Temporary carbon dioxide removals to offset methane emissions

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ABSTRACT

Methane (CH_4) is between 30 and 100 times more powerful a Greenhouse Gas than Carbon Dioxide (CO_2). This range depends on the time horizon considered, because time profile of higher temperatures caused by CH_4 is concentrated in the first 20 years after the initial impulse, in contrast to the lower, more permanent effects on temperature of CO_2 emissions. Here, we argue that these largely temporary temperature effects of CH_4 emissions are apt to be offset by temporary CO_2 removals, administered by temporary contracts. The advantages of this approach are that short term, say 20-year, contracts are more credibly monitored and enforced than the eternal contracts for permanent removals. In addition, the temporal matching of offsetting temperature reductions to the temperature impulse of CH_4 removes the major intertemporal transfers associated with the sharp changes in temperature due to CH_4 when offset by equivalent permanent solutions. For this reason, agreement on the appropriate quantity of temporary carbon offsets is insensitive to otherwise controversial parameters such as the social discount rate, climate change damages and emissions scenario (RCP). Assigning temporary carbon removal projects (usually Nature Based Solutions) to offset methane emissions therefore leverages projects which are otherwise viewed as low quality to nullify short-lived yet damaging temperature effects. Separate markets could then be organized around offsetting CH_4 emissions in the agricultural sector, where difficult to remove so-called 'residual' emissions abound. Credits in this market for CH_4 offsets could be based on metrics of equivalence between CH_4 and CO_2 over an agreed horizon. Using the equivalence based on avoided economic damages suggests that, for 20 year contracts, 136 temporary CO_2 removals are needed to offset 1-tonne of CH_4. This level of equivalence therefore provides strong incentives for reducing emissions for all but the most expensive cases, rather then offsetting them using temporary projects.
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1 Introduction

Anthropogenic methane (CH_4) emissions are the second largest cause of climate change after carbon dioxide (CO_2) emissions, contributing 0.5 [0.3 to 0.8]°C to the 2010–2019 warming relative to 1850–1900.[1] Unlike CO_2, CH_4 emissions have a particularly large short-term effect on temperature.[2] As a result, various initiatives have been taken to reduce CH_4 emissions, most notably the global methane pledge which aims to reduce CH_4 emissions by at least 30% below 2020 levels by 2030.[3] However, about 40 percent of global CH_4 emissions come from the agricultural sector, of which about a third is considered to be residual, i.e. emissions that are too costly to reduce.[4] In modelled scenarios that limit warming to 1.5°C with limited or no temperature overshoot (C1), average, global CH_4 emissions are still 125.12 [SD 35.62] and 121.50 [SD 40.47] Mt in the agriculture, forestry and other land uses (AFOLU) sector in the year 2050 and 2070, respectively.[5] At the same time, the AFOLU sector is critical for climate change mitigation by removing atmospheric CO_2 via so called nature-based solutions (NBS) to offset residual CO_2 and other greenhouse gas (GHG) emissions. While this type of offsetting can result in net-zero GHG emissions in simulated emission scenarios based on a 100-year global warming potential (GWP), it does not achieve the near-term climate benefits of CH_4 emission reductions.[6–11] Nor does it address the question of how offsetting with temporary CO_2 removal, for example through afforestation in this sector, can be appropriately integrated into national and international emissions trading.

Here, we show that there are several practical advantages that arise from undertaking equivalent temporary CO_2 removals to offset the short-term warming effect of CH_4 emissions. Principally, temporary CO_2 removals that are scheduled to coincide with the large short-run temperature effect of CH_4 emissions can virtually nullify methane's short-term temperature effect. Beyond addressing the physical mismatch in the timing of permanent offset solutions to the temporary climate effects of CH_4, taking action in the short-run can ameliorate concerns about the credibility of monitoring and enforcing eternal contracts for CO_2 removals. Shorter term contracts, it can be argued, are more easily monitored to evaluate performance and allow for renegotiation of terms in the event of under-performance,[12,13] both important weaknesses of eternal contracts.

Furthermore, by virtually nullifying temperature changes from CH_4 emissions over time, short-run contracts for temporary solutions do a much better job of smoothing out the damages of climate change across generations. In the context of CH_4 emissions, therefore, shorter term contracts over temporary CO_2 removals not only make sense in terms of ameliorating the temporary warming effect, but also make more sense from the perspective of administering a CO_2 removal contract and managing well-being across time. Indeed, 20 year contracts would seem sensible, being both in line with existing well-monitored contracts in the economy at large, but also covering the duration of the main temperature effect of CH_4 emissions.

