Article

Temporary carbon dioxide removal to offset short-lived climate forcers

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Carbon dioxide removal (CDR) is considered for achieving the long-term temperature objectives of the Paris Agreement and national net-zero emission targets[1–5]. The durability of these CDR methods varies widely, ranging from decades to theoretically permanent[6]. Temporary CDR dominates present deployment, whereas permanent solutions face further feasibility and cost challenges at scale[1]. However, efforts to integrate temporary CDR into climate policies have relied on equivalency assumptions between temporary and permanent CDR that contradict physical climate science: temporary CDR cannot fully offset CO_2 emissions as permanent CDR can[6,7]. Here we show that temporary CDR can serve as compensation for non-CO_2 climate forcers, particularly for short-lived species whose compensation ratios are fairly insensitive to the choice of time horizon. For instance, offsetting 1 kg CH_4 requires 498 kg CO_2 with 20-year temporary storage (such as bioplastics) or 101 kg CO_2 with 100-year storage (such as durable wood products). We suggest a critical lifetime threshold separating short-lived and long-lived species for temporary CDR applications, with implementation requiring differentiated reporting of these categories. This framework can provide a physical basis for crediting temporary CDR activities in sectors such as agriculture, in which non-CO_2 emissions dominate and direct emission reductions remain challenging.

CDR is essential for achieving the long-term temperature objectives of the Paris Agreement and national net-zero emission targets, receiving increasing attention from scientists, policymakers and industry[1–5]. The durability of these CDR methods varies widely, ranging from decades to theoretically permanent sequestration[6]. However, true permanence remains challenging to achieve in practice, owing to economic and technical barriers, as well as reversal risks from land management changes and natural disturbances[8–10]. Consequently, most CDR methods in use today are inherently temporary[7,11–13]. Yet, although permanent CDR would straightforwardly integrate into climate policies as negative CO_2 emissions, temporary CDR presents far greater complexity owing to its transient nature[6]. This creates an urgent need for robust frameworks to accurately assess and integrate temporary CDR into climate policies.

Previous scientific attempts have sought to establish direct equivalency factors between temporary and permanent CDR[14–18], as also suggested in recent versions of the United Nations Framework Convention on Climate Change (UNFCCC) information note[19]. However, emerging research demonstrates that such equivalency is fundamentally flawed[6,7]. These equivalency approaches assume that temporary and permanent CDR can be used interchangeably to offset CO_2 emissions, but this assumption contradicts the physics of the climate system: CO_2-induced warming is proportional to cumulative emissions, with CO_2 persisting in the atmosphere for centuries to millennia[6,20]. Although permanent CDR reduces this cumulative burden, temporary CDR only creates transient reductions without altering long-term totals. Consequently, temporary CDR cannot offset CO_2 emissions as permanent CDR does[6,7], yet the transient nature of its climate effects suggests alternative applications within climate accounting frameworks.

Here we propose a physics-based framework to account for temporary CDR against non-CO_2 climate forcers. Our approach builds on impulse response functions (IRFs), which underpin established climate metrics such as global warming potential (GWP) and global temperature change potential (GTP) used in the Intergovernmental Panel on Climate Change (IPCC) reports[21–23] (see details in Supplementary Note 1). Using this approach, we systematically quantify compensation ratios between temporary CDR and various non-CO_2 climate forcers across different storage timescales. This foundation ensures transparency, tractability and direct compatibility with the UNFCCC, enabling immediate application in climate action.

A physics-based framework

Figure 1 illustrates our framework for assessing the potential of temporary CDR to compensate for anthropogenic non-CO_2 emissions. We illustrate it with CH_4 and N_2O owing to their substantial roles as short-lived and long-lived climate forcers, respectively. A positive pulse of CH_4 or N_2O emission (Fig. 1a) decays at different rates in the atmosphere depending on the lifetime of each species (Fig. 1b), leading to progressive global warming that is markedly different between the two species (Fig. 1c): CH_4 shows an earlier peak in induced warming

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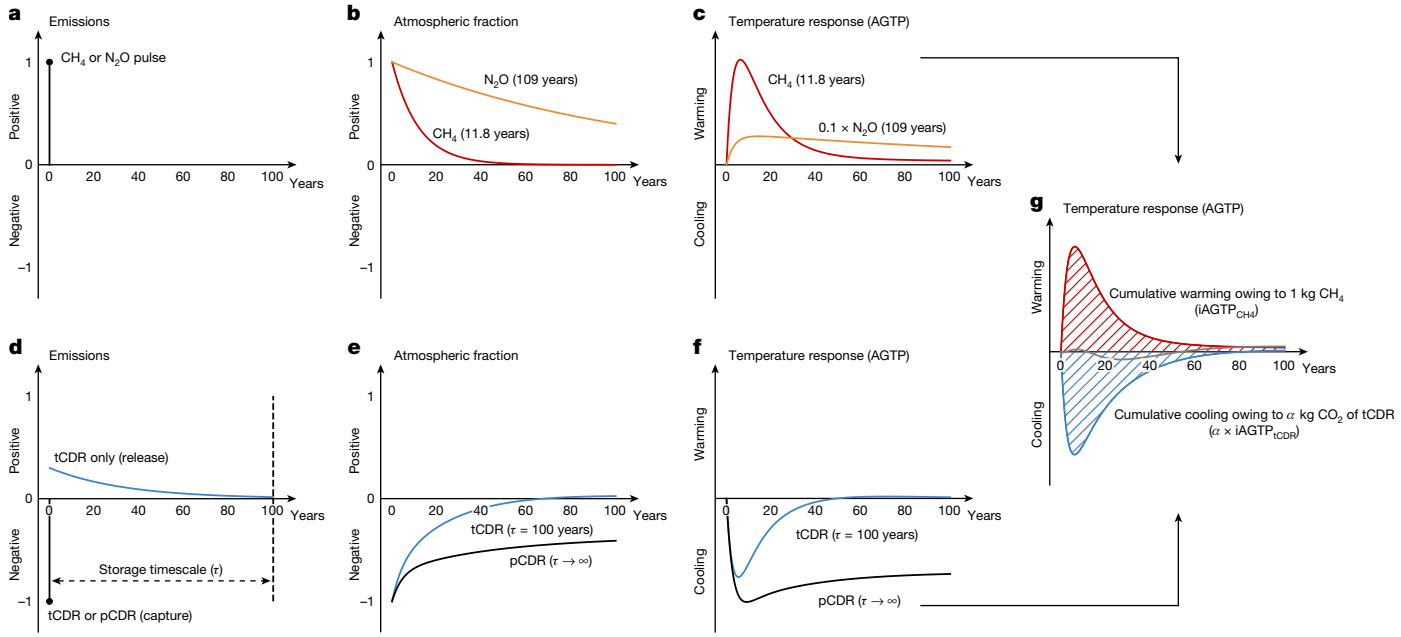

