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Net zero approaches must consider Earth system impacts to achieve climate goals

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Commitments to net zero carbon dioxide (CO_2) or greenhouse gas emission targets now cover 88% of countries' emissions. Underlying the accounting behind net zero frameworks is the assumption that emissions can be balanced with removals such that their net climate effect is zero. However, when considering the full climate impacts of CO_2 emissions and removals, there are reasons to expect that the two are not equivalent in terms of their climate outcomes. We identify potential contributors to non-equivalence, including impermanence, biophysical and non-CO_2 greenhouse gas effects, and argue that these non-equivalencies need to be accounted for to achieve climate goals. Given key uncertainties about the full climate impact of CO_2 removal, it is prudent to prioritize emission reductions over removals.

Many countries, institutions and companies have set targets to reach net zero carbon dioxide (CO_2) or greenhouse gas (GHG) emissions during this century. These targets, if rigorously set[1], aim to contribute to the goal of the Paris Agreement to limit warming to well-below 2°C and to pursue efforts to limit warming to 1.5°C relative to pre-industrial levels. Net zero CO_2 or GHG targets now cover 88% of countries' emissions[2].

Underlying the concept of net zero CO_2 is the assumption that a CO_2 emission into the atmosphere can be balanced by a removal of the same magnitude ("one ton in equals one ton out"), such that the net effect on atmospheric CO_2 levels and climate is equivalent to that of actual zero emissions. Framing the mitigation challenge in terms of *net* zero allows for residual CO_2 emissions to be balanced by removals, recognizing that reaching zero CO_2 emissions for some sectors (e.g. cement or steel production) will be difficult[3].

From an Earth system perspective, an emission of CO_2 into the atmosphere by burning coal, oil or gas extracted from the geologic reservoir is a fundamentally different process than removing an equivalent amount of CO_2 from the atmosphere by biological, geochemical or chemical processes and storing it in vegetation, soils, the ocean or even returning it to a geological reservoir[4]. CO_2 stored in biomass and soils is part of the fast carbon cycle (average timescale of decades[4]) and may ultimately be released back into the atmosphere, resulting in a storage timescale that will be far shorter than the lifetime of the warming induced by CO_2 emissions[5,6]. Furthermore, CO_2 emissions and removals have very different non-CO_2 climate effects, such as biophysical effects[7–11] and effects of non-CO_2 GHGs and aerosols[12–17], that are unlikely to compensate each other.

Therefore, it is expected that balancing a fossil fuel CO_2 emission with a removal of equal magnitude will result in a different climate outcome than would occur in the case of avoiding the fossil fuel emission (Figure 1). To ensure that reaching net zero CO_2 is successful at stabilizing global temperatures, it is essential that net zero policies and accounting frameworks, particularly those that regulate carbon offsets, take into consideration the broader climate impacts of CO_2 emissions and removals.

In this Perspective, we review the factors that can lead to non-equivalence of CO_2 emissions and removals, show the effect of neglecting these factors on warming, and lay out directions for future research to inform policy. We limit the discussion to factors that arise from an Earth system science perspective, and do not consider other aspects of carbon offsets such as additionality (whether a particular project would have occurred without the incentive of an offset program) or leakage (the effect of shifting emissions elsewhere as a result of preventing carbon loss at some location) that could also result in ineffective climate mitigation, and have been discussed in detail elsewhere[18–20].

Non-equivalence of CO_2 emissions and removals

There are many reasons to expect that CO_2 emissions and CO_2 removals (CDR) will not produce equivalent climate outcomes. Here, we review four important potential contributors to non-equivalence: (1) potential impermanence of CO_2 sequestered and stored by CDR; (2) biophysical climate effects of CDR associated with altered surface characteristics; (3) non-CO_2 effects of CDR and fossil-fuel emissions resulting from co-emitted GHGs and aerosol precursors; and (4) nonlinearities in the Earth system that could result in asymmetric climate responses to CO_2 emissions and removals. These effects are reviewed from most to least significant, with the magnitude of the effect dependent on the scale and region or ecosystem targeted by CDR.

Permanence of carbon storage

Each ton of CO_2 added to the atmosphere through burning of fossil fuels results in additional warming that is irreversible on timescales of centuries to millennia[5,21–23]. In contrast, carbon that is sequestered in non-geologic reservoirs is unlikely to remain permanently removed from the atmosphere[24,25]. If fossil fuel emissions are offset by temporary carbon sequestration that is released after a certain period of time, the cumulative CO_2 emissions would be higher (by the amount of sequestered CO_2 that is re-released) and result in additional warming compared to the case where the fossil fuel emissions were avoided.

