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Methane Emissions Offsetting With Temporary Carbon Sinks

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ABSTRACT

Methane accounts for more than 20% of current anthropogenic warming. While fossil methane emissions can likely be reduced substantially, biogenic methane from agriculture and waste will remain difficult to fully abate. Achieving climate neutrality therefore requires counterbalancing the warming effect of residual emissions. The rapid atmospheric decay of methane suggests that temporary carbon sinks can serve this purpose, yet current accounting approaches do not consistently quantify their time-dependent cooling effect. Here we develop a time-explicit method that enables offsetting the 100-year warming impact of a methane emission pulse with an equally sized cooling effect delivered by carbon dioxide removal over 20 years. Based on a CO_2 atmospheric impulse–response function (IRF), we define the total climate effect (TCE) as time-integrated warming and cooling of greenhouse gas emissions and dynamic carbon sinks expressed in CO_2-equivalent units. The developed method yields the amount of CO_2 removal and storage duration over a chosen time horizon to counterbalance methane-induced warming. For example, over a 20-year horizon, complete offsetting of 1 t CH_4 of biogenic origin requires 94.6 t CO_2e stored in a constant C-sink. The method allows differentiation between temporary and geologically persistent carbon dioxide removal by explicitly accounting for storage duration and time horizon. By providing a physically grounded basis for valuing temporary carbon storage—a question actively debated in the EU Carbon Removals and Carbon Farming Regulation and Article 6.4 of the Paris Agreement—the approach supports near-term climate mitigation and may bridge the decades required for scaling permanent CDR solutions by creating financial incentives for temporary carbon sink technologies.

1 | Introduction

The methane concentration in the atmosphere is only about 1.9 ppm compared to roughly 420 ppm of CO_2. Due to its high radiative forcing, methane is estimated to be responsible for about 20%–30% of the observed anthropogenic warming since pre-industrial times (IEA, 2022; IPCC 2023; UNEP 2021). In addition to its high radiative forcing, methane is characterized by its short effective atmospheric lifetime of approximately 12 years (IPCC 2023, 2013; Myhre et al. 2013). Assuming first-order removal, this implies that ~19% of a methane pulse remains after 20 years in the atmosphere and ~0.02% after 100 years (Figure 1). Methane is continuously removed from the atmosphere primarily by oxidation reactions with hydroxyl radicals (•OH) and other reactive species, as well as by microbial and chemical processes at the soil–atmosphere interface. Its oxidation products, which include CO_2, tropospheric ozone, and stratospheric water vapor, continue to exert a small but significant warming effect after most of the initial methane pulse has been decayed (Figure 1). For fossil methane, the CO_2 produced by oxidation represents a net addition of carbon to the active carbon cycle and must be accounted for separately; for biogenic methane, this CO_2 is part of the short-cycle carbon that was recently fixed from the atmosphere and does not constitute an additional forcing.

The short residence time of methane and the comparatively small long-term forcing of its oxidation products have three major consequences for methane offsetting:

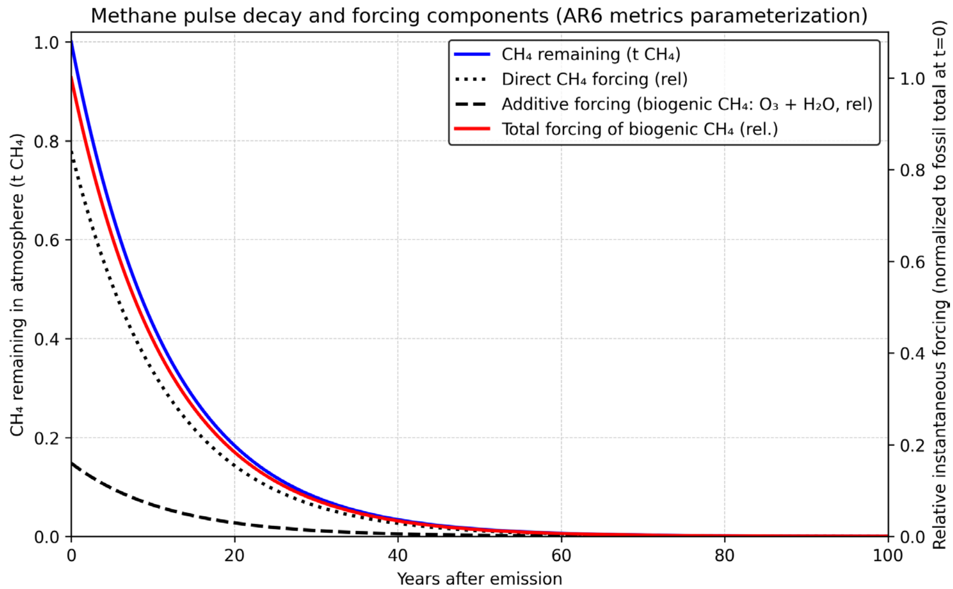

FIGURE 1 | Approximate decay of a methane pulse in the atmosphere (blue; left axis), assuming first-order removal with a mean lifetime of 11.8 years. ~19% of the initial pulse remains after 20 years and ~0.02% after 100 years (IPCC 2013; Myhre et al. 2013; Smith, Forster, et al. 2021). The corresponding radiative forcing of the emission over time (red; right axis) is shown in relative units. It consists of the direct methane forcing (black dotted line) and additional chemically mediated forcing (black dashed line) associated with methane-driven changes in tropospheric ozone and stratospheric water vapour, following the AR6 greenhouse gas metrics parameterization (Smith, Forster, et al. 2021). For fossil methane, an additional contribution from CO_2 formed by methane oxidation would need to be included.

1. There is no physical need to compensate methane's warming using geological, millennial-scale carbon sinks, as would be required to offset CO_2 emissions. Instead, temporary carbon sinks that deliver a negative radiative forcing over a period of years to decades can be used. Deploying geological or equivalently persistent carbon storage to offset methane's short-lived warming is therefore neither necessary nor economically efficient.
2. If methane is offset using the 100-year global warming potential (GWP100) and compensation is spread evenly over 100 years, the resulting cooling would be mis-timed: it would be too small during the first two decades—when methane's warming is strongest—and too large in later decades, after most of the methane has already been removed from the atmosphere.
3. To counterbalance the instantaneous global warming effect of a methane pulse, compensation must occur soon after the emission. The decades up to mid-century constitute a decisive period for limiting anthropogenic warming and avoiding climate tipping points (McKay et al. 2022). As methane emitted today has a disproportionate influence on temperatures until 2050, methane emissions should be offset over short time horizons—ideally within 10 to 20 years—consistent with methane's short-lived but intense warming impact and with recommendations in the literature (Balcombe et al. 2018; Venmans et al. 2025).

Approximately 35% of global anthropogenic methane emissions originate from the fossil fuel sector (IEA, 2022; UNEP 2021). While these emissions could in principle be eliminated by phasing out fossil fuels and improving methane management in oil and gas systems, many nonfossil methane emissions are difficult or impossible to fully avoid. These include enteric fermentation, manure management, rice paddies, landfills, wastewater treatment, and—as a climate feedback—increasing emissions from thawing permafrost and other waterlogged landscapes. A substantial share of these biogenic emissions is therefore likely to persist in both the near term and the longer term, even though numerous reduction pathways are being explored (Mundra and Lockley 2024; UNEP 2021). Atmospheric methane removal is being researched (Jackson et al. 2019), but given methane's low atmospheric concentration, technical scale-up may not be feasible in the foreseeable future (Köhler and Joerss 2025). Consequently, counterbalancing residual biogenic methane emissions through carbon dioxide removal (CDR), may be one of the few available strategies to achieve net climate neutrality.

CDR is already being pursued and implemented using a range of technologies and nature-based solutions that create carbon sinks in which carbon removed from the atmosphere is sequestered for a measured or predictable period of time. Because methane and CO_2 emissions both contribute to global warming through radiative forcing—albeit with very different time profiles—CO_2 removal can, in principle, counterbalance the climate effect of methane and other greenhouse gas emissions. Compensation of methane emissions using carbon sinks was discussed as early as 2013 (Lauder et al. 2013). However, converting methane emissions into the required amount of carbon removal and the necessary storage period in the corresponding sink is nontrivial.

While the Global Warming Potential (GWP) was developed as a reporting metric to express the integrated warming effect of a greenhouse gas relative to CO_2, its application to offsetting becomes problematic when the relevant time horizon differs from the standard 100-year framing, and when removals occur at different times than the emissions they are intended to counterbalance. As early as 1998, Wigley demonstrated that two distinct emissions profiles—potentially involving different gases and different time evolutions—are equivalent in climate impact if they produce the same radiative forcing as a function of time, an insight formalized as the Forcing Equivalence Index (FEI) (Wigley 1998). The FEI thus provides, in principle, a rigorous definition of emissions equivalence. However, because it requires matching the full time-dependent forcing trajectory rather than a single scalar value, it has not been adopted in carbon accounting or crediting frameworks. The challenge, therefore, is to find a workable middle ground between the physical rigor of the FEI and the operational simplicity of the GWP. These limitations motivate the development of a time-horizon-specific framework that links methane emissions to temporary carbon storage by matching their climate forcing over defined periods.

Although methane emissions are short-lived, their radiative forcing during the first two decades is 81.2 times as potent as CO_2 (Forster et al. 2021), while the forcing declines rapidly thereafter (Figure 1). The time profile explains why the GWP20 of methane is nearly three times higher than its 100-year value of 27.9. Nevertheless, greenhouse-gas inventories and climate-accounting frameworks almost universally rely on GWP100, which averages methane's impact over a century. This masks the short-term importance of methane and complicates efforts to offset methane emissions through CDR.

Offsetting methane with CDR requires quantifying how much CO_2 must be removed from the atmosphere and for how long it must be stored outside the atmosphere to generate a cooling effect equivalent to the total warming that a methane emission pulse will produce over time. The conventional approach uses the Absolute Global Warming Potentials (AGWP) of CO_2 and CH_4 from the IPCC's Sixth Assessment Report (AR6) to calculate the required CO_2 removal over 100 years. However, we suggest a more targeted approach by offsetting methane's $AGWP_{100}$ with temporary C-sinks that delivers the same total climate effect within the first 20 years, when most of the warming from methane actually occurs. Addressing methane's warming impact during the time it occurs, rather than averaging it over multigenerational timescales, would limit the risk of accelerating climate change during the next decades.