Fig. 1 | Illustration of the impacts of anthropogenic emissions and CDR strategies on temperature change. a, Positive pulse emission of CH_4 and N_2O, representing short-lived and long-lived climate forcers, respectively. **b**, Atmospheric fraction remaining after pulse emissions of CH_4 (red line) and N_2O (orange line), with their atmospheric lifetimes indicated in brackets. **c**, AGTP-based temperature response profiles for CH_4 (red line) and N_2O (orange line). **d**, CO_2 fluxes of CDR strategies. Permanent CDR (denoted pCDR) is indicated by a negative pulse emission of CO_2 (black line), representing infinite storage without release. Temporary CDR (denoted tCDR) is depicted as a two-phase process with a negative pulse (black line) for removal and an exponential decay (blue line) for release over a specified storage timescale (τ). **e**, Atmospheric fraction of CO_2 for permanent CDR (black line) and temporary CDR (blue line; over a 100-year storage timescale). **f**, AGTP-based temperature response profiles for temporary CDR (blue line; over a 100-year storage timescale) and permanent CDR (black line; over an infinite period). **g**, Comparison of the temperature responses between CH_4 and temporary CDR. The red line represents the temperature response owing to 1 kg CH_4 ($AGTP_{CH_4}$), with the shaded area illustrating the cumulative warming ($iAGTP_{CH_4}$). Similarly, the blue line represents the temperature response owing to α kg CO_2 of temporary CDR ($\alpha \times AGTP_{tCDR}$), with the shaded area illustrating the cumulative cooling ($\alpha \times iAGTP_{tCDR}$). The grey line tracks the net temperature change between $AGTP_{CH_4}$ and $\alpha \times AGTP_{tCDR}$ (Methods).

compared with N_2O, owing to a much shorter lifetime, whereas the magnitude of the warming per unit emission is mainly dictated by the radiative efficiencies of the species. As presented in Supplementary Note 1, the temperature response to a unit pulse emission of species x is the absolute GTP_x ($AGTP_x$). The time-integrated $AGTP_x$ (denoted $iAGTP_x$)[22,24,25] quantifies the cumulative warming effect over a chosen time horizon (denoted TH):

$$iAGTP_x(TH) = \int_0^{TH} AGTP_x(t)dt \quad (1)$$

In contrast to the positive pulse emission shown in Fig. 1a, temporary CDR is a two-phase process comprising the removal and the release of CO_2 across a designated storage timescale (Fig. 1d). Under this framing, permanent CDR is equivalent to temporary CDR with an infinite storage timescale. The CO_2 removal and release dynamics of the temporary CDR system can follow various trajectories, mostly dictated by the exact CDR technology considered. Here we focus on a simple representation combining a negative pulse of removal with an exponentially decaying release. This model effectively balances theoretical depth with practical applicability, as it matches the mathematical foundation of IRFs and metrics such as GWP, while describing a large range of potential temporary CDR technologies. For instance, direct air capture or annual plants can rapidly remove CO_2 from the atmosphere and, once turned into products or materials such as bioplastics[26] or biochar[27], the stored carbon typically follows an exponential decay profile of release over time. Nevertheless, other types of temporary CDR can be included in our framework by altering the time profiles (Supplementary Figs. 1 and 2).

Following carbon removal, the atmospheric CO_2 fraction decreases initially for both CDR methods but follows distinct trajectories thereafter (Fig. 1e), resulting in different temperature responses (Fig. 1f). Both methods produce an initial cooling in the years immediately following carbon removal from the atmosphere, irrespective of whether temporary or permanent. Over time, however, the climate benefits of permanent and temporary CDR diverge. Permanent CDR provides a sustained climate cooling by permanently removing carbon from the atmosphere and ensuring a lasting reduction in atmospheric CO_2 levels. Temporary CDR exhibits a transient nature: the initial cooling gradually diminishes as the stored carbon is eventually released back into the atmosphere. Although the net CO_2 fluxes within the temporary CDR system balance out to zero over time, the cumulative climate impact remains non-zero. The efficacy of temporary CDR in providing climate benefits hinges on its storage timescale: the longer the carbon is stored in the system, the larger the cumulative cooling effect achieved (Extended Data Fig. 1).

Offsetting warming with temporary CDR

Notably, we observe that the temperature response of temporary CDR intuitively mirrors that of CH_4 emission (Fig. 1g). This prompts us to define α, the ratio of cumulative warming from a pulse emission of species x over the cumulative cooling from temporary CDR (denoted tCDR):

$$\alpha(TH,\tau) = -\frac{\int_0^{TH} AGTP_x(t)dt}{\int_0^{TH} AGTP_{tCDR}(t,\tau)dt} = -\frac{iAGTP_x(TH)}{iAGTP_{tCDR}(TH,\tau)} \quad (2)$$