Finally, because both warming by CH_4 emissions and cooling by temporary CO_2 removal take place in the short-run, the calculation of how much CO_2 removal is equivalent to 1-ton of methane emissions is insensitive to key determinants of inter-temporal trade-offs of welfare: the social discount rate, economic damage parameters and the expected RCP scenario.

We illustrate all of these points using a storage period of 20 years. This we consider suitable for implementing appropriate and, above all, sufficient monitoring and verification measures for CO_2 removal and storage. This duration is also important in the context of international emissions trading. In terms of the value of damages avoided in the long-run, we show that 1 tonne of methane emitted can be offset by 136 to 156 CO_2 short-removals with a duration of 20 years. This narrow range depends on assumptions about failure risk within the 20 storage years, the future development of global GHG emissions and the discount rate. We then compare the 20 year contract to both a temporary 40 year contract and a permanent (infinite horizon) contract, each of which are equivalent in the sense that they offset the damages of CH_4 emissions in present value terms. Naturally, longer time horizons for the removals reduce the equivalence-ratio below 136-157 tons. However, longer term contracts introduce less credible contract durations, less smoothing of temperatures/damages over time and consequently greater sensitivity of the equivalence to the the choice of RCP scenario and the discount rate. These results illustrate clearly the advantages of short-term offset contracts in the case of CH_4.

The implications for policy of these results are clear and important. Since most residual CH_4 emissions and temporary CO_2 removals occur in the AFOLU sector, offsetting organised around the short-term equivalence approach discussed here could be limited to this pillar of climate policy. Such a design might support the development of separate markets where operators of durable CO_2 removal projects have incentives to take additional measures to prove permanent storage such that they can supply removal credits at more favorable exchange rate in other markets than those operators of less durable but potentially cheap carbon removal projects. The latter would then be willing to accept the less favorable exchange rate, while still realizing an overall climate benefit compared to a situation without separated markets. At the same time, the high exchange (equivalence) rate keeps the incentives for CH_4 emissions reductions (rather than offsetting with removals) in place.

Matching schedules of CH_4 emissions to temporary CO_2 removals

CH_4 is a more powerful greenhouse gas than carbon, albeit with a shorter atmospheric lifetime. The chief concern about CH_4 emissions is the large short-run effect in temperatures more than the much smaller long-run effect due to the residual CO_2 that CH_4 eventually turns into. It is estimated that 0.5°C of the current 1.3°C temperature increase stems from the day to day flow of CH_4 emissions.[1] A popular measure for the impact of a greenhouse gas is its Global Warming Potential (GWP_X), defined as the extra energy that is absorbed by the earth as a consequence of a tonne of emission over a given number of years (X). Over 20 (100) years the GWP of 1 tonne of methane is approximately 82.5 (29.8) times larger than a tonne of carbon (Values for non-fossil methane emissions are slightly lower (79.7 and 27.0 respectively) because the carbon atom of methane originates from atmospheric CO_2 for non-fossil methane, IPCC AR6, WGI, Table 7.15). The difference in GWP between CH_4 and CO_2 reflects the different energy forcing and how this forcing gradually dissipates over time. CH_4 oxidizes to CO_2 within decades and CO_2 is absorbed by oceans over centuries. As a result, when establishing GWP equivalence of CH_4 and CO_2, even over a long period of X = 100 years (as is typical for GWP equivalence), the effect of CO_2 beyond 100 years is ignored. This makes trade-offs between both gases hard to assess.[6–11] When offsetting CH_4 emissions with temporary CO_2 removals, this mismatch in temporal horizons is avoided, with both actions havingnegligible effect after a century, as shown in Panels (a) and (b) of Figure 1.

Panel (a) in Figure 1 shows the time profile of temperature change resulting from an offsetting strategy for methane emissions with permanent carbon removal based on GWP_{100}. Based on GWP equivalence, 30 tons of permanent CO_2 removal are required to offset 1 tonne of CH_4. The blue line shows the temperature impact of an emission of 1 tonne of CH_4, which rises quickly and then almost as quickly dissipates. The green lines show the temperature path arising from an offsetting (GWP_{100}) equivalent) permanent carbon removal. Since CO_2 and CH_4 have a different impact over time, warming is not perfectly offset

