potential of forests. Science 368, eaaz7005 (2020).
168. Peng, S., Lin, X., Thompson, R.L. et al. Wetland emission and atmospheric sink changes explain methane growth in 2020. Nature 612, 477–482 (2022).
169. Rigby, M. et al. Role of atmospheric oxidation in recent methane growth. PNAS. 114(21) 5373-5377 (2017).
170. Bowerman, N., Frame, D., Huntingford, C. et al. The role of short-lived climate pollutants in meeting temperature goals. Nature Clim Change 3, 1021–1024 (2013).
171. Lawrence, M.L. et al. Global polycrisis: the causal mechanisms of crisis entanglement. Global Sustainability. (2024).
172. Richardson, K. et al. Earth beyond six of nine planetary boundaries. Science Advances. 9(37) (2023).
173. IPCC. in Climate Change 2022: Mitigation of Climate Change. Working Group III Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (eds Shukla, P. R. et al.) 3–48 (Cambridge Univ. Press, 2022).
174. Gidden, M.J., Gasser, T., Grassi, G. et al. Aligning climate scenarios to emissions inventories shifts global benchmarks. Nature 624, 102–108 (2023)
175. Ehlert, D., & Zickfeld, K. What determines the warming commitment after cessation of CO2 emissions? Environ. Res. Lett. 12 015002 (2017).
176. Weber, J. Chemistry-albedo feedbacks offset up to a third of forestations' CO2 removal benefits. Science. 383:6685 (2024)
177. Lawrence, D., Coe, M., Walker, W., Verchot, L. & Vandecar, K. The unseen effects of deforestation: biophysical effects on climate. Front. Glob. Change 5, 756115 (2022)
178. Hasler, N., Williams, C.A., Denney, V.C. et al. Accounting for albedo change to identify climate-positive tree cover restoration. Nat Commun 15, 2275 (2024).

179. Harmsen, J.H.M et al. Long-term marginal abatement cost curves of non-CO2 greenhouse gasses. Environmental Science & Policy. 99: 136-149 (2019).