To fully balance the climate effects of fossil fuel emissions, CDR needs to result in permanent carbon storage, meaning that the carbon needs to remain undisturbed for centuries to millennia. CO_2 sequestered and stored by biological processes on land and in the ocean, however, can have a storage timescale of well less than a century[4,26]. Carbon stored by land-based CDR methods in the form of above-ground biomass is vulnerable to an increasing frequency of climate-related disturbances such as droughts, fires, insect and pathogen outbreaks and windthrow[24], as well as future land-use and land management decisions. For example, drought and heat-induced tree mortality has been observed in many regions of the globe[27–30]. Disturbances are projected to become more frequent and severe in many regions as global mean temperature continues to increase[29], increasing the risk of loss of carbon stored in biomass. Key vulnerable carbon stocks include forests subject to growing drought and fire activity[31–33], and carbon in coastal ecosystems exposed to a growing frequency of marine heat waves[34]. Furthermore, carbon purposefully stored in biomass or soils is subject to changes in land use and management practices, which could lead to the release of the totality or a substantial fraction of the sequestered CO_2[35].

Similar considerations of permanence apply to ocean-based CDR methods such as nutrient fertilization or artificial upwelling of deep waters, which sequester CO_2 through the stimulation of ocean productivity and subsequent sinking of organic matter. A large fraction of the carbon sequestered by these methods is estimated to return to the atmosphere on timescales of less than a century, with the exact time scale of re-release depending strongly on the depth to which the biomass sinks, and the upwelling pathway of the CO_2 produced by decomposition in the water column[25]. Carbon storage in geologic reservoirs may also be vulnerable to loss, releasing part of the initially sequestered CO_2, if storage is inadequately regulated[36]. Furthermore, if the captured CO_2 is sequestered in usable materials, the time scale of sequestration ranges from centuries (e.g. for aggregates) to weeks (e.g. for fuels), depending on the utilization pathway[37]. While temporary carbon storage can help mitigate short-term warming if used alongside ambitious emission reductions[38], offsetting fossil fuel emissions with non-permanent carbon storage would result in additional long-term warming compared to a scenario with avoided fossil fuel emissions.

Biophysical effects of CDR

A range of CDR methods involve modification of the land surface and associated vegetation cover changes. Land surface modifications, when deployed at large scale, affect temperature through so-called biophysical effects. These include changes in surface reflectivity (albedo), the partitioning of available energy into sensible and latent heat fluxes, and surface roughness. These changes have a direct effect on the surface energy balance, as well as indirect effects via changing cloud cover, leading to temperature changes at regional and potentially global scales. For instance, replacing a non-forested surface with trees decreases albedo, leading to stronger absorption of incoming solar radiation[7,8,11,39]. This effect is particularly pronounced in, but not limited to, regions with seasonal snow cover, where trees “mask” the high albedo of snow. Tree growth can also increase evapotranspiration and cloud cover, both of which have a cooling effect on Earth’s surface[10,40,41]. The net effect of reforestation on surface temperature is strongly latitude and region dependent. At high latitudes the albedo decrease from forestation tends to dominate, resulting in regional warming, while at low latitudes the cooling effect of enhanced evapotranspiration tends to exceed the warming effect due to albedo decrease[9–11] (Figure 2). At mid latitudes, the net effect on temperature is less certain[9,10,39,42]; a recent study suggests that reforestation in temperate regions could result in an increase in cloud cover and surface cooling[40]. For large-scale reforestation, substantial non-local effects on surface air temperature can occur in regions outside of those where the land-use change is implemented[43,44].

While discussed most prominently for measures that change forest cover, other land-based CDR measures also generate biophysical effects on climate. Cultivation of herbaceous and woody bioenergy crops for the use in bioenergy with carbon capture and storage in agricultural areas is found to have a cooling effect, primarily due to enhanced evapotranspiration and larger surface roughness[45,46]. Agricultural practices aimed at enhancing soil carbon sequestration such as reduced- or no-tillage and introduction of cover crops during the fallow period have been shown to increase surface albedo and result in local cooling[47–49]. In contrast, application of biochar to agricultural soils can result in lower surface albedo and hence local warming[50,51].

Ocean-based CDR methods can affect surface albedo through the stimulation of growth of aquatic plants, from microscopic phytoplankton to macro-algae, or addition of limestone particles to seawater in the case of ocean alkalinization. These interventions are estimated to result in a negligible or increased albedo, with the magnitude of the effect poorly quantified[25,52]. The most significant biophysical effect from ocean-based CDR methods is likely associated with artificial upwelling of deep, cold seawater, which would result in widespread cooling[53,54].

The extent to which biophysical effects have an effect on global mean temperature depends on the scale of CDR deployment. Most modelling studies implement global or continental-scale changes for the biophysical effect to be detectable at a global scale; the scale at which CDR needs to be deployed to have a measurable global effect is uncertain.