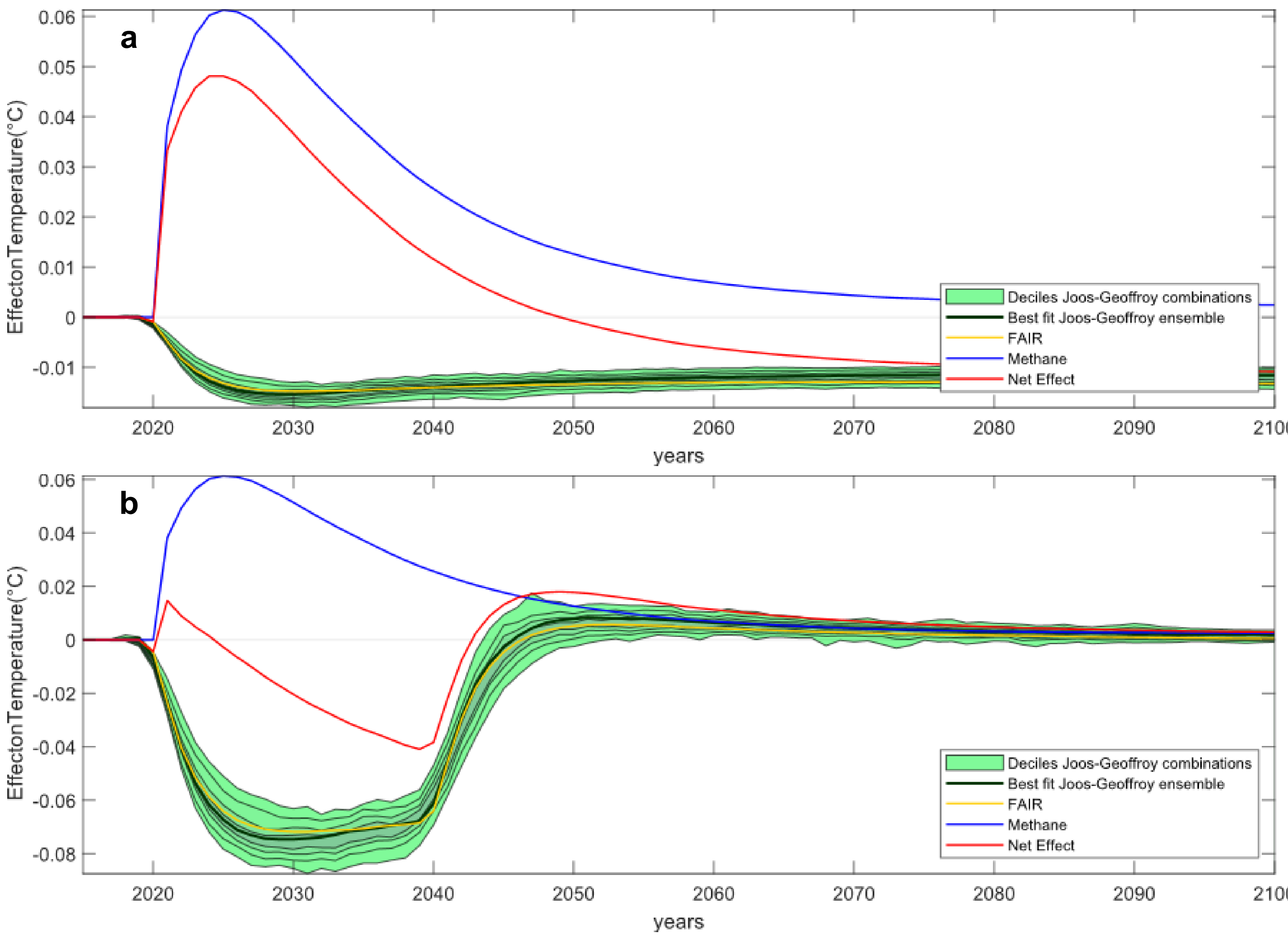

Figure 1. The effect on temperature of a CH_4 emission offset by 30 permanent CO_2 removals (Panel a) and by 136 temporary CO_2 removals (Panel b): The effects on temperature are estimated using the FAIR model of Joos et al.[14]. The blue line is the impulse response function for a CH_4 emission. The yellow line reflects the effect of thetemporary CO_2 removal. The red line charts the temperature change when the CH_4 emission is offset by 30 permanent CO_2 removals or 136 20-year temporary carbon removals (equivalence ratio for RCP1 2.6, at 2,5% discount rate and no risk). The other lines in green are the 16 absorption models of Joos et al.[14] combined with 16 energy balance models from the CMIP 5 ensemble (as in Geoffroy et al.[15]). The black lines show the deciles of the 256 possible combinations of models. The FAIR model uses the best fit of the CMIP5 models but adds saturation of carbon sinks. The climate sensitivity of all energy balance models has been harmonized to 3.1°C.

over time, despite GWP equivalence over 100 years. The red line shows the net effect on temperature when CH_4 emissions and CO_2 removal happen simultaneously based on this long run trade-off.

