

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

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53 **Preface:** Achieving net zero global emissions of carbon dioxide (CO₂), with declining emissions of
54 other greenhouse gases, is widely expected to halt global warming. CO₂ emissions will continue to
55 drive warming until fully balanced by active anthropogenic CO₂ removals. For practical reasons,
56 however, many greenhouse gas accounting systems allow some “passive” CO₂ uptake, such as
57 enhanced vegetation growth due to CO₂ fertilisation, to be included as removals in the definition of
58 net anthropogenic emissions. By including passive CO₂ uptake, nominal net zero emissions would not
59 halt global warming, undermining the Paris Agreement. Here we discuss measures addressing this
60 problem, to ensure residual fossil fuel use does not cause further global warming: land management
61 categories should be disaggregated in emissions reporting and targets to better separate the role of
62 passive CO₂ uptake; where possible, claimed removals should be additional to passive uptake; and
63 targets should acknowledge the need for Geological Net Zero, meaning one tonne of CO₂ permanently
64 restored to the solid Earth for every tonne still generated from fossil sources. We also argue that
65 scientific understanding of net zero provides a basis for allocating responsibility for the protection of
66 passive carbon sinks during and after the transition to Geological Net Zero.

67
68 **The Problem:** The UAE Consensus¹, agreed at the COP28 climate conference, called on Parties “to
69 achieve net zero by 2050 in keeping with the science” without specifying precisely to what net zero
70 refers.² The concept dates back to a series of papers^{3–8} in 2009 that established the cumulative impact
71 of anthropogenic carbon dioxide (CO₂) emissions on global temperatures, and the need to reduce net
72 CO₂ emissions to zero to halt global warming. This was affirmed⁹ in the Intergovernmental Panel on
73 Climate Change (IPCC)’s 5th Assessment Report (AR5) which informed Article 4.1 of the Paris
74 Agreement: “In order to achieve the long-term temperature goal set out in Article 2 (“Holding the
75 increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing
76 efforts to limit the temperature increase to 1.5°C”), Parties aim ... to achieve a balance between
77 anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of
78 this century”. This wording, the foundation of subsequent national and corporate¹⁰ net zero pledges,
79 makes clear that the purpose of “balance” is to limit global warming. The IPCC’s Special Report on
80 1.5°C (SR1.5)¹¹ stated what this entails: “Reaching and sustaining net-zero global anthropogenic CO₂
81 emissions and declining net non-CO₂ radiative forcing would halt anthropogenic global warming on
82 multi-decadal timescales (*high confidence*)”, reaffirmed by subsequent research^{12,13} and the IPCC 6th
83 Assessment (AR6).^{14–16}

84
85 It is, however, increasingly clear that many current interpretations of net zero CO₂ emissions, if
86 applied globally, are not consistent with the goal of halting the rise in global temperatures.^{17–19} The
87 problem is ambiguity in the definition of anthropogenic CO₂ removals (called “removals” for brevity
88 hereon). The definition of removal used in IPCC Scientific Assessments²⁰ explicitly “excludes natural
89 CO₂ uptake not directly caused by human activities” (here we use IPCC Scientific Assessment
90 definitions²⁰ unless otherwise specified). Yet methods used by many greenhouse gas reporting
91 systems, including those informed by the IPCC guidelines for national greenhouse gas inventories
92 (NGHGs),²¹ implicitly allow indirect or passive uptake (so-called because it is occurring as a
93 consequence of past emissions and not as a result of active ongoing human intervention) to be classed
94 as a removal if it takes place on “managed land”.^{22–24} The concept of managed land was originally
95 introduced, in part, because differentiating between active land-based removal of atmospheric CO₂
96 and passive CO₂ uptake²⁵ requires modelling a counterfactual i.e. what would have happened if the
97 action leading to a claimed land-based removal had not occurred? This cannot be inferred from
98 observations alone. Model-based approaches²³ allow a global mapping between different removal
99 classification systems, but ambiguities remain, such as the classification of ongoing regrowth
100 following reforestation. As pressure to reduce net emissions rises, more land may be deemed
101 managed, reclassifying passive uptake as active removal. Already, not all claimed land-based CO₂
102 emission reductions²⁶ and removals²⁷ are verifiably additional to what would have occurred without
103 any active human intervention. These problems are compounded by the risk of terrestrial carbon
104 stocks being re-released through Earth system feedbacks. Similar problems may arise in the future
105 with an increased focus on “blue carbon”³¹ uptake by the oceans.

106

107 Hence, under the Global Stocktake,¹ pathways to net-zero are determined by models that use a narrow
 108 definition of CO₂ removals, excluding²⁰ all passive uptake, yet countries³² and corporations^{10,27}
 109 typically assess their progress using the broader NGHGI definition, which includes some passive
 110 uptake. If the definition of anthropogenic removals includes passive uptake then nominal “net zero”
 111 CO₂ emissions could fail to halt global warming in time to deliver the goals of the Paris Agreement.
 112

113 **Scientific context:** CO₂-induced warming ΔT_{CO_2} over a multi-decade time-interval Δt (such as 2025-
 114 2050, or 2050-2100) is, to a good approximation, given by¹⁸

$$115 \Delta T_{\text{CO}_2} = \kappa_E [E_{\text{GEO}} + E_{\text{LUC}} + (\rho_F - \rho_E)G] \Delta t . \quad (1)$$

116
 117 The variables, affected by policy, are E_{GEO} , the average global net rate of geological-origin CO₂
 118 emissions over that time-interval (total CO₂ produced from fossil fuels and industrial processes minus
 119 CO₂ captured at source or recaptured from the atmosphere and committed to permanent geological
 120 storage, in billions of tonnes per year); E_{LUC} , the net biogenic CO₂ emissions that result from ongoing
 121 direct anthropogenic land-use change (e.g., active deforestation, afforestation, reforestation and
 122 ecosystem restoration, including coastal habitats^{33,34}), but not including passive (indirect) uptake
 123 driven by past emissions³⁵ (including CO₂ fertilisation of existing forests as well as temperature,
 124 precipitation, and growing season effects); and G , cumulative net CO₂ emissions that have resulted
 125 directly from all human activities from pre-industrial times up to the mid-point of the time-interval in
 126 question, in billions of tonnes. Total human-induced warming comprises ΔT_{CO_2} plus non-CO₂
 127 warming (see Methods).
 128
 129