Emissions of non-CO_2 greenhouse gases and aerosol precursors

The activities that result in CO_2 emissions and removals have very different climate effects related to emissions of non-CO_2 GHGs and aerosol precursors that are unlikely to compensate each other. Deployment of a range of CDR methods can result in increased emissions of nitrous oxide (N_2O) and methane (CH_4), two powerful GHGs, through alteration of biogeochemical cycles. Methods that require nitrogen fertilization, such as bioenergy with carbon capture and storage (BECCS), or soil carbon sequestration practices that employ nitrogen-fixing cover crop species, organic soil amendments or conservation tillage, could result in enhanced N_2O emissions[48,55,56]. Afforestation and reforestation can either raise or lower N_2O emissions, with the net effect depending on several partially unresolved factors, such as the previous land use, selected tree species, use of fertilizers, soil type and climatic factors[12–15]. Expansion of forest cover also increases emissions of Biogenic Volatile Organic Compounds (BVOCs), which oxidize quickly in the atmosphere and produce organic aerosols and ozone (O_3), and lengthen the atmospheric lifetime of methane, with the net effect on temperature subject to uncertainty[16,17]. Use of biochar as a soil amendment can decrease CH_4 emissions in inundated and acid soils such as rice fields[57,58] and has also been reported to decrease soil N_2O emissions[59–61]. Restoration of seagrass coastal ecosystems such as seagrass meadows, as well as ocean-based CDR methods that stimulate marine productivity, such as nutrient fertilization and artificial upwelling, are estimated to result in an increase in CH_4 and N_2O emissions[62–64]. Co-emissions also need to be considered in a CDR strategy using carbon capture methods, where capture efficiency might not be 100% and co-emissions occur, both of which are particularly relevant for bioenergy with carbon capture and storage or energy production for direct air capture[65].

The production and use of fossil fuels not only emits CO_2 into the atmosphere, but also a range of other gases such as CH_4, N_2O and sulphur dioxide, a precursor of sulphate aerosols. The exact mix of co-emitted species depends on the particular type of fuel as well as the production process and the management of fugitive emissions. CDR only targets CO_2, leaving the other gases unmitigated. Of these gases, aerosol-precursor substances such as SO_2 are targeted by clean-air legislation due to their detrimental health effects, particularly in developed countries. Depending on the mix of gases emitted by fossil fuel production and combustion, balancing the CO_2 emitted with CO_2 removed could result either in warming (e.g. when the warming effect of co-emitted GHGs dominates over the climate effects of sulphate aerosols) or cooling (if the aerosol effect dominates).

Asymmetry of carbon-cycle and temperature response

Non-equivalence between CO_2 emissions and removals can also arise because of asymmetries in the carbon cycle and climate response. There are three possible sources of asymmetry: inertia in the carbon cycle and climate systems, state dependence and nonlinear carbon cycle and climate processes. The first two arise when there is a delay between emissions and removals, as is the case for temperature overshoot scenarios, where CDR is used to achieve net-negative CO_2 emissions and recover a carbon budget consistent with a given temperature limit. Because of inertia in the carbon cycle and climate systems, largely driven by the slow response time scale of the deep ocean, the temperature response following CDR implementation will be partly masked by the lagged response to past emissions[66–68]. As a result, a removal that occurs years after an emission will not fully neutralize the warming immediately. Also, atmospheric CO_2 and temperature will rise in response to the emission and the climate-carbon cycle system will be in a different state when the removal occurs. Because of state-dependencies of carbon cycle and physical climate processes[4,69] the cooling following the removal will be of different magnitude than the warming following the emission.

In scenarios where net zero CO_2 is achieved and maintained with simultaneous CO_2 emissions and removals, the climate and carbon cycle can still exhibit asymmetries resulting from nonlinear carbon cycle and physical climate processes[4,69]. For example, the CO_2 fertilization effect, by which plants are more productive under elevated atmospheric CO_2 concentration, declines at higher atmospheric CO_2 levels[70]. Also, the ability of the ocean to buffer excess CO_2 – which is key to its ability to take up additional CO_2 from the atmosphere – diminishes with increasing atmospheric CO_2 levels[71]. These nonlinearities in carbon cycle processes are partly compensated by another nonlinear process – the effect of changes in atmospheric CO_2 on radiative forcing, which diminishes at higher atmospheric CO_2 levels. Multi-model simulations with CO_2 emissions and removals applied from the same pre-industrial equilibrium state suggest that as result of these nonlinearities the surface temperature change following CO_2 removal is asymmetric, with the magnitude and even sign of the asymmetry exhibiting strong model dependence[4]. Therefore, balancing a CO_2 emission with a CO_2 removal of the same magnitude could result in an imperfect cancellation of the effects and lead to either lower or higher surface temperature than avoiding the CO_2 emission. While the effect of these asymmetries is likely smaller than that of the other non-equivalencies reviewed above, asymmetry effects may not be negligible.