Temporary C-sinks store carbon in living biomass, soils, or biomaterials for a limited period and generate a measurable reduction in radiative forcing, referred to as their climate cooling effect. Because the duration of the cooling is limited to years or centuries, temporary C-sinks cannot completely offset the long-term warming effect of CO_2 emissions, which persists for millennia. Recent studies highlight the potential of temporary C-sinks for climate change mitigation (Edenhofer et al. 2023; Matthews et al. 2023; Venmans et al. 2025), but they remain largely undervalued in current carbon-crediting systems. Current market frameworks prioritize long-term permanence, leaving the short-term climate services provided by temporary sinks essentially unaccounted for (Stoefs 2023).

Accurately quantifying the total climate effect of temporary sinks for methane offsetting requires a transparent, temporally consistent method to determine the required amount and duration of storage for a given methane emission. It must further account for changes that may occur in C-sink stocks. Some C-sinks diminish predictably, such as the semi-persistent carbon (SPC) fraction of biochar as defined in the Global Biochar C-Sink Standard (Schmidt et al. 2022; Schmidt, Abiven, et al. 2025; Schmidt, Hagemann, and Kammann 2025). Here, two carbon pools are distinguished based on their persistence after soil application: a geologically persistent carbon (GPC) pool, defined as the fraction that persists beyond 1000 years and thus enters the geological carbon cycle, and the SPC pool, which provides temporary storage and gradually decays within this timeframe. Other C-sinks build up over time, such as growing biomass, where annual removals accumulate progressively. The atmospheric benefit of a CO_2 removal depends not only on how much carbon is removed, but also on when the removal occurs relative to the chosen offset horizon.

The purpose of this study is to provide a general, impulse–response–function (IRF) based method for calculating the amount and storage time of CO_2 removals required to offset the warming effect of a methane emission over a specified time horizon. We then extend the framework to diminishing C-sinks, using the SPC fraction of biochar as a representative example, and to increasing sinks using tree growth as an illustrative case. All mathematical derivations are presented in the Methods section and the Python code to calculate all examples are accessible via GitHub for full transparency. The resulting framework is intended to support carbon-removal standards, climate-accounting methodologies, policy design and industrial practice in contexts where methane offsetting is required.

2 | Methods—Theoretical Framework

2.1 | Atmospheric Impulse–Response Function (IRF)

To quantify the time-dependent atmospheric response to CO_2 emissions and removals, we use an atmospheric impulse–response function (IRF), which describes the fraction of a positive or negative CO_2 pulse that remains in the atmosphere after time t. The time integral of the IRF provides the cumulative atmospheric effect of a unit CO_2e pulse over a given horizon and therefore forms the basis for calculating the total climate effect (TCE) of greenhouse gas emissions and carbon sinks.

The atmospheric CO_2 impulse–response function, IRF(t), describes the fraction of a CO_2 pulse emission that remains in the atmosphere t years after the emission. It reflects the combined effects of ocean uptake, terrestrial carbon exchange (mainly biomass uptake and biomass decay), and slower geochemical processes such as natural rock weathering (Jeltsch-Thömmes and Joos 2019; Winkler and Sierra 2025).

For quantifying the atmospheric impact of carbon dioxide removal, the same IRF(t) can be applied in reverse (i.e., to a negative pulse). It describes how much of the initial atmospheric CO_2 reduction persists over time as carbon gradually flows back (i.e., re-equilibrates) from the ocean and terrestrial reservoirs into the atmosphere. Given that the carbon-cycle response to small and moderate perturbations is approximately linear, the atmospheric response to a CO_2 removal pulse is, to a very good approximation, symmetric to the response to an emission pulse of the same magnitude (IPCC 2023, 2013; Joos et al. 2013; Zickfeld et al. 2016). In practice, this means that the same IRF(t) quantifies both the persistence of an emission in the atmosphere and the persistence of the atmospheric CO_2 reduction achieved by a removal.

This near-symmetry between CO_2 emissions and removals has been demonstrated in carbon-cycle studies (Zickfeld et al. 2016) and implies that, for perturbations relevant to CDR accounting, differences between emission-IRFs and removal-IRFs are negligible. Only at much larger, multi-Gt scales of CO_2 removal, nonlinear carbon-cycle responses may become significant and the emission–removal symmetry could disrupt (Winkler and Sierra 2025). The present study therefore assumes the linear regime applicable to current and near-term CDR accounting.

In this study, we use the five-term exponential IRF of Jeltsch-Thömmes and Joos (2019), which extends the earlier three-term function used in Joos et al. (2013) and provides an improved representation of long-term carbon-cycle dynamics. The IRF is written as:

$$\mathrm{IRF}(t) = a_0 + \sum_{i=1}^{5} a_i\, e^{-\frac{t}{\tau_i}} \tag{1}$$

with parameter values:

$$\begin{aligned} &a_0 = 0.008 \\ &a_1 = 0.044 \quad \tau_1 = 68{,}521\ \mathrm{yr} \\ &a_2 = 0.112 \quad \tau_2 = 5312\ \mathrm{yr} \\ &a_3 = 0.224 \quad \tau_3 = 362\ \mathrm{yr} \\ &a_4 = 0.310 \quad \tau_4 = 47\ \mathrm{yr} \\ &a_5 = 0.297 \quad \tau_5 = 6\ \mathrm{yr} \end{aligned}$$

The IRF represents a weighted combination of exponential decay processes with characteristic lifetimes (i.e., τ_1 to τ_5) ranging from years to tens of thousands of years. Physically, the short lifetimes correspond to the rapid initial uptake of CO_2 by the ocean mixed layer and terrestrial biosphere, whereas the long lifetimes describe slow deep-ocean equilibration and carbonate–silicate buffering.

A CO_2 removal at time $t = 0$ produces an atmospheric response that is equal in magnitude and opposite in sign to that of an equally sized CO_2 emission. Accordingly, IRF(t) can be interpreted as the fraction of the initial atmospheric CO_2 removal that remains at time t, i.e. the portion not yet replaced by net CO_2 return from other carbon reservoirs.

For methane offsetting, two cumulative climate effects must be quantified: (1) the integrated warming effect of a methane emission expressed in CO_2e units over a reference period, and (2) the integrated cooling effect of a CO_2 removal over a defined time horizon H. The latter is chosen to reflect the period during which methane exerts most of its climate impact and is therefore substantially shorter than the conventional 100-year reporting horizon. Both cumulative climate effects are obtained from the time integral of the impulse–response function:

$$\mathrm{IRF}_{\mathrm{int}}(H) = \int_0^H \mathrm{IRF}(t)\,\mathrm{d}t. \tag{2}$$

The integral $\mathrm{IRF}_{\mathrm{int}}(H)$ describes the cumulative atmospheric response to a unit CO_2e pulse at $t = 0$ over the horizon H. The unit of $\mathrm{IRF}_{\mathrm{int}}(H)$ is years (y). It is proportional to the absolute global warming potential of CO_2 over H, $\mathrm{AGWP}_{CO_2}(H)$, via the radiative efficiency of CO_2 (IPCC 2021, 2023; Joos et al. 2013):

$$\mathrm{AGWP}_{CO_2}(H) = \alpha_{CO_2}\ \mathrm{IRF}_{\mathrm{int}}(H), \tag{3}$$

where α_{CO_2} is the radiative efficiency of CO_2 ($\mathrm{W\,m^{-2}}$ per unit mass). The quantity $\mathrm{IRF}_{\mathrm{int}}(H)$ therefore provides the scaling factor needed to express integrated climate effects over horizon H in CO_2-equivalent units. We denote the chosen time horizon by H to avoid confusion with the time variable t.

2.2 | Total Climate Effect (TCE)

To compare the warming effect of methane and other greenhouse gas emissions with the cooling effect of CO_2 removals, we introduce the concept of the Total Climate Effect (TCE). The TCE provides a unified measure of the net time-integrated climatic impact of greenhouse gas emissions and removals over a specified time horizon H, expressed in tons CO_2e years (tCO2e·yr).

By definition, a positive TCE corresponds to net warming caused by emissions, whereas a negative TCE corresponds to net cooling achieved through removals. The TCE is derived from time-integrated radiative forcing using the impulse–response framework introduced above and is expressed as the mass of CO_2 that would produce the same integrated radiative forcing over the same horizon H.

For a CO_2-equivalent pulse exchange with the atmosphere at $t = 0$, the TCE over horizon H is given by:

$$\mathrm{TCE}(H) = M_{CO_2e}\ \mathrm{IRF}_{\mathrm{int}}(H) \tag{4}$$

Here, M_{CO_2e} is the CO_2-equivalent amount exchanged with the atmosphere (positive for emissions, negative for removals). $\mathrm{IRF}_{\mathrm{int}}(H)$ is defined in Equation (2).

2.3 | Cooling–Warming Equivalence (Net-Zero TCE)

Offsetting is achieved when the TCE of the compensating sink balances (or exceeds) the TCE of the emission over their respective time horizons. In the general case, different processes may be evaluated over different horizons:

$$\sum_{\mathrm{i}} \mathrm{TCE_i}\left(H_{\mathrm{i}}\right) \le 0. \tag{5}$$

To avoid cases in which compensation is shifted to earlier years or to shorter horizons in a way that can temporarily increase warming, we impose the following consistency constraints:

1. The time horizon H_{ref} used to quantify the emissions to be offset must be no shorter than the delivery horizon H_{del} used to quantify the removals ($H_{ref} \geq H_{del}$). In other words, the credited cooling effect may not postdate the warming effect being offset.
2. Removals must not be accounted for before the corresponding emissions occur; hence, the climate effect of the C-sink must only be accounted for from the year in which the emission occurred. Climate effects occurring earlier are not attributable to that emission.

In the specific case of methane offsetting, we quantify methane's warming effect over a reference horizon of $H_{ref} = 100$ years, while requiring the offsetting C-sink to deliver the counter-effect within a delivery horizon of $5 \leq H_{del} \leq 20$ years. The lower time horizon is set to 5 years to avoid very short-term carbon sinks, for which long-term carbon storage could be fragmented into many short-term sinks with higher economic returns. The upper time horizon is set to 20 years to ensure that the climate cooling is delivered during the period in which the methane emission causes the greatest climate warming. The choice of 20 years as the upper delivery horizon reflects the period of strongest methane forcing and is consistent with recommendations in the literature (Balcombe et al. 2018; Venmans et al. 2025). However, this value is not a physical constant but a policy-relevant parameter. Longer delivery horizons of, e.g., 25 or 30 years could be adopted in regulatory frameworks or voluntary carbon markets, and the method accommodates any such choice, as all calculations can be straightforwardly repeated for alternative values of H_{del}.