130 The coefficients, not affected by policy, are κ_E , the Transient Climate Response to Emissions
 131 (TCRE)^{8,20}; ρ_F , the fractional Rate of Adjustment to Constant Forcing (RACF)^{18,36,37}; and ρ_E , the
 132 Slow Carbon-cycle Adjustment Rate¹⁸ or the fractional rate of CO₂ radiative forcing²⁰ decline under
 133 zero emissions.^{38,39} Both rates are approximately 0.3% per year.^{16,40} Equation 1 reproduces, within
 134 uncertainties due to internal climate variability, the response of coupled climate-carbon-cycle models
 135 to a broad range of emissions scenarios up to the time of peak warming.¹³ Limiting CO₂-induced
 136 warming, or reducing ΔT_{CO_2} to zero, is necessary to halt total greenhouse-gas-induced global warming
 137 on multi-decadal timescales, while reductions in other greenhouse gas emissions are also required to
 138 meet Paris temperature goals. Henceforth, net zero refers to net zero CO₂ emissions unless specified
 139 otherwise.
 140

141 The first insight of the 2009 papers was that κ_E is largely time- and scenario-independent,^{9,15,41-43} so
 142 that cumulative CO₂ emissions since pre-industrial times determine the level of CO₂-induced
 143 warming.⁴⁴ The second was that $\rho_E \approx \rho_F$, so the difference between them, or Rate of Adjustment to
 144 Zero Emissions,^{13,18} is approximately zero.¹² This cancellation means that no substantial further CO₂-
 145 induced warming or cooling of the climate system will occur as long as $E_{\text{GEO}} + E_{\text{LUC}} = 0$. These two
 146 findings give “net zero” its force: achieving net zero CO₂ emissions, in this sense, is approximately
 147 sufficient to halt CO₂-induced warming under ambitious mitigation. More complex behaviour⁴² may
 148 emerge at much higher levels of warming or much longer timescales.⁴⁵
 149

150 The $\kappa_E(\rho_F - \rho_E)G\Delta t$ term in equation 1 represents two mutually cancelling processes: a thermal
 151 adjustment (ρ_F) and a carbon cycle adjustment (ρ_E). If emissions are only reduced to the level
 152 required to stabilise CO₂ concentrations, such that $E_{\text{GEO}} + E_{\text{LUC}} \approx \rho_E G$ over a multi-decadal period,
 153 then CO₂-induced warming would continue at a rate $\rho_F \kappa_E G$, or about 0.45°C per century if
 154 concentrations are stabilised when temperatures reach 1.5°C (dotted scenario in fig 1 and Extended
 155 Data Fig. 1 a-c). This situation would correspond to all passive CO₂ uptake being included in net zero
 156 calculations. Temperatures would eventually converge to a level determined by the Equilibrium
 157 Climate Sensitivity (ECS),^{5,36,37} but the range of uncertainty and especially the risk of a high ECS
 158 remains contested.^{36,46-49} Even if atmospheric concentrations were stabilised immediately, the most
 159 likely eventual warming would still exceed 2°C,⁵⁰ so simply reducing the net flow of CO₂ into the
 160 atmosphere to zero is not sufficient to limit warming to below 2°C.

161
162 If, however, CO₂ emissions directly resulting from ongoing human activity are reduced to net zero
163 ($E_{\text{GEO}} + E_{\text{LUC}} = 0$) then CO₂-induced radiative forcing declines at a fractional rate ρ_E over the
164 following decades (solid scenario in fig 1 and Extended Data Fig. 1 d-f) because of ongoing passive
165 uptake of atmospheric carbon by the oceans and biosphere in response to historical emissions.^{12,13}
166 This durable component of passive uptake would continue for many decades even if all human
167 activity were to cease (conversely, if activity continues, measures may be required to protect it). There
168 is no fundamental reason why $\rho_E = \rho_F$,⁵¹ but current best estimates of the difference between them
169 are of order 0.1% per year.¹³
170

171 Although the dominant drivers of terrestrial CO₂ uptake are sometimes contested, its overall scale is
172 not. Active net land-use emissions release about 5 GtCO₂ per year into the atmosphere, comprising 7
173 GtCO₂ per year from deforestation plus 2 GtCO₂ other land cover change minus about 4 GtCO₂ per
174 year due to forest regrowth from past disturbances.⁵² In comparison, the current passive land carbon
175 sink is about 12 GtCO₂ per year, estimated from vegetation models, atmospheric inversions, or a
176 simple closure of the global carbon budget.^{15,52} How much of this passive land sink is due to CO₂
177 fertilisation versus other drivers is poorly constrained. The impact of forest demographics, partly an
178 active driver, may be underestimated,⁵³ which would affect the future of the land sink (demographic
179 changes may saturate sooner than CO₂ fertilisation). Multiple lines of evidence, however, suggest that
180 CO₂ fertilization is likely the single most important driver.⁵⁴ When this is added to other passive
181 drivers (temperature and/or precipitation changes, and the passive component of forest regrowth), it
182 becomes likely that the large majority of the global net sink on managed land, as reported in NGHGI
183 and accounted as negative emissions towards countries' emission targets, is passive.
184

185 Figure 1 shows a stylized scenario (solid black lines) of global CO₂ emissions, $E_{\text{GEO}} + E_{\text{LUC}}$, reduced
186 to net zero in 2050, following the definitions used in those 2009 papers and subsequent IPCC
187 Assessment Reports, hence not including any net passive uptake (solid green lines) in CO₂ removals.
188 This results in CO₂ concentrations peaking before 2050 and declining thereafter, stabilizing global
189 temperatures.⁵⁵ Dotted lines show a concentration stabilization scenario in which the net
190 anthropogenic flux of CO₂ into the atmosphere (i.e. the difference between net emissions due to
191 ongoing human activities, dotted grey line in panel a, and net passive uptake in response to historical
192 emissions, or dotted green line) is reduced linearly to zero in 2050 and maintained at zero thereafter.
193 This is sufficient to stabilize atmospheric concentrations but does not halt global warming for many
194 centuries. The dashed lines show a hypothetical “extreme offsetting” scenario in which all passive
195 uptake on land and oceans is progressively re-classified as anthropogenic removals (green shaded area
196 in panel a) and used to offset ongoing emissions to the maximum extent possible to avoid actual
197 emission reductions or active removals. This allows $E_{\text{GEO}} + E_{\text{LUC}}$ to remain constant past the mid-
198 2030s while nominal emissions, including these offsets, appear to follow the same anthropogenic net-
199 zero pathway as the black solid line. This illustrates the danger of including passive sinks in the
200 definition of net emissions without revisiting climate targets accordingly.²³ Even in the absence of any
201 uncertainty in the climate response, ambiguity in the definition of removals could make the difference
202 between achieving the goals of the Paris Agreement and failing to do so.²⁴
203

204 [Insert figure 1 here]