Warming effects of offsetting fossil-fuel emissions with CDR

The temperature effect of two of the non-equivalencies of CO_2 emissions and removals – impermanent carbon storage and biophysical effects – described in the previous section is illustrated relative to a scenario that reaches net zero CO_2 emissions in 2056 and net negative emissions thereafter ("Baseline") (blue curve, Figure 3A). In this scenario, warming peaks around the year 2040 when the combined radiative forcing from CO_2 and non-CO_2 GHGs and aerosols reaches its maximum. The Baseline scenario implicitly includes CDR as the mechanism by which net zero and then net negative CO_2 emissions are achieved, though here we treat the net emissions from this scenario as the Baseline reference case against which to show the effect of implementing additional CDR to offset additional fossil fuel emissions. This additional set of scenarios includes additional fossil fuel CO_2 emissions and CDR relative to the Baseline to attain the same net CO_2 emissions as in the Baseline (grey dashed curve, Figure 3A). Each of these scenarios represents a type of CDR for which the specified non-equivalency is dominant. For example, the Impermanence scenario illustrates a case where CO_2 sequestered and stored by CDR is re-released into the atmosphere over several decades after net-zero CO_2 is reached (see Methods in SI).

The effect of offsetting fossil-fuel emissions with temporary carbon storage on peak warming depends on the time until the CO_2 sequestered and stored by CDR is re-released. In a scenario where CO_2 is re-released after the time CO_2 emissions reach net zero, impermanence would not affect peak warming but would result in higher end-of-century warming (Figure 3B). If, on the other hand, the sequestered CO_2 is re-released before CO_2 emissions reach net zero, temporary carbon storage would also result in higher peak warming. In either case, the temporary carbon storage scenario does not reduce peak warming (as in [38]) because we have applied temporary storage here as an offset to fossil fuel emissions rather than as CDR that is additional to fossil fuel emissions reductions.

As discussed previously, biophysical effects of CDR can have either a net warming or cooling effect. A net warming effect would result in higher peak warming and year-2100 warming in the case where CDR is used to offset additional emissions compared to the case where these emissions are avoided (Figure 3B). The temperature effects of non-equivalencies have been discussed separately, but in most cases these effects are compounded. For example, in the case of reforestation in a region where the biophysical effects result in net warming and the (re-)planted forest is impacted by disturbances, warming would remain elevated relative to the baseline, first due to the biophysical effects and subsequently due the effect of CO_2 re-release (Figure 3B). These scenarios illustrate that even if CDR were successfully implemented to fully compensate for additional fossil fuel CO_2 emissions, peak and year-2100 warming could be higher than in a case where these additional emissions are avoided.

How research can inform policy

Policy frameworks and accounting systems designed to regulate net zero need to take into account the various sources of non-equivalence between fossil-fuel emissions and CO_2 removals to ensure mitigation policies do not fall short of achieving the climate outcomes intended by net zero targets. While integrated assessment models that are used to generate emission pathways consistent with such targets consider some aspects of non-equivalence (such as co-emissions of non-CO_2 gases and aerosols), they do not take into account most other aspects. At smaller scales, such as countries, sub-national jurisdictions or companies, most carbon offset protocols consider risks to permanence, e.g. through insurance mechanisms that spread risks across a range of projects[72], but do not address other sources of non-equivalence.

Design of effective policies and protocols needs to be supported by scientific evidence, leveraging advances in process-based modeling, large-scale field observations and remote sensing.

Permanence. Where carbon stocks in terrestrial ecosystems are targeted for CDR, a rigorous risk assessment of the vulnerability of these stocks is required. Assessment of permanence risks should be region-specific and take into account all potential disturbance factors, including extreme weather and climate events (extreme fire weather, droughts, heat waves, windfall), insect and pathogen infestations, as well as anthropogenic disturbances. Natural disturbances are sensitive to climate conditions and therefore, changes to the frequency and severity of disturbance events in a warming climate must also be considered. A promising research avenue to inform such risk assessments is the integration of advances in process-based ecosystem modelling, particularly with regard to ecosystem ecology and ecophysiology, large-scale ecological observations, and remote sensing products that are now available at high resolution and over increasingly long time periods[24,73]. However, challenges remain, and improving the representation of disturbance processes (e.g. fire, drought, insect outbreaks), their impact on vegetation at different stages of maturity, and subsequent vegetation dynamics in ecosystem models are all high priority to better capture current and future impacts of disturbance regimes on carbon stocks at the regional level and over time. Research into the design of CDR governance frameworks that ensure the longevity of land use and land management decisions to protect carbon stocks from reversal while addressing sustainable development and land stewardship concerns is also key[74,75].