The net effect of these two interventions is a steep increase in temperature in the short run which is compensated by lower temperatures from 2050 onwards. Using permanent CO_2 removals (30 tonnes) to offset 1 tonne of CH_4 emissions in terms of GWP_{100} leads to large increases in temperature in the short run followed by offsetting yet smaller reductions in temperature in the long-run (to 100 years). These interventions entail an intertemporal trade-off reflecting the different respective climate physics of CH_4 and CO_2, and the focus on permanent CO_2 removals, i.e. removals with storage duration of at least the considered permanence period of 100 years.

The use of permanent CO_2 removals to offset CH_4 emissions does little to remove this large short-term effect, leaving significant intertemporal fluctuations in temperatures and hence climate damages faced by the intervening economies and ecosystems. Yet the main problem associated with this strategy is practical: permanent CO_2 removals require eternal contracts which have low credibility for monitoring and enforcement reasons. It is rare to find contracts which last for such long-time periods in real life, precisely for this reason.[16]

To address this point, Panel (b) in Figure 1 illustrates an alternative strategy to offsetting CH_4 emissions, using temporary

CO_2 removals with contracts lasting for 20 years. We choose a 20 year duration for these removal projects because contracts of this length are frequently undertaken in practice (e.g. mortgages, bonds, property rental contracts and other leases). Since equivalence is still calculated in terms of GWP over the 100-year horizon, the number of temporary 1-ton CO_2 removal projects must increase to be equivalent in GWP to permanent CO_2 removal projects. In this example, 136 temporary 20-year projects are equivalent to 30 permanent ones. The blue line in Panel (b) of Figure 1 reflects the temperature impact of 1 tonne of CH_4 emitted, as in Panel (a). The green lines in Panel (b) in Figure 1 reflect the temperature impact of the 136 temporary, 20 year, 1 tonne CO_2 removal projects. The impact of these temporary CO_2 removals is approximately a step function for the FAIR model (see method section). The red line shows the net effect on temperatures of this offsetting strategy, i.e. the net effect on temperature when CH_4 emissions and temporary CO_2 removal happen simultaneously.

Beyond having a more realistic contracting period of 20 years, there are several further advantages of the use of temporary CO_2 removals to offset CH_4. Firstly, by using temporary CO_2 removals, the time profile of temperature reductions from CO_2 removals is matched more closely to the profile of temperature increases from the CH_4 emission. This smooths out the net temperature effect (red line) over time, reducing the extent of the intertemporal transfers that arose using permanent offsets. A large temperature increase for the first 30 years followed by a small temperature decrease from 2050 in Figure 1 Panel (a) should be contrasted with a small temperature increase in the very short run (5 years), followed by a temperature reduction until 2040, followed by a small increase in temperature from 2040 onwards, which converges to the long-run impact of an uncompensated methane emission (See Panel (b) of Figure 1). Secondly, 20 year contracts are also convenient for CO_2 removal projects which store carbon for much longer. It is sufficient to allow project developers to be credited with new certificates for a new 20-year period, after the first period has ended (provided that the project is still additional).

Further insights can be obtained by evaluating the resulting paths of temperature from a welfare perspective by comparing the value of climate damages avoided in each case. The following section provides a framework with which to undertake this analysis. Yet even without this, the use of temporary CO_2 removals to attenuate the short-run effects of CH_4 emissions seems to directly address the general concern about their impact: the short-run spikes in temperature rather than the much smaller long-run effect. Provided the costs and integrity (contracts, monitoring, additionality) support such a strategy, there is already a prima facie case for using temporary CO_2 removals in this context.