205
206 If natural systems were to fail to provide the ecosystem service represented by the $\rho_E G$ term in
207 equation 1, due to Earth system feedbacks or other stresses,²⁸ $E_{\text{GEO}} + E_{\text{LUC}}$ would need to be further
208 reduced to $-\rho_F G$ to prevent further warming. This “equivalent removal” rate is substantial: 0.3% of
209 total historical CO₂ emissions consistent with a peak warming between 1.5 and 2°C (2900-3700
210 GtCO₂) is 9-11 GtCO₂ per year.⁵² The actual rate of passive CO₂ uptake in the decades after the date
211 of net zero (solid green line in figure 1a) would be about half this equivalent removal rate because
212 active removal of two tonnes of CO₂ is required to reduce the amount of CO₂ in the atmosphere by
213 one tonne.⁵⁶ Passive CO₂ uptake plays a bigger role in mitigating the warming impact of ongoing
214 emissions before net zero is achieved, and a smaller role as the carbon cycle begins to re-equilibrate.
215 Yet its continued existence, and the fact that it is not included as a removal in the definition of net

216 anthropogenic emissions, are both essential conditions for net zero CO₂ emissions to halt CO₂-
217 induced warming on multi-decadal timescales. Both conditions are potentially at risk.

218

219 **Emerging risks to Net Zero:** The first, unavoidable, risk is that Earth system feedbacks such as
220 carbon release from thawing permafrost,⁵⁷ drying of some wetlands or increased forest fire activity^{28,30}
221 could compromise the net magnitude of biosphere carbon sinks, weakening passive uptake. This effect
222 is partially accounted for by the use of a constant TCRE, which implies some increase in CO₂
223 airborne fraction²⁰ with cumulative CO₂ emissions cancelling the logarithmic dependence of radiative
224 forcing on CO₂ concentrations.^{42,51,57,58} Even models that represent the full range of Earth system
225 feedbacks find that this cancellation approximately holds up to 2°C of warming,⁵⁹ but it becomes
226 progressively less certain at higher warming levels¹⁵ and for “overshoot” scenarios.⁶⁰ Ultimately, the
227 only way to minimise the amplifying effect of Earth system feedbacks is to minimise peak warming.
228 Measures to protect and restore the integrity of biosphere sinks must therefore be additional, not
229 alternatives, to measures that reduce E_{GEO} and E_{LUC} . Ongoing fossil fuel emissions and deforestation
230 put all carbon stored in the biosphere at risk.⁶¹

231

232 The second “risk” (or moral hazard) arises from policy choices rather than geophysical processes, but
233 is real nonetheless: unlike the global earth system models and integrated assessment models that
234 inform IPCC Assessment Reports,²⁰ greenhouse gas accounting systems, including systems based on
235 NGHGs²² and most corporate systems, classify passive uptake that takes place on “managed land”²³
236 as an anthropogenic greenhouse gas removal.⁶² At present, over 6.5 billion tonnes of CO₂ per year,⁶²
237 or about 60% of total terrestrial carbon uptake,⁵² predominantly resulting from passive uptake by
238 standing forests, are classified as CO₂ removals in national inventories.²³ Most countries define all
239 their forests as managed for UNFCCC. These accounting systems include this passive uptake in E_{LUC} ,
240 making it available to offset ongoing fossil fuel emissions (Fig. 1, panel a). Indeed, some countries
241 have used it to declare themselves net zero already.¹⁰

242

243 These differences in how removals are defined between national inventories and global net zero
244 pathways are well documented, including by the IPCC.^{22–24,62} Although UNFCCC inventory
245 guidelines^{21,63,64} consider all removals on any land declared as managed to be human-induced (i.e.
246 active), there is potential to add information to NGHGs, including CO₂ uptake on unmanaged land,⁶⁵
247 that would help countries understand better the magnitude of active and passive components of their
248 carbon sinks. The availability of this information would make it even more important that the
249 implications of including passive sinks in emissions targets are understood. It has therefore been
250 argued^{23,24,62} that net emissions in scenarios and targets should be translated to the NGHGI approach
251 using Dynamic Global Vegetation Models (DGVMs) to include CO₂ uptake on managed lands
252 explicitly in calculations of E_{LUC} , despite inter-DGVM differences.³⁵ In ambitious mitigation scenarios
253 the necessary adjustments are small (less than 20%)^{23,24} relative to required emission reductions
254 because only about half to two-thirds of terrestrial carbon uptake is currently classified as taking place
255 on managed land and passive uptake is expected to decline as emissions fall.¹⁵ Hence, if ambitious
256 mitigation occurs, ambiguity over passive carbon sinks has an important but limited impact on
257 allowable emissions at a global level,^{23,24} although potentially a much bigger impact at the level of an
258 individual country or corporation.

259

260 The real problem, however, is that ambiguity in the classification of passive CO₂ uptake may forestall
261 mitigation getting started. Pressure to classify land as managed (which countries self-determine) will
262 increase as climate policy requires stronger reductions in net CO₂ emissions. Rising effective carbon
263 prices increase incentives to monetise all allowable CO₂ removals. The vast majority of countries⁶²
264 already use their managed land sink to assess compliance with emission reduction targets under the
265 Paris Agreement, even though the Kyoto Protocol attempted to limit^{66,67} such use. There is also
266 increasing interest in monetising “blue carbon” uptake by the oceans.³¹ If all passive uptake were
267 claimed as CO₂ removal, then nominal “net zero CO₂ emissions” would imply only a net zero
268 atmospheric CO₂ growth rate, or $E_{GEO} + E_{LUC} - \rho_E G = 0$ on multi-decadal timescales. This would
269 stabilise CO₂ concentrations, which is sufficient to slow further global warming but would not halt it
270 for centuries. This may seem an extreme scenario (dashed lines in Fig. 1), but it is impossible to

271 predict how accounting conventions will respond to very high effective global carbon prices
272 associated with ambitious mitigation. A coastal or island state could argue it has a right to take credit
273 for passive uptake into the oceans of its exclusive economic zone (EEZ) if other countries take credit
274 for passive uptake into their forests. EEZs account for 30% of global ocean area and an uncertain (but
275 estimable) fraction of ocean carbon uptake.⁶⁸ Credits are already being sold for carbon capture into
276 the open oceans without clear standards to ensure additionality,⁶⁹ raising the prospect of all ocean
277 passive carbon uptake being claimed as removals, as has already occurred in many regions on land.

