Geological Net Zero and the need for disaggregated accounting for carbon sinks

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Achieving net-zero global emissions of carbon dioxide (CO_2), with declining emissions of other greenhouse gases, is widely expected to halt global warming. CO_2 emissions will continue to drive warming until fully balanced by active anthropogenic CO_2 removals. For practical reasons, however, many greenhouse gas accounting systems allow some 'passive' CO_2 uptake, such as enhanced vegetation growth owing to CO_2 fertilization, to be included as removals in the definition of net anthropogenic emissions. By including passive CO_2 uptake, nominal net-zero emissions would not halt global warming, undermining the Paris Agreement. Here we discuss measures to address this problem, to ensure residual fossil fuel use does not cause further global warming: land management categories should be disaggregated in emissions reporting and targets to better separate the role of passive CO_2 uptake; where possible, claimed removals should be additional to passive uptake; and targets should acknowledge the need for Geological Net Zero, meaning one tonne of CO_2 permanently restored to the solid Earth for every tonne still generated from fossil sources. We also argue that scientific understanding of Net Zero provides a basis for allocating responsibility for the protection of passive carbon sinks during and after the transition to Geological Net Zero.

The UAE Consensus[1], agreed at the 28th Conference of the Parties (COP28) climate change conference, called on parties "to achieve net zero by 2050 in keeping with the science" without specifying precisely what net zero refers to[2]. The concept dates back to a series of papers[3–8] in 2009 that established the cumulative impact of anthropogenic carbon dioxide (CO_2) emissions on global temperatures, and the need to reduce net CO_2 emissions to zero to halt global warming. This was affirmed[9] in the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report, which informed Article 4.1 of the Paris Agreement: "In order to achieve the long-term temperature goal set out in Article 2 ("Holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 °C"), Parties aim … to achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century." This wording, the foundation of subsequent national and corporate[10] net-zero pledges, makes clear that the purpose of 'balance' is to limit global warming. The IPCC Special Report on 1.5 °C (ref. 11) stated what this entails: "Reaching and sustaining net-zero global anthropogenic CO_2 emissions and declining net non-CO_2 radiative forcing would halt anthropogenic global warming on multi-decadal timescales (*high confidence*)." This was reaffirmed by subsequent research[12,13] and the IPCC Sixth Assessment Report[14–16].

It is, however, increasingly clear that many current interpretations of net-zero CO_2 emissions, if applied globally, are not consistent with the goal of halting the increase in global temperatures[17–19]. The problem is ambiguity in the definition of anthropogenic CO_2 removals (called 'removals' for brevity hereon). The definition of removal used in the IPCC Scientific Assessments[20] explicitly "excludes natural CO_2 uptake not directly caused by human activities" (here we use IPCC Scientific

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Assessment definitions[20] unless otherwise specified). However, methods used by many greenhouse gas reporting systems, including those informed by the IPCC guidelines for national greenhouse gas inventories (NGHGIs)[21], implicitly allow indirect or passive uptake (so-called because it is occurring as a consequence of past emissions and not as a result of active ongoing human intervention) to be classed as a removal if it takes place on 'managed land'[22–24]. The concept of managed land was originally introduced, in part, because differentiating between active land-based removal of atmospheric CO_2 and passive CO_2 uptake[25] requires modelling a counterfactual, that is, what would have happened if the action leading to a claimed land-based removal had not occurred. This cannot be inferred from observations alone. Model-based approaches[23] allow a global mapping between different removal classification systems, but ambiguities remain, such as the classification of ongoing regrowth following reforestation. As the pressure to reduce net emissions increases, more land may be deemed managed, reclassifying passive uptake as active removal. Already, not all claimed land-based CO_2 emissions reductions[26] and removals[27] are verifiably additional to what would have occurred without any active human intervention. These problems are compounded by the risk of terrestrial carbon stocks being re-released through Earth system feedbacks. Similar problems may arise in the future with an increased focus on 'blue carbon'[28] uptake by the oceans.

Hence, under the Global Stocktake[1], pathways to Net Zero are determined by models that use a narrow definition of CO_2 removals, excluding[20] all passive uptake; however, countries[29] and corporations[10,27] typically assess their progress using the broader NGHGI definition, which includes some passive uptake. If the definition of anthropogenic removals includes passive uptake then nominal 'net zero' CO_2 emissions could fail to halt global warming in time to deliver the goals of the Paris Agreement.

Scientific context

CO_2-induced warming ΔT_{CO2} over a multi-decade time interval Δt (such as 2025–2050 or 2050–2100) is, to a good approximation, given by[18]

$$\Delta T_{CO2} = \kappa_E[E_{GEO} + E_{LUC} + (\rho_F - \rho_E)G]\Delta t. \quad (1)$$

The variables, affected by policy, are: E_{GEO}, the average global net rate of geological-origin CO_2 emissions over that time interval (total CO_2 produced from fossil fuels and industrial processes minus CO_2 captured at source or recaptured from the atmosphere and committed to permanent geological storage, in billions of tonnes per year); E_{LUC}, the net biogenic CO_2 emissions that result from ongoing direct anthropogenic land-use change (for example, active deforestation, afforestation, reforestation and ecosystem restoration, including coastal habitats[30,31]), but not including passive (indirect) uptake driven by past emissions[32] (including CO_2 fertilization of existing forests as well as temperature, precipitation and growing-season effects); and G, cumulative net CO_2 emissions that have resulted directly from all human activities from pre-industrial times up to the mid-point of the time interval in question, in billions of tonnes. Total human-induced warming comprises ΔT_{CO2} plus non-CO_2 warming (Methods).

The coefficients, not affected by policy, are: κ_E, the Transient Climate Response to Emissions[8,20]; ρ_F, the fractional Rate of Adjustment to Constant Forcing[18,33,34]; and ρ_E, the Slow Carbon-cycle Adjustment Rate[18] or the fractional rate of CO_2 radiative forcing[20] decline under zero emissions[35,36]. Both rates are approximately 0.3% per year[16,37]. Equation (1) reproduces, within uncertainties owing to internal climate variability, the response of coupled climate–carbon-cycle models to a broad range of emissions scenarios up to the time of peak warming[13]. Limiting CO_2-induced warming, or reducing ΔT_{CO2} to zero, is necessary to halt total greenhouse gas-induced global warming on multi-decadal timescales, and reductions in other greenhouse gas emissions are also required to meet Paris temperature goals. Henceforth, Net Zero refers to net-zero CO_2 emissions unless specified otherwise.

The first insight of the 2009 papers was that κ_E is largely time and scenario independent[9,15,38–40], so that cumulative CO_2 emissions since pre-industrial times determine the level of CO_2-induced warming[41]. The second was that $\rho_E \approx \rho_F$, so the difference between them, or rate of adjustment to zero emissions[13,18], is approximately zero[12]. This cancellation means that no substantial further CO_2-induced warming or cooling of the climate system will occur as long as $E_{GEO} + E_{LUC} = 0$. These two findings give 'net zero' its force: achieving net-zero CO_2 emissions, in this sense, is approximately sufficient to halt CO_2-induced warming under ambitious mitigation. More complex behaviour[39] may emerge at much higher levels of warming or much longer timescales[42].

The $\kappa_E(\rho_F - \rho_E)G\Delta t$ term in equation (1) represents two mutually cancelling processes: a thermal adjustment (ρ_F) and a carbon-cycle adjustment (ρ_E). If emissions are reduced to only the level required to stabilize CO_2 concentrations, such that $E_{GEO} + E_{LUC} \approx \rho_E G$ over a multi-decadal period, then CO_2-induced warming would continue at a rate $\rho_F \kappa_E G$, or about 0.45 °C per century if concentrations are stabilized when temperatures reach 1.5 °C (dotted scenario in Fig. 1 and Extended Data Fig. 1a–c). This situation would correspond to all passive CO_2 uptake being included as anthropogenic removals in net-zero calculations. Temperatures would eventually converge to a level determined by the equilibrium climate sensitivity[5,33,34], but the range of uncertainty and especially the risk of a high equilibrium climate sensitivity remains contested[33,43–46]. Even if atmospheric concentrations were stabilized immediately, the most likely eventual warming would still exceed 2 °C (ref. 47), so simply reducing the net flow of CO_2 into the atmosphere to zero is not sufficient to limit warming to below 2 °C.

If, however, CO_2 emissions directly resulting from ongoing human activity are reduced to net zero ($E_{GEO} + E_{LUC} = 0$) then CO_2-induced radiative forcing declines at a fractional rate ρ_E over the following decades (solid scenario in Fig. 1 and Extended Data Fig. 1d–f) because of ongoing passive uptake of atmospheric carbon by the oceans and biosphere in response to historical emissions[12,13]. This durable component of passive uptake would continue for many decades even if all human activity were to cease (conversely, if activity continues, measures may be required to protect it). There is no fundamental reason why $\rho_E = \rho_F$ (ref. 48), but current best estimates of the difference between them are of the order of 0.1% per year[13].