Welfare equivalence of temporary CO_2 removals to CO_4 emissions

Equivalence of temporary CO_2 removals to CH_4 emissions has so far been assessed on the basis of the physical aspects of GWP. As discussed in Groom et al.[17], by basing equivalence on concentrations of CO_2 in the atmosphere, GWP ignores several physical phenomena that determine temperature change, such as thermal inertia. Ultimately, temperature (levels, change or rate of change) is the key concern in climate policy and GWP ignores some of its key determinants. Economic factors are also poorly treated by the GWP approach. First, there is an implicit assumption that economic damages do not depend on the temperature level (linear damages), when they likely to be highly non-linear ([18]). Second, the implicit discount rate is zero in the first 100 years and infinite thereafter (removals after 100 years do not count). Including the physical and economic aspects to the analysis makes an important difference in the context of evaluating permanent removals. (Table S1 in Groom and Venmans[13] provides a comprehensive overview of these methods). To overcome these issues, we use the Social Value of Offsets approach of Groom and Venmans[13] and associated welfare equivalent framing.

In this approach the economic value of the damages associated with a 1 tonne CH_4 or CO_2 emission is given by the present value sum of marginal damages over time and known respectively as the Social Cost of Methane (SCM) (e.g. Azar et al.[19]) and the Social Cost of Carbon (SCC) (e.g. Dietz et al.[18]). The different time profiles of the temperature effects in each case (see Figures in the SI) mean that the damages also have different time profiles, and so the relative values of the SCM and SCC depend on the value of time reflected by the social discount rate. The Methods Section provides a more formal definition of these quantities. With these definitions in hand, the impact of CH_4 and CO_2 emissions on atmospheric temperatures can be compared in terms of the economic damages they cause, taking into account the different time-profiles of temperature changes. Azar et al.[19] show that for reasonable assumptions the SCM is \$1000 compared to \$100 for the SCC. This difference is sensitive to the choice of the discount rate and the functional representation of climate damages (i.e. the damage function parameter γ in the SI), yet reflects the differences in both magnitude and timing (higher and earlier for CH_4) of the effect on damages arising from these different GHGs.

Table 1 shows the equivalence analysis associated with the SVO approach for different time horizons for removals: temporary removals of 20 years and 40 years, as well as permanent removals (∞). Columns 1 - 3 show the RCP (2.6, 4.0 and 6.0), the discount rate and the annual failure risk (hazard rate) of a project. Columns 4-6 show the number of temporary CO_2 removals that would be welfare equivalent to a 1-tonne CH_4 emission in terms of damages offset for horizons of 20, 40 and ∞. Taking row 1 as an example, we see that in RPC 2.6 the equivalent permanent CO_2 removal is 14 tonnes. This is different from the GWP_{100} ratio of 30 because the SVO approach takes into account the warming effect of CO_2 after 100 years. This value rises by over 100% to 36 tonnes when yearly failure risk increase from 0% to 1% (third row): as risk compounds over

RCP	Discount rate	Failure Risk ϕ	Duration 20 Year	40 year	∞	Social Cost of Methane US$ per tonne
2.6	2.5%	0.0%	136	67	14	2331
2.6	2.5%	0.5%	144	75	24	2331
2.6	2.5%	1.0%	153	84	36	2331
2.6	3.0%	0.0%	133	70	22	2154
2.6	3.0%	0.5%	142	78	34	2154
2.6	3.0%	1.0%	150	86	46	2154
2.6	3.5%	0.0%	131	72	31	1997
2.6	3.5%	0.5%	139	80	42	1997
2.6	3.5%	1.0%	148	88	54	1997
4.5	2.5%	0.0%	139	66	10	2447
4.5	2.5%	0.5%	148	73	19	2447
4.5	2.5%	1.0%	157	82	30	2447
4.5	3.0%	0.0%	136	68	18	2254
4.5	3.0%	0.5%	145	76	28	2254
4.5	3.0%	1.0%	154	84	39	2254
4.5	3.5%	0.0%	134	70	26	2084
4.5	3.5%	0.5%	142	78	36	2084
4.5	3.5%	1.0%	151	86	47	2084
6.0	2.5%	0.0%	141	65	9	2492
6.0	2.5%	0.5%	150	73	17	2492
6.0	2.5%	1.0%	159	81	27	2492
6.0	3.0%	0.0%	138	67	16	2293
6.0	3.0%	0.5%	146	75	25	2293
6.0	3.0%	1.0%	156	83	36	2293
6.0	3.5%	0.0%	135	69	23	2117
6.0	3.5%	0.5%	144	77	33	2117
6.0	3.5%	1.0%	152	85	44	2117
GWP	0%	0.0%	167	81	0	

Table 1. Equivalence table for temporary and risky CO_2 offsets to CH_4 emissions: The equivalence is measured in terms of damages avoided via temporary removal of a ton of CO_2 from the atmosphere compared to a permanent emissions of a ton of CH_4. The last line reports the equivalence in terms of the Global Warming Potential, assuming a GWP at a 100 year horizon of 30 (IPCC) and carbon sequestration by sinks from FAIR.

time, it requires more projects to be equivalent. Being welfare/damages related, this equivalence is sensitive to the discount rate, increasing with higher discount rates as the longer term effect CO_2 removal has a smaller effect on the present value of damages avoided.