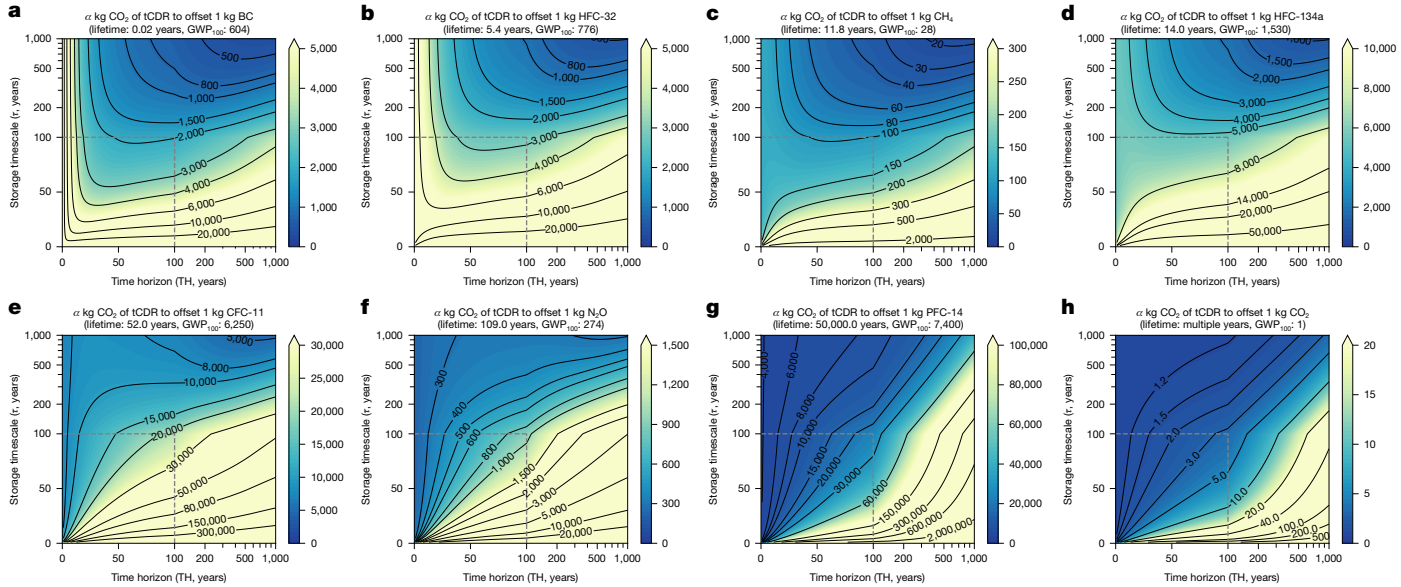

Fig. 2 | Amount of temporary CDR (α) required to offset a unit pulse emission of different species across various storage timescales (τ) and time horizons. Values of α for each species x are calculated using equation (2). The panels are arranged in ascending order of species lifetimes from panels **a** to **h** (see Table 1 for details). The scales of both axes for time horizon and storage timescale are linear between 0 and 100 and logarithmic afterwards. The GWP_{100} value is also shown in each panel title for reference.

Expressed in kg CO_2 per kg species x, α quantifies the amount of temporary CDR with storage timescale (τ) required to achieve cumulative temperature neutrality over time horizon. Annual temperature deviations may still occur and are discussed in the next section.

Figure 2 shows α for selected species x, as a function of time horizon and storage timescale, obtained using the IPCC Sixth Assessment Report (AR6) best-estimate parameters for IRFs[23] (Supplementary Tables 1–3). For a given species and time horizon, there is a clear trade-off between α and τ: the longer the captured CO_2 is stored, the larger the total cooling effect and thus the lower the amount of temporary CDR required. For instance, to offset the overall warming impact of 1 kg CH_4 within a 100-year time horizon, we would need to remove 498 kg CO_2 with a technology having a storage timescale of 20 years (such as bioplastics in industrial machinery applications[28]) or 101 kg CO_2 with a storage timescale of 100 years (such as durable wood products in residential construction[29]) (Fig. 2c and Table 1). More broadly, α differs markedly among species, reflecting their diverse atmospheric lifetimes and radiative efficiencies, which together determine cumulative climate impacts. Species with longer lifetimes and higher radiative efficiencies require larger amounts of temporary CDR for compensation.

Although our analysis also quantifies α between temporary CDR and CO_2 emissions (Fig. 2h), this relationship depends critically on the choice of time horizon, a temporal boundary beyond which impacts are ignored[11,30,31]. As the time horizon extends to infinity, balancing CO_2 emission with temporary CDR becomes unfeasible, given the permanent climate effect of CO_2 and the transient nature of that of temporary CDR (Table 1). Therefore, temporary CDR can offset CO_2 emissions within a limited time horizon but cannot do so indefinitely in the way permanent CDR can. Furthermore, this relationship (Fig. 2h) can also be viewed as an equivalency factor between temporary and permanent CDR, as permanent CDR is effectively a negative pulse of CO_2 emission. However, we do not find a single, universal equivalency factor between temporary and permanent CDR as assumed by previous studies[14–16], which confirms that, although temporary CDR does have climate benefits, its value is not interchangeable with that of permanent CDR[7]. Tonne-year accounting methods have been widely used to derive such equivalency factors; we compare our framework with these methods and demonstrate their limitations in Supplementary Note 2 and Supplementary Table 4.

Two broad patterns in the behaviour of α across climate forcers emerge. For short-lived species, the value of α remains relatively stable beyond a certain time horizon that is typically >20 years, as reflected in the flatter contours in Fig. 2. For long-lived species, by contrast, the value of α varies strongly with the time horizon, as epitomized by the case of CO_2. Table 1 shows the divergence in α between the widely used 100-year time horizon and an infinite one. This shows that the choice of time horizon is a less critical factor for short-lived species than for long-lived ones, making temporary CDR better suited for short-lived climate forcers in policy applications.

Beyond the idealized case

Our main results assume exponential carbon release from temporary CDR, as used in recent studies to approximate a variety of CDR methods[6], but other release profiles are possible, such as constant leakage from CO_2-derived biodegradable plastics or abrupt release after a fixed period (for example, sustainably harvested wood used in construction, later demolished and combusted), as illustrated in Supplementary Fig. 1. The climate impacts of these alternative temporary CDR profiles and their corresponding compensation ratios (α) are shown in Supplementary Fig. 2 and Supplementary Tables 5–7, demonstrating the broad applicability of the framework. Moreover, real-world CDR technologies may involve more complex carbon removal and release dynamics[32], as illustrated with afforestation/reforestation, which requires decades to reach peak sequestration. Integrating these complex profiles within the framework is entirely feasible but introduces further considerations as to the counterfactual profile of permanent CDR used to evaluate the efficacy of a temporary CDR technology, as shown in Supplementary Fig. 3.

As shown in equation (2), the amount of temporary CDR calculated for a given storage timescale within a chosen time horizon aims for a net-zero cumulative temperature change (that is, $iAGTP_x(TH) + \alpha \times iAGTP_{tCDR}(TH, \tau) = 0$). However, this does not inherently guarantee

Table 1 | Amount of temporary CDR (α) required to offset a unit pulse emission of different species

Species	Lifetime (years)	Radiative efficiency ($W m^{-2} kg^{-1}$)	TH=100			TH→∞		
			Bioplastics (τ=20)	Wood products (τ=100)	Biochar (τ=500)	Bioplastics (τ=20)	Wood products (τ=100)	Biochar (τ=500)
BC	0.02	2.54×10^{-9}	10,900	2,210	895	15,500	4,070	894
HFC-32	5.4	1.21×10^{-11}	13,900	2,810	1,140	19,600	5,150	1,130
CH_4[a]	11.8	2.00×10^{-13}	498	101	40.8	716	188	41.3
HFC-134a	14.0	9.24×10^{-12}	27,200	5,490	2,220	39,200	10,300	2,260
CFC-11	52.0	1.19×10^{-11}	106,000	21,400	8,660	188,000	49,400	10,900
N_2O	109	3.56×10^{-13}	4,540	918	372	11,800	3,090	680
PFC-14	50,000	6.32×10^{-12}	119,000	24,100	9,770	96,000,000	25,200,000	5,530,000
CO_2[b]	Multiple	1.71×10^{-15}	16.4	3.32	1.34	∞	∞	∞