The methane offsetting condition is therefore:

$$\mathrm{TCE}_{CH_4}(H_{ref}) + \mathrm{TCE}_{sink}(H_{del}) = 0, \quad 5 \leq H_{del} \leq 20 \tag{6}$$

Using the IRF-based definition of $\mathrm{TCE}(H) = M_{CO_2e}\ \mathrm{IRF}_{int}(H)$ (Equation 4) methane offsetting is achieved when the methane warming effect over the 100-year reference horizon is balanced by the cooling effect delivered by the compensating sink within the delivery horizon $H_{del} \leq 20$ years (Equation 5). Inserting the methane pulse expressed in CO_2e units into Equation (6) yields the required CO_2 removal as a function of H_{del}.

$$\mathrm{TCE}_{sink}(H_{del}) = M_{sink} \cdot \mathrm{IRF}_{int}(H_{del}).$$

Substituting into Equation (6) yields the required removal:

$$M_{sink} = \mathrm{GWP}_{100}(CH_4)\ \frac{\mathrm{IRF}_{int}(100)}{\mathrm{IRF}_{int}(20)}\ M_{CH_4}. \tag{7}$$

with $\mathrm{GWP}_{100}(CH_4) = 27.0$ for biogenic methane and 29.8 $\frac{tCO_2}{tCH_4}$ for fossil methane (IPCC 2022). When methane origin is unspecified, the AR6 default value of 27.9 $\frac{tCO_2}{tCH_4}$ applies.

As the $\mathrm{IRF}_{int}(100) = 50.48$ years and the $\mathrm{IRF}_{int}(20) = 14.402$ years the constant, leakage-free C-sink to offset 1 tonne of biogenic methane is

$$27.0 \frac{tCO_2}{tCH_4} * \frac{50.48\ yr}{14.402\ yr} * 1\ t\ CH_4 = 94.64\ t\ CO_2e.$$

For mixed origin methane with GWP(100) of 27.9 and fossil origin methane with a GWP(100) of 29.8, the required mass of the C-sink would be 97.8 $t\ CO_2e$ and 102.3 $t\ CO_2e$, respectively.

Using the values above, the TCEsink(20) to offset an emission of 1 t CH4 of biogenic origin is

$$\mathrm{TCE}_{sink}(H_{del}) = -94.64\ t\ CO_2e * 14.402\ yr = -1363.0\ t\ CO2e \cdot yr.$$

Equation (8) forms the basis for the subsequent extensions to temporary sinks with dynamic carbon stocks (e.g., declining biochar SPC or increasing tree C-sinks), in which the effective $\mathrm{TCE}_{sink}(H_{del})$ differs from the constant, leakage-free case.

2.4 | Methane Offsetting Using AGWP Ratios from IPCC AR6

A second way to derive the CO_2 removal required to offset a methane pulse is to use the Absolute Global Warming Potentials (AGWP) reported in Chapter 7 of the IPCC AR6 WG1 (IPCC 2022; Smith, Gasser, et al. 2021). AGWP expresses the time-integrated radiative forcing of a pulse emission and provides the basis for GWP metrics.

Using the AR6 values for $\mathrm{AGWP}_{100}(CH_4)$ and $\mathrm{AGWP}_{20}(CO_2)$, the condition that a methane emission over 100 years is balanced by a CO_2 removal delivered over 20 years can be written as:

$$M_{sink} \cdot \mathrm{AGWP}_{20}(CO_2) = M_{CH_4} \cdot \mathrm{AGWP}_{100}(CH_4). \tag{8}$$

The CO_2-equivalent mass that must be removed and stored for 20 years to offset a methane emission is thus:

$$M_{sink} = \frac{\mathrm{AGWP}_{100}(CH_4)}{\mathrm{AGWP}_{20}(CO_2)}\ M_{CH_4}. \tag{9}$$

Inserting the AR6 values yields:

$$M_{sink} = \frac{24.93\ \mathrm{pW\ m^{-}2\ yr\ kg^{-}1}}{0.243\ \mathrm{pW\ m^{-}2\ yr\ kg^{-}1}} \cdot \mathrm{MCH4-emission}$$
$$= 102.59 \cdot \mathrm{MCH4-emission}$$

Using the AR6 AGWP-ratio method yields a 4.9% higher required mass of CO_2 removal than the TCE(IRF)-based approach derived in Section 2.3 (102.6 vs. 97.8 t CO_2e per t CH_4 for mixed-origin methane). This difference arises primarily from the choice of CO_2 impulse–response function. The AR6 AGWP values are based on the carbon-cycle IRF of Joos et al. (2013), whereas Section 2.3 applies the updated IRF of Jeltsch-Thömmes and Joos (2019). When the Joos et al. (2013) IRF is used within our TCE(IRF)-based framework, the required constant-sink CO_2 removal over a 20-year storage horizon would increase from 97.8 to 102.6 t CO_2e per t CH_4, matching the AR6 AGWP-ratio result. This confirms that the discrepancy between the two approaches is largely explained by differences in the assumed CO_2 carbon-cycle response rather than by the methane forcing formulation. The newer IRF exhibits a slightly faster early decline in atmospheric CO_2, increasing the efficacy of CO_2 removal over a 20-year horizon. The divergence between the AGWP-ratio method and the TCE(IRF)-based result therefore reflects two legitimate modelling choices. We use the TCE(IRF)-based approach in this study because it readily supports the selection of any time horizon and nontrivial time profiles of temporary carbon sinks using simple mathematical expressions.

The TCE(IRF) model increases the constant-sink 20-year requirement by only +4.9% compared to the AR6 AGWP, which lies well within the uncertainty range of current carbon-cycle parameterizations. We adopt the newer IRF because it represents the most recent assessment of the carbon-cycle response and provides a more complete description of atmospheric CO_2 decay. Future IPCC assessment reports may adopt updated carbon-cycle IRFs, which would also imply revisions of tabulated AGWP and GWP values. All calculations presented here can be straightforwardly reproduced and adapted to alternative IRF parameterizations using the accompanying open-source code.

2.5 | Methane Offsetting Using Annually Quantified C-Sinks

2.5.1 | General TCE Calculation of Temporary C-Sinks

Permanent C-sinks whose persistence extends beyond 1000 years—such as those from DACCS or the geo-persistent carbon (GPC) pool of biochar—constitute stable C-sinks without relevant temporal evolution over the offset horizon. In contrast, many carbon sinks exhibit temporal dynamics and may increase or decrease over time, with characteristic time scales ranging from years to centuries. Examples include biogenic sinks such as forests, biomass storage, biomaterials used in construction, soil organic carbon, and the semi-persistent carbon (SPC) pool of biochar.

Most evolving sinks do not follow a deterministic functional form (e.g., linear, exponential, or sigmoidal) that can be confidently extrapolated over decades and certified into the future (ex ante). Accordingly, most CDR standards do not accept ex-ante certification based on projected uptake. Instead, crediting is typically ex post, i.e., based on measured and verified changes in carbon stock determined retrospectively after monitoring campaigns (Delacote et al. 2025). Such C-sinks may lose carbon (e.g., through wildfire or decomposition) and thus emit CO_2, or gain carbon (e.g., through biomass growth) and thus remove CO_2 from the atmosphere.

Because monitoring is generally performed at discrete intervals, evolving C-sinks are typically reported as annual stock changes. It is the empirical stock-difference method where each annual increment of CO_2 release or removal is treated as a separate CO_2 pulse and weighted by the atmospheric CO_2 impulse response function *IRF*(t). The total climate effect (TCE) over an offset horizon H is the sum of the climate effects of all annual pulses occurring within that horizon.

Let $M_{sink}(t)$ denote the certified carbon stock (tCO_2e) at the end of year t, with $M_{sink}(0)$ being the baseline stock at implementation. The net CO_2 emission or removal during year t is given by the annual increment in stock,

$$\Delta M_{sink}(t) = M_{sink}(t) - M_{sink}(t-1). \quad (10)$$

This increment is not a single pulse at a specific moment, but the net carbon added and/or lost continuously throughout year t. Because certification is ex post, $\Delta M_{sink}(t)$ is only known after the end-of-year measurement. Representing atmospheric carbon exchange at sub-annual resolution typically offers little additional accuracy relative to uncertainties in measurement and sink dynamics. We therefore discretize the sink trajectory into one effective (positive or negative) CO_2 pulse per year. For consistency with Sections 2.2 and 2.4, and in line with the midpoint convention used in IPCC stock-change accounting for LULUCF sinks (IPCC, 2006, 2019), each annual increment is treated as an effective pulse located at the midpoint of the year, i.e., at time $t-\frac{1}{2}$, corresponding to atmospheric carbon exchange distributed over the interval $[t-1, t]$.

We first define the midpoint stock for year $t \geq 1$ as

$$M_{mid}(t) = \frac{M_{sink}(t-1) + M_{sink}(t)}{2}, t = 1, \ldots, H, \quad (11)$$

with $M_{mid}(0) = M_{sink}(0)$. The annual CO2 pulse credited at time $t-\frac{1}{2}$ is then the increment in midpoint stock,

$$M_{impulse}(t) = M_{mid}(t) - M_{mid}(t-1), t = 1, \ldots, H. \quad (12)$$

The total climate effect delivered by an increasing sink over the horizon H is

$$\mathrm{TCE}_{sink}(H) = -\sum_{t=1}^{H} M_{impulse}(t)\,\mathrm{IRF}_{int}\left(H - t + \frac{1}{2}\right). \quad (13)$$

Given any annually certified sink-stock time series $M_{sink}(t)$, Equation (13) directly yields the TCE delivered up to horizon H, and can therefore be compared to methane warming $\mathrm{TCE}_{CH_4}(100)$ to assess offsetting. Here $\mathrm{IRF}_{int}(x) = \int_0^x \mathrm{IRF}(u)\,du$ is the integrated atmospheric CO_2 response of a 1 tCO_2 pulse over a duration x. The weighting $\mathrm{IRF}_{int}\left(H - t + \frac{1}{2}\right)$ reflects that the CO_2 pulse in year t is assigned to the midpoint of the year (time $t-\frac{1}{2}$) and therefore has only the remaining time until the end of the horizon to generate cooling. In other words, carbon removed or emitted during year t causes a climate effect only over the remaining interval from $t-\frac{1}{2}$ to H. As an example, for $H = 20$ years, the pulse assigned to year $t = 20$ occurs at time 19.5 and therefore contributes to the total climate effect only for the remaining 0.5 years. Accordingly, the integrated response is evaluated as $\mathrm{IRF}_{int}\left(20 - 20 + \frac{1}{2}\right) = \mathrm{IRF}_{int}(0.5)$.

Equation (13) is a general expression for the TCE of any evolving CO_2 sink represented as an annual sequence of removal and reversal pulses, and is applicable to both increasing and decreasing sinks. It requires only a certified time series of annual stock changes and naturally accommodates partial loss of sink integrity through negative annual impulses. When a functional description of sink dynamics is available (e.g., a retention function for biochar SPC), the annual impulse series can be generated from the function, and Equation (15) approaches the corresponding continuous-time integral form used in Section 2.7.