Net zero accounting systems need to take into account the different climate impact of potentially temporary and permanent CO_2 storage. There is renewed interest in approaches that seek to establish equivalency between short-term CO_2 storage and CO_2 stored permanently (referred to as ton-year accounting[76]). These approaches, however, are not grounded in climate science and are inadequate to ensure equivalency of temporary and permanent storage in terms of climate outcomes[77,78]. Recognizing the inherent challenge of establishing equivalency between short-term and permanent storage, another approach proposes a clear distinction between CDR methods that store CO_2 in soils and biomass and those that store CO_2 in long-term reservoirs (timescale of thousands to hundred thousand years)[79,80]. According to this "like-for-like" approach, only CDR methods with long-term CO_2 storage (e.g. direct air capture and BECCS with geologic storage, ocean alkalinization) should be used to balance fossil fuel emissions. Correspondingly, CDR methods employing temporary storage reservoirs should not be used as offsets for fossil fuel CO_2 emissions, but rather quantified as an independent contribution to reducing the near-term warming rate and potential peak temperature[38]. Given the mitigation potential of CDR methods targeting biomass and soils[81] research is needed into novel accounting approaches that take into account risks to permanence while ensuring that achievement of climate goals is not compromised[82].

Biophysical effects. Net zero protocols need to account for biophysical effects resulting from CDR deployment in addition to biogeochemical effects from changing fluxes of CO_2 and other gases. To compare biophysical climate effects of CDR with the effects of CO_2 sequestration, region-specific estimates of the biophysical effect are required, alongside metrics that translate biophysical effects into a CO_2 equivalent[7,11,83,84]. While the effects of forestation on Earth's surface energy balance have been extensively investigated, their net effect on surface temperature remains uncertain in many regions, particularly at mid latitudes and in semi-arid regions[85]. A key uncertainty is the coupling of changes in the water cycle due to altered land surface with the atmosphere that can lead to regional climate feedbacks[4]. For other CDR methods (e.g. soil carbon storage, peatland and wetland restoration, ocean-based methods) biophysical effects have only recently begun to receive attention and remain poorly constrained[4,86]. Remote sensing and in-situ observations[10,41] have been used alongside Earth system model simulations[7,9,42,44] to derive regional distributions of the biophysical effects of land-use changes on the surface energy balance. With the use of metrics that translate either the radiative forcing or the surface temperature change from biophysical processes into a CO_2 equivalent, such approaches allow to identify regions where the biophysical and biogeochemical (i.e. carbon sequestration) effects are synergistic, and regions where the biophysical effects risks to negate the climate benefit of carbon sequestration. These approaches often do not consider non-local effects or temporal dynamics, and are based on current climate conditions, and research is needed to improve their accuracy at the regional scale. Despite these challenges, an assessment of the potential warming or cooling impacts from CDR projects should play an important role in the selection of the types of projects and regions in which to be deployed.

Non-CO_2 gas balance. Net zero protocols must also consider the full GHG and aerosol footprint of CDR methods and the fossil fuel activities they may offset. Comparing the climate effects of CO_2 and non-CO_2 gases requires the use of metrics that place non-CO_2 gases on a CO_2 equivalence scale. Numerous metrics have been proposed and there is a large body of literature that assesses the advantages and disadvantages of these metrics with regard to specific policy goals[87–90]. A barrier to a comprehensive assessment of the full GHG balance of land and ocean-based CDR methods is that emissions of non-CO_2 GHGs and aerosols (e.g. methane, nitrous oxide, biogenic aerosols) and their temporal dynamics are poorly constrained. Expansion of observation networks of GHG fluxes in affected ecosystems and data integration across spatial scales is a high priority to better assess the full climate impact of CDR methods.

Asymmetry. Findings suggesting asymmetry in the carbon cycle and climate response to CO_2 emissions and removals are based on a limited number of studies[4,69]. Confidence in the magnitude and sign of the asymmetry, particularly for temperature, is low and existing evidence will need to be corroborated by improved process understanding and simulations with a range of models to establish equivalency between CO_2 emissions and removals. Trade-offs and balances in ocean heat and carbon uptake, for example, need to be better constrained.

Holistic quantification of the full climate effects of CDR methods requires an ‘Earth systems’ approach, which accounts not only for the effects of carbon sequestration, but also non-CO_2 effects, as well as their interactions and feedbacks. Earth system models (ESMs), configured globally or for specific regions, are the tools of choice for quantifying such interactions and feedbacks. State-of-the-art ESMs include representation of the land and ocean surface and ecosystem processes, including fluxes of energy, water and CO_2. Representation of the nitrogen and methane cycles[91,92] is at the forefront of ESM development. Increasing computing power makes it increasingly feasible to port new developments from stand-alone ecosystem models (e.g. ecosystem demographics, disturbance regimes, land management practices) into ESMs, with growing potential for ESMs to quantify the full climate effects of CDR in a changing climate.