Values of α for each species x are calculated using equation (2). Three cases of temporary CDR strategy categorized by short, medium and long storage timescales (τ), specifically bioplastics, durable wood products and biochar, are shown for illustration at two different time horizons (TH). Lifetimes and radiative efficiencies of the species are sourced from the IPCC AR6 (ref. 23) except for BC. For BC, lifetime data are taken from ref. 52 and radiative efficiency is recalculated to match the value from the IPCC AR6 for aerosol–radiation interactions only. The amount of temporary CDR is rounded to three significant figures for clarity. [a]Values for CH_4 do not account for the oxidation or biogenic correction; see Supplementary Fig. 8 and Supplementary Table 9 for the amount of temporary CDR required to offset CH_4 from fossil fuel sources and biogenic sources. [b]For CO_2, the decay of a CO_2 pulse has a non-zero asymptote, so integrating its AGTP over an infinite time horizon yields an infinite result, making the calculation of a finite amount of temporary CDR for CO_2 impractical (indicated as ∞ in the table).

a net-zero temperature change on an annual basis (that is, $AGTP_x(t) + \alpha \times AGTP_{tCDR}(t, \tau) \neq 0$, for each year t). Although α ensures climate neutrality by matching the magnitude of cumulative cooling to cumulative warming, annual deviations arise, notably because of temporal misalignment between the cooling and warming peaks. Because the cooling peak depends on storage timescale and the warming peak on species lifetime, we propose a lifetime threshold to distinguish short-lived from long-lived species in this study (Fig. 3a). Under our default exponential temporary CDR release profile, the threshold is 12.7 years for a storage timescale of 100 years and up to 30.9 years for near-infinite storage (Fig. 3b,c). Although alternative temporary CDR release profiles yield different threshold values at finite storage timescales (Supplementary Figs. 4–6), the upper limit of 30.9 years remains constant across all profiles. Long-lived non-CO_2 species such as CFC-11 and N_2O exceed this threshold, with warming peaks occurring later than the cooling peak of permanent CDR, making large annual deviations unavoidable should CDR be used to compensate for the warming of these species.

For short-lived species, however, annual deviations can be substantially reduced through appropriate selection of α and τ, enabling more effective like-for-like compensation. As shown in Fig. 4a,b for CH_4, two extreme combinations of α and τ (denoted P1 and P2) lead to a cumulative net temperature change of zero over 100 years but a marked annual temperature deviation. Although in reality this deviation might not manifest because of a heterogeneous deployment in time and space of varied temporary CDR technologies, particularly given that asynchronous regional implementation and continuous emissions would smooth the temporal profile compared with our idealized pulses, it can also be intentionally reduced by adjusting both the temporary CDR quantity α and the storage timescale τ, with the optimal combination (P3) illustrated in Fig. 4c. Although the annual deviation cannot be fully reduced to zero (Fig. 4d), which means that it is impossible to perfectly offset warming on an annual basis, we could use this information to improve offset mechanisms, for instance by setting thresholds or penalties to favour temporary CDR technologies whose cooling profile better matches that of a given warming species. The optimal combinations of α and τ for all short-lived species (using a lifetime threshold of 30.9 years) are summarized in Extended Data Table 1. Also, although the preceding analysis is based on idealized pulse emissions, the framework is equally applicable to continuous emissions scenarios. We illustrate this in a scenario in which temporary CDR is deployed to offset two decades of higher-than-expected CH_4 emissions under SSP1-2.6 (Supplementary Fig. 7 and Supplementary Note 3).

Implications

The large-scale deployment of CDR is seen as essential to achieving net-zero greenhouse gas (GHG) emissions and remains a key part of most mitigation strategies[1,33,34]. However, the role of temporary CDR, which cannot store carbon permanently, remains unclear in present policy frameworks. At present, most of carbon removal—nearly 2 Gt CO_2 per year—is achieved through conventional land-based CDR[1], which is arguably temporary CDR. Although new methods of durable CDR (achieving millennial-scale storage, referred to as permanent in theoretical frameworks) have been proposed, their present availability remains minimal, with most deployment slated for the future[34,35]. Previous attempts to include temporary CDR into existing GHG accounting have proved problematic (also demonstrated in this paper), as temporary CDR cannot offset the long-term warming effect of CO_2 emissions. Alternative policy instruments such as temporary crediting under the Kyoto Protocol address the reversal risk of non-permanent storage through periodic verification and credit renewal[36] but do not quantify the climate benefit that temporary storage actually delivers. Therefore, it is important to evaluate and credit temporary CDR properly.

Here we demonstrate that temporary CDR, with its transient climate effect, can robustly compensate for short-lived non-CO_2 species but cannot fully offset long-lived CO_2 emissions[6,7]. On the basis of this principle, we have developed a physics-based accounting framework that quantifies required compensation ratios (α) for temporary CDR with different storage timescales (τ), enabling practical implementation of like-for-like compensation strategies. Because this compensation achieves cumulative rather than annual temperature neutrality, some residual annual temperature oscillation remains even at the optimal compensation ratio (Fig. 4). Policymakers assigning priority to temperature stabilization during critical periods may therefore choose to overcompensate by deploying higher α values than the minimum required or by estimating α so that even the peak warming of species x is compensated (that is, $AGTP_x(t) + \alpha \times AGTP_{tCDR}(t, \tau) \leq 0$, for each year t).

A key feature of our methodology is its strategic alignment with the analytical framework underpinning the GWPs already in use under the UNFCCC. Although GWP has well-documented limitations in representing short-lived climate forcers[30,37], and alternative metrics such as GWP* have been proposed to address these issues[38], these alternatives have not yet been officially adopted; we therefore align our framework with the present policy structure to facilitate practical implementation. The compensation metric α can be calculated using either temperature change (iAGTP, as we presented) or radiative forcing (AGWP, shown in Supplementary Table 8 and Extended Data