278
279 **How did this situation arise?** Passive CO₂ uptake was not classed as anthropogenic CO₂ removal in
280 the 2009 papers that established the need for net zero. While the potential role of, and challenge of
281 quantifying, land-based removals had long been acknowledged,⁷⁰ those original papers equated zero
282 CO₂ emissions with $E_{\text{GEO}} + E_{\text{LUC}} = 0$ and did not even envisage a substantial negative E_{LUC}
283 compensating for ongoing fossil fuel emissions. The only compensatory mechanism considered at that
284 time for residual fossil use was engineered CO₂ capture (or recapture from the atmosphere) and
285 geological storage.⁷¹⁻⁷³

286
287 The emphasis on global “net” emissions emerged in the Synthesis Report of the IPCC 5th Assessment
288 (AR5)⁷⁴, but still did not include passive uptake and envisaged a limited role for negative E_{LUC} : figure
289 SPM.14 of that report shows approximately zero net agriculture, forestry and other land-use
290 (AFOLU) emissions in the majority of technology-neutral mitigation scenarios likely to limit
291 warming to 2°C. Scenarios limiting warming closer to 1.5°C⁷⁵ rely more on negative net AFOLU
292 emissions but this reliance may be inconsistent with assumed bioenergy use,⁷⁶ other sustainable
293 development goals^{77,78} and even international law⁷⁹. This exclusion of passive uptake and limited role
294 for E_{LUC} propagated into the Structured Expert Dialogue (SED)⁸⁰ that informed the Paris Agreement.
295 Annex II, paragraph 69, states: “...if we stop emissions today entirely, there will be no further
296 warming. Essentially, the commitment to future warming is in future emissions. A stable
297 concentration, however, will result in further warming.” Crucially, these first two sentences are only
298 true if passive uptake is not classified as a CO₂ removal, while the final sentence makes clear that
299 SED participants were aware of the importance of the difference between net zero emissions and net
300 zero atmospheric CO₂ growth rate.

301
302 Article 4 of the Paris Agreement⁸¹ does not specify precisely what is included in “removals by sinks”.
303 While it builds on inventory guidelines used under the UNFCCC and Kyoto Protocol, which treat all
304 carbon stock changes on managed lands as anthropogenic and hence include some passive uptake in
305 removals, Article 4 also makes clear that its objective is to deliver Article 2. If “removals” were, in an
306 extreme case, to include all passive uptake, then achieving the “balance” of Article 4 would imply
307 only a stabilization of atmospheric CO₂ concentrations (dotted and dashed scenarios in Fig. 1). This
308 would not halt ongoing warming in time to deliver the goal of Article 2, as was made clear in the
309 SED. Hence only a restrictive definition of “removals” that excludes passive (indirect) sinks renders
310 the Paris Agreement’s long-term temperature goal (Art. 2.1a) and the implementing objective (Art.
311 4.1) jointly consistent with the underlying climate science as it has been understood since 2009.

312
313 **Scale of the problem:** Figure 2 shows fluxes of CO₂ into and out of the atmosphere under a range of
314 scenarios. Panel a shows the current situation, with fossil CO₂ emissions and active land-use-change,
315 E_{GEO} and E_{LUC} , only partially compensated for by passive uptake by land and ocean sinks, leading to a
316 net accumulation of CO₂ in the atmosphere. All panels illustrate the breakdown of fluxes used in the
317 2009 papers, in equation 1, and by IPCC Assessment Reports. Under the breakdown used by
318 NGHGs, 6-7 GtCO₂/year of the passive land sink in panel a would be reallocated to E_{LUC} , reducing it
319 close to zero.

320
321 [Insert figure 2 here]

322
323 Panel b shows the fluxes implied by an instantaneous reduction of fossil fuel emissions by 40-50%
324 and full compensation of ongoing land-use change emissions with active land-based CO₂ removal.
325 Atmospheric CO₂ growth rate (pale blue bar) would be reduced to net zero, albeit only momentarily.

326 While the rate of passive uptake would start to decline as soon as CO₂ concentrations stop rising,⁵⁶
327 this scenario is relevant to net zero claims by sub-global entities, both countries and corporations.
328 Current accounting rules allow an entity to offset its ongoing emissions against carbon uptake on
329 managed land, including passive uptake. If all passive uptake were classed as a removal, almost 50%
330 of global emissions could be fully offset, allowing the entities responsible for them to declare they had
331 achieved net zero⁸² without reducing active emissions at all. If remaining emitters then chose not to
332 participate in mitigation (plausible, given “ambitious” countries and corporations would be doing
333 nothing more than offset their emissions against uptake that is occurring anyway), this situation could
334 persist indefinitely.

335
336 If the instantaneous balance shown in panel b were achieved globally, passive CO₂ uptake would
337 decline over the following decades, but emissions would not need to decline all the way to zero to
338 stabilize atmospheric CO₂ concentrations (panel c, and dotted scenario in fig. 1). Temperatures would
339 continue to rise at the RACF, ρ_F . To halt global warming, excess atmospheric CO₂ concentrations
340 must be allowed to decline by ρ_F , or 0.3% per year (panel d), corresponding to a total absolute uptake
341 rate (rate of decrease of atmospheric CO₂ content through both passive uptake and net negative
342 emissions) of about 5 GtCO₂/year for peak warming in the range 1.5-2°C.⁵⁶ In current Earth System
343 Models $\rho_E \approx \rho_F$ so it is sufficient to reduce $E_{\text{GEO}} + E_{\text{LUC}}$ to net zero to achieve this, but the required
344 rate of CO₂ decline is set by the need to balance the thermal adjustment, independent of carbon cycle
345 uncertainties. If current models overstate the scale of passive uptake, then $E_{\text{GEO}} + E_{\text{LUC}}$ would need to
346 be net negative to stabilise global temperatures.

347
348 Over decades, the scope for maintaining a substantial net negative E_{LUC} to balance a net positive E_{GEO} ,
349 as in panel d, is limited by earth system feedbacks,²⁸ the need to balance emissions associated with
350 food production,⁷⁷ and, possibly, the need to compensate for weaker-than-expected passive uptake.
351 Hence, a durable net zero (panel e and solid scenario in Fig. 1) is likely to require¹⁷ that any remaining
352 fossil-origin CO₂ production is balanced by CO₂ capture or recapture and geological-timescale
353 storage, meaning secure storage over multi-century to millennial timescales without ongoing human
354 intervention. Current evidence suggests that well-managed geological sequestration can meet this
355 standard.⁸³ Options such as biochar or biomass burial would need to demonstrate a similar level of
356 security and durability. So only panel e represents a durable halt to global warming but, if all passive
357 uptake including blue carbon is treated as an anthropogenic removal, then all four of panels b to e
358 could be regarded as some kind of net zero CO₂ emissions.