For permanent sinks, all carbon is removed at the start of the accounting horizon (year 0 → year 1), the only nonzero increment is $\Delta M_{sink}(1)$. All subsequent ΔM_{sink} vanish. In this case, the general expression reduces to the permanent-sink formulation used in Section 2.2, as the sum contains only a single impulse. For decreasing sinks the annual increments ΔM_{sink} become negative, while for increasing sinks the annual increments ΔM_{sink} become positive.

2.5.2 | Quantifying the Methane Offset Potential of Temporary C-Sinks

For any given annually certified C-sink stock time series $M_{sink}(t)$, Equation (13) yields the total climate effect delivered by the evolving sink up to horizon H. Methane offsetting requires that the magnitude of the integrated cooling delivered by the C-sink equals the integrated warming of the methane emission over 100 years (Equation 6):

$$-\mathrm{TCE}_{sink}(H) = \mathrm{TCE}_{CH_4}(100). \quad (14)$$

For a methane pulse of magnitude M_{CH_4} (tCH_4), the methane climate effect is

$$\mathrm{TCE}_{CH_4}(100) = M_{CH_4} \cdot \mathrm{GWP}_{100}(\mathrm{CH}_4) \cdot \mathrm{IRF}_{int}(100), \quad (15)$$

where $\mathrm{IRF}_{int}(100)$ is obtained from the Jeltsch–Thömmes & Joos IRF formulation (Section 2.1). Substituting Equations (13) and (15) into the offset condition (14) yields the methane mass that can be offset by the evolving C-sink over horizon H:

$$-\sum_{t=1}^{H} M_{impulse}(t)\,\mathrm{IRF}_{int}\left(H - t + \frac{1}{2}\right) = M_{CH_4} \cdot \mathrm{GWP}_{100}(\mathrm{CH}_4) \cdot \mathrm{IRF}_{int}(100), \quad (16)$$

and therefore

$$M_{CH_4-offset} = \frac{-\sum_{t=1}^{H} M_{impulse}(t)\,\mathrm{IRF}_{int}\left(H - t + \frac{1}{2}\right)}{\mathrm{GWP}_{100}(CH_4) \cdot \mathrm{IRF}_{int}(100)}. \quad (17)$$

Equation (17) directly quantifies the methane offset potential of any evolving C-sink based solely on its annually certified stock-change series. It applies equally to increasing sinks, declining sinks, and sinks subject to partial reversals, since negative annual impulses are naturally represented in $M_{impulse}(t)$. Each year's stock change contributes to cooling or warming according to how much time remains for its atmospheric CO_2 response to act before the horizon ends. Early CO_2 removal therefore counts more strongly than late removal, while reversals (i.e., net CO_2 release) directly reduce the net offset potential. In practice, Equation (17) converts a certified C-sink stock time series into an equivalent methane mass M_{CH_4} whose 100-year integrated warming can be offset by the evolving C-sink within the chosen horizon H.

2.6 | Calculations—GitHub Repository

All calculations and figures that are not fully reproduced in the equations below were implemented in Python and are provided in the associated GitHub repository: https://github.com/ithaka-hp/CH4-offset. The repository contains executable notebooks that reproduce the numerical results and figures presented in this paper and allow the reader to modify assumptions (e.g., time horizon, methane metric selection, or sink dynamics) and rerun the analyses. The Python code accompanying this paper was developed with the assistance of Claude and Claude Code (Anthropic). Gemini (Google) and/or ChatGPT (Open AI) were used to verify algorithms, calculations, and results. All code was reviewed, verified, and validated by the authors.

3 | Results

The TCE framework developed in Section 2 yields, for a constant, leakage-free carbon sink, the benchmark removal requirements against which evolving sinks can be compared. In the following sections, we apply the framework to three classes of carbon sinks with distinct temporal dynamics: an ex-post certified evolving sink with partial reversals (Section 3.1), a diminishing sink represented by the semi-persistent carbon pool of soil-applied biochar (Section 3.2), and an increasing sink represented by a teak plantation (Section 3.3). These applications illustrate how sink dynamics—timing, decay, and growth—determine the amount of CO_2 removal required to offset a methane emission within a 20-year delivery horizon.

3.1 | Ex-Post Certified Evolving Sinks

To illustrate the application of the general discrete TCE formulation (Equations 13, 17), we consider an example time series of annually certified end-of-year C-sink stocks $M_{sink}(t)$ over a 20-year period. The trajectory represents a typical temporary C-sink that accumulates carbon over several years but also experiences partial reversals (e.g., through decomposition, disturbance, harvesting, or management changes), as commonly observed in real-world monitored sinks (Figure 2).

As described in Section 2.5.1, the annual change in sink stock is converted into an effective mid-year removal or emission pulse $M_{impulse}(t)$ using the midpoint convention (Equations 10–12). Each annual pulse is weighted by the integrated atmospheric CO_2 response remaining within the chosen horizon, $\mathrm{IRF}_{int}(H - t + 1/2)$, and summed according to Equation (13). For the sink trajectory shown in Figure 2, using a horizon H = 20 years and $\mathrm{GWP}_{100}(\mathrm{CH}_4) = 27$, the total climate effect delivered by the evolving sink is:

$$\mathrm{TCE}_{sink}(20) = -\sum_{t=1}^{20} M_{impulse}(t)\,IRF_{int}\left(20 - t + \frac{1}{2}\right) = 3910.4\ \mathrm{tCO_2e \cdot yr}$$

Here, increases in C-sink stocks lead to negative M_impulse values (removals) and reversals to positive $M_{impulse}$ values (emissions). This integrated cooling effect can be expressed as

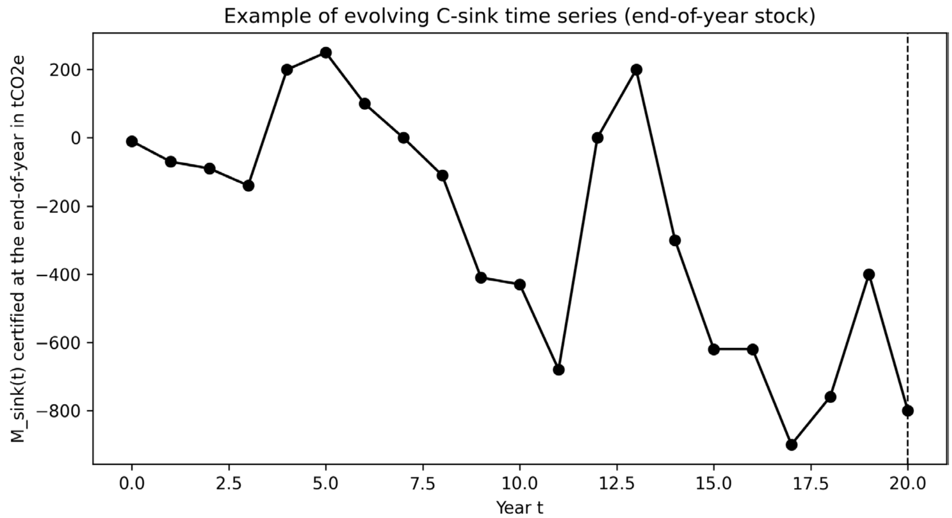

FIGURE 2 | Example of an end-of-year certified C-sink stock time series $M_{sink}(t)$ over 20 years (tCO_2e). The trajectory shows net carbon accumulation with partial reversals, representative of monitored temporary sinks.

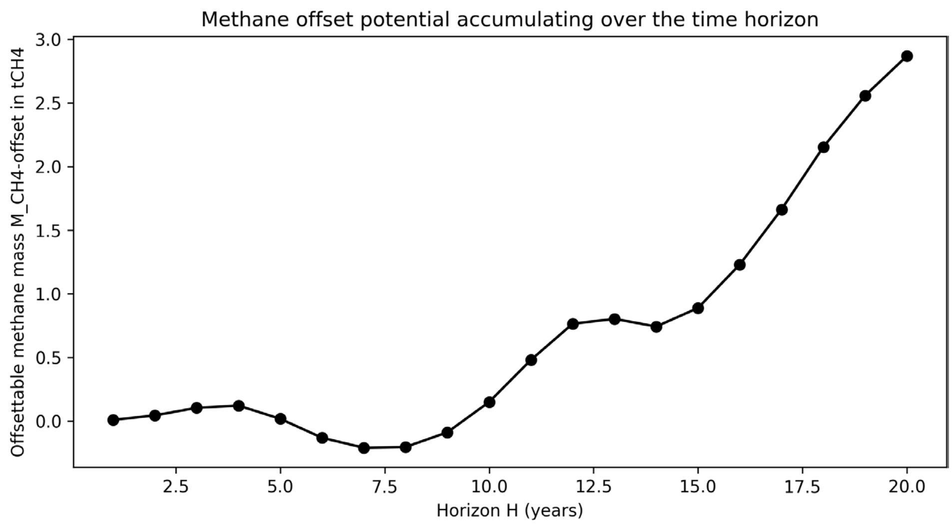

FIGURE 3 | Net methane offset potential $M_{CH_4-offset}$ accumulated over horizons $H = 1 \ldots 20$ years for the sink stock series shown in Figure 2, computed using Equation (17).

an equivalent methane mass whose 100-year integrated warming is offset by the C-sink over the 20-year horizon. Using Equation (17):

$$M_{CH_4-offset} = \frac{TCE_{sink}(20)}{GWP_{100}(CH_4)\,IRF_{int}(100)} = 2.87\ tCH_4.$$

Figure 3 shows the net methane offset potential accumulated for offset horizons H = 1…20 years. The curve illustrates a key physical insight of the method: CO_2 removals occurring early in the horizon contribute more strongly than removals occurring late, because they generate cooling over a longer remaining period. Conversely, late reversals (net CO_2 releases) reduce the net offset potential, even if the total sink stock remains positive.

This example demonstrates that the discrete TCE formulation (Equation 17) is fully compatible with evolving temporary sinks that include partial reversals and yields a methane-equivalent offset capacity based solely on the certified annual stock-change record without requiring a functional sink model.

3.2 | Methane Offsetting Using Mathematical C-Sink Functions

The discrete, ex-post framework applied above (Section 3.1) makes no assumptions about the functional form of a C-sink trajectory. However, some CDR methods exhibit sufficiently predictable dynamics that their time evolution can be described by a mathematical function—for example, biogenic growth curves for trees (Salas-Eljatib et al. 2021) or the degradation curve of the semi-persistent carbon (SPC) fraction of biochar when applied to soil (Schmidt, Abiven, et al. 2025; Schmidt, Hagemann, and Kammann 2025). For such sinks, the TCE can be evaluated analytically rather than from annual stock-change records. In the following two sections, we present the sink-specific parameterizations, integrate them into the TCE framework developed in Section 2, and report the resulting methane offset potentials for a diminishing sink (biochar SPC) and an increasing sink (teak plantation).