Conclusions

Reaching zero CO_2 emissions is a scientific requirement for stabilizing warming[21,93]. However, it may be technologically challenging or too costly to eliminate CO_2 emissions from all sectors. Therefore, aiming for a certain amount of CO_2 emissions to be balanced by CDR to achieve *net* zero CO_2 emissions will increase the likelihood of meeting climate goals such as those stipulated by the Paris Agreement. However, CO_2 emissions and removals are not equivalent in terms of their effects on climate, and rigorous and comprehensive quantification of the climate effects of CDR is crucial to ensuring that balancing CO_2 emissions and removals will be successful at stabilizing warming. This is particularly important when CDR is implemented as an offset, as neglecting non-CO_2 effects could cause additional warming and result in societal harm. Estimation of the full climate effects of CDR requires a holistic Earth system approach that integrates advance in Earth system modeling, large-scale field observations and remote sensing, while continuing to improve GHG inventories with regionally-based observations. To support governments, industry and civil organizations towards a robust and traceable pathway to net zero it is essential to strengthen science-policy links and develop science-based climate accounting systems. Even with continued scientific advances, many remaining uncertainties about the climate effects of CDR are unlikely to be fully resolved in the short timeframe available to design and implement climate policies consistent with the Paris Agreement climate targets. This constraint further underscores the need to prioritize reducing emissions as rapidly and as much as possible.

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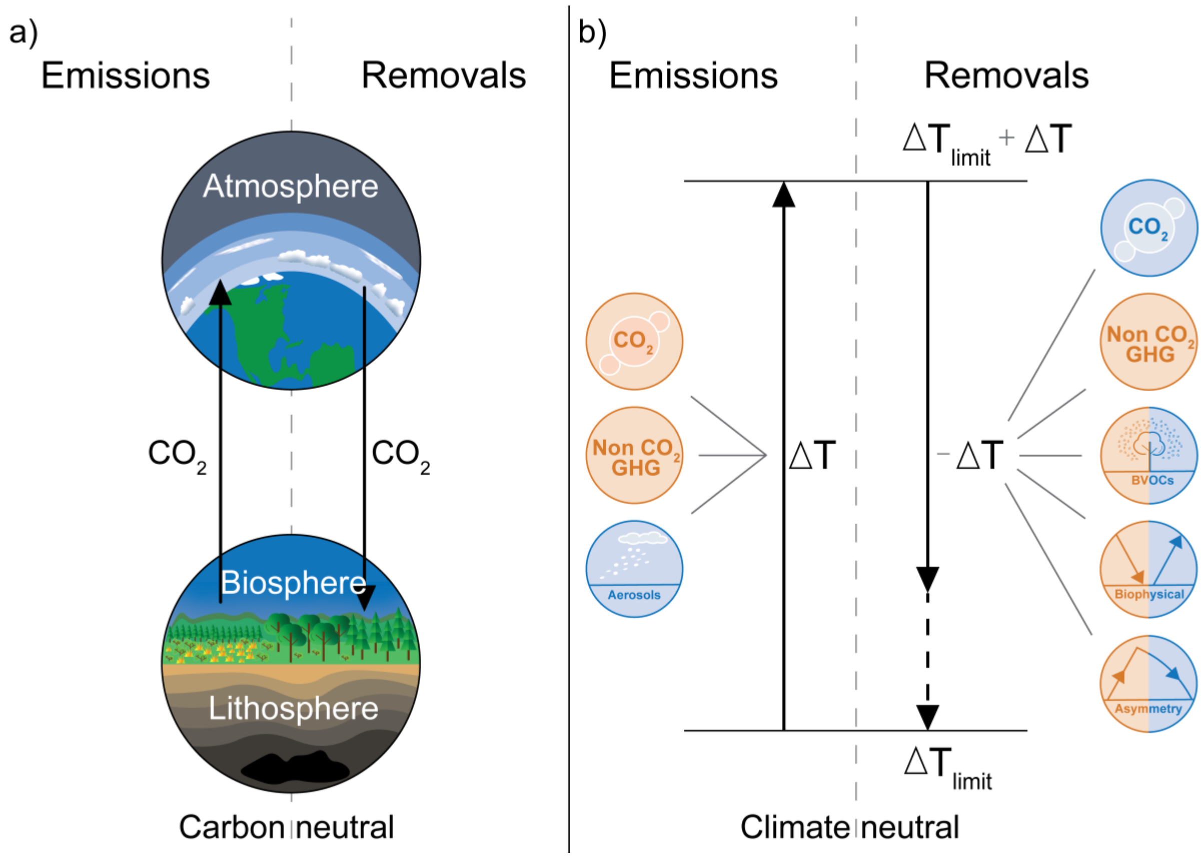