359
360 **Moving forward:** It is difficult to justify definitions of balance and net zero in individual
361 commitments that, if replicated globally, would not deliver the Paris Agreement goal of limiting
362 global warming. Yet²³ it will also be difficult to revise UNFCCC reporting rules to exclude all passive
363 CO₂ uptake from anthropogenic CO₂ removals. There are genuine issues of capacity, resources and
364 pragmatism in bringing all countries on board with reporting and accounting following IPCC
365 Guidelines. Furthermore, many countries are relying on passive uptake to contribute to their emission
366 goals and may object to its exclusion from international transfers under Article 6 of the Paris
367 Agreement. Care must also be taken not to jeopardise other benefits of reforestation, such as for
368 biodiversity.³³ There are, however, some measures that can be taken to mitigate the problem.

369
370 First, we need wider acknowledgement across both science and policy communities that the problem
371 exists: achieving and maintaining ‘net zero’ emissions under accounting rules that allow passive CO₂
372 uptake to count as CO₂ removal will only slow down global warming. UNFCCC reporting is separate
373 from target-setting: while countries should be encouraged to report emissions and CO₂ uptake on
374 managed land, they do not need to treat these “biological” removals as fungible with “geological”
375 fossil fuel emissions in climate targets.³² Indeed, accounting methods used by the Kyoto Protocol
376 discouraged this.⁶⁷ Accounting under the Global Stocktake and under Article 6 of the Paris Agreement
377 should learn from and improve on the Kyoto Protocol approaches to try to separate out what is
378 “additional” (the result of direct anthropogenic activity) in reported removals.²⁷ A global effort to
379 report passive CO₂ uptake separately⁶⁵ in greenhouse gas inventories, analogous to separate
380 specification of short-lived climate pollutants,⁸⁴ would help. Discussions have already begun between

381 modellers and inventory compilers on this issue,^{62,77} including in the context of the 2024 IPCC Expert
382 Meeting on Reconciling Land Emissions, and will continue in the 7th Assessment Report. At the same
383 time, countries could be encouraged to document in more detail how passive CO₂ uptake is included
384 in their approaches to reporting and setting their Nationally Determined Contributions.²⁴ Such
385 transparency would allow an assessment of the scale of the problem, and whether it may be increasing
386 as climate ambition strengthens. It is arguably also in countries' long-term interest to acknowledge the
387 contribution of passive uptake to their emission goals because, unlike emission reductions or active
388 removals, passive uptake is contingent on other countries' mitigation decisions: as soon as global CO₂
389 emissions start to fall, the rate of uptake in most passive sinks will fall in response.²³

390
391 Second, voluntary markets, standard-setters and ambitious countries and corporations can go beyond
392 the current UNFCCC requirements and exclude passive or indirect uptake from removal credits and
393 net zero claims. For example, if the CO₂ flux into an ecosystem is claimed to be net zero, then the
394 land occupied by that ecosystem should absorb CO₂ at the same average multidecadal rate that an
395 unmanaged ecosystem would given current conditions (location and maturity, level and recent rate of
396 increase in atmospheric CO₂ concentrations, climate and so on). This rate can either be calculated
397 with a vegetation model or inferred from observations of similar regions: such methods are already
398 used²⁶ to assess the extent to which claimed emission reductions are additional to processes that
399 would have occurred in the absence of an intervention. Even if passive uptake can be quantified and
400 excluded from claims at an individual project level, however, carbon leakage means that a clear
401 separation is likely to remain challenging as long as reporting systems are still in widespread use that
402 allow it to count as a removal.⁸⁵

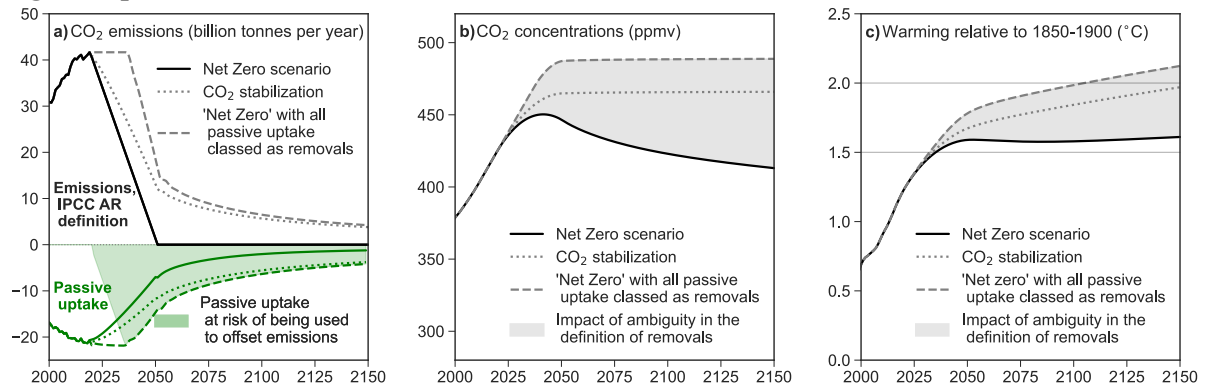
403
404 Finally, much of the remaining carbon-absorbing capacity of the biosphere may be required to
405 compensate for emissions associated with food production, such as fertilizer production and use,
406 particularly if biological carbon sinks are compromised by climate change itself.^{28,86,87} Until it can be
407 shown that total CO₂ uptake by the biosphere and oceans is large enough to halt CO₂-induced
408 warming, it is dangerously optimistic to assume that there will be additional capacity for a negative
409 E_{LUC} to compensate substantially for ongoing fossil fuel emissions.^{13,88} Hence, the third and most
410 important measure is to recognise the likely long-term infeasibility of balancing substantial ongoing
411 net positive geological-origin CO₂ emissions with enhanced carbon uptake in the biosphere and
412 oceans that is genuinely additional to the passive uptake that is already required for net zero emissions
413 to halt warming. All entities committed to the long-term temperature goal of the Paris Agreement
414 therefore need to plan to jointly achieve global Geological Net Zero.^{13,17,18} This means either
415 eliminating fossil fuel and fossil carbonate (for cement) use entirely or achieving a balance between
416 any remaining CO₂ production from geological sources and CO₂ committed to permanent geological
417 storage, potentially as soon as mid-century. Unlike the biosphere, all significant geological sources
418 and sinks of CO₂ are unambiguously anthropogenic, clarifying emissions accounting. Acknowledging
419 the geophysical imperative of Geological Net Zero would allow countries and corporations to future-
420 proof climate mitigation strategies by planning on a progressive transition to like-for-like balancing of
421 sources and sinks¹⁷ without waiting for consensus on any change to reporting rules. Differentiating in
422 greenhouse gas accounting systems between avoided emissions, removals to temporary storage and
423 removals to permanent storage is, however, essential to track progress to Geological Net Zero.⁸⁹