The methane-offsetting capacity can be quantified by combining a sink evolution function with the atmospheric CO_2 impulse response function IRF(t). The advantage of this approach is that $TCE_{sink}(H)$ can be calculated directly from the continuous sink function, yielding an exact integral representation without relying on annual discretization. However, because mathematically defined sink trajectories are only approximations of natural processes, the apparent increase in precision should not be overemphasized. Alternatively, mathematically defined sink trajectories may be converted into annual end-of-year stocks $M_{sink}(t)$, allowing the general discrete formulation (Equation 13) and methane offset potential equation (Equation 17) to be applied in the same manner as for any ex-post-certified C-sink.

In the following two subsections, we demonstrate the method for a decreasing sink trajectory using the SPC decay function, and then for an increasing C-sink using an exponential tree growth function for teak plantations.

3.3 | Offsetting Methane Emissions with SPC Pool of Soil-Applied Biochar

The semi-persistent carbon (SPC) fraction of biochar is defined as the portion of biochar carbon that does not persist for 1000 years after soil application. The remaining fraction after 1000 years is assigned to the geo-persistent carbon (GPC) pool. Accordingly, the SPC retention function is parameterized such that $f_{SPC}(0)=1$, the time to 50% remaining is $\approx$ 50 years, and $f_{SPC}(1000) \approx 0$, i.e., the SPC pool is effectively exhausted over a millennium. On the basis of conservative fits to biochar decomposition datasets, the SPC retention is described by a two-exponential function (Schmidt, Abiven, et al. 2025; Schmidt, Hagemann, and Kammann 2025):

$$f_{SPC}(t) = 0.1787\, e^{-0.5337t} + 0.8237\, e^{-0.00997t}. \quad (18)$$

where t is time in years after soil application.

To calculate the total climate effect of an SPC fraction of biochar, the atmospheric effect of the CO_2e remaining in the C-sink must therefore be weighted by the IRF function over the same time interval. Consistent with the definition in Section 2.2, the TCE delivered from the start ($t=0$) until the end of the considered time horizon (H) is

$$TCE_{SPC}(H) = -M_{sink} \int_0^H f_{SPC}(t) \cdot IRF(t)\, dt. \quad (19)$$

This combines the exponentially decreasing SPC mass with the exponentially decreasing atmospheric CO_2 response along consistent year-based intervals. The integral has units of years; multiplication by the mass of the SPC C-sink (M_{sink}) in tCO_2e yields $tCO_2e \cdot yr$.

Methane offsetting requires that the magnitude of integrated cooling delivered by the SPC sink over horizon H (with $H \le 20$ year) equals the integrated warming of the methane pulse over 100 years (see equation 6):

$$-\,TCE_{SPC}(H) = TCE_{CH_4}(100).$$

Inserting Equation (19) and solving for the required initial SPC C-sink mass gives

$$M_{sink,SPC}(H) = \frac{TCE_{CH_4}(100)}{\int_0^H f_{SPC}(t)\, IRF(t)\, dt}. \quad (20)$$

For a 1 t biogenic methane pulse (see chapter 2.3),

$$\begin{aligned} TCE_{CH_4}(100) &= GWP_{100}(CH_4) \cdot IRF_{int}(100) \cdot 1\, tCH_4 \\ &= 27.0 \frac{tCO_2e}{tCH_4} \cdot 50.481\ yr \cdot 1\, tCH_4 \\ &= 1363.0\, tCO_2e \cdot yr. \end{aligned}$$

Using $H = 20$ year. and

$$\int_0^{20} f_{SPC}(t)\, IRF(t)\, dt = 11.15\ yr,$$

we obtain

$$M_{sink,SPC}(20) = \frac{1363.0\, tCO_2e \cdot yr}{11.15\ yr} = 122.2\ tCO_2e.$$

Thus, applying biochar to soil requires 122.2 tCO_2e of the SPC fraction maintained over 20 years to offset the warming impact of 1 t CH_4. For comparison, a permanent CO_2 sink would require only 94.6 tCO_2e to offset the same 1 t CH_4 emission. The SPC pool must therefore be about 30% larger because part of the initially removed carbon is lost during the 20 years due to degradation. This difference quantifies the cooling potential forfeited when the carbon sink declines over time rather than remaining permanent.

To calculate the methane mass that can be offset by any given SPC pool of soil-applied biochar, we solve Equation (20) for $M_{CH_4-offset}$:

$$M_{CH_4-offset}(H) = \frac{M_{sink,SPC} \cdot \int_0^H f_{SPC}(t)\, IRF(t)\, dt}{GWP_{100}(CH_4) \cdot IRF_{int}(100)}. \quad (21)$$

For an SPC pool of 1000 tCO_2e, this yields

$$M_{CH_4-offset}(20) = \frac{1000\, tCO_2e \cdot 11.15 \cdot yr}{27.0 \frac{tCO_2e}{tCH_4} \cdot 50.481 \cdot yr} = 8.2\, t\, CH_4.$$

Sequestering 1000 tCO_2e in the form of biochar SPC for 20 years can therefore offset the emission of 8.2 t CH_4 (Figure 4). After 20 years, approximately 675 tCO_2e remain in the SPC pool and continue to provide cooling. If this remaining portion is used for further offsetting beyond year 20, the IRF and SPC integrals must be evaluated from $t = 20$ onward (i.e., shifted by 20 years), because the removal occurred 20 years earlier.

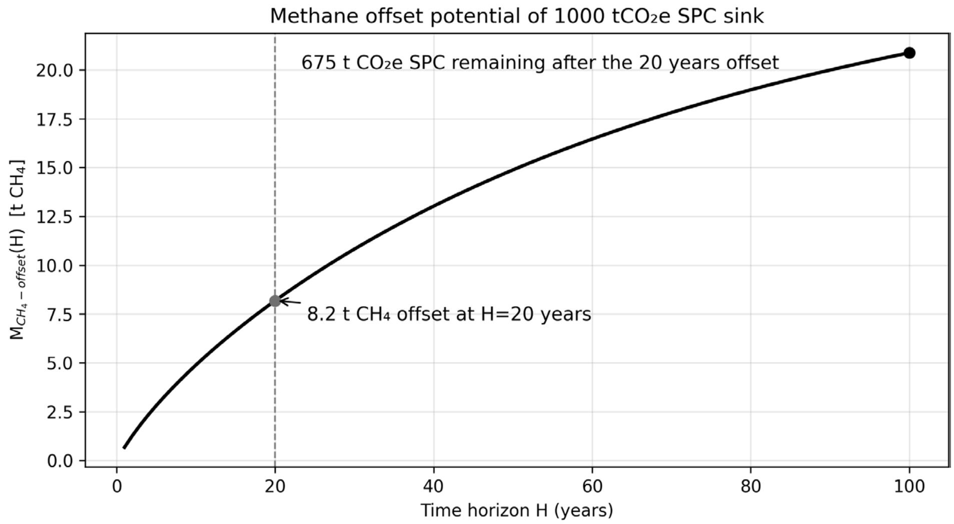

FIGURE 4 | Methane offset potential $M_{CH_4-offset}(H)$ of a fixed 1000 tCO_2e soil-applied biochar SPC sink as a function of the chosen time horizon H, calculated with Equation (21). The vertical dashed line marks the manuscript reference horizon H = 20 years, for which the SPC pool offsets 8.1 t CH_4.

3.4 | Using Tree Growth for Methane Offsetting

As for most living organisms, tree carbon stocks typically evolve sigmoidally with time (Salas-Eljatib et al. 2021). This S-shaped development can be approximated by three growth phases: (i) an early phase with accelerating growth, often well described by an exponential function; (ii) a middle phase with near-linear annual increments; and (iii) a late phase with declining growth rates as stands mature. While this general behavior is inherent to trees, actual growth rates depend on climate, soil, species, and management. Consequently, growth functions must be parameterized for the local context and cannot generally be extrapolated far beyond the defined tree stand.

For newly established plantations under favorable conditions, carbon stock increments are often well approximated by an exponential growth function during the first 10–30 years, depending on species and site conditions. In mature forests or long-lived urban tree populations, the relative growth rate is lower but often more regular than in young plantations with roughly constant increments per year. The early phase is particularly well suited for methane offsetting, because most of the IRF-weighted cooling must occur within 20 years and offsetting may become a valuable co-benefit for establishing new tree stands.

This pattern is documented for *Tectona grandis* (teak) plantations in Costa Rica, where above- and below-ground biomass was measured at stand ages of 5, 10, 15, and 20 years (Perez Cordero and Kanninen 2003). We fitted an exponential allometric function to these biomass data and used the resulting continuous growth curve as a mathematically predictable increasing C-sink trajectory.

Using a nonlinear least-squares fitting and converting the biomass to CO_2e with a carbon content of 0.47 in woody biomass, the formula for the cumulative sink stock is

$$M_{\text{sink-forest}}(t) = 134.8\left(e^{0.106t}1\right)\ \text{tCO}_2\text{e ha}^{-1}, \text{for } 0 \leq t \leq 20. \quad (22)$$

This continuous function approximates the annual sink stocks per hectare for the first 20 years after the plantation. The fitted function is exponential and therefore represents only the early-growth phase of the sigmoidal tree development as the middle phase is usually not reached in such rapid wood production plantations. We now calculate the integrated total climate effect delivered by this increasing sink within horizon H, and determine the land area required to offset a methane pulse of 1 tCH_4.

The annual CO_2 removal rate (the derivative) is:

$$\dot{M}_{\text{sink-forest}}(t) = \frac{dM_{\text{sink-forest}}}{dt} = 134.8 * 0.106 * e^{0.106*t}.$$

The total climate effect of the continuously increasing C-sink is calculated analogous to Equation (19) for SPC:

$$\text{TCE}_{\text{forest}}(H) = -A \int_0^H \dot{M}_{\text{sink-forest}}(t)\,\text{IRF}_{\text{int}}(H-t)\,dt. \quad (23)$$

Here, A is the plantation area in ha. The term $\text{IRF}_{\text{int}}(H-t)$ is used because the removal at time t affects the climate only during the remaining time interval $H-t$.

Wesolvetheequationfortherequiredplantationareatooffsetmethane using the general condition: $-\text{TCE}_{\text{forest}}(H) = \text{TCE}_{CH_4}(100)$.