Importantly, equivalence also increases as one moves from permanent removals to shorter-run temporary removals, ranging from 14 for permanent removal to 136 tonnes for a 20 year project. Comparing permanent and temporary removals within the 20-year-column illustrates the insensitivity of equivalence to both the discount rate, yearly failure risk and the choice of the emissions scenario. For temporary 20-year projects the equivalence ranges from 131 (RCP 2.6, discount rate 3.5% and failure risk of 0%) to 159 (6.0, 2.5%, 1%), which is equal to a mere 21% increase. By contrast, the equivalence of an offset programme using permanent removals varies from 9 to 54 (a %500 increase) depending on the discount rate, risk level and emission scenario selected.

The insensitivity of welfare equivalence associated with short-run contracts merely reflects that all the offsetting action takes place in the short run, with temporary CO_2 removals matching the timing of the temperature and welfare effects of CH_4 emissions, virtually nullifying the net effect on temperature compared to equivalent permanent solutions. By removing the intergenerational transfers and trade-offs, this approach largely removes the influence of the social discount rate on equivalence, whose main effect is to reduce long-run damage valuations. Given the major disagreements on discounting and intergenerational fairness that have arisen in the past, this non-sensitivity is a useful and practical feature for policy.[20] The same cannot be said about the permanent removal offerings.

The final row of Table 1 shows the outcome using GWP for different time horizons assuming that at the typical 100 year horizon the equivalence of CO_2 to CH_4 is 30 to 1. The zero value in column 6 reflects the fact that a permanent CO_2 removal causes a permanent reduction in GWP in the very long run (the infinite horizon). Whereas the long run effect of a methane emission is zero, a pulse of CO_2 emissions leads to a new long term chemical equilibrium with more CO_2 in the ocean as well as in the atmosphere, resulting in a permanent residual forcing. A permanent CO_2 removal does the opposite. What this means in practice is that, measured using GWP rather than damages, any microscopic yet permanent removal of CO_2 is equivalent in terms of GWP in the long-run to an emission of CH_4. Over an infinite horizon, equivalence is therefore approximately zero. This *singularity* result is a natural consequence of using a zero discount rate for future CO_2 removals. To avoid this GWP equivalence metrics have an arbitrary, truncated definition of permanence, typically 100 years. Measuring equivalence in terms of well-being/damages is a theoretically grounded alternative.

Discussion and Conclusion

There is general agreement that Nature Based Solutions have potential to contribute to climate mitigation yet doubts have been cast upon their credibility due to concerns about their permanence, risk of failure and additionality, particularly with regard to the voluntary carbon offset market. Failure to permanently remove CO_2 can lead to a failure to meet climate targets. Doubts about CO_2 offsetting relate to at least two underlying issues, one practical and one ethical. On the practical side, eternal contracts for permanent CO_2 removals are beyond the temporal scope of traditional liability frameworks in economic or political domains.[16] On the ethical side, intergenerational fairness is a key concern where actions (failures of NBS) today determine the damages to future generations.[21–24] Nevertheless, applied to short term problems such as the temporary effect on temperatures caused by CH_4 emissions, the temporariness of NBS, or indeed other technologies, can be exploited as part of a net-zero or climate change mitigation strategy.

Practically speaking, the use of NBS forces us to think about the need for temporary contracts, which are more easily monitored and enforced. This logic is particularly applicable for NBS, where concerns about permanence are manifest, and is especially relevant for offsetting CH_4 emissions. The logic also extends to contracts for permanent removals to offset CH_4.

On the ethical side, offsetting CH_4 also forces us to confront intergenerational fairness. Due to their pronounced short term effect on temperatures, when CH_4 emissions are offset with permanent CO_2 removals, future generations are better off (lower temperatures) while the current generation is worse off (higher temperatures), compared to a situation without emissions and offsets. If CO_2 emissions are offset with CH_4 reduction projects, the opposite occurs. In each case, what is deemed a fair distribution of outcomes depends on the weights placed on outcomes at different points in time, hence, implicitly or explicitly, on a social discount rate. In theory, the social discount rate captures societal inequality aversion between generations, placing lower (higher) weight on richer (poorer) generations in weighing up outcomes. Introspection is required concerning what a fair distribution over time looks like and hence the level and schedule of social discount rates.[20] These are difficult issues to find agreement on, yet avoiding discounting tends to give rise to arbitrary rules to facilitate decision-making over long-term horizons, such as the finite definition of permanence in GWP calculations.