424
425 **Responsibility for protection of passive sinks:** Equation 1 also makes clear the paramount
426 importance of protecting natural CO₂ sinks both during and after the transition to Geological Net
427 Zero. This will entail opportunity costs, as land or coastal oceans that could be used for food or
428 bioenergy production are allowed to absorb carbon instead, but this passive uptake cannot be used to
429 compensate for ongoing fossil fuel emissions if net zero is to achieve a durable halt to global
430 warming. Fortunately, equation 1 also suggests a possible basis for allocating these costs. To prevent
431 further warming after emissions reach net zero, annual uptake by passive sinks must be greater than or
432 equal to $\phi\rho_F G$, where ϕ is the Perturbation Airborne Fraction (see Methods).⁵⁶ This is approximately
433 0.15% of cumulative global CO₂ emissions G over the entire industrial period. Any addition to this
434 cumulative total increases the size of the passive carbon sink that must be maintained for many
435 decades after global warming has halted. Whether this causal responsibility translates into a moral or

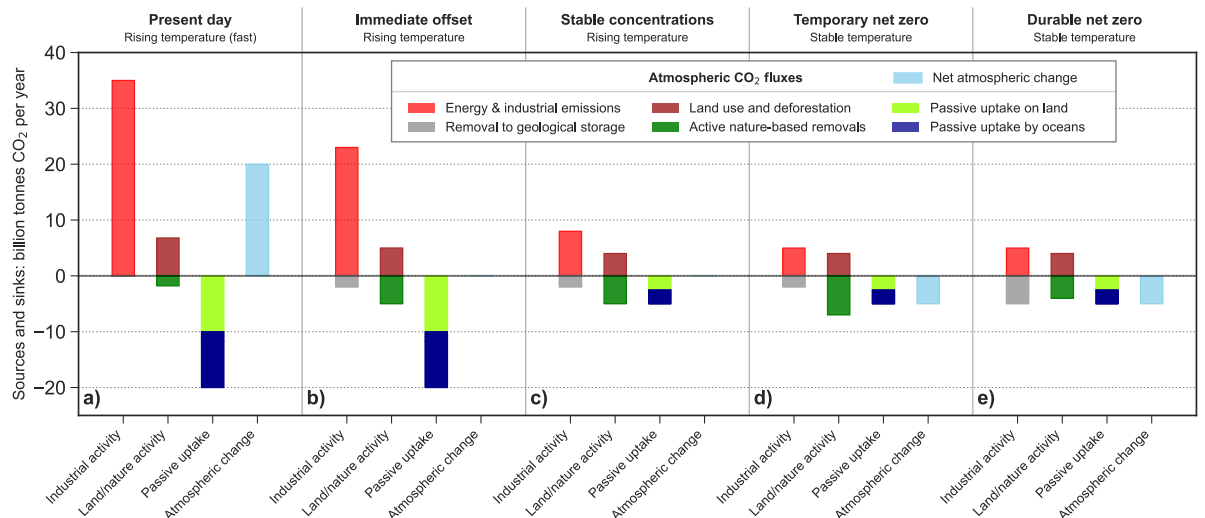
436 legal responsibility to contribute to maintaining that sink is not a scientific question, but science can
437 quantify the scale of the challenge: for example, even if the United Kingdom were to achieve net zero
438 CO₂ emissions before 2050, 0.15% of the U.K.'s contribution to historical cumulative emissions will
439 be 120 MtCO₂ per year. Should this exceed the passive sink capacity of the U.K.'s land and coastal
440 oceans,⁹⁰ then to genuinely end the U.K.'s contribution to ongoing global warming, the U.K. would
441 arguably need to undertake active CO₂ removal at approximately double ($1/\phi$) the rate of any
442 shortfall (in addition to removals to compensate for any ongoing residual emissions) or to rely on
443 passive uptake in other jurisdictions. Mechanisms for redistributing the costs of maintaining passive
444 carbon sinks after the date of net zero may therefore be needed.⁹¹ Likewise, undertakings by private
445 corporations to maintain passive carbon sinks could be seen as addressing the impact of their
446 historical cumulative emissions, not compensation for future emissions. The traditional concept of
447 historical responsibility, linking past emissions with future emission reduction rates,⁹² remains
448 complex and multi-faceted.⁹³ In contrast, the responsibility that we highlight here is a simple
449 geophysical one: by adding to cumulative emissions, any entity, country or corporation adds to the
450 total passive carbon sink that needs protection for the foreseeable future.

451
452 **Actionable implications:** Acknowledging the need for Geological Net Zero makes clear what it takes
453 for any continued fossil fuel use to be consistent with Paris Agreement goals. Offsetting emissions
454 with enhanced CO₂ uptake in the oceans and biosphere can provide immediate benefits³³ if and only if
455 it is genuinely additional to passive CO₂ uptake. In a durable net zero world, 100% of the CO₂
456 generated by any continued fossil fuel or fossil carbonate use will almost certainly need to be either
457 captured at source or recaptured from the atmosphere and committed to geological-timescale storage.
458 A commitment from high-ambition participants to report and scale up this 'geologically stored
459 fraction'⁹⁴ is needed urgently: it is currently about 0.1% globally,⁹⁵ even including CO₂ injection for
460 enhanced hydrocarbon recovery, and accelerates smoothly over time to reach 100% at the date of
461 geological net zero in cost-effective scenarios that meet the goals of the Paris Agreement.^{96,97} This
462 implies, in addition to reducing emissions, achieving a 10% geologically stored fraction by the mid
463 2030s⁹⁸ and investing now for a further ten-fold increase in stored fraction over the following 20
464 years, including demonstrating secure and verifiable geological CO₂ storage capacity to match any
465 new fossil fuel reserves. These are ambitious but achievable goals for the fossil fuel industry and its
466 customers.

467 **Figure captions:**



468
 469 **Fig 1: Impact of ambiguity in the definition of removals in net zero.** Black and grey lines in panel
 470 a show net CO₂ emissions, $E_{GEO} + E_{LUC}$, calculated using the definition of removals adopted in IPCC
 471 Assessment Reports (ARs). Green lines show corresponding passive uptake by the oceans and
 472 biosphere. Panels b and c show a central estimate⁵⁵ of the response of CO₂ concentrations and global
 473 average surface temperature assuming constant non-CO₂ forcing after 2020 (which requires
 474 immediate rapid reductions in methane emissions to compensate for other changes). Line-styles in all
 475 three panels indicate three scenarios corresponding to different interpretations of net zero. Solid lines
 476 assume net emissions are reduced linearly to zero in 2050, halting warming. Dotted lines assume net
 477 CO₂ flux into the atmosphere (net emissions minus passive uptake) is reduced linearly to zero in
 478 2050, stabilising concentrations. Dashed lines show a scenario that follows the same nominal
 479 emissions pathway as the solid scenario but assumes “reductions” are achieved as far as possible by
 480 reclassifying passive uptake (into both land and oceans) as removals and using it to offset ongoing
 481 (assumed constant) emissions.