Therefore, the required area to offset a methane emission with the mass M_{CH4} is:

$$A_{\text{req}}(H) = \frac{\text{TCE}_{CH_4}(100) \cdot M_{CH_4}}{\int_0^H \dot{M}_{\text{sink-forest}}(t)\,\text{IRF}_{\text{int}}(H-t)\,dt}, \quad (24)$$

And the mass of a CH_4 emission that can be offset with a given surface area A of a teak plantation with a tree density of 1100 trees per hectare can be calculated for horizons $H = 0 \ldots 20$ years, as shown in Figure 5 for a 1 ha plantation:

$$M_{CH_4-\text{offset}}(H) = \frac{-TCE_{\text{forest}}(H)}{GWP_{100}(CH_4) \cdot IRF_{\text{int}}(100)} \quad (25)$$

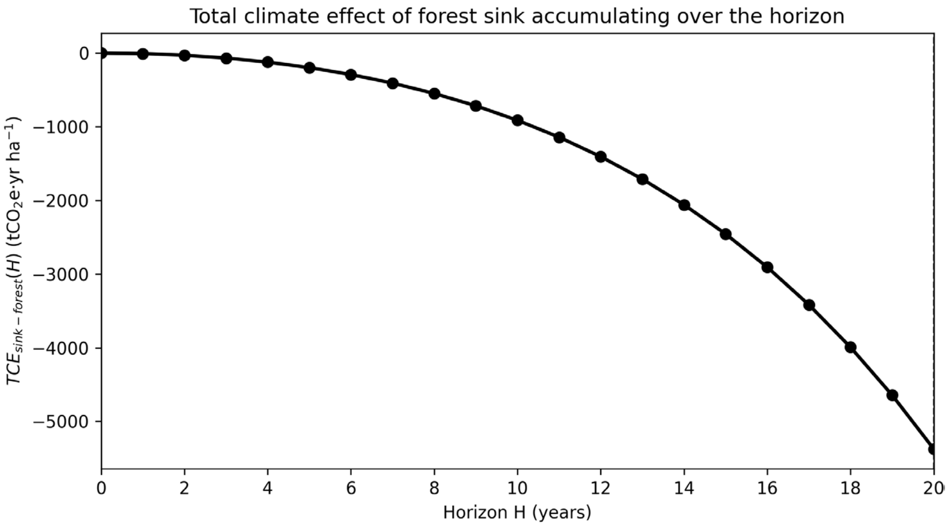

FIGURE 5 | Methane offset potential of the teak plantation sink trajectory per hectare, $M_{CH_4\text{–offset,ha}}(H)$, accumulated over horizons $H = 0 \ldots 20$ years. The curve is derived from the exponential teak sink stock function (Equation 22) combined with the IRF-weighted total climate effect integral (Equation 23, with $A = 1$ ha) and converted into methane-equivalent offset mass using Equation (25). The graph illustrates that methane offset potential accumulates slowly during the first years and increases more strongly in later years as the stand enters its rapid biomass accumulation phase, although late removals contribute less strongly to cooling within a fixed horizon because they have less remaining time to generate cooling.

For $H = 20$ years, the teak plantation offsets 3.95 tCH_4 per hectare. Therefore, offsetting 1 tCH_4 requires 0.25 ha of plantation, corresponding to ≈279 teak trees at a density of 1100 trees ha^{-1} (Figure 4). The example illustrates how an empirically derived tree-growth trajectory, representing an exponential increasing C-sink, can be translated into an integrated cooling effect within the IRF framework to offset methane emissions.

Despite the rapid carbon uptake of young teak, the IRF-weighted cooling delivered over a 20-year horizon remains modest for two structural reasons:

- Early-stage carbon removals are small, even for fast-growing species
- The large biomass increments occurring in years 10–20 have very little remaining cooling time before reaching the 20-year horizon

Increasing C-sinks such as trees are fundamentally disadvantaged for methane offsetting because most of their carbon is accumulated late and, thus, receives only very limited IRF-weighted cooling. It highlights the inherent difficulty of using "slow-starting, fast-finishing" biological systems to offset "fast-acting" methane within a short deadline.

4 | Discussion

The presented methods and results underscore the necessity of time-dependent climate accounting when evaluating methane offsetting. Static metrics such as GWP100 average climate impacts over a century and thereby obscure the highly asymmetric temporal profiles of radiative forcing caused by methane emissions and CO_2 removals. This black-box character of GWP100 has been widely discussed in the methane literature and led among others to the introduction of the GWP* metric (Cain et al. 2019; Lynch et al. 2020), which represents the temperature response to methane emissions using CO_2-equivalent pulses that reflect better methane's short-lived, rate-dependent warming. Yet while GWP* improves the representation of methane's flow-like behavior, it does not provide a mechanism for quantifying the global cooling effect delivered by CO_2 removals. The framework developed here fills precisely this gap by providing a physically explicit, stock-based method for establishing time-aligned equivalence between a methane emission and sequences of CO_2 removals.

A brief validation against standard methods reinforces this claim. For constant sinks, the IRF-based method presented here yields CO_2-removal requirements that differ by less than 5% from values derived using the Absolute Global Warming Potentials (AGWP) reported in IPCC AR6. This close correspondence over standard time horizons of 20 and 100 years demonstrates that the approach aligns with established carbon-cycle physics when applied to permanent storage, while providing additional transparency and flexibility when extended to temporary C-sinks or those that vary in time. The model is, therefore, not an alternative to AR6 physics but a generalization that becomes indispensable when temporal dynamics matter.

The IRF-based approach shows that equivalence depends on matching the temporal structure of warming and cooling: fast warming must be counterbalanced by fast cooling. This principle is confirmed by the near-linear behavior of the carbon cycle for the perturbation sizes considered by negative emission technologies (Rogelj et al. 2015). Carbon sinks of this magnitude allow the modelling of atmospheric responses to removals symmetrically to emissions. The result is a framework that resolves the timing of both positive and negative radiative forcing, enabling the quantification of equivalence over any chosen time horizon.

The central metric in our framework is the total climate effect (TCE), which expresses the time-integrated radiative forcing over a chosen horizon expressed in $tCO_2e \cdot yr$. To reach a net-zero status between emissions and removals over defined time horizons, the total climate effect (TCE) as defined in the method section must be zero. If no other conditions are set, a removal that delivers a cumulative cooling of X $tCO_2e \cdot yr$. could offset an emission that causes X $tCO_2e \cdot yr$. of warming, regardless of whether the cooling occurs immediately or is delayed. Over very long horizons, the difference becomes negligible in terms of integrated forcing, but from a near-term climate perspective, the mathematical equivalence of X $tCO_2e \cdot yr$. is incomplete. If the removal is delayed by, e.g., 20 years, the climate system experiences two decades of unmitigated positive forcing, followed only later by the compensating cooling. Such a scenario would produce higher transient warming, a different peak forcing profile, and potentially different temperature impacts and risks, even if the integrated forcing is identical over the full horizon of several thousand to millions of years.

This example shows that additional offset conditions, beyond TCE equivalence between emission and removal, must be defined. The “yr” in the $tCO_2e \cdot yr$. unit of the TCE carries implicit timing information, as the same cumulative cooling can have very different climate relevance depending on when it occurs. For practical climate mitigation and offsetting, TCE equivalence must therefore be constrained by the relative timing and shape of warming and cooling. In particular, offsetting claims typically require that:

i. Cooling occurs within a defined offsetting window after the emission;

ii. The cooling begins early enough to prevent a prolonged period of unmitigated near-term warming;

iii. The compensation is delivered over a time span comparable to the duration of the warming impact being offset (for methane, on the order of decades).

While equivalence under an integrated-forcing metric such as TCE does not imply equivalence in peak temperature, the rate of temperature change, or climate damages (Fuglestvedt et al. 2010; IPCC 2021), the above guardrails constrain the timing and shape of cooling relative to warming. They are intended to limit such divergences by avoiding near-term forcing overshoots.

Tonne-year metrics have been used to assign value to temporary carbon storage, but they often do so by equating a year of storage with a fraction of permanent mitigation—an economic abstraction that has been widely critiqued (Groom and Venmans 2023). Such approaches typically ignore the shape of the atmospheric forcing curve, treating each storage year as if it provided uniform benefit. The IRF-based method bypasses these limitations by grounding the valuation of temporary storage directly in atmospheric physics: rather than converting temporary storage into a discounted substitute for permanence, it quantifies the actual cooling delivered over a defined horizon and compares it to the warming profile to be offset.

For methane, this distinction is particularly important. Because methane's warming largely dissipates within a few decades, temporary cooling of comparable duration is not a compromise but the physically appropriate counterpart. Whereas tonne-year accounting for CO_2 offsetting requires repeated stacking of temporary credits to approximate permanence, methane offsetting requires only a finite-duration sink stack matched to the decay of the methane warming pulse. This shifts the debate away from economic exchange rates and toward physically defined equivalence.

The results presented for diminishing sinks illustrate this principle of physically defined equivalence clearly. Biochar's semi-persistent carbon (SPC) pool decays over time, and this decay is often treated in standard carbon accounting as a loss of permanence disqualifying this type of C-sinks for carbon crediting. In the IRF-based framework, however, decay is neither a failure nor a flaw—it is an input variable that determines how much initial CO_2 removal is required to deliver the needed cooling over the offset horizon. For a 20-year methane offset, the SPC pool requires roughly 122 t CO_2e of initial SPC-removal per tonne of CH_4 emitted, compared with about 96 t CO_2e for a permanent sink. This difference reflects both the decay of SPC carbon over the offset period and the time-dependent atmospheric response of CO_2 to a pulse removal, which gradually diminishes as carbon is exchanged with other reservoirs.

Increasing carbon sinks, such as tree growth, reveal an important timing constraint for methane offsetting. In carbon-cycle physics, terrestrial biomass uptake is already one of the processes that shape the CO_2 IRF; in climate policy, however, tree growth is additionally credited as a discrete CO_2 removal and widely promoted as a nature-based solution. Yet its suitability for offsetting short-lived climate pollutants has rarely been analyzed in time-explicit terms. The results here indicate that plantations are structurally disadvantaged for methane offsetting because early carbon accumulation is modest, while the largest carbon uptake occurs in later years, when there is little time left to generate IRF-weighted cooling within a 20-year offsetting horizon. Consequently, hundreds of trees may be required to offset a single tonne of methane over the first twenty years after plantation, and reliance on the later high-uptake phase would increase reversal risks from wildfire, drought, and pests (Anderegg et al. 2020).