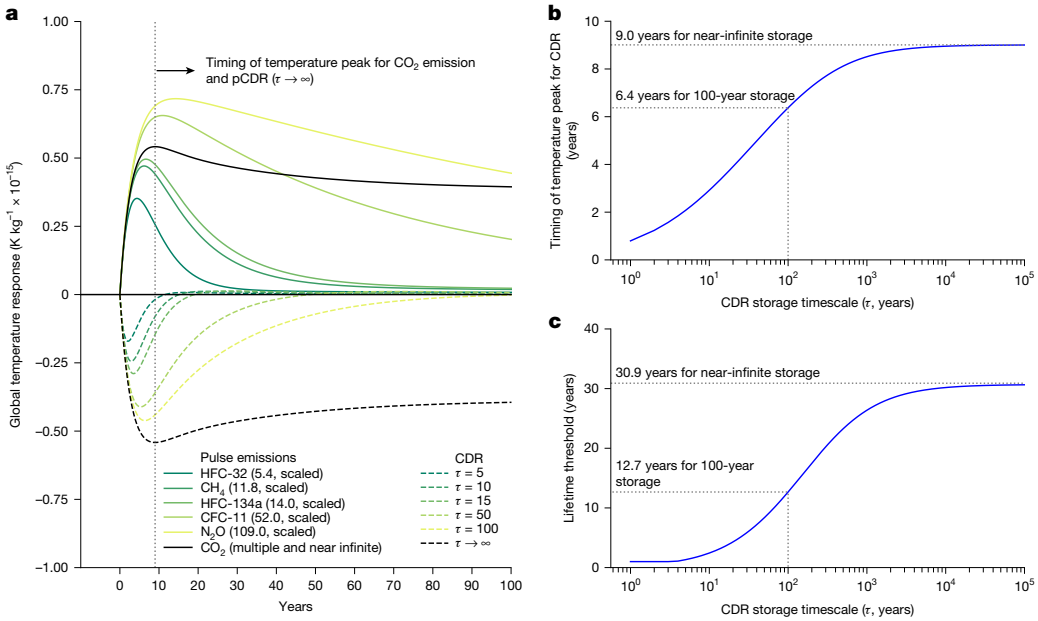

Fig. 3 | Lifetime threshold for effective offsetting with temporary CDR. **a**, Induced temperature change from pulse emissions with varying lifetimes and CDR with different storage timescales (τ). The warming peak of emissions depends on their atmospheric lifetime, whereas the cooling peak of CDR is determined by its storage timescale. Numbers in parentheses indicate atmospheric lifetimes for non-CO_2 species, in years. For simplicity in comparison, magnitudes of non-CO_2 temperature curves are scaled by the radiative efficiency of CO_2 to isolate the effect of lifetimes on temporal profiles. **b**, Relationship between CDR storage timescale and the timing of its cooling peak. Although longer storage durations delay the cooling peak, it cannot occur later than that of a CO_2 negative pulse under permanent storage (that is, permanent CDR). **c**, Relationship between CDR storage timescale and the lifetime threshold. The lifetime threshold separates short-lived from long-lived non-CO_2 species. For panels **b** and **c**, the *x*-axis is shown on a logarithmic scale to better exhibit the temporal profiles.

Fig. 2). In the latter case, $1/\alpha$ is mathematically equivalent to a GWP for temporary CDR, although we have refrained from presenting it in such a way for two reasons. First, it has long been argued by the climate science community that temperature-related metrics better describe climate impacts than those derived from radiative forcing[39]. Second, and more importantly, because temporary CDR cannot fully offset long-lived GHGs and notably CO_2, assuming a GWP for temporary CDR in the present UNFCCC accounting framework is tantamount to assuming full fungibility with other climate forcers. This approach is not only physically incorrect but it could lead to strong distortions and disincentives if applied in a market or credit context. Therefore, implementing temporary CDR in climate policies and carbon markets requires at least a 'two-basket' approach to emissions accounting, segregating long-lived and short-lived climate forcers to reflect their differing fundamental behaviour[40]. This approach avoids the inaccuracies that arise when lumping all forcers together, offering a more precise and physically correct metric aligned with existing reporting frameworks[20,41], and now enabling appropriate inclusion of temporary CDR. For instance, carbon already tracked in harvested wood product pools under national GHG inventories constitutes a form of temporary CDR whose potential to compensate for short-lived climate forcers can be directly quantified by applying the corresponding α values to carbon inputs, assuming their associated storage timescales but without requiring detailed tracking of product-pool decay dynamics. With this word of caution about the applicability of standard metrics, we provide a table for GWPs, GTPs and iGTPs of temporary CDR in Extended Data Table 2.

This framework has immediate relevance for agricultural sectors, in which emissions are dominated by short-lived species such as CH_4. For countries with substantial hard-to-abate pastoral sectors, such as Brazil and New Zealand, our framework provides quantitative guidance for using temporary CDR to compensate livestock emissions. This sector-specific approach complements recent proposals for differentiated mitigation strategies, which emphasize that fossil CO_2 requires permanent geological storage[42]. That said, direct emission reductions of air pollutants such as CH_4 and black carbon (BC) provide substantial health co-benefits through improved air quality that CDR cannot replicate[43]. Temporary CDR should therefore be reserved for genuinely hard-to-abate sources rather than substituting for achievable pollution control. Conversely, our framework identifies a valuable application in which temporary CDR can support public health objectives: compensating for the unmasked warming from cleaning up short-lived cooling agents such as sulfate aerosols[44], thereby enabling air quality improvements without compromising climate goals.

Although these applications demonstrate the potential of the framework, successful implementation requires careful attention to several operational and institutional considerations. First, for continuous emissions such as agricultural methane, maintaining climate benefits requires continuous deployment of temporary CDR through new or rotating projects, matching the temporal pattern of emissions (Supplementary Fig. 7). Second, although our framework provides scientifically consistent accounting, it does not eliminate reversal risks or moral hazard. Whether implemented through governmental regulations or voluntary corporate schemes, successful deployment requires strict adherence to the physics-based quantification identified here, transparent verification systems to ensure the integrity of temporary storage and prevent reversal risks, and complementary governance mechanisms to address moral hazard and prevent misuse. These considerations suggest that temporary CDR has strategic importance as a bridging mechanism but also clear limitations as an offsetting tool, and that appropriate safeguards in accounting rules would be needed to ensure its proper use[45].

Beyond these implementation considerations, we emphasize that the metrics used at present under the UNFCCC rely only on physical science, thereby avoiding complications and arbitrary choices related to economics (such as the discounting rate used in tonne-year accounting methods), and possibly increasing the transparency of assessments[46,47] and acceptability within the policymaking community.