Although the dominant drivers of terrestrial CO_2 uptake are sometimes contested, its overall scale is not. Active net land-use emissions release about 5 $GtCO_2$ per year into the atmosphere, comprising 7 $GtCO_2$ per year from deforestation plus 2 $GtCO_2$ other land-cover change minus about 4 $GtCO_2$ per year due to forest regrowth from past disturbances[49]. In comparison, the current passive land carbon sink is about 12 $GtCO_2$ per year, estimated from vegetation models, atmospheric inversions or a simple closure of the global carbon budget[15,49]. How much of this passive land sink is owing to CO_2 fertilization versus other drivers is poorly constrained. The impact of forest demographics, partly an active driver, may be underestimated[50], which would affect the future of the land sink (demographic changes may saturate sooner than CO_2 fertilization). Multiple lines of evidence, however, suggest that CO_2 fertilization is probably the single most important driver[51]. When this is added to other passive drivers (temperature and/or precipitation changes, and the passive component of forest regrowth), it becomes likely that the large majority of the global net sink on managed land, as reported in NGHGIs and accounted as negative emissions towards countries' emissions targets, is passive.

Figure 1 shows a stylized scenario (solid black lines) of global CO_2 emissions, $E_{GEO} + E_{LUC}$, reduced to net zero in 2050, following the definitions used in those 2009 papers and subsequent IPCC Assessment Reports, hence not including any net passive uptake (solid green lines) with CO_2 removals. This results in CO_2 concentrations peaking before 2050 and declining thereafter, stabilizing global temperatures[52].

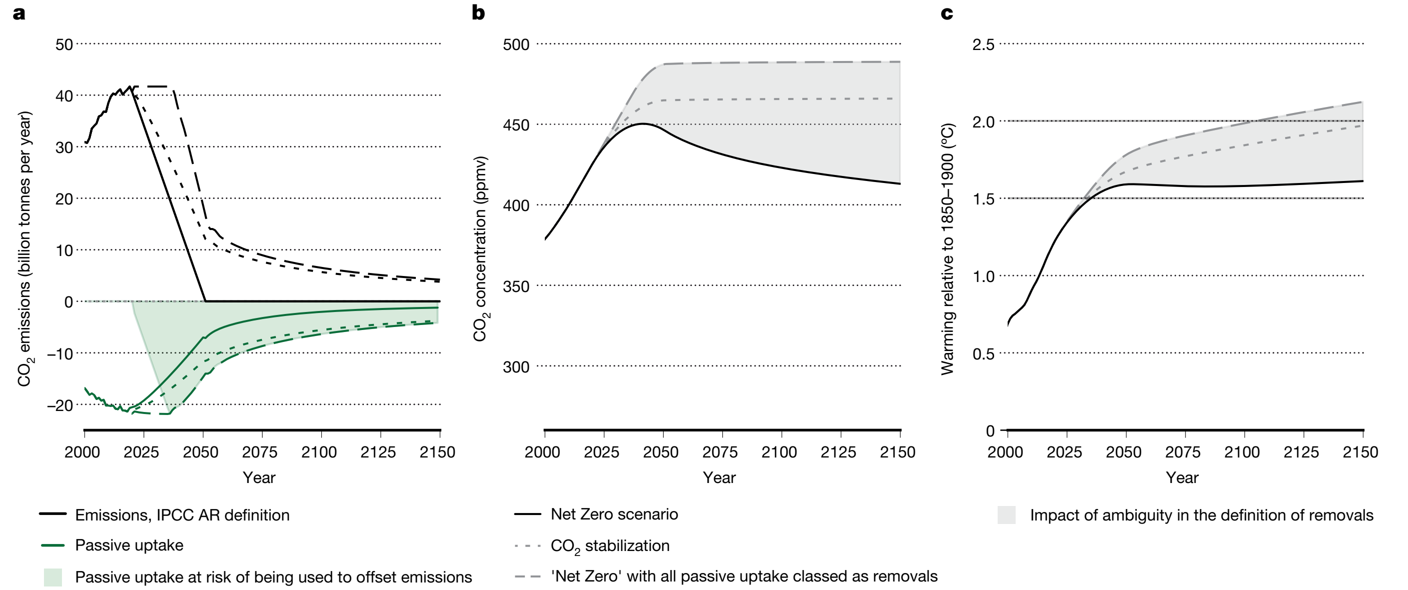

Fig. 1 | Impact of ambiguity in the definition of removals in Net Zero. a, The black lines show net CO_2 emissions, $E_{GEO} + E_{LUC}$, calculated using the definition of removals adopted in IPCC Assessment Reports (ARs). The green lines show the corresponding passive uptake by the oceans and the biosphere. **b**,**c**, A central estimate[52] of the response of CO_2 concentration (**b**) and global average surface temperature (**c**) assuming constant non-CO_2 forcing after 2020 (which requires immediate rapid reductions in methane emissions to compensate for other changes). The line styles in all three panels indicate three scenarios corresponding to different interpretations of net zero. The solid lines assume net emissions are reduced linearly to zero in 2050, halting warming. The dotted lines assume net CO_2 flux into the atmosphere (net emissions minus passive uptake) is reduced linearly to zero in 2050, stabilizing concentrations. The dashed lines show a scenario that follows the same nominal emissions pathway as the solid scenario but assumes that 'reductions' are achieved as far as possible by reclassifying passive uptake (into both land and oceans) as removals and using it to offset ongoing (assumed constant) emissions.

The dotted lines show a concentration-stabilization scenario in which the net anthropogenic flux of CO_2 into the atmosphere (that is, the difference between net emissions owing to ongoing human activities, dotted grey line in Fig. 1a, and net passive uptake in response to historical emissions, dotted green line) is reduced linearly to zero in 2050 and maintained at zero thereafter. This is sufficient to stabilize atmospheric concentrations but does not halt global warming for many centuries. The dashed lines show a hypothetical 'extreme offsetting' scenario in which all passive uptake on land and oceans is progressively re-classified as anthropogenic removals (green shaded area in Fig. 1a) and used to offset ongoing emissions to the maximum extent possible to avoid actual emissions reductions or active removals. This allows $E_{GEO} + E_{LUC}$ to remain constant past the mid-2030s whereas nominal emissions, including these offsets, appear to follow the same anthropogenic net-zero pathway as the black solid line. This illustrates the danger of including passive sinks in the definition of net emissions without revisiting climate targets accordingly[23]. Even in the absence of any uncertainty in the climate response, ambiguity in the definition of removals could make the difference between achieving the goals of the Paris Agreement and failing to do so[24].

If natural systems were to fail to provide the ecosystem service represented by the $\rho_E G$ term in equation (1), owing to Earth system feedbacks or other stresses[53,54], $E_{GEO} + E_{LUC}$ would need to be further reduced to $-\rho_F G$ to prevent further warming. This 'equivalent removal' rate is substantial: 0.3% of total historical CO_2 emissions consistent with a peak warming between 1.5 °C and 2 °C (2,900–3,700 $GtCO_2$) is 9–11 $GtCO_2$ per year[49]. The actual rate of passive CO_2 uptake in the decades after the date of net zero (solid green line in Fig. 1a) would be about half this equivalent removal rate because active removal of two tonnes of CO_2 is required to reduce the amount of CO_2 in the atmosphere by one tonne[55]. Passive CO_2 uptake has a bigger role in mitigating the warming impact of ongoing emissions before Net Zero is achieved, and a smaller role as the carbon cycle begins to re-equilibrate. However, its continued existence and the fact that it is not included as a removal in the definition of net anthropogenic emissions are both essential conditions for net-zero CO_2 emissions to halt CO_2-induced warming on multi-decadal timescales. Both conditions are potentially at risk.

Emerging risks to Net Zero

The first, unavoidable, risk is that Earth system feedbacks such as carbon release from thawing permafrost[56], drying of some wetlands or increased forest fire activity[53] could compromise the net magnitude of biosphere carbon sinks, weakening passive uptake. This effect is partially accounted for by the use of a constant transient climate response to emissions, which implies some increase in CO_2 airborne fraction[20] with cumulative CO_2 emissions cancelling the logarithmic dependence of radiative forcing on CO_2 concentrations[39,48,56,57]. Even models that represent the full range of Earth system feedbacks find that this cancellation approximately holds up to 2 °C of warming[58], but it becomes progressively less certain at higher warming levels[15] and for 'overshoot' scenarios[59]. Ultimately, the only way to minimize the amplifying effect of Earth system feedbacks is to minimize peak warming. Measures to protect and restore the integrity of biosphere sinks must therefore be additional, not alternatives, to measures that reduce E_{GEO} and E_{LUC}. Ongoing fossil fuel emissions and deforestation put all carbon stored in the biosphere at risk[60].

The second 'risk' (or moral hazard) arises from policy choices rather than geophysical processes, but is real nonetheless: unlike the global Earth system models and integrated assessment models that inform the IPCC Assessment Reports[20], greenhouse gas accounting systems, including systems based on NGHGIs[22] and most corporate systems, classify passive uptake that takes place on 'managed land'[23] as an anthropogenic greenhouse gas removal[61]. At present, over 6.5 billion tonnes of CO_2 per year[61], or about 60% of total terrestrial carbon uptake[49], predominantly resulting from passive uptake by standing forests, are classified as CO_2 removals in national inventories[23]. Most countries define all their forests as managed for the United Nations Framework

Convention on Climate Change (UNFCCC). These accounting systems include this passive uptake in E_{LUC}, making it available to offset ongoing fossil fuel emissions (Fig. 1a). Indeed, some countries have used it to declare themselves Net Zero already[10].