This does not imply that tree plantations are “inefficient”. Afforestation and plantations are primarily established for forest restoration, ecosystem services, biodiversity, and the production of durable wood products, with climate benefits accruing over multi-decadal to century time scales. In our teak example, plantations can neutralize the 100-year integrated warming effect of a methane pulse within a 20-year horizon, but the requirement remains substantial (≈0.25 ha and 279 trees per tonne of CH_4). However, if methane offsetting draws only on the early-growth increments of the first 20 years, later years of growth remain available to deliver additional climate benefits. Delivering the 20-year cooling service does not deplete the underlying carbon stock. The further years of tree growing would remain eligible for additional, nonoverlapping mitigation or compensation claims under appropriate accounting rules. In this sense, near-term methane offsetting can be treated as an additional co-benefit of plantations—one that is largely overlooked in conventional crediting schemes that value tree-based removals primarily through relative long-term permanence claims rather than through the timing of cooling.

These findings address a recurring policy confusion. In most carbon-market frameworks, tree-based removals are treated as fungible with other removals, implicitly assuming that the carbon stock of the future mature forest can be used to offset present-day emissions (Li and Zhang 2024). The time-resolved analysis here shows why this is physically incorrect for methane: using the end state of a decades-long forest growth trajectory to counterbalance a short-lived warming pulse misaligns the timing of warming and cooling. Even under idealized ex-ante growth curves, plantations deliver most of their cooling too late to neutralize methane's near-term warming within a 20-year offset horizon. Fungibility based on end-point carbon stocks therefore creates an implicit time-shift of mitigation—and for methane, time-shifting is precisely what undermines physical equivalence.

The limitations of this study stem primarily from the use of linear IRF models, which do not capture potential nonlinear feedbacks in the carbon cycle or interactions with co-emitted species. Nonlinearities may emerge when components of the Earth system respond in ways that amplify or dampen atmospheric CO_2 changes outside the range represented by impulse–response functions. For example, large-scale warming can weaken natural land and ocean carbon sinks through reduced soil carbon storage, increased wildfire activity and changes in marine stratification that slow deep-ocean uptake, processes emphasized in recent assessments of carbon–cycle feedbacks (Chimuka et al. 2023; Williams et al. 2019). Warming-induced thaw of permafrost represents another positive feedback, potentially mobilizing large stores of previously frozen carbon as additional CO_2 and CH_4 and shifting high-latitude regions from net sinks to net sources (MacDougall 2021). Such processes can, in principle, extend the net atmospheric lifetime of anthropogenic CO_2 or introduce additional greenhouse gas emissions that are not captured by linear IRF formulations. Also, recent work by Winkler and Sierra (2025) suggests that the atmospheric response to incremental CO_2 emissions or removals depends on the evolving background concentration and sink state. State-aware, time- and space-dependent IRFs are therefore an active research direction and could imply shifts in IRF-weighted equivalence and in time-dependent GWPs relative to the fixed-parameter used here. The present framework remains directly applicable under alternative IRF parameterizations, as only the CO_2 IRF function needs to be substituted.

A further class of nonlinear feedbacks arises from atmospheric chemistry. Methane, carbon monoxide, and hydroxyl radicals are tightly coupled, so perturbations in methane or co-emitted species can alter the global OH burden and thus methane's effective lifetime. Interactive-chemistry studies show that neglecting these feedbacks can bias inferred methane sources over decadal timescales, and that changes in CO or NO_X emissions can either lengthen or shorten methane lifetime in a nonlinear manner (Nguyen et al. 2020; Stevenson et al. 2020). Methane oxidation also produces tropospheric ozone and stratospheric water vapour, both of which add radiative forcing and are influenced by climate-driven changes in stratospheric chemistry and transport (Revell et al. 2016; Robrecht et al. 2019). These coupled chemical and dynamical responses are not resolved in simple IRF representations. Despite these limitations, the linear approximation remains robust for the small to moderate perturbations analyzed here and is consistent with established approaches for computing AGWP and GWP. The framework is therefore best interpreted as a physically consistent offsetting tool within the parameter space where impulse–response models have been validated.

A closely related and timely contribution is provided by Venmans et al. (2025), who independently develop an impulse-response–based framework to assess the offsetting of methane emissions by temporary CO_2 removals. Their analysis reaches a conclusion that is directionally consistent with ours: because methane causes predominantly short-lived warming, temporally matched, temporary CO_2 removal can provide a more appropriate counterbalance than permanent removal. However, their approach is framed in terms of welfare equivalence and avoided economic damages, explicitly incorporating discounting, damage functions, and the costs of delayed action, rather than restricting equivalence to physical compensation of radiative forcing and temperature effects. As a consequence, the treatment of carbon sinks remains largely abstracted from project-level carbon accounting constraints, permanence definitions, and sink-specific dynamics. In contrast, the present study focuses explicitly on physical equivalence under defined guardrails and on the accounting implications for different classes of carbon sinks, including diminishing and increasing biological sinks. Earlier work by Rodríguez et al. (2012) proposed compensatory actions for methane emissions from tunnelling activities based on forestation, illustrating an applied form of methane compensation, but without a time-resolved climate response framework or explicit equivalence criteria. Lauder et al. (2013) developed an early IRF-based "mixed metric" concept for methane, arguing that offsets should compare ongoing CH_4 emissions (or reductions) to one-off CO_2 sequestration rather than relying on GWP-based emission equivalence. They show that the timing of CO_2 uptake (e.g., gradual sequestration trajectories) strongly affects the degree of radiative cancellation over decadal to multi-century timescales—reinforcing the core point of this paper that temporal forcing profiles, not end-state carbon stocks, determine physical equivalence. Together, these studies underline growing interest in methane-specific offsetting approaches, while highlighting the need for physically grounded, time-explicit methods that can be directly mapped onto carbon-sink accounting rules and offset integrity requirements.

That this need extends beyond methane to CDR valuation more broadly is confirmed by Watson and Bui (2026) who reach a complementary conclusion through a systematic sensitivity analysis of three prominent economic equivalency ratios—the climate repair value, discounted tonne-year accounting, and the social value of an offset. They demonstrate that these ratios are highly sensitive to arbitrary input choices such as discount rates and policy-defined time horizons, and argue that physical "like-for-like" equivalence offers a more robust basis for valuing CDR. However, they also note that physical equivalence methods "remain underdeveloped and vulnerable to criticism for over-simplifying the complex scientific relationships between GHG emissions, CDR, and temperature response." The IRF-based TCE framework developed here directly addresses this gap: it provides a quantitative, time-explicit method for establishing physical equivalence between methane emissions and temporary CO_2 removals, accounting for sink-specific dynamics such as decay and growth. Within Watson and Bui's taxonomy of Carbon Cycle Matching and Atmospheric Longevity Matching, the present framework can be understood as an operationalization of Atmospheric Longevity Matching—one that moves from the conceptual principle to a calculable, sink-resolved equivalence suitable for carbon-accounting and crediting applications.

With 390 million tonnes of anthropogenic methane emitted each year and roughly half of these emissions being difficult or impossible to avoid (around 145 Mt. CH_4 from agricultural sources alone), the potential market for methane offsetting is substantial (Brazzola et al. 2021). Using the IRF-based equivalence developed in Section 2.2, fully neutralizing these agricultural emissions over a 20-year horizon would require around 14 Gt CO_2e of temporary C-sinks (145 Mt. $CH_4 \times 96.4\,t$ CO_2e per t CH_4). If temporary C-sinks are valued at around 30 € per tonne CO_2e over 20 years—roughly one-fifth of the price currently charged for C-sinks considered permanent over a > 100-year horizon—the resulting market volume would be on the order of 420 billion € per year.

This illustrates two points. First, the economic stakes of time-aligned methane offsetting are very high: temporary sinks capable of delivering near-term cooling could become a major climate-service sector in their own right. Second, a market of this size requires crediting rules that explicitly value the timing of CDR, rather than permanence alone. Moreover, the scale of this potential market indicates that temporary sinks could play a significant role in bridging the next several decades until durable, high-capacity CDR technologies scale to maturity (Edenhofer et al. 2023).

More broadly, the framework reveals a decisive conceptual shift: the TCE of a CO_2 emission should be compensated by the TCE of carbon sinks over the same time horizon, rather than being offset once and forever by weak claims of permanence that are hard to guarantee in practice. Temporary C-sinks can fully compensate for the global warming effect of CO_2 emissions—but only for limited periods, after which they must be replaced by either a new temporary sink or a permanent sink (Matthews et al. 2023; Stoefs 2023). This is not a weakness of temporary sinks but the basis for a time-synchronized climate-risk management strategy.

Incorporating this distinction into climate strategies and carbon-crediting frameworks would enable the construction of targeted removal portfolios and establish credible tools for temporary climate action as emphasized by recent climate strategies (Edenhofer et al. 2023). Time-aligned global cooling is essential for limiting near-term warming during the decades ahead and for bridging the period until durable, high-capacity removal technologies—such as DACCS and enhanced rock weathering—become available at scale.

As an outlook, the same IRF-based logic allows temporary and permanent removals to be integrated into dynamic portfolios that track climatic needs over time. Temporary C-sinks can deliver strong, immediate cooling when it is, likely, the most valuable—in the next one to three decades—while permanent sinks ensure long-term stabilization once scalable technologies mature. This turns temporary C-sinks from being viewed as "second-class removals" into essential components of a time-responsive climate-mitigation architecture.

The framework, therefore, offers a consistent, and universal tool for evaluating all forms of carbon sinks, irrespective of whether their carbon stocks decrease, remain stable, or increase over time.

Author Contributions

Nikolas Hagemann: conceptualization, validation, writing – review and editing, investigation, funding acquisition. **Hans-Peter Schmidt:** conceptualization, investigation, writing – original draft, methodology, validation, writing – review and editing, software.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are openly available in GitHub at https://github.com/ithaka-hp/CH4-offset.

References

Anderegg, W. R. L., A. T. Trugman, G. Badgley, et al. 2020. "Climate-Driven Risks to the Climate Mitigation Potential of Forests." *Science (1979)* 368, no. 6497: eaaz7005. https://doi.org/10.1126/science.AAZ7005.

Balcombe, P., J. F. Speirs, N. P. Brandon, and A. D. Hawkes. 2018. "Methane Emissions: Choosing the Right Climate Metric and Time Horizon." *Environmental Science. Processes & Impacts* 20: 1323–1339. https://doi.org/10.1039/C8EM00414E.

Brazzola, N., J. Wohland, and A. Patt. 2021. "Offsetting Unabated Agricultural Emissions With CO2 Removal to Achieve Ambitious Climate Targets." *PLoS One* 16: e0247887. https://doi.org/10.1371/JOURNAL.PONE.0247887.