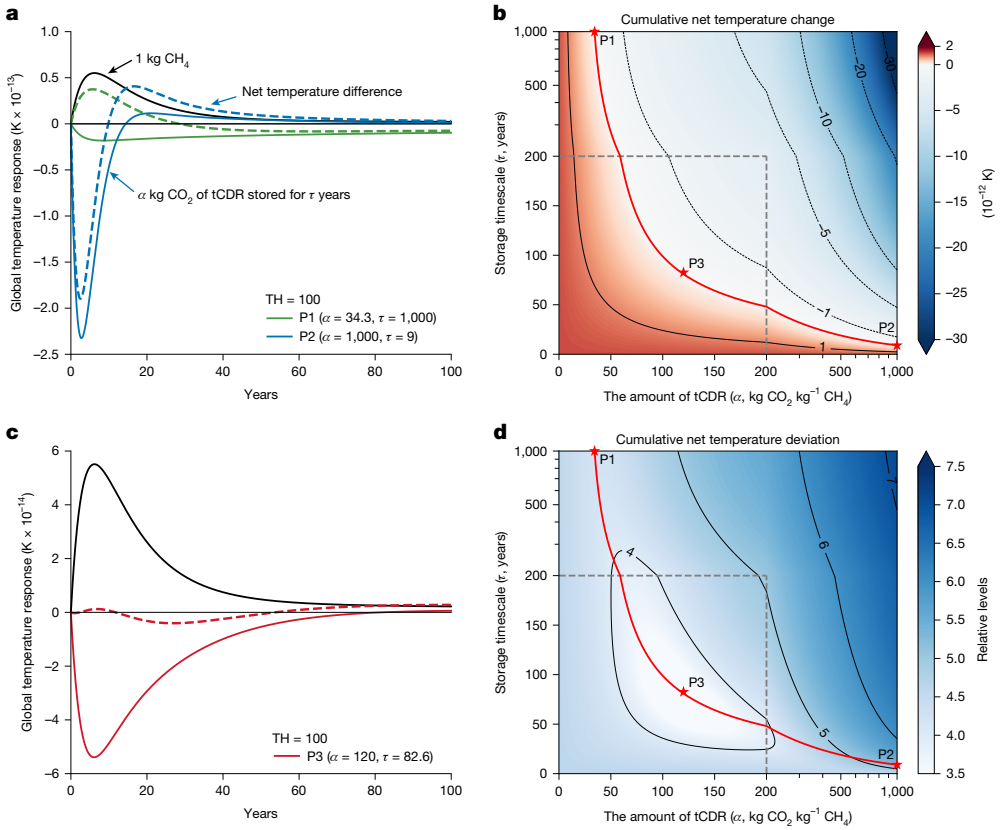

Fig. 4 | Optimization of temporary CDR strategies to offset anthropogenic emissions in the case of CH_4. **a**, Comparison of temperature responses between CH_4 and different temporary CDR strategies. Amount of CDR (α) and storage timescale (τ) for each strategy are provided at reference points P1 and P2. Dashed lines denote the net temperature change in temperature outcomes between CH_4 and each temporary CDR strategy (Methods). **b**, Cumulative net temperature change owing to 1 kg CH_4 emission and various temporary CDR strategies, represented by all combinations of α and τ values ranging from 0 to 1,000. **c**, Same as **a** but with the parameters of temporary CDR corresponding to the optimal point P3. **d**, Cumulative net temperature deviation owing to 1 kg CH_4 emission and various temporary CDR strategies, represented by all combinations of α and τ values ranging from 0 to 1,000. Relative levels are shown on the *z*-axis for visual clarity (Methods). For all panels, a 100-year time horizon is used. For panels **b** and **d**, the scale of α and τ are both linear between 0 and 200 and logarithmic afterwards; all points on the red zero-contour line, including P1, P2 and P3, achieve a net-zero cumulative net temperature change. Notably, P3 is identified as the optimal point at which minimal cumulative net temperature deviation is also achieved.

However, the integration of economic factors into this framework remains a possible extension, especially as previous work in that direction has failed to properly capture the physical climate dynamic[18,48,49]. If the costs associated with temporary CDR technologies are quantified, it becomes feasible to compare the physical effectiveness of temporary CDR strategies at reducing climate impacts against their financial implications within a more holistic analysis[50,51]. However, we note that limitations are substantial, both for costs of future climate impacts as well as reliability of the temporary carbon storage. Future work could seek to bridge this gap by integrating this compensation metric and financial costs in integrated assessment models to estimate a scientifically guided pricing of different temporary CDR strategies, while accounting for the implementation limitations discussed above.

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/s41586-026-10607-3.

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Methods

Conceptual framework for temporary CDR

We investigate temporary CDR strategies through a theoretical framework based on a two-phase process: capturing CO_2 from the atmosphere and then releasing it back within a specific storage timescale (τ; Supplementary Fig. 1). We express this process mathematically as:

$$F_{\mathrm{tCDR}}(t,\tau) = c(t) + r(t,\tau) \tag{3}$$

Here $c(t)$ denotes the carbon removal function, conceptualized as a negative pulse of CO_2 emission by means of the Dirac delta function, $c(t) = -\delta(t)$. The use of this function is a common practice in existing works in the literature for both emissions and removals of CO_2 (refs. 21,53–55). This form is chosen in our study for its simplicity and for mirroring the way anthropogenic emissions are modelled—as positive pulses.

For the subsequent carbon release phase, we explore four distinct functional forms to characterize the release dynamics: (1) the exponential release function, simulating natural decay processes, such as the decomposition of organic matter or the slow release of biochar; (2) the linear release function, representing controlled carbon release scenarios, as observed in some industrial carbon capture and storage systems in which leakage rates are actively managed; (3) the constant release function, simulating scenarios with a fixed leakage rate, which could represent well-characterized but unavoidable emissions from certain geological storage sites; and (4) the positive pulse (Dirac delta function), representing a delayed but abrupt release event, as might occur in the case of durable wood products used in construction, in which carbon is stored for decades but eventually released if the material is incinerated at end of life without carbon capture. For all release scenarios, the storage duration τ represents the characteristic timescale of carbon retention: for exponential decay, it corresponds to the 95% release time; for linear and constant release, it defines the total duration of the release period; for the pulse function, it indicates the delay before release. All functional forms of F_{tCDR} and their corresponding dynamics are detailed in Supplementary Fig. 1 and the resultant metrics are shown in Table 1 and Supplementary Tables 5–7, respectively. Note that, although temporary CDR strategies achieve carbon neutrality within the storage timescale—capturing and releasing equivalent amounts of carbon ($\int F_{\mathrm{tCDR}}(t) = 0$)—the climate impact is not neutral, as discussed in the following section.

Climate metrics calculations

Using the analytical IRFs from the IPCC AR6 (detailed in Supplementary Note 1), we calculate the temperature response (based on AGTP) for anthropogenic emissions of seven species spanning a broad range of atmospheric lifetimes: BC, HFC-32, CH_4, HFC-134a, CFC-11, N_2O, PFC-14 and CO_2 (Table 1). Notably, we include climate–carbon feedback for AGTP calculations of both CO_2 and non-CO_2 species consistently[21]. In contrast to the AR6, however, this inclusion uses a closed-form formula and not numerical solving, which is more robust mathematically but leads to a very slight difference with the values reported in the AR6.