These differences in how removals are defined between national inventories and global net-zero pathways are well documented, including by the IPCC[22–24,61]. Although UNFCCC inventory guidelines[21,62,63] consider all removals on any land declared as managed to be human-induced (that is, active), there is potential to add information to NGHGIs, including CO_2 uptake on unmanaged land[64], that would help countries understand better the magnitude of active and passive components of their carbon sinks. The availability of this information would make it even more important that the implications of including passive sinks in emissions targets are understood. It has therefore been argued[23,24,61] that net emissions in scenarios and targets should be translated to the NGHGI approach using dynamic global vegetation models to include CO_2 uptake on managed lands explicitly in calculations of E_{LUC}, despite inter-dynamic global vegetation model differences[32]. In ambitious mitigation scenarios, the necessary adjustments are small (less than 20%)[23,24] relative to required emissions reductions because only about half to two-thirds of terrestrial carbon uptake is currently classified as taking place on managed land and passive uptake is expected to decline as emissions fall[15]. Hence, if ambitious mitigation occurs, ambiguity over passive carbon sinks has an important but limited impact on allowable emissions at a global level[23,24], although potentially a much bigger impact at the level of an individual country or corporation.

The real problem, however, is that ambiguity in the classification of passive CO_2 uptake may forestall mitigation getting started. Pressure to classify land as managed (which countries self-determine) will increase as climate policy requires stronger reductions in net CO_2 emissions. Rising effective carbon prices increase incentives to monetize all allowable CO_2 removals. The vast majority of countries[61] already use their managed land sink to assess compliance with emissions reduction targets under the Paris Agreement, even though the Kyoto Protocol attempted to limit[65,66] such use. There is also increasing interest in monetizing 'blue carbon' uptake by the oceans[28]. If all passive uptake were claimed as CO_2 removal, then nominal 'net-zero CO_2 emissions' would imply only a net-zero atmospheric CO_2 growth rate, or $E_{GEO} + E_{LUC} - \rho_E G = 0$ on multi-decadal timescales. This would stabilize CO_2 concentrations, which is sufficient to slow further global warming but would not halt it for centuries. This may seem an extreme scenario (dashed lines in Fig. 1), but it is impossible to predict how accounting conventions will respond to very high effective global carbon prices associated with ambitious mitigation. A coastal or island state could argue that it has a right to take credit for passive uptake into the oceans of its exclusive economic zone if other countries take credit for passive uptake into their forests. Exclusive economic zones account for 30% of global ocean area and an uncertain (but estimable) fraction of ocean carbon uptake[67]. Credits are already being sold for carbon capture into the open oceans without clear standards to ensure additionality[68], raising the prospect of all ocean passive carbon uptake being claimed as removals, as has already occurred in many regions on land.

How this situation arose

Passive CO_2 uptake was not classed as anthropogenic CO_2 removal in the 2009 papers that established the need for Net Zero. Although the potential role of, and challenge of quantifying, land-based removals had long been acknowledged[69], those original papers equated zero CO_2 emissions with $E_{GEO} + E_{LUC} = 0$ and did not even envisage a substantial negative E_{LUC} compensating for ongoing fossil fuel emissions. The only compensatory mechanism considered at that time for residual fossil use was engineered CO_2 capture (or recapture from the atmosphere) and geological storage[70–72].

The emphasis on global 'net' emissions emerged in the Synthesis Report of the Fifth Assessment Report[73], but still did not include passive uptake and envisaged a limited role for negative E_{LUC}: Fig. SPM.14 of that report shows approximately zero net agriculture, forestry and other land-use (AFOLU) emissions in the majority of technology-neutral mitigation scenarios likely to limit warming to 2 °C. Scenarios limiting warming closer to 1.5 °C (ref. 74) rely more on negative net AFOLU emissions but this reliance may be inconsistent with assumed bioenergy use[75], other sustainable development goals[76,77] and even international law[78]. This exclusion of passive uptake and limited role for E_{LUC} propagated into the Structured Expert Dialogue (SED)[79] that informed the Paris Agreement. Annex II, paragraph 69, states: "if we stop emissions today entirely, there will be no further warming. Essentially, the commitment to future warming is in future emissions. A stable concentration, however, will result in further warming." Crucially, these first two sentences are only true if passive uptake is not classified as a CO_2 removal, whereas the final sentence makes clear that SED participants were aware of the importance of the difference between net-zero emissions and net-zero atmospheric CO_2 growth rate.

Article 4 of the Paris Agreement[80] does not specify precisely what is included in 'removals by sinks'. While it builds on inventory guidelines used under the UNFCCC and Kyoto Protocol, which treat all carbon stock changes on managed lands as anthropogenic and hence include some passive uptake in removals, Article 4 also makes clear that its objective is to deliver Article 2. If 'removals' were, in an extreme case, to include all passive uptake, then achieving the 'balance' of Article 4 would imply only a stabilization of atmospheric CO_2 concentrations (dotted and dashed scenarios in Fig. 1). This would not halt ongoing warming in time to deliver the goal of Article 2, as was made clear in the SED. Hence, only a restrictive definition of 'removals' that excludes passive (indirect) sinks renders the Paris Agreement's long-term temperature goal (Article 2.1a) and the implementing objective (Article 4.1) jointly consistent with the underlying climate science as it has been understood since 2009.

Scale of the problem

Figure 2 shows fluxes of CO_2 into and out of the atmosphere under a range of scenarios. Figure 2a shows the current situation, with fossil CO_2 emissions and active land-use change, E_{GEO} and E_{LUC}, only partially compensated for by passive uptake by land and ocean sinks, leading to a net accumulation of CO_2 in the atmosphere. All panels in Fig. 2 illustrate the breakdown of fluxes used in the 2009 papers, in equation (1) and by IPCC Assessment Reports. Under the breakdown used by NGHGIs, 6–7 $GtCO_2$ per year of the passive land sink in Fig. 2a would be reallocated to E_{LUC}, reducing it close to zero.

Figure 2b shows the fluxes implied by an instantaneous reduction of fossil fuel emissions by 40–50% and full compensation of ongoing land-use-change emissions with active land-based CO_2 removal. The atmospheric CO_2 growth rate (pale blue bar) would be reduced to net zero, albeit only momentarily. Although the rate of passive uptake would start to decline as soon as CO_2 concentrations stop rising[55], this scenario is relevant to net-zero claims by subglobal entities, both countries and corporations. Current accounting rules allow an entity to offset its ongoing emissions against carbon uptake on managed land, including passive uptake. If all passive uptake were classed as a removal, almost 50% of global emissions could be fully offset, allowing the entities responsible for them to declare that they had achieved net zero[81] without reducing active emissions at all. If remaining emitters then chose not to participate in mitigation (plausible, given 'ambitious' countries and corporations would be doing nothing more than offset their emissions against uptake that is occurring anyway), this situation could persist indefinitely.

If the instantaneous balance shown in Fig. 2b were achieved globally, passive CO_2 uptake would decline over the following decades,