Figure 1: Carbon versus climate neutrality. a) Net-zero CO_2 emissions or carbon neutrality, whereby CO_2 emissions are balanced by CO_2 removals globally[94]. b) Because of additional climate effects of CO_2 emissions and removals (co-emissions of non-CO_2 GHGs and aerosol precursors, biophysical effects, asymmetry in the climate response), carbon neutrality will not necessarily result in climate neutrality, that is, a situation in which the net effect of CO_2 emissions and removals on global mean surface temperature is zero. In both cases illustrated above, carbon and climate neutrality are represented as an instantaneous balance of carbon flows or temperature drivers; however, the potential impermanence of removals adds an additional temporal non-equivalence such that instantaneous carbon or climate neutrality does not guarantee neutrality over time. Orange icons indicate a warming effect and blue icons indicate a cooling effect.

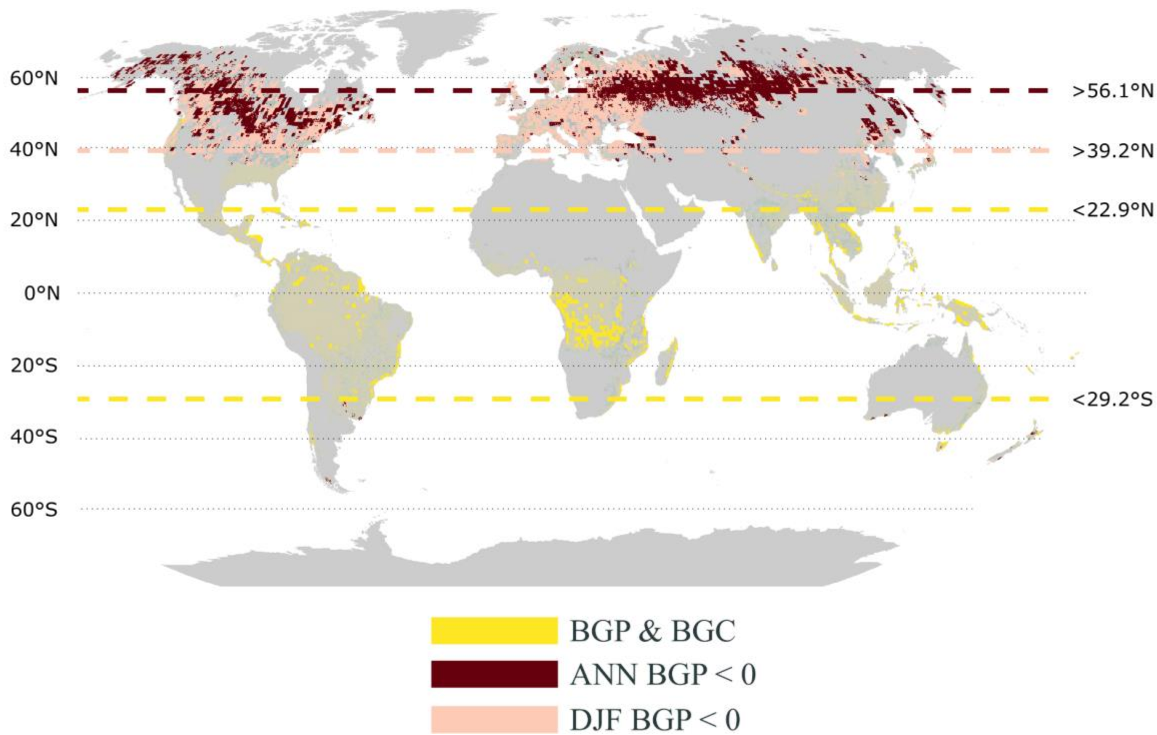

Figure 2: Synergy and opposing effects between the biogeophysical (BGP) and biogeochemical (BGC) effects of forestation. Biogeochemical here refers to the effect of CO_2 sequestration. Sites in which the BGP influence opposes the response to BGC annually/in boreal winter are coloured in dark/light red. Areas of synergy between both effects (exceeding the mean plus standard deviation in both simultaneously) are shown in yellow. Emphasized by dashed lines are the lowest northern latitudes at which the latitudinal median BGP effect opposes the carbon uptake annually (56.1° N, dark red) and during boreal winter (39.2° N, light red). Further, the latitudinal bounds that envelope 98% of all synergetic areas (<22.9° N, >29.2° S) are shown by the dashed yellow lines. Source: Windisch et al., 2021[11].