With these issues in mind, robust and practical carbon accounting schemes is crucial for the development of international emissions and CO_2 removal trading, which will become increasingly important for future net-zero GHG policies and in light of latest text on offsets in Article 6 agreed at the recent climate COP meeting.[25] Failing to properly account for carbon storage over time is considered a major obstacle for the required implementation of nature-based solutions to enhance atmospheric CO_2 removal.[26–28] Nowhere is this more pertinent than in relation to measures interfering with terrestrial, biological carbon pool, which currently accounts for the overwhelming majority of countries' active CO_2 removal activities.[29] In 2023, afforestation measures removed 1.22 GtC from the atmosphere. However, this was more than offset by 1.66 GtC emissions from deforestation.[30] Providing incentives to increase the former and reduce the latter, is essential to unlock short-term climate change mitigation potential of the terrestrial biosphere,[31,32] but also to develop other CO_2 removal methods with potentially temporary carbon storage prospects.

Various accounting approaches aim to deal with the potential non-permanence of (biological) carbon storage. Additional measures like buffer accounts attempt to ensure that issued credits have a permanent carbon storage underlying (e.g., the Reversal Risk Buffer Pool Account in Paris Agreement Crediting Mechanism[33]). These approaches and measures focus on the integration of CO_2 removals into carbon markets where long-term storage is supposed to offset the long-term impacts of CO_2 emissions.[34,35] A complement to these approaches is to view temporary storage as a feature to deal with short-term climate impacts. Using potentially non-permanent CO_2 removal projects to compensate for short-term climate impacts, particularly those resulting from CH_4 emissions, is a useful addition to carbon accounting. Temporally matching the problem and remedy by matching the short time horizon of temperature effects associated with CH_4 with the opposite effect of similarly temporary CO_2 removal, has the benefit of largely avoiding the inter-temporal trade-offs that make the discount rate so important. As a result, the prescription of this framework (how much temporary CO_2 offsets a CH_4 emission) is rather insensitive to disagreement on intergenerational fairness and the matter of discounting. For similar reasons the approach is insensitive to other contested issues including climate damages and emissions scenarios.

There are no free lunches however, and there is a cost implication of the proposed strategy. Equivalence requires in the baseline scenario 136 20-year-1-tonne CO_2 removals projects, compared to 30 permanent ones, increasing the compensation ratio by a factor of about 5. At the same time, several nature-based carbon removal projects, and in particular various forest-based measures (i.e., including reduced deforestation), are reported to provide offsets at very low costs, well below US$20/tCO$_2$,[29,36] or even at negative costs if other co-benefits are monetized.[37] Realization of these low-cost removal projects is often hampered by the fact that they are risky in the long run and require unreasonable efforts in terms of monitoring, verification and insurance. This uncertainty and the general concern about quality of NBS effectively prevents a market for these removals developing. Yet, recent voluntary market transactions show that buyers are willing to pay a premium for the proven climate benefits of CO_2 removal.[38] Our re-purposing of temporary offsets would improve their quality from this perspective. Furthermore, several nature based solutions are potentially additional for much longer than 20 years. That means that when the first removal contract expires after 20 years, the same project can get certified again for a new period of 20 years and compensate another methane emission. The updated contract will increase credibility and reduce insurance costs in the market. This is useful, because some so-called "residual" methane emissions, especially in agriculture, are unavoidable and will continue to exist beyond 2100.

Naturally, a net zero society will also require permanent removals, such as geological storage or mineral weathering.[34] The general proposition here is that there are advantages in matching the remedy to the problem. For the temporary effects of CH_4 emissions, temporary CO_2 removals have advantages. For permanent CO_2 emissions, permanent CO_2 removals (e.g. geological storage, or repeated temporary projects) are more appropriate. Separate markets for each could allow both to flourish where they are most appropriate.

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Materials and Methods

The theoretical framework is an adaptation of Groom and Venmans[13] that incorporates insights from Azar et al.[19] on the characterisation of social cost of methane.