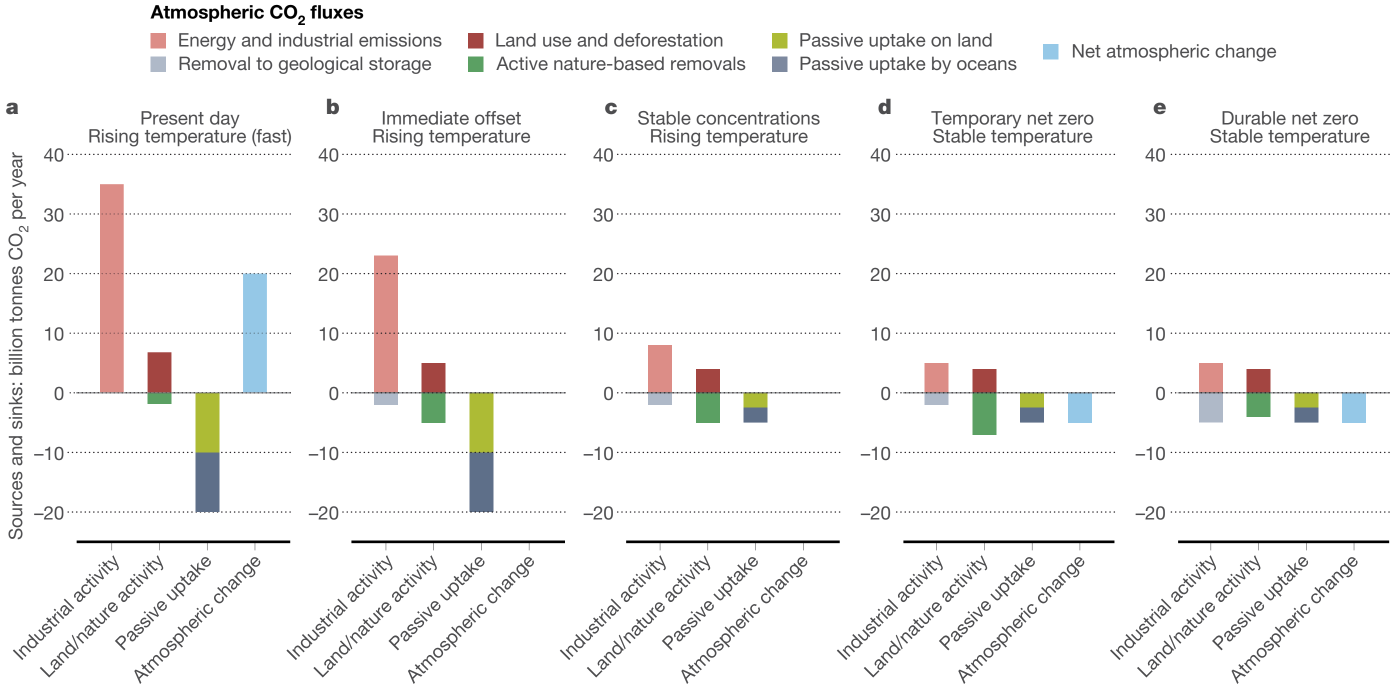

Fig. 2 | Fluxes of CO_2 into and out of the atmosphere under different interpretations of Net Zero. **a**–**e**, The pink and light grey bars indicate energy and industrial emissions and active removal to geological storage, which net to E_{GEO}; the brown and dark green bars indicate land-use-change emissions and active land-based removals (using the IPCC Assessment Report definition[20] of removals, including active reforestation and nature-based solutions), which net to E_{LUC}; the light green and dark grey bars indicate passive uptake by land and oceans; the light blue bars indicate the net rate of change in the amount of CO_2 in the atmosphere. **a**, Present day[49] conditions. **b**, Fossil fuel emissions reduced instantaneously, but only to the level required halt the net flow of CO_2 into the atmosphere (mid-twenty-first-century dashed scenario in Fig. 1). **c**, Emissions consistent with stable CO_2 concentrations over decades after warming reaches about 1.5–2 °C (dotted scenario in Fig. 1). **d**, Emissions consistent with stable temperatures (solid scenario in Fig. 1), which requires ongoing passive uptake reducing atmospheric CO_2 concentrations (negative pale blue bar) but allowing some temporary compensation of geological-origin emissions with biogenic removals. **e**, Durable net zero, both E_{GEO} and E_{LUC} equal to zero.

but emissions would not need to decline all the way to zero to stabilize atmospheric CO_2 concentrations (Fig. 2c, and dotted scenario in Fig. 1). Temperatures would continue to rise at the rate of adjustment to constant forcing, ρ_F. To halt global warming, excess atmospheric CO_2 concentrations must be allowed to decline by ρ_F, or 0.3% per year (Fig. 2d), corresponding to a total absolute uptake rate (rate of decrease of atmospheric CO_2 content through both passive uptake and net negative emissions) of about 5 $GtCO_2$ per year for peak warming in the range of 1.5–2 °C (ref. 55). In current Earth system models $\rho_E \approx \rho_F$, so it is sufficient to reduce $E_{GEO} + E_{LUC}$ to net zero to achieve this, but the required rate of CO_2 decline is set by the need to balance the thermal adjustment, independent of carbon-cycle uncertainties. If current models overstate the scale of passive uptake, then $E_{GEO} + E_{LUC}$ would need to be net negative to stabilize global temperatures.

Over decades, the scope for maintaining a substantial net negative E_{LUC} to balance a net-positive E_{GEO}, as in Fig. 2d, is limited by Earth system feedbacks[53], the need to balance emissions associated with food production[76], and, possibly, the need to compensate for weaker-than-expected passive uptake. Hence, a durable net zero (Fig. 2e and solid scenario in Fig. 1) is likely to require[17] that any remaining fossil-origin CO_2 production is balanced by CO_2 capture or recapture and geological-timescale storage, meaning secure storage over multi-century to millennial timescales without ongoing human intervention. Current evidence suggests that well-managed geological sequestration can meet this standard[82]. Options such as biochar or biomass burial would need to demonstrate a similar level of security and durability. So only Fig. 2e represents a durable halt to global warming but, if all passive uptake including blue carbon is treated as an anthropogenic removal, then all Fig. 2b–e could be regarded as some kind of net-zero CO_2 emissions.

Moving forward

It is difficult to justify definitions of balance and net zero in individual commitments that, if replicated globally, would not deliver the Paris Agreement goal of limiting global warming. However[23], it will also be difficult to revise UNFCCC reporting rules to exclude all passive CO_2 uptake from anthropogenic CO_2 removals. There are genuine issues of capacity, resources and pragmatism in bringing all countries on board with reporting and accounting following IPCC guidelines. Furthermore, many countries are relying on passive uptake to contribute to their emissions goals and may object to its exclusion from international transfers under Article 6 of the Paris Agreement. Care must also be taken not to jeopardize other benefits of reforestation, such as for biodiversity[30]. There are, however, some measures that can be taken to mitigate the problem.

First, we need wider acknowledgement across both science and policy communities that the problem exists: achieving and maintaining 'net zero' global emissions under accounting rules that allow passive CO_2 uptake to count as CO_2 removal will only slow down global warming. UNFCCC reporting is separate from target-setting: although countries should be encouraged to report emissions and CO_2 uptake on managed land, they do not need to treat these 'biological' removals as fungible with 'geological' fossil fuel emissions in climate targets[29]. Indeed, accounting methods used by the Kyoto Protocol discouraged this[66]. Accounting under the Global Stocktake and under Article 6 of the Paris Agreement should learn from and improve on the Kyoto Protocol approaches to try to separate out what is 'additional' (the result of direct anthropogenic activity) in reported removals[27]. A global effort to report passive CO_2 uptake separately[64] in greenhouse gas inventories, analogous to separate specification of short-lived climate pollutants[83], would help. Discussions have already begun between modellers and inventory compilers on this issue[61,76], including in the context of the 2024 IPCC Expert Meeting on Reconciling Land Emissions, and will continue in the Seventh Assessment Report. At the same time, countries could be encouraged to document in more detail how passive CO_2 uptake is included in their approaches to reporting and setting their Nationally Determined Contributions[24]. Such transparency would allow an assessment of the scale of the problem, and whether it may be increasing as climate ambition strengthens. It is arguably also in countries' long-term interest to acknowledge the contribution of passive uptake to their emissions goals because, unlike emissions reductions or active removals, passive uptake is contingent on other countries' mitigation decisions: as soon as global CO_2 emissions start to fall, the rate of uptake in most passive sinks will fall in response[23].

Second, voluntary markets, standard-setters, and ambitious countries and corporations can go beyond the current UNFCCC requirements and exclude passive or indirect uptake from removal credits and net-zero claims. For example, if the CO_2 flux into an ecosystem is claimed to be net zero, then the land occupied by that ecosystem should absorb CO_2 at the same average multidecadal rate that an unmanaged ecosystem would given current conditions (location and maturity, level and recent rate of increase in atmospheric CO_2 concentrations, climate and so on). This rate can be either calculated with a vegetation model or inferred from observations of similar regions: such methods are already used[26] to assess the extent to which claimed emissions reductions are additional to processes that would have occurred in the absence of an intervention. Even if passive uptake can be quantified and excluded from claims at an individual project level, however, carbon leakage means that a clear separation is likely to remain challenging as long as reporting systems are still in widespread use that allow it to count as a removal[84].

Finally, much of the remaining carbon-absorbing capacity of the biosphere may be required to compensate for emissions associated with food production, such as fertilizer production and use, particularly if biological carbon sinks are compromised by climate change itself[53,74,85]. Until it can be shown that total CO_2 uptake by the biosphere and oceans is large enough to halt CO_2-induced warming, it is dangerously optimistic to assume that there will be additional capacity for a negative E_{LUC} to compensate substantially for ongoing fossil fuel emissions[13,86]. Hence, the third and most important measure is to recognize the likely long-term infeasibility of balancing substantial ongoing net-positive geological-origin CO_2 emissions with enhanced carbon uptake in the biosphere and oceans that is genuinely additional to the passive uptake that is already required for net-zero emissions to halt warming. All entities committed to the long-term temperature goal of the Paris Agreement therefore need to plan to jointly achieve global Geological Net Zero[13,17,18]. This means either eliminating fossil fuel and fossil carbonate (for cement) use entirely or achieving a balance between any remaining CO_2 production from geological sources and CO_2 committed to permanent geological storage, potentially as soon as mid-century. Unlike the biosphere, all significant geological sources and sinks of CO_2 are unambiguously anthropogenic, clarifying emissions accounting. Acknowledging the geophysical imperative of Geological Net Zero would allow countries and corporations to future-proof climate mitigation strategies by planning on a progressive transition to like-for-like balancing of sources and sinks[17] without waiting for consensus on any change to reporting rules. Differentiating in greenhouse gas accounting systems between avoided emissions, removals to temporary storage and removals to permanent storage is, however, essential to track progress to Geological Net Zero[87].