482
 483 **Fig 2: Fluxes of CO₂ into and out of the atmosphere under different interpretations of net zero.**
 484 Red and grey bars indicate energy and industrial emissions and active removal to geological storage,
 485 which net to E_{GEO} ; brown and dark green indicate land-use-change emissions and active land-based
 486 removals (using the IPCC Assessment Report definition²⁰ of removals, including active reforestation
 487 and nature-based solutions), which net to E_{LUC} ; light green and dark blue bars indicate passive uptake
 488 by land and oceans; light blue bars indicate net rate of change in the amount of CO₂ in the
 489 atmosphere. (a) present day⁵² conditions; (b) fossil fuel emissions reduced instantaneously, but only to
 490 the level required halt the net flow of CO₂ into the atmosphere (mid-21st-century dashed scenario in
 491 fig 1); (c) emissions consistent with stable CO₂ concentrations over decades after warming reaches
 492 about 1.5-2°C (dotted scenario in fig 1); (d) emissions consistent with stable temperatures (solid
 493 scenario in fig 1), which requires ongoing passive uptake reducing atmospheric CO₂ (negative pale
 494 blue bar) but allowing some temporary compensation of geological-origin emissions with biogenic
 495 removals; (e) durable net zero, both E_{GEO} and E_{LUC} equal to zero.

496 **Methods:**

497

498 The origins of equation 1 are detailed in Ref. 18, equations 8 and 14, and summarised here. The total
 499 anthropogenic change in global average temperature over a multi-decade time-interval is given by the
 500 following generalisation of equation 1:

501

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

502

503 where $\Delta G = (E_{\text{GEO}} + E_{\text{LUC}})\Delta t$ is the total CO₂ emitted or actively removed by human activities over
 504 the time-interval Δt , G is cumulative CO₂ emissions from pre-industrial to around the middle of that
 505 time-interval, ΔF is the change in, and F is the average, net non-CO₂ radiative forcing, also over that
 506 time-interval. The Transient Climate Response to Emissions²⁰ (TCRE) $\kappa_E = 0.45(\pm 0.18)$ °C per 1,000
 507 GtCO₂,¹⁴ while $\kappa_F = 0.49(\pm 0.1)$ °C per Wm⁻² is the Transient Climate Response to Forcing, or the
 508 Transient Climate Response²⁰ (TCR) divided by the radiative forcing due to a doubling of
 509 atmospheric CO₂ concentrations. The $\kappa_F\Delta F$ term represents the fast component³⁶ of the response to
 510 radiative forcing (defining ΔF as the difference between the decade prior to the beginning and the
 511 decade prior to the end of the time-interval accounts for sub-decadal adjustments), while $\kappa_F\rho_FF\Delta t$
 512 represents the gradual adjustment to a constant forcing.³⁷ Hence the Rate of Adjustment to Constant
 513 Forcing¹⁸ (RACF) $\rho_F = (\text{ECS} - \text{TCR})/(\text{TCR} \times s_2)$, or about 0.3% per year,⁴⁰ where ECS is the
 514 Equilibrium Climate Sensitivity, and s_2 the multi-century adjustment timescale associated with
 515 warming of the deep oceans³⁶ and the evolution of feedbacks as the climate system re-equilibrates.⁴⁶
 516

517

518 The $\kappa_E\Delta G$ term in equation 2 represents the familiar cumulative impact of CO₂ emissions on global
 519 temperature while the $\kappa_E(\rho_F - \rho_E)G\Delta t$ term may be understood by considering the limiting case of
 520 $\rho_E = 0$: if there were no durable component to passive uptake, and hence CO₂ concentrations and
 521 CO₂-induced forcing were to remain constant following net zero emissions, temperatures would
 522 continue to rise at a fractional rate ρ_F , or absolute rate $\kappa_E\rho_F G$, after an injection of CO₂ taking place
 523 over a time-scale shorter than ρ_F^{-1} , which is about 300 years. Studies with coupled climate-carbon-
 524 cycle models calibrated against available observations^{12,13} indicate that temperatures are actually
 525 expected to change very little after emissions reach net zero: hence $\rho_E \approx \rho_F$.
 526

527

528 We now explain the approximations behind the expressions for CO₂-induced warming in equations 1
 529 and 2. Over a decade to century time-interval Δt (not longer), the change in atmospheric CO₂ loading
 530 resulting from anthropogenic CO₂ emissions can be approximated by

531

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

532

533 ϕ being the Perturbation Airborne Fraction, or the change in ΔC_A resulting from a unit increase in ΔG
 534 over that period.⁵⁶ Unlike the instantaneous airborne fraction, $\Delta C_A/\Delta G$, which necessarily becomes
 535 undefined as $\Delta G \rightarrow 0$, ϕ can remain close to its historical value (approximately 50%) even in
 536 ambitious mitigation scenarios. Similarly, on these timescales, the externally-driven change in global
 537 mean surface temperature is approximately

538

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

539

540 where ΔF_{tot} and F_{tot} are, respectively, the change in and average level of total radiative forcing from
 541 all sources.^{36,37} For CO₂-induced radiative forcing, $\Delta F_{\text{CO}_2} = \alpha\Delta C_A$, where α is the radiative efficacy in
 542 Wm⁻² per additional billion tonnes of CO₂ in the atmosphere. For emissions concentrated into a time
 543 much less than ρ_E^{-1} (as is the case for the historical record), the second term on the right-hand side of
 544 equation 3 is small, so $F_{\text{CO}_2} = \alpha\phi G$. Neither α nor ϕ is constant, but the non-linearities cancel, such
 545 that $\alpha\phi$, the change in radiative forcing on decade to century timescales per tonne of CO₂ emitted, is
 546 approximately constant. Substitution of equation 3 into equation 4 and introducing $\kappa_E = \alpha\phi\kappa_F$ yields
 547 the expression for CO₂-induced warming in equations 1 and 2.
 548

549

550 Equation 2 also implies that, before emissions reach net zero, total passive CO₂ uptake by both
 551 terrestrial biosphere and oceans consists of a transient component (driven by redistribution of recent
 552 emissions into rapidly-equilibrating carbon reservoirs) and a durable component that is, on multi-
 553 decade timescales, proportional to cumulative emissions since pre-industrial:¹⁸