Assume total damages of global warming T are quadratic and proportional to the size of the economy Y, that is $Y = Y_0 \exp\left(\frac{-\gamma}{2}T^2\right)$. As a result, the marginal damage of extra warming is $MD(t) = \frac{\partial Y}{\partial T} = \gamma Y(t)T(t)$. Call $\Delta T_{CH4}(t)$ the temperature impact response function of a pulse of one tonne of methane emissions. This temperature impact response function corresponds to the blue line in figure 1. The Social Cost of Methane is the discounted sum of all marginal damages of the extra warming ΔT resulting from a pulse of emissions

$$SCM = \int_0^\infty exp\,(-rt)\,\Delta T_{CH4}(t)MD(t)dt, \tag{1}$$

where r is the discount rate according to the Ramsey rule.

Similarly, the Social Value of an Offset can be calculated using the temperature impact response function of the temporary carbon removal, $\Delta T_{CO2}(t)$, defined as a positive deviation from the baseline temperature. This temperature impact response function corresponds to the the yellow line in figure 1.[1] The Social Value of the Offset is the discounted sum of all marginal damages avoided by the temporary cooling from the offset,

$$SVO = \int_0^\infty exp\,(-rt)\,\Delta T_{CO2}(t)MD(t)dt \tag{2}$$

For simplicity, we have approximated the temperature impact response function as a step function with 3 years of delay, due to thermal inertia.[2] The step-function with a delay of ξ is in line with the common assumption that warming ($T_{t+\xi}$) is proportional to cumulative CO_2 emissions (S) between the pre-industrial period and time t: $T_{t+\xi} = \zeta S_t$, where ζ is the Transient Climate Response to cumulative Emissions (TCRE). The TCRE is remarkably stable over time and across emission scenarios[18,39,40]. Groom and Venmans[13] have shown that this approximation performs very well. As a result, the SVO of a long term project (say 2020 to 2100) will have the same net present value as two subsequent contracts covering the same project (say from 2020 until 2050 and from 2050 until 2100).

In the case of a risky removal project, we assume a constant failure rate ϕ, which leads to a likelihood of survival of $\exp(-\phi t)$ after t years. This boils down to increasing the discount rate with failure rate ϕ in the formula for the SVO.

The approximation allows us to provide an excel sheet where practitioners can set their tailored project duration and calculate the value of projects with gradually increasing (and decreasing) carbon removal. Call $q(t)$ the quantity of carbon (in equivalents of CO2) stored by the project at each point in time. The SVO of the removal project is now

$$SVO = \int_0^\infty exp\,(-(r+\phi)t)\,q(t)\Delta T_{CO2}(t)MD(t)dt. \tag{3}$$

Table 1 reports SCM/SVO for different parameter values and one tonne of each gas. Note that the damage function parameter γ does not affect this ratio, because it appears as a constant in both the numerator and the denominator. The other factors (GDP, background temperature T and the discount factor) will have a limited effect to the extent that the impact response functions ΔT_{CH4} and ΔT_{CO2} mirror each other over time.

[1] In the case of a 20 year project, the impact response function's amplitude will be 157 times smaller than in figure 1a.

[2] for example, for the 20 year project $\Delta T_{CO2}(t) = \zeta$ for t between 3 and 23, else zero.

Supplementary Information: Impulse functions and damages for methane and carbon

Our carbon and methane forcing impact response functions are based on FAIR 2.0.0[1]. The carbon forcing response function shows how a pulse of emissions is gradually absorbed over time by biomass and oceans, leading to a gradually declining climate forcing over time. Similarly, the methane forcing response function shows how methane is gradually decomposed into water and CO_2 and how this affects forcing over time. The integral of the forcing response function up to year X, defines the GWP of a particular gaz with horizon X.

Next, an energy balance model translates this climate forcing into a temperature impact response function. Our energy balance model is based on Geoffroy et al.[15], which embedded in FAIR and is structurally the same as DICE, but with different parameters. Azar et al.[19](Fig 11) produce temperature impact response functions for both CO_2 and methane based on these models.

Figure 2 shows more in detail the impact response function of an absorption of one Giga tonne in 2020, re-emitted in 2070. For the temperature response function of a temporary carbon absorption in Figure 1 and 2, we produce deciles of 256 combinations of 16 CO2 absorption models of Joos et al.[14] combined with 16 energy balance models in Geoffroy et al.[15]. We also report the temperature response of the FAIR model[1]. FAIR 1.0 is based on Joos et al.[14