Responsibility for protection of passive sinks

Equation (1) also makes clear the paramount importance of protecting natural CO_2 sinks both during and after the transition to Geological Net Zero. This will entail opportunity costs, as land or coastal oceans that could be used for food or bioenergy production are allowed to absorb carbon instead, but this passive uptake cannot be used to compensate for ongoing fossil fuel emissions if Net Zero is to achieve a durable halt to global warming. Fortunately, equation (1) also suggests a possible basis for allocating these costs. To prevent further warming after emissions reach net zero, annual uptake by passive sinks must be greater than or equal to $\phi\rho_F G$, where ϕ is the perturbation airborne fraction[55] (Methods). This is approximately 0.15% of cumulative global CO_2 emissions G over the entire industrial period. Any addition to this cumulative total increases the size of the passive carbon sink that must be maintained for many decades after global warming has halted. Whether this causal responsibility translates into a moral or legal responsibility to contribute to maintaining that sink is not a scientific question, but science can quantify the scale of the challenge: for example, even if the United Kingdom were to achieve net-zero CO_2 emissions before 2050, 0.15% of the United Kingdom's contribution to historical cumulative emissions will be 120 $MtCO_2$ per year. Should this exceed the passive sink capacity of the United Kingdom's land and coastal oceans[88], then to genuinely end the United Kingdom's contribution to ongoing global warming, the United Kingdom would arguably need to undertake active CO_2 removal at approximately double ($1/\phi$) the rate of any shortfall (in addition to removals to compensate for any ongoing residual emissions) or to rely on passive uptake in other jurisdictions. Mechanisms for redistributing the costs of maintaining passive carbon sinks after the date of net zero may therefore be needed[89]. Likewise, undertakings by private corporations to maintain passive carbon sinks could be seen as addressing the impact of their historical cumulative emissions, not compensation for future emissions. The traditional concept of historical responsibility, linking past emissions with future emissions reduction rates[90], remains complex and multifaceted[91]. In contrast, the responsibility that we highlight here is a simple geophysical one: by adding to cumulative emissions, any entity, country or corporation adds to the total passive carbon sink that needs protection for the foreseeable future.

Actionable implications

Acknowledging the need for Geological Net Zero makes clear what it takes for any continued fossil fuel use to be consistent with Paris Agreement goals. Offsetting emissions with enhanced CO_2 uptake in the oceans and biosphere can provide immediate benefits[30] if and only if it is genuinely additional to passive CO_2 uptake. In a durable net-zero world, 100% of the CO_2 generated by any continued fossil fuel or fossil carbonate use will almost certainly need to be either captured at source or recaptured from the atmosphere and committed to geological-timescale storage. A commitment from high-ambition participants to report and scale up this 'geologically stored fraction'[92] is needed urgently: it is currently about 0.1% globally[93], even including CO_2 injection for enhanced hydrocarbon recovery, and accelerates smoothly over time to reach 100% at the date of Geological Net Zero in cost-effective scenarios that meet the goals of the Paris Agreement[92,94]. This implies, in addition to reducing emissions, achieving a 10% geologically stored fraction by the mid-2030s[95] and investing now for a further 10-fold increase in the stored fraction over the following 20 years, including demonstrating secure and verifiable geological CO_2 storage capacity to match any new fossil fuel reserves. These are ambitious but achievable goals for the fossil fuel industry and its customers.

Online content

Any methods, additional references, Nature Portfolio reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41586-024-08326-8.