Also, the AGTP for temporary CDR can be calculated with a convolution between its time series (F_{tCDR}) and $\mathrm{AGTP}_{\mathrm{CO_2}}$:

$$\mathrm{AGTP}_{\mathrm{tCDR}}(\mathrm{TH},\tau) = \int_{t=0}^{\mathrm{TH}} F_{\mathrm{tCDR}}(t,\tau)\,\mathrm{AGTP}_{\mathrm{CO_2}}(\mathrm{TH}-t)\,\mathrm{d}t \tag{4}$$

in which F_{tCDR} is a two-phase process comprising both the removal and the release of CO_2 across a designated storage timescale τ. The closed-form analytical solutions for both AGTP_x (for CO_2 and non-CO_2 species) and $\mathrm{AGTP}_{\mathrm{tCDR}}$ were calculated using the Wolfram Mathematica software (version 13.3).

Temporary CDR offset optimization

In this study, we define the net temperature change ΔT as the temperature impact resulting from a 1-kg pulse emission of species x and a tailored temporary CDR strategy. This dynamic relationship is dependent on the amount of CDR required (α), the storage timescale (τ) and the time at which the impact is assessed (t):

$$\Delta T(t,\alpha,\tau) = \mathrm{AGTP}_x(t) + \alpha \times \mathrm{AGTP}_{\mathrm{tCDR}}(t,\tau) \tag{5}$$

To achieve a near-symmetric temperature counterbalance, we design an optimization model that closely mirrors the warming trajectory of anthropogenic emissions with the cooling trajectory of temporary CDR. The objective of this model is to minimize the cumulative net temperature deviation over a specific time horizon:

$$\text{Minimize} \int_0^{\mathrm{TH}} [\Delta T(t,\alpha,\tau)]^2 \mathrm{d}t \tag{6}$$

The model incorporates a constraint requiring net-zero cumulative temperature change over the same time horizon, aligning with broader climate policy goals:

$$\text{Subject to} \int_0^{\mathrm{TH}} \Delta T(t,\alpha,\tau)\mathrm{d}t = 0, \alpha > 0, \tau > 0 \tag{7}$$

To evaluate this optimization problem, we explore a parameter space of α and τ to visualize both the constraint (cumulative net temperature change; Fig. 4b) and the objective function (cumulative net temperature deviation; Fig. 4d). The objective function values (Z) are transformed as $Z_{\mathrm{scaled}} = \log_{10}(Z \times 10^{30})$ to show relative levels. We analyse this optimization framework across two time horizons: a near-term horizon of 100 years (TH = 100) and an indefinite horizon (Extended Data Table 1). This dual-horizon approach enables us to customize temporary CDR strategies for both immediate and long-term climate mitigation, offering a robust framework for policymakers to evaluate the temporal dynamics of these strategies.

Uncertainty quantification

We conducted uncertainty analysis following IPCC AR6 Working Group I Chapter 7 and its Supplementary Material[23]. Key parameters with uncertainties include: radiative efficiency, atmospheric lifetime, IRF parameters for both temperature and CO_2 responses, fractional molar yield of CO_2 from CH_4 oxidation and the chemical lifetime of CH_4 with respect to OH. We performed 5,000 Monte Carlo simulations to propagate these uncertainties through our calculations of α. For clarity, the main text figures and tables present mean values only; uncertainty ranges are provided in Supplementary Table 10.

Data availability

Data sharing is not applicable to this article as no datasets were generated or analysed during this study.

Code availability

The analytical solutions and parameters for all climate metrics presented in this paper are available at GitHub (https://github.com/yuehe1313/tCDR).

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Author contributions T.G. designed the research. Y.H. developed the methodology, performed the analysis and wrote the original draft. S.P., T.W., M.J.G. and K.R. contributed to the discussion of results, critical revision of the manuscript and interpretation of results.

Competing interests The authors declare no competing interests.