Cain, M., J. Lynch, M. R. Allen, J. S. Fuglestvedt, D. J. Frame, and A. H. Macey. 2019. "Improved Calculation of Warming-Equivalent Emissions for Short-Lived Climate Pollutants." *NPJ Climate and Atmospheric Science* 2, no. 1: 29. https://doi.org/10.1038/s41612-019-0086-4.

Chimuka, V. R., C. M. Nzotungicimpaye, and K. Zickfeld. 2023. "Quantifying Land Carbon Cycle Feedbacks Under Negative CO2emissions." *Biogeosciences* 20: 2283–2299. https://doi.org/10.5194/BG-20-2283-2023.

Delacote, P., S. Chabé-Ferret, A. Creti, et al. 2025. "Restoring Credibility in Carbon Offsets Through Systematic ex Post Evaluation."

Nature Sustainability 8: 733–740. https://doi.org/10.1038/s41893-025-01589-7.

Edenhofer, O., M. Franks, M. Kalkuhl, and A. Runge-Metzger. 2023. "On the Governance of Carbon Dioxide Removal – A Public Economics Perspective." *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.4422845.

Forster, P., K. Alterskjaer, C. Smith, et al. 2021. "SPM 923 7 Coordinating Lead Authors: Contributing Authors: Review Editors: Chapter Scientists: The Earth's Energy Budget, Climate Feedbacks and Climate Sensitivity 923–1054." https://doi.org/10.1017/9781009157896.009.

Fuglestvedt, J. S., K. P. Shine, T. Berntsen, et al. 2010. "Transport Impacts on Atmosphere and Climate: Metrics." *Atmospheric Environment* 44: 4648–4677. https://doi.org/10.1016/J.ATMOSENV.2009.04.044.

Groom, B., and F. Venmans. 2023. "The Social Value of Offsets." *Nature* 619, no. 7971: 768–773. https://doi.org/10.1038/s41586-023-06153-x.

IPCC. 2013. "Climate Change 2013: The Physical Science Basis Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge. ed. Cambridge."

IPCC. 2021. "The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change." Cambridge.

IPCC. 2022. "IPCC Sixth Assessment Report (AR6) –Working group III contribution, UNEP."

IPCC. 2023. "The Earth's Energy Budget, Climate Feedbacks and Climate Sensitivity. Climate Change 2021 – The Physical Science Basis 923–1054." https://doi.org/10.1017/9781009157896.009.

Jackson, R., E. Solomon, J. Canadel, M. Cargnello, and C. Field. 2019. "Methane Removal and Atmospheric Restoration." *Nature Sustainability* 2: 436–438.

Jeltsch-Thömmes, A., and F. Joos. 2019. "The Response to Pulse-Like Perturbations in Atmospheric Carbon and Carbon Isotopes." *Climate of the Past* 2: 1–36.

Joos, F., R. Roth, J. S. Fuglestvedt, et al. 2013. "Carbon Dioxide and Climate Impulse Response Functions for the Computation of Greenhouse Gas Metrics: A Multi-Model Analysis." *Atmospheric Chemistry and Physics* 13: 2793–2825. https://doi.org/10.5194/ACP-13-2793-2013.

Köhler, A. R., and W. Joerss. 2025. "Technical Approaches to Removing Methane From the Atmosphere (Methane Removal) | Umweltbundesamt."

Lauder, A. R., I. G. Enting, J. O. Carter, et al. 2013. "Offsetting Methane Emissions—An Alternative to Emission Equivalence Metrics." *International Journal of Greenhouse Gas Control* 12: 419–429. https://doi.org/10.1016/J.IJGGC.2012.11.028.

Li, L., and D. Zhang. 2024. "Forest Carbon Offset Protocols in Compliance Carbon Markets." *Forest Policy and Economics* 165: 103253. https://doi.org/10.1016/J.FORPOL.2024.103253.

Lynch, J., M. Cain, R. Pierrehumbert, and M. Allen. 2020. "Demonstrating GWP*: A Means of Reporting Warming-Equivalent Emissions That Captures the Contrasting Impacts of Short- and Long-Lived Climate Pollutants." *Environmental Research Letters* 15: e044023. https://doi.org/10.1088/1748-9326/AB6D7E.

MacDougall, A. H. 2021. "Estimated Effect of the Permafrost Carbon Feedback on the Zero Emissions Commitment to Climate Change." *Biogeosciences* 18: 4937–4952. https://doi.org/10.5194/BG-18-4937-2021.

Matthews, H. D., K. Zickfeld, A. Koch, and A. Luers. 2023. "Accounting for the Climate Benefit of Temporary Carbon Storage in Nature." *Nature Communications* 14, no. 1: 5485. https://doi.org/10.1038/s41467-023-41242-5.

McKay, D. I. A., A. Staal, J. F. Abrams, et al. 2022. "Exceeding 1.5°C Global Warming Could Trigger Multiple Climate Tipping Points." *Science (1979)* 377: eabn7950. https://doi.org/10.1126/SCIENCE.ABN7950.

Mundra, I., and A. Lockley. 2024. "Emergent Methane Mitigation and Removal Approaches: A Review." *Atmospheric Environment: X* 21: 100223. https://doi.org/10.1016/J.AEAOA.2023.100223.

Myhre, G. D., F. M. Shindell, W. Breon, J. Collins, J. Fuglestvedt, et al. 2013. "Anthropogenic and Natural Radiative Forcing." In *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by T. Stocker, D. Qin, M. Platner, et al., 712. IPCC.

Nguyen, N. H., A. J. Turner, Y. Yin, M. J. Prather, and C. Frankenberg. 2020. "Effects of Chemical Feedbacks on Decadal Methane Emissions Estimates." *Geophysical Research Letters* 47: e2019GL085706. https://doi.org/10.1029/2019GL085706.

Perez Cordero, L. D., and M. Kanninen. 2003. "Aboveground Biomass of Tectonia Grandis Plantations in Costa Rica." *Journal of Tropical Forest Science* 15: 199–213.

Revell, L. E., A. Stenke, E. Rozanov, W. Ball, S. Lossow, and T. Peter. 2016. "The Role of Methane in Projections of 21st Century Stratospheric Water Vapour." *Atmospheric Chemistry and Physics* 16: 13067–13080. https://doi.org/10.5194/ACP-16-13067-2016.

Robrecht, S., B. Vogel, J. U. Grooß, et al. 2019. "Mechanism of Ozone Loss Under Enhanced Water Vapour Conditions in the Mid-Latitude Lower Stratosphere in Summer." *Atmospheric Chemistry and Physics* 19: 5805–5833. https://doi.org/10.5194/ACP-19-5805-2019.

Rodríguez, R., M. B. Díaz-Aguado, and C. Lombardía. 2012. "Compensation of CH4 Emissions During Tunneling Works in Asturias: A Proposal With Benefits Both for Local Councils and for the Affected Population." *Journal of Environmental Management* 104: 175–185. https://doi.org/10.1016/J.JENVMAN.2012.03.020.

Rogelj, J. G., R. C. Luderer, E. Pietzcker, et al. 2015. "Energy System Transformations for Limiting End-Of-Century Warming Below 1.5 Degress C." *Nature Climate Change* 5: 519.

Salas-Eljatib, C., L. Mehtätalo, T. G. Gregoire, D. P. Soto, and R. Vargas-Gaete. 2021. "Growth Equations in Forest Research: Mathematical Basis and Model Similarities." *Current Forestry Reports* 2021 7, no. 4: 230–244. https://doi.org/10.1007/S40725-021-00145-8.

Schmidt, H., S. Abiven, A. Cowie, et al. 2025. "Biochar Permanence—A Policy Commentary." *GCB Bioenergy* 17: e70092. https://doi.org/10.1111/GCBB.70092;PAGE:STRING:ARTICLE/CHAPTER.

Schmidt, H., S. Abiven, N. Hagemann, and J. Meyer zu Drewer. 2022. "Permanence of Soil Applied Biochar." *Biochar Journal* 1: 69–74.

Schmidt, H., N. Hagemann, and C. I. Kammann. 2025. *Global Biochar C-Sink Standard 3.2 [WWW Document]*. Carbon Standards International.

Smith, C., P. Forster, M. Palmer, et al. 2021. "IPCC WGI AR6 Chapter 7 [WWW Document]." https://doi.org/10.5281/zenodo.5211358.

Smith, C., T. Gasser, Z. Nicholls, et al. 2021. "The Earth's Energy Budget, Climate Feedbacks and Climate Sensitivity Supplementary Material Lead Authors: Contributing Authors."

Stevenson, D. S., A. Zhao, V. Naik, et al. 2020. "Trends in Global Tropospheric Hydroxyl Radical and Methane Lifetime Since 1850 From AerChemMIP." *Atmospheric Chemistry and Physics* 20: 12905–12920. https://doi.org/10.5194/ACP-20-12905-2020.

Stoefs, W. 2023. "A Framework for Assessing the Climate Value of Temporary Carbon Storage–Carbon Market Watch."

UNEP. 2021. "Global Methane Assessment - Benefits and Costs of Mitigating Methane Emissions."

Venmans, F., W. Rickels, and B. Groom. 2025. "Temporary Carbon Dioxide Removals to Offset Methane Emissions." *Nature Climate Change* 16: 1–6. https://doi.org/10.1038/s41558-025-02487-8.

Watson, C., and M. Bui. 2026. "Can Temporary Carbon Dioxide Removal Fix a Long-Term Climate Problem? An Analysis of Equivalency Ratios and the Like-For-Like Approach." *Environmental Research: Climate* 5: e015022. https://doi.org/10.1088/2752-5295/ae4058.

Wigley, T. M. L. 1998. "The Kyoto Protocol: CO2, CH4 and Climate Implications." *Geophysical Research Letters* 25: 2285–2288. https://doi.org/10.1029/98GL01855.

Williams, R. G., A. Katavouta, and P. Goodwin. 2019. "Carbon-Cycle Feedbacks Operating in the Climate System." *Current Climate Change Reports* 5: 282–295. https://doi.org/10.1007/S40641-019-00144-9/TABLES/2.

Winkler, A. J., and C. A. Sierra. 2025. "Towards a New Generation of Impulse-Response Functions for Integrated Earth System Understanding and Climate Change Attribution." *Geophysical Research Letters* 52: e2024GL112295. https://doi.org/10.1029/2024GL112295.

Zickfeld, K., A. H. MacDougall, and H. Damon Matthews. 2016. "On the Proportionality Between Global Temperature Change and Cumulative CO_2 Emissions During Periods of Net Negative CO_2 Emissions." *Environmental Research Letters* 11: e055006. https://doi.org/10.1088/1748-9326/11/5/055006.