1. *Outcome of the First Global Stocktake* FCCC/PA/CMA/2023/L.17 (UNFCCC, 2023); https://unfccc.int/sites/default/files/resource/cma2023_L17_adv.pdf?download.
2. Parris, H., Anger-Kraavi, A. & Peters, G. P. Does a change in the 'global net zero' language matter? *Glob. Sustain.* **6**, e13 (2023).
3. Solomon, S., Plattner, G.-K., Knutti, R. & Friedlingstein, P. Irreversible climate change due to carbon dioxide emissions. *Proc. Natl Acad. Sci. USA* **106**, 1704–1709 (2009).
The first of six papers (that is, refs. 3–8) published in 2009 recognizing the irreversible and cumulative impact of CO_2 emissions on global mean surface temperature and consequent need to reduce CO_2 emissions effectively to zero to limit global warming.
4. Meinshausen, M. et al. Greenhouse-gas emission targets for limiting global warming to 2 °C. *Nature* **458**, 1158–1162 (2009).
5. Allen, M. R. et al. Warming caused by cumulative carbon emissions towards the trillionth tonne. *Nature* **458**, 1163–1166 (2009).
6. Matthews, H. D., Gillett, N. P., Stott, P. A. & Zickfeld, K. The proportionality of global warming to cumulative carbon emissions. *Nature* **459**, 829–832 (2009).
7. Zickfeld, K., Eby, M., Matthews, H. D. & Weaver, A. J. Setting cumulative emissions targets to reduce the risk of dangerous climate change. *Proc. Natl Acad. Sci. USA* **106**, 16129–16134 (2009).
8. Gregory, J. M., Jones, C. D., Cadule, P. & Friedlingstein, P. Quantifying carbon cycle feedbacks. *J. Clim.* **22**, 5232–5250 (2009).
9. Collins, M. et al. in *Climate Change 2013*: *The Physical Science Basis* (eds Stocker, T. F. et al.) 1029–1136 (IPCC, Cambridge Univ. Press, 2013).
10. Lang, J. et al. *Net Zero Tracker* (Energy and Climate Intelligence Unit, Data-Driven EnviroLab, NewClimate Institute, Oxford Net Zero, 2024); https://zerotracker.net.
11. IPCC Summary for Policymakers. In *Special Report on Global Warming of 1.5 °C* (eds Masson-Delmotte, V. et al.) (Cambridge Univ. Press, 2018).
12. MacDougall, A. H., Frölicher, T. L. & Jones, C. D. Is there warming in the pipeline? A multi-model analysis of the Zero Emissions Commitment from CO_2. *Biogeosciences* **17**, 2987–3016 (2020).
Results of the Zero Emission Commitment Model Intercomparison Project demonstrating approximately net-zero warming following reduction of CO_2 emissions to zero, further analysed in ref. 13 to demonstrate the range of CO_2 emissions consistent with no further warming.
13. Jenkins, S. et al. The multi-decadal response to net zero CO_2 emissions and implications for emissions policy. *Geophys. Res. Lett.* **49**, e2022GL101047 (2022).
14. IPCC Summary for Policymakers. In *Climate Change 2021: The Physical Science Basis* (eds Masson-Delmotte, V. et al.) (IPCC, Cambridge Univ. Press, 2021).
15. Canadell, J. G. et al. in *Climate Change 2021*: *The Physical Science Basis* (eds Masson-Delmotte, V. et al.) 673–816 (IPCC, Cambridge Univ. Press, 2021).
16. Forster, P. M. et al. in *Climate Change 2021*: *The Physical Science Basis* (eds Masson-Delmotte, V. et al.) 923–1054 (IPCC, Cambridge Univ. Press, 2021).
17. Fankhauser, S. et al. The meaning of net zero and how to get it right. *Nat. Clim. Change* **12**, 15–21 (2022).
This paper highlights the importance of different interpretations of net zero, noting that durable net zero requires a like-for-like balance between sources and sinks, with only active removals to permanent geological storage being used to compensate for any ongoing emissions of geological-origin CO_2, for example, from burning fossil fuels. See also ref. 19.
18. Allen, M. R. et al. Net Zero: science, origins, and implications. *Annu. Rev. Environ. Resour.* **47**, 849–887 (2022).
This paper reviews the science of net zero, demonstrating the central role of the compensation between the rate of adjustment to constant forcing and slow carbon-cycle adjustment rate, or rate of CO_2 forcing decline under zero emissions, and introducing the conceptual framework of equation (1).
19. Rogelj, J. Net zero targets in science and policy. *Environ. Res. Lett.* **18**, 021003 (2023).
20. Matthews, J. B. R. et al. in *Climate Change 2021: The Physical Science Basis* (eds Masson-Delmotte, V. et al.) 2215–2256 (IPCC, Cambridge Univ. Press, 2021).
21. Eggleston, S. et al. (eds) *2006 IPCC Guidelines for National Greenhouse Gas Inventories Volume 4: Agriculture, Forestry and Other Land Use* (IGES, 2006).
22. Grassi, G. et al. Reconciling global-model estimates and country reporting of anthropogenic forest CO_2 sinks. *Nat. Clim. Change* **8**, 914–920 (2018).
23. Grassi, G., Stehfest, E., Rogelj, J. & van Vuuren, D. Critical adjustment of land mitigation pathways for assessing countries' climate progress. *Nat. Clim. Change* **11**, 425–434 (2021).
This paper details the correction required to global Paris-aligned pathways to account for national reporting of passive uptake on managed land as a CO_2 removal, developing the issues raised by ref. 22 and further updated in refs. 24 and 61.
24. Gidden, M. J. et al. Aligning climate scenarios to emissions inventories shifts global benchmarks. *Nature* **624**, 102–108 (2023).
25. Canadell, J. G. et al. Factoring out natural and indirect human effects on terrestrial carbon sources and sinks. *Environ. Sci. Policy* **10**, 370–384 (2007).
26. West, T. A. P., Börner, J., Sills, E. O. & Kontoleon, A. Overstated carbon emission reductions from voluntary REDD+ projects in the Brazilian Amazon. *Proc. Natl Acad. Sci. USA* **117**, 24188–24194 (2020).
27. Smith, S. M. et al. *The State of Carbon Dioxide Removal* 2nd edn (Smith School of Enterprise and the Environment, Univ. Oxford, 2024); https://osf.io/f85qj/.
28. Bertram, C. et al. The blue carbon wealth of nations. *Nat. Clim. Change* **11**, 704–709 (2021).
29. den Elzen, M. G. J. et al. Updated nationally determined contributions collectively raise ambition levels but need strengthening further to keep Paris goals within reach. *Mitig. Adapt. Strateg. Glob. Change* **27**, 33 (2022).
30. Seddon, N. et al. Understanding the value and limits of nature-based solutions to climate change and other global challenges. *Phil. Trans. R. Soc. B* **375**, 20190120 (2020).
31. Girardin, C. A. J. et al. Nature-based solutions can help cool the planet—if we act now. *Nature* **593**, 191–194 (2021).
32. Ruehr, S. et al. Evidence and attribution of the enhanced land carbon sink. *Nat. Rev. Earth Environ.* **4**, 518–534 (2023).
33. Held, I. M. et al. Probing the fast and slow components of global warming by returning abruptly to preindustrial forcing. *J. Clim.* **23**, 2418–2427 (2010).
34. Seshadri, A. K. Fast–slow climate dynamics and peak global warming. *Clim. Dyn.* **48**, 2235–2253 (2017).
35. Seshadri, A. K. Origin of path independence between cumulative CO_2 emissions and global warming. *Clim. Dyn.* **49**, 3383–3401 (2017).
36. Allen, M. R. & Dube, O. P. in *Special Report on Global Warming of 1.5 °C* (eds Masson-Delmotte, V. et al.) 49–92 (IPCC, Cambridge Univ. Press, 2018).
37. Cain, M. et al. Improved calculation of warming-equivalent emissions for short-lived climate pollutants. *npj Clim. Atmos. Sci.* **2**, 29 (2019).
38. Matthews, H. D., Solomon, S. & Pierrehumbert, R. Cumulative carbon as a policy framework for achieving climate stabilization. *Phil. Trans. R. Soc. A* **370**, 4365–4379 (2012).
39. Herrington, T. & Zickfeld, K. Path independence of climate and carbon cycle response over a broad range of cumulative carbon emissions. *Earth Syst. Dyn.* **5**, 409–422 (2014).
40. MacDougall, A. H. & Friedlingstein, P. The origin and limits of the near proportionality between climate warming and cumulative CO_2 emissions. *J. Clim.* **28**, 4217–4230 (2015).
41. Seshadri, A. K. Cumulative emissions accounting of greenhouse gases due to path independence for a sufficiently rapid emissions cycle. *Clim. Dyn.* **57**, 787–798 (2021).
42. Frölicher, T. L., Winton, M. & Sarmiento, J. L. Continued global warming after CO_2 emissions stoppage. *Nat. Clim. Change* **4**, 40–44 (2014).
43. Armour, K. C., Bitz, C. M. & Roe, G. H. Time-varying climate sensitivity from regional feedbacks. *J. Clim.* **26**, 4518–4534 (2013).
44. Sherwood, S. C. et al. An assessment of Earth's climate sensitivity using multiple lines of evidence. *Rev. Geophys.* **58**, e2019RG000678 (2020).
45. Huntingford, C., Williamson, M. S. & Nijsse, F. J. M. M. CMIP6 climate models imply high committed warming. *Climatic Change* **162**, 1515–1520 (2020).
46. Lewis, N. Objectively combining climate sensitivity evidence. *Clim. Dyn.* **60**, 3139–3165 (2023).
47. Abrams, J. F. et al. Committed global warming risks triggering multiple climate tipping points. *Earths Future* **11**, e2022EF003250 (2023).
48. Williams, R. G., Goodwin, P., Roussenov, V. M. & Bopp, L. A framework to understand the transient climate response to emissions. *Environ. Res. Lett.* **11**, 015003 (2016).
A complete conceptual framework to understand the cumulative impact of CO_2 emissions on global temperatures and the balance between thermal and carbon cycle adjustments that results in no further CO_2-induced warming following net-zero CO_2 emissions.
49. Friedlingstein, P. et al. Global carbon budget 2023. *Earth Syst. Sci. Data* **15**, 5301–5369 (2023).
50. Yang, H. et al. Global increase in biomass carbon stock dominated by growth of northern young forests over past decade. *Nat. Geosci.* **16**, 886–892 (2023).
51. Walker, A. P. et al. Integrating the evidence for a terrestrial carbon sink caused by increasing atmospheric CO_2. *New Phytol.* **229**, 2413–2445 (2021).
52. 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).
53. Zickfeld, K. et al. Net-zero approaches must consider Earth system impacts to achieve climate goals. *Nat. Clim. Change* **13**, 1298–1305 (2023).
This paper highlights the risk that Earth system feedbacks weaken terrestrial carbon sinks, limiting the degree to which climate goals can be met through balancing ongoing emissions with terrestrial uptake.
54. Ke, P. et al. Low latency carbon budget analysis reveals a large decline of the land carbon sink in 2023. *Natl Sci. Rev.* https://doi.org/10.1093/nsr/nwae367 (2024).
55. Jones, C. D. et al. Simulating the Earth system response to negative emissions. *Environ. Res. Lett.* **11**, 095012 (2016).
56. MacDougall, A. H. Estimated effect of the permafrost carbon feedback on the zero emissions commitment to climate change. *Biogeosciences* **18**, 4937–4952 (2021).
57. Millar, R., Allen, M., Rogelj, J. & Friedlingstein, P. The cumulative carbon budget and its implications. *Oxf. Rev. Econ. Policy* **32**, 323–342 (2016).
58. Williams, R. G., Ceppi, P. & Katavouta, A. Controls of the transient climate response to emissions by physical feedbacks, heat uptake and carbon cycling. *Environ. Res. Lett.* **15**, 0940c1 (2020).
59. Tachiiri, K., Hajima, T. & Kawamiya, M. Increase of the transient climate response to cumulative carbon emissions with decreasing CO_2 concentration scenarios. *Environ. Res. Lett.* **14**, 124067 (2019).
60. Hubau, W. et al. Asynchronous carbon sink saturation in African and Amazonian tropical forests. *Nature* **579**, 80–87 (2020).
61. Grassi, G. et al. Harmonising the land-use flux estimates of global models and national inventories for 2000–2020. *Earth Syst. Sci. Data* **15**, 1093–1114 (2023).
62. *Revisiting the Use of Managed Land as a Proxy for Estimating National Anthropogenic Emissions and Removals—IPCC Expert Meeting Report* (IPCC, 2010).
63. *Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC, 2019).
64. Nabuurs, G.-J., Ciais, P., Grassi, G., Houghton, R. A. & Sohngen, B. Reporting carbon fluxes from unmanaged forest. *Commun. Earth Environ.* **4**, 337 (2023).
65. Fry, I. Twists and turns in the jungle: exploring the evolution of land use, land–use change and forestry decisions within the Kyoto Protocol. *Rev. Eur. Community Int. Environ. Law* **11**, 159–168 (2002).
66. Macintosh, A. K. LULUCF in the post-2012 regime: fixing the problems of the past? *Clim. Policy* **12**, 341–355 (2012).
67. Gruber, N. et al. Trends and variability in the ocean carbon sink. *Nat. Rev. Earth Environ.* **4**, 119–134 (2023).
68. Palter, J. B., Cross, J., Long, M. C., Rafter, P. A. & Reimers, C. E. The science we need to assess marine carbon dioxide removal. *Eos* http://eos.org/opinions/the-science-we-need-to-assess-marine-carbon-dioxide-removal (2023).