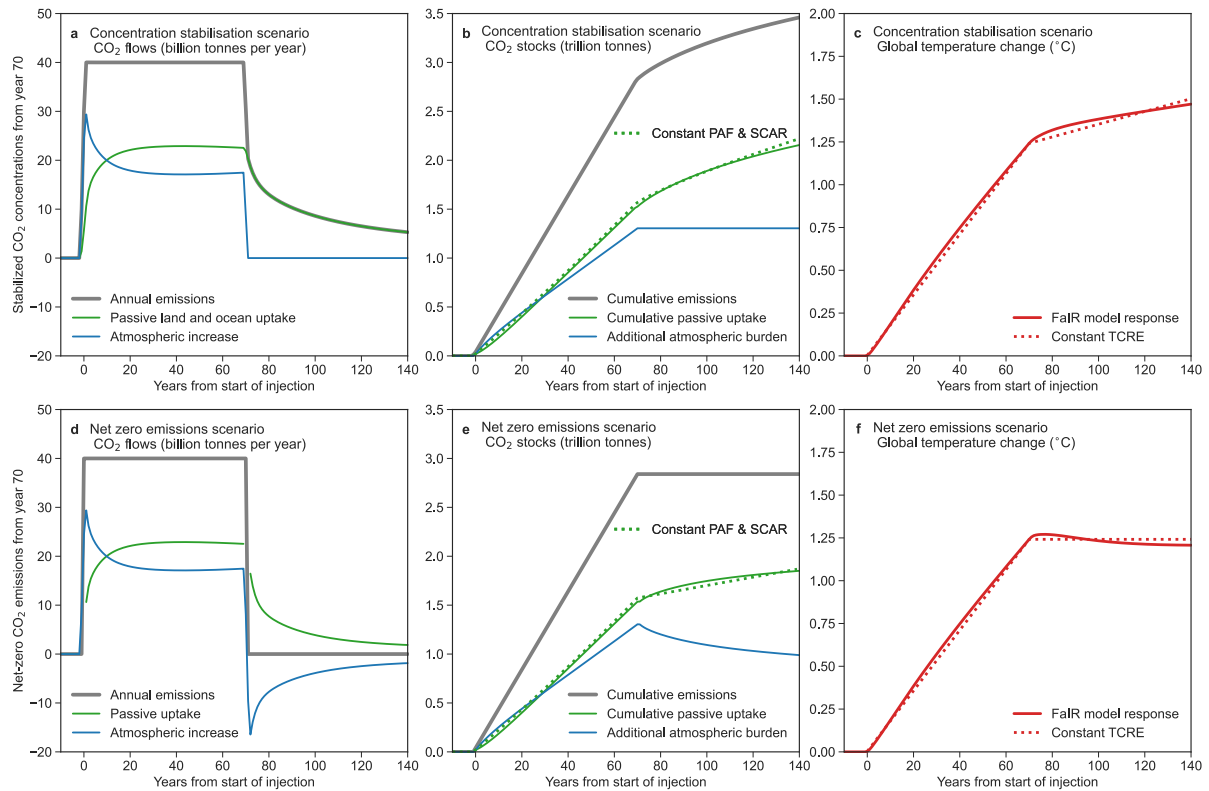
$$554 \quad \Delta G - \Delta C_A \approx [(1 - \phi) \times (E_{\text{GEO}} + E_{\text{LUC}}) + \phi \rho_E G] \Delta t. \quad (5)$$

557 The accuracy of these approximations is illustrated in Extended Data Fig. 1 using the response of the
 558 FaIR simple climate model⁵⁵ to stylized concentration-stabilization and net zero emission scenarios,
 559 compared with the expressions for passive uptake and temperature response given by equations 5 and
 560 1, respectively. The FaIR model has been shown¹³ to be consistent with the behaviour of much more
 561 complex Earth System Models over a broad range of scenarios, so agreement with FaIR is indicative
 562 of agreement with a wider range of models.

564 Under net zero emissions, meaning $E_{\text{GEO}} + E_{\text{LUC}} = 0$, the annual rate of passive CO₂ uptake converges
 565 to $\phi \rho_E G$, which has the same impact as active removal of $\rho_E G$ GtCO₂ per year, or approximately
 566 0.3% per year of cumulative historical CO₂ emissions. Figure 2 assumes this passive uptake continues
 567 to be partitioned equally between the terrestrial biosphere and oceans, consistent with the range of
 568 results of the ZECMIP model intercomparison project (figure 8 of ref. 12). If contributions to the
 569 protection of these passive sinks were to reflect physical contributions to this committed ongoing
 570 carbon uptake, research into the geographic location of land and ocean sinks, and the evolution of
 571 both transient and durable components of passive uptake as emissions decline, is clearly a priority.⁹⁰

573 The level of CO₂-induced warming after a period of positive emissions starting from pre-industrial
 574 equilibrium is $\kappa_E G$ if and only if the time-scale over which those emissions take place is much less
 575 than $(\rho_F - \rho_E)^{-1}$. Since $\rho_F^{-1} \approx 300$ years and $\rho_E > 0$, $(\rho_F - \rho_E)^{-1}$ is of order 1,000 years.¹⁸ Hence
 576 the observation that warming is proportional to cumulative CO₂ emissions for CO₂ injections
 577 primarily taking place over a century or less (which includes the historical record and most
 578 experiments used as evidence for this cumulative impact) does not imply that net zero emissions
 579 would automatically be associated with no further warming or cooling. Likewise, if κ_E is not constant
 580 (but instead increases with G , for example), CO₂-induced warming would still remain constant under
 581 net zero CO₂ emissions provided $\rho_F = \rho_E$. The linear relationship between cumulative CO₂ emissions
 582 and CO₂-induced warming is neither necessary nor sufficient for there to be no further warming or
 583 cooling following net zero CO₂ emissions: these are independent observations, both of which are
 584 supported by modelling and observations to date.⁴⁴

585
 586 **Extended Data Figure Captions:**



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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 model⁵⁵ to an emission of 40 billion tonnes of CO₂ per year for 70 years, followed by stabilisation of atmospheric concentrations (panels a-c) or net zero ongoing emissions (panels d-f). Annual CO₂ flows are shown in panels a and d, changes in CO₂ stocks in b and e and temperature response in c and f. Grey, green and blue lines show CO₂ 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 CO₂ burden (panels d and e), stabilising global temperatures (panel f). Dotted green line shows cumulative passive CO₂ uptake $\Delta G - \Delta C_A$ predicted by equation 5 (Methods) with a constant Perturbation Airborne Fraction, PAF,⁵⁶ $\phi = 0.5$, 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.

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