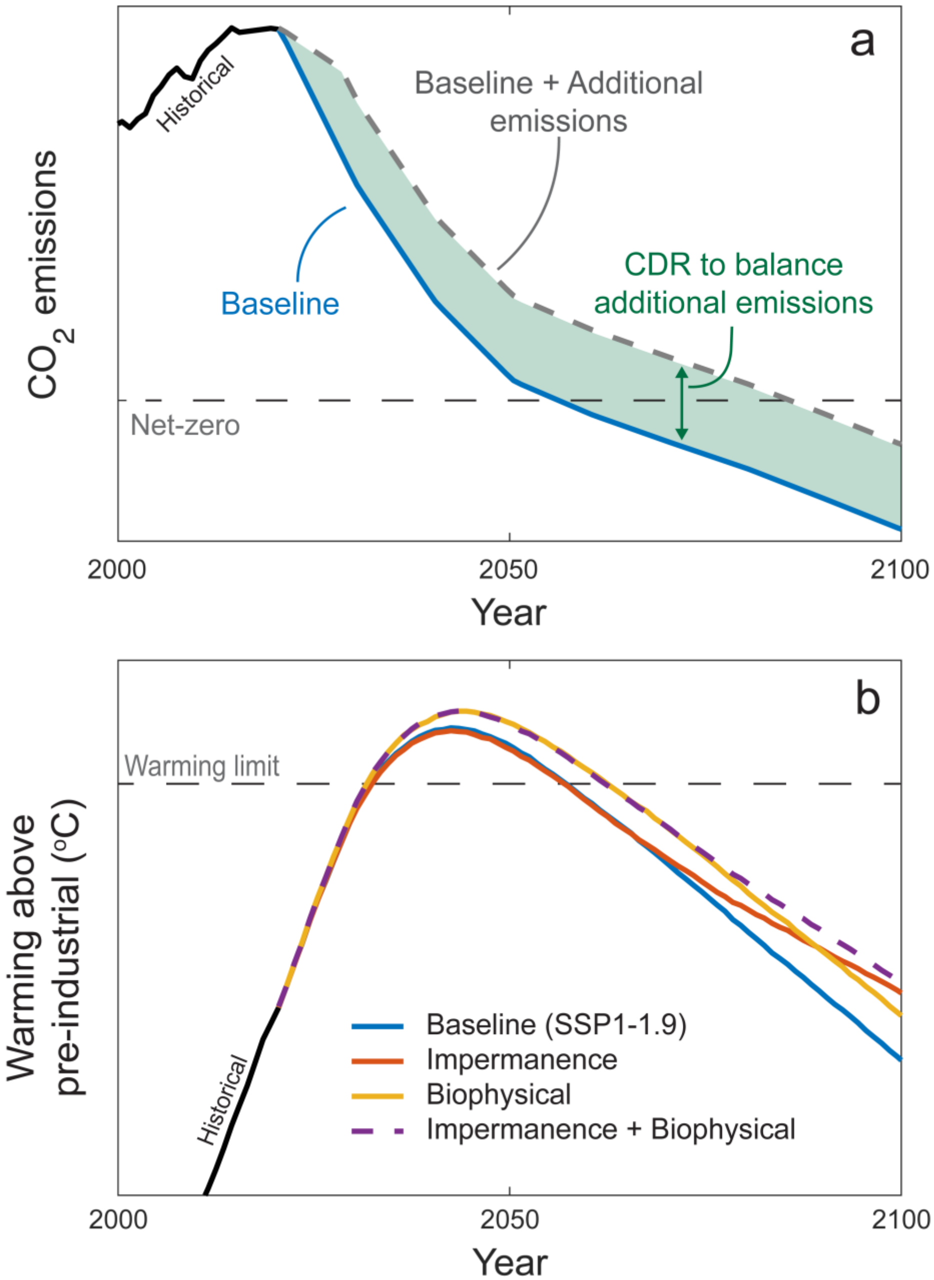

Figure 3: Effect of non-equivalencies on peak and end-of century warming. a) Net total (fossil fuel and land-use) CO_2 emissions in a reference scenario ("Baseline") that reaches net zero CO_2 emissions in year 2056 and net negative emissions thereafter (blue curve), and a scenario with additional CO_2 emissions (grey dashed curve) offset by CDR to reach the same CO_2 emissions as in the Baseline. b) Global mean surface air temperature change from pre-industrial (1850-1900). The difference relative to the Baseline (blue curve) illustrates the temperature effect of various non-equivalencies: impermanent carbon storage with CO_2 sequestered by CDR re-released within several decades after peak warming is

reached (red curve), biophysical effects of large-scale afforestation (yellow curve), and the combined effect of CO_2 re-release and biophysical effect (purple dashed curve). The temporal evolution and magnitude of the temperature effects is based on simulations with the University of Victoria Earth System Climate Model (UVic ESCM[95]) forced with idealized CDR scenarios (see Methods in SI).