69. Prentice, I. C. et al. in *Climate Change 2001: The Scientific Basis* (eds Houghton, J. T. et al.) 185–237 (IPCC, Cambridge Univ. Press, 2001).
70. Weaver, A. J., Zickfeld, K., Montenegro, A. & Eby, M. Long term climate implications of 2050 emission reduction targets. *Geophys. Res. Lett.* **34**, L19703 (2007).
71. Allen, M. et al. The exit strategy. *Nat. Clim. Change* **1**, 56–58 (2009).
72. Allen, M. R., Frame, D. J. & Mason, C. F. The case for mandatory sequestration. *Nat. Geosci.* **2**, 813–814 (2009).
73. IPCC *Climate Change 2014: Synthesis Report* (eds Core Writing Team, Pachauri, R. K. & Meyer, L. A.) (IPCC, 2014).
74. IPCC: Summary for Policymakers. In *Climate Change 2022: Mitigation of Climate Change* (eds Shukla, P. R. et al.) (Cambridge Univ. Press, 2022).
75. Harper, A. B. et al. Land-use emissions play a critical role in land-based mitigation for Paris climate targets. *Nat. Commun.* **9**, 2938 (2018).
This paper identifies the essential role of the land carbon sink in 1.5-°C scenarios and raises questions about compatibility with other Sustainable Development Goals.
76. Shukla, P. R., Skea, J. & Calvo Buendia, E. *Special Report on Climate Change and Land* (eds Shukla, P. R. et al.) (IPCC, 2019).
77. Cobo, S., Galán-Martín, Á., Tulus, V., Huijbregts, M. A. J. & Guillén-Gosálbez, G. Human and planetary health implications of negative emissions technologies. *Nat. Commun.* **13**, 2535 (2022).
This paper documents the potential conflict between human and ecosystem health and the heavy dependence on terrestrial carbon removal to achieve climate goals.
78. Stuart-Smith, R. F., Rajamani, L., Rogelj, J. & Wetzer, T. Legal limits to the use of CO_2 removal. *Science* **382**, 772–774 (2023).
79. *Report on the Structured Expert Dialogue on the 2013–2015 Review. Note by the Co-Facilitators of the Structured Expert Dialogue* (UNFCCC, 2015); https://unfccc.int/documents/8707.
Report of the 2013–2014 SED, providing essential context of how net-zero science was communicated to the negotiators of the Paris Agreement.
80. *Adoption of the Paris Agreement* (UNFCCC, 2015); https://unfccc.int/sites/default/files/english_paris_agreement.pdf.
81. Mitchell-Larson, E. & Bushman, T. *Carbon Direct Commentary: Release of the Voluntary Registry Offsets Database* (Carbon Direct, 2021); https://carbon-direct.com/wp-content/uploads/2021/04/CD-Commentary-on-Voluntary-Registry-Offsets-Database_April-2021.pdf.
82. Daniels, S. et al. *Deep Geological Storage of CO_2 on the UK Continental Shelf: Containment Certainty* (UK Government, 2023); https://www.gov.uk/government/publications/deep-geological-storage-of-carbon-dioxide-co2-offshore-uk-containment-certainty.
83. Allen, M. R. et al. Indicate separate contributions of long-lived and short-lived greenhouse gases in emission targets. *npj Clim. Atmos. Sci.* **5**, 5 (2022).
84. Searchinger, T. D., Wirsenius, S., Beringer, T. & Dumas, P. Assessing the efficiency of changes in land use for mitigating climate change. *Nature* **564**, 249–253 (2018).
85. Nabuurs, G.-J. et al. in *Climate Change 2022: Mitigation of Climate Change* (eds Shukla, P. R. et al.) 747–860 (Cambridge Univ. Press, 2022).
86. Matthews, H. D. et al. Temporary nature-based carbon removal can lower peak warming in a well-below 2 °C scenario. *Commun. Earth Environ.* **3**, 65 (2022).
87. Schenuit, F. et al. Secure robust carbon dioxide removal policy through credible certification. *Commun. Earth Environ.* **4**, 349 (2023).
88. Chandra, N. et al. Estimated regional CO_2 flux and uncertainty based on an ensemble of atmospheric CO_2 inversions. *Atmos. Chem. Phys.* **22**, 9215–9243 (2022).
89. Ciais, P. et al. Attributing the increase in atmospheric CO_2 to emitters and absorbers. *Nat. Clim. Change* **3**, 926–930 (2013).
90. Shue, H. Historical responsibility, harm prohibition, and preservation requirement: core practical convergence on climate change. *Moral Philos. Politics* **2**, 7–31 (2015).
91. Sardo, M. C. Responsibility for climate justice: political not moral. *Eur. J. Political Theory* **22**, 26–50 (2023).
92. Jenkins, S., Mitchell-Larson, E., Ives, M. C., Haszeldine, S. & Allen, M. Upstream decarbonization through a carbon takeback obligation: an affordable backstop climate policy. *Joule* **5**, 2777–2796 (2021).
93. Steyn, M. et al. *Global Status of CCS 2022* (Global CCS Institute, 2023); https://status22.globalccsinstitute.com/wp-content/uploads/2023/03/GCCSI_Global-Report-2022_PDF_FINAL-01-03-23.pdf.
94. Jenkins, S., Kuijper, M., Helferty, H., Girardin, C. & Allen, M. Extended producer responsibility for fossil fuels. *Environ. Res. Lett.* **18**, 011005 (2023).
95. Skidmore, C. *Mission Zero: Independent Review of Net Zero* (UK Government, 2022); https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1128689/mission-zero-independent-review.pdf.

Methods

The origins of equation (1) are detailed in ref. 18, equations (8) and (14), and are summarized here. The total anthropogenic change in global average temperature over a multi-decade time interval is given by the following generalization of equation (1):

$$\Delta T = \kappa_E[\Delta G + (\rho_F - \rho_E)G\Delta t] + \kappa_F(\Delta F + \rho_F F \Delta t), \quad (2)$$

where $\Delta G = (E_{GEO} + E_{LUC})\Delta t$ is the total CO_2 emitted or actively removed by human activities over the time interval Δt, G is cumulative CO_2 emissions from pre-industrial to around the middle of that time interval, ΔF is the change in, and F is the average, net non-CO_2 radiative forcing, also over that time interval. The Transient Climate Response to Emissions[20] κ_E = 0.45(±0.18) °C per 1,000 $GtCO_2$ (ref. 14), whereas κ_F = 0.49(±0.1) °C per W m^{-2} is the Transient Climate Response to Forcing, or the Transient Climate Response (TCR)[20] divided by the radiative forcing due to a doubling of atmospheric CO_2 concentrations. The $\kappa_F\Delta F$ term represents the fast component[33] of the response to radiative forcing (defining ΔF as the difference between the decade before the beginning and the decade before the end of the time-interval accounts for subdecadal adjustments), whereas $\kappa_F\rho_F F\Delta t$ represents the gradual adjustment to a constant forcing[34]. Hence the Rate of Adjustment to Constant Forcing[18] $\rho_F = (\mathrm{ECS} - \mathrm{TCR})/(\mathrm{TCR} \times s_2)$, or about 0.3% per year[37], where ECS is the Equilibrium Climate Sensitivity and s_2 is the multi-century adjustment timescale associated with warming of the deep oceans[33] and the evolution of feedbacks as the climate system re-equilibrates[43].

The $\kappa_E\Delta G$ term in equation (2) represents the familiar cumulative impact of CO_2 emissions on global temperature whereas the $\kappa_E(\rho_F - \rho_E)G\Delta t$ term may be understood by considering the limiting case of $\rho_E = 0$: if there were no durable component to passive uptake, and hence CO_2 concentrations and CO_2-induced forcing were to remain constant following net-zero emissions, temperatures would continue to rise at a fractional rate ρ_F, or absolute rate $\kappa_E\rho_F G$, after an injection of CO_2 taking place over a timescale shorter than ρ_F^{-1}, which is about 300 years. Studies with coupled climate–carbon-cycle models calibrated against available observations[12,13] indicate that temperatures are actually expected to change very little after emissions reach net zero: hence $\rho_E \approx \rho_F$.

We now explain the approximations behind the expressions for CO_2-induced warming in equations (1) and (2). Over a decade-to-century time interval Δt (not longer), the change in atmospheric CO_2 loading resulting from anthropogenic CO_2 emissions can be approximated by

$$\Delta C_A \approx \phi(\Delta G - \rho_E G\Delta t), \quad (3)$$

where ϕ is the Perturbation Airborne Fraction, or the change in ΔC_A resulting from a unit increase in ΔG over that period[55]. Unlike the instantaneous airborne fraction, $\Delta C_A/\Delta G$, which necessarily becomes undefined as $\Delta G \to 0$, ϕ can remain close to its historical value (approximately 50%) even in ambitious mitigation scenarios. Similarly, on these timescales, the externally driven change in global mean surface temperature is approximately

$$\Delta T \approx \kappa_F(\Delta F_{tot} + \rho_F F_{tot}\Delta t), \quad (4)$$

where ΔF_{tot} and F_{tot} are the change in and average level of total radiative forcing from all sources, respectively[33,34]. For CO_2-induced radiative forcing, $\Delta F_{CO2} = \alpha\Delta C_A$, where α is the radiative efficacy in W m^{-2} per additional billion tonnes of CO_2 in the atmosphere. For emissions concentrated into a time much less than ρ_E^{-1} (as is the case for the historical record), the second term on the right-hand side of equation (3) is small, so $F_{CO2} = \alpha\phi G$. Neither α nor ϕ are constant, but the nonlinearities cancel, such that $\alpha\phi$, the change in radiative forcing on decade-to-century timescales per tonne of CO_2 emitted, is approximately constant. Substitution of equation (3) into equation (4) and introducing $\kappa_E = \alpha\phi\kappa_F$ yields the expression for CO_2-induced warming in equations (1) and (2).