Additional information

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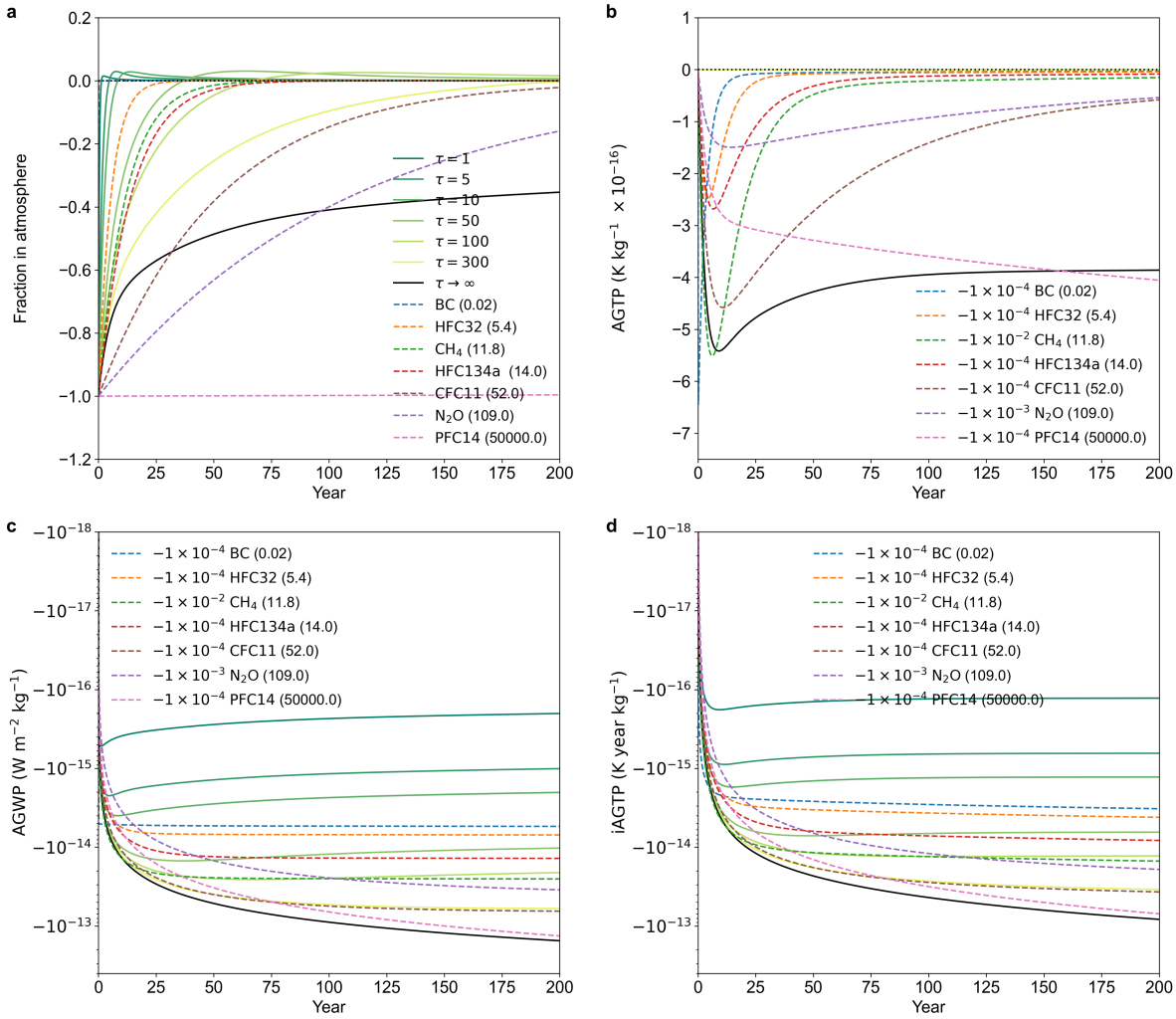
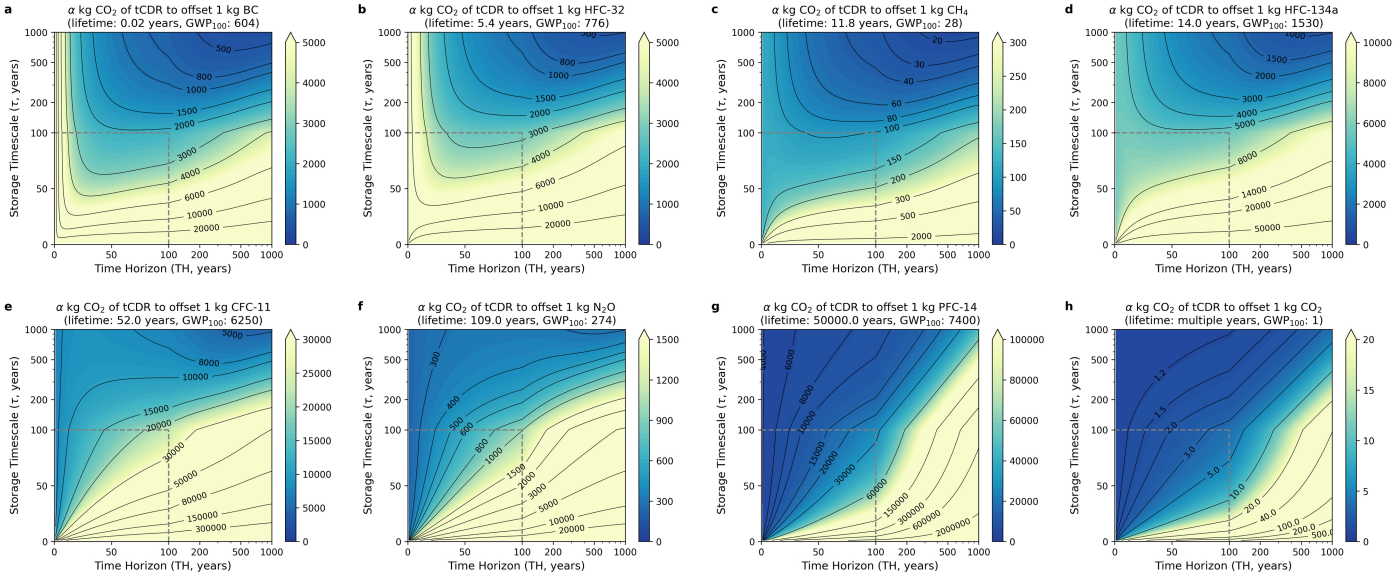


Extended Data Fig. 1 | Climate impact of temporary CDR and non-CO_2 emissions at different points of the carbon–climate cause–effect chain. **a**–**d**, Results for temporary CDR are represented by solid lines, each differentiated by colour to indicate different storage timescales (τ). Non-CO_2 emissions are shown as dashed lines, with their specific lifetimes indicated in parentheses. Consistent with the main text, the function form of temporary CDR is illustrated using a combination of a negative pulse followed by an exponential release.



Extended Data Fig. 2 | Amount of temporary CDR (α) required to offset a unit pulse emission of different species across various storage timescales (τ) and time horizons. Same as Fig. 2 but the mitigation metric α is calculated using AGWP instead of iAGTP. The scale of both axes for time horizon (TH) and storage timescale (τ) are linear between 0 and 100 and logarithmic afterwards. The panels are arranged in ascending order of species lifetimes from panels **a** to **h** (see Table 1 for details).

Extended Data Table 1 | Optimization of temporary CDR strategies for near-symmetric temperature offsetting

	TH = 100		TH → ∞	
	Optimal	Optimal τ	Optimal	Optimal τ
BC	9,150	23.9	1,350	330
HFC-32	5,930	46.4	2,410	171
CH_4	120	82.6	83.6	246
HFC-134a	5,760	94.9	4,160	271

This table summarizes the optimized parameters for temporary CDR strategies: the amount of temporary CDR (α) and storage timescale (τ). These parameters are optimized to minimize the cumulative net temperature deviation while maintaining net-zero cumulative temperature change over a chosen time horizon (TH) (Methods). Values are rounded to three significant figures for clarity.

Extended Data Table 2 | GWPs, GTPs and iGTPs for anthropogenic emissions and temporary CDR

	GWP20	GWP100	GWP500	GTP20	GTP100	GTP500	iGTP20	iGTP100	iGTP500
CO_2	1	1	1	1	1	1	1	1	1
BC	2,170	604	176	206	112	32	2,570	665	199
HFC-32	2,700	776	226	873	148	41.9	3,050	847	255
CH_4	81.3	28	8.17	52.7	5.58	1.55	86.8	30.3	9.19
HFC-134a	4,150	1,530	448	2,960	317	85.7	4,380	1,650	504
CFC-11	8,330	6,250	2,150	8,490	3,580	477	8,290	6,440	2,380
N_2O	273	274	133	297	235	41.6	269	276	143
PFC-14	5,300	7,400	10,700	6,110	9,110	13,200	5,150	7,270	10,500
tCDR(τ=20)	-0.288	-0.053	-0.0102	-0.0292	0.00583	0.00208	-0.338	-0.0609	-0.0124
tCDR(τ=100)	-0.735	-0.277	-0.0519	-0.559	-0.00456	0.0102	-0.769	-0.301	-0.0623
tCDR(τ=500)	-0.938	-0.728	-0.273	-0.891	-0.508	-0.0109	-0.947	-0.744	-0.305

The functional form of temporary CDR (tCDR) follows that shown in the main text (Supplementary Fig. 1a). Time horizons of 20, 100 and 500 years are chosen as illustration, with storage timescales (τ) of 20, 100 and 500 years used for temporary CDR.