Equation (2) also implies that, before emissions reach net zero, total passive CO_2 uptake by both the terrestrial biosphere and oceans consists of a transient component (driven by redistribution of recent emissions into rapidly equilibrating carbon reservoirs) and a durable component that is, on multi-decade timescales, proportional to cumulative emissions since pre-industrial[18]:

$$\Delta G - \Delta C_A \approx [(1-\phi) \times (E_{GEO} + E_{LUC}) + \phi\rho_E G]\Delta t. \quad (5)$$

The accuracy of these approximations is illustrated in Extended Data Fig. 1 using the response of the Finite-amplitude Impulse Response (FaIR) simple climate model[52] to stylized concentration-stabilization and net-zero emission scenarios, compared with the expressions for passive uptake and temperature response given by equations (5) and (1), respectively. The FaIR model has been shown[13] to be consistent with the behaviour of much more complex Earth system models over a broad range of scenarios, so agreement with FaIR is indicative of agreement with a wider range of models.

Under net-zero emissions, meaning $E_{GEO} + E_{LUC} = 0$, the annual rate of passive CO_2 uptake converges to $\phi\rho_E G$, which has the same impact as active removal of $\rho_E G$ $GtCO_2$ per year, or approximately 0.3% per year of cumulative historical CO_2 emissions. Figure 2 assumes that this passive uptake continues to be partitioned equally between the terrestrial biosphere and oceans, consistent with the range of results of the Zero Emissions Commitment Model Intercomparison Project (ZECMIP; Fig. 8 in ref. 12). If contributions to the protection of these passive sinks were to reflect physical contributions to this committed ongoing carbon uptake, research into the geographic location of land and ocean sinks, and the evolution of both transient and durable components of passive uptake as emissions decline, is clearly a priority[88].

The level of CO_2-induced warming after a period of positive emissions starting from pre-industrial equilibrium is $\kappa_E G$ if and only if the timescale over which those emissions take place is much less than $(\rho_F - \rho_E)^{-1}$. As $\rho_F^{-1} \approx 300$ years and $\rho_E > 0$, $(\rho_F - \rho_E)^{-1}$ is of order 1,000 years[18]. Hence the observation that warming is proportional to cumulative CO_2 emissions for CO_2 injections primarily taking place over a century or less (which includes the historical record and most experiments used as evidence for this cumulative impact) does not imply that net-zero emissions would automatically be associated with no further warming or cooling. Likewise, if κ_E is not constant (but instead increases with G, for example), CO_2-induced warming would still remain constant under net-zero CO_2 emissions provided that $\rho_F = \rho_E$. The linear relationship between cumulative CO_2 emissions and CO_2-induced warming is neither necessary nor sufficient for there to be no further warming or cooling following net-zero CO_2 emissions: these are independent observations, both of which are supported by modelling and observations so far[41].

Data availability

All data and software required for the reproduction of figures is provided through CodeOcean https://codeocean.com/capsule/f7396914-3276-44a6-a7a4-81df82d2451c/. Datasets include the Sixth Assessment Report global radiative forcing times series AR6_ERF_1750-2019.csv available on https://doi.org/10.5285/0dd364e74c254b64bb5fddb5dceed364 and the emissions time series Global_Carbon_Budget_2023v1.1.xlsx available on https://doi.org/10.18160/GCP-2023.

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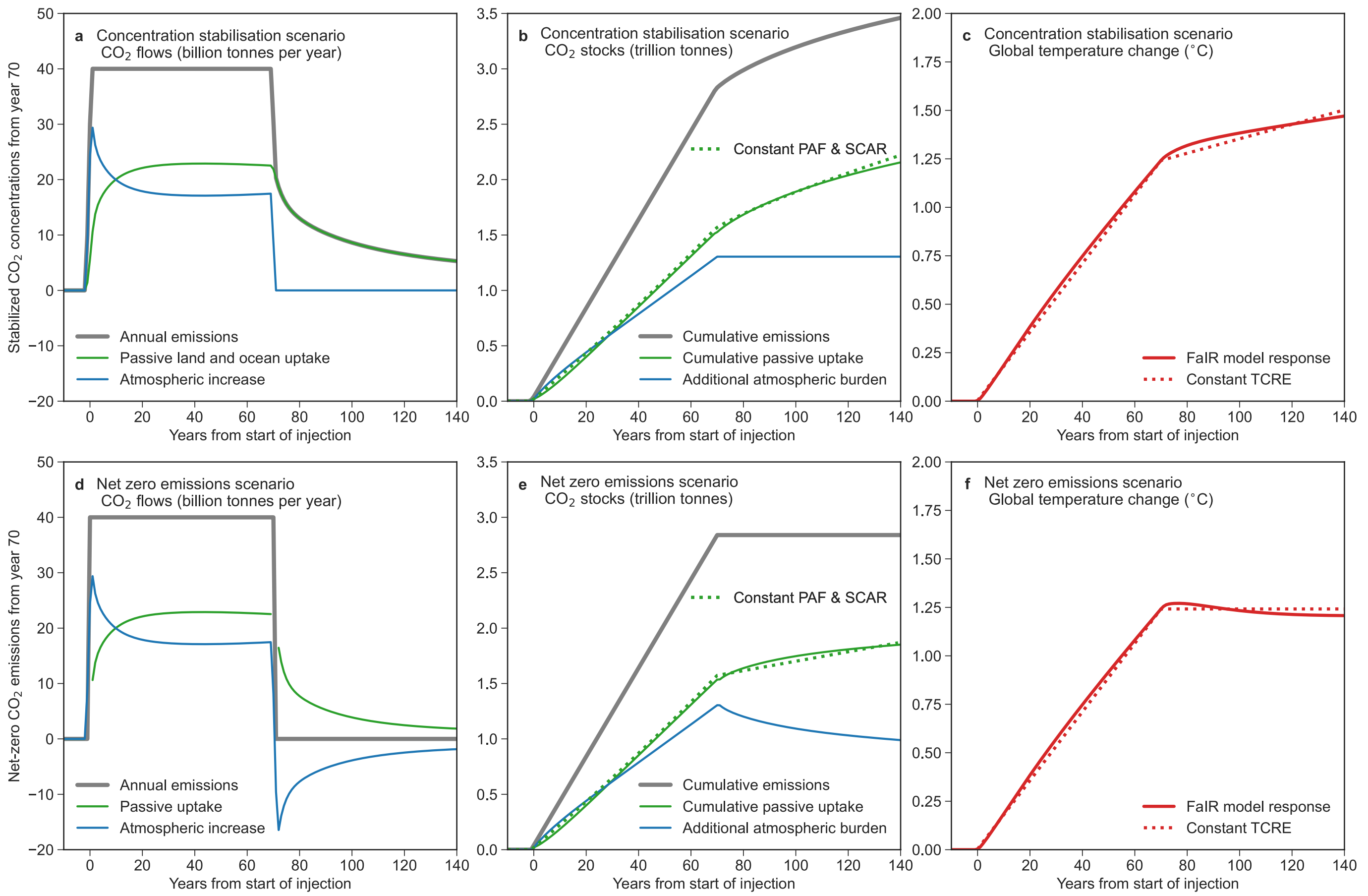

Extended Data Fig. 1 | Response to a stylized emission to illustrate the role of passive uptake. The figure shows the response of the FaIR2.0 simple climate model[52] to an emission of 40 billion tonnes of CO_2 per year for 70 years, followed by stabilisation of atmospheric concentrations (panels a-c) or net zero ongoing emissions (panels d-f). Annual CO_2 flows are shown in panels a and d, changes in CO_2 stocks in b and e and temperature response in c and f. Grey, green and blue lines show CO_2 emissions, passive uptake and atmospheric increase, annual (panels a and d) and cumulative (panels b and e), respectively. Blue and green lines add up to grey lines by construction. Red lines (panels c and f) show temperature response. Emissions consistent with stable concentrations are equal to passive uptake after concentrations stabilise (panel a) because the rate of atmospheric increase (panel b) is then zero. They are initially halved (see Fig. 2b of main text), halved again after about 20 years (Fig. 2c of main text), but do not decline to zero, and temperatures continue to rise for many decades at an approximately constant rate (panel c). If emissions are reduced to net zero and passive sinks are not compromised, passive uptake immediately draws down the atmospheric CO_2 burden (panels d and e), stabilising global temperatures (panel f). Dotted green line shows cumulative passive CO_2 uptake $\Delta G - \Delta C_A$ predicted by equation 5 (Methods) with a constant Perturbation Airborne Fraction, PAF[55], $\phi = 0.5$, and constant Slow Carbon-cycle Adjustment Rate, SCAR[18], $\rho_E = 0.3\%$ per year. Dotted red line shows temperature approximated by cumulative emissions, or equation 1 with $\rho_E = \rho_F$ and constant Transient Climate Response to Emissions, TCRE[8], κ_E. These approximations are accurate relative to the uncertainties in the climate response both while emissions are positive and for the first few decades after emissions reach net zero, but not over a broader range of timescales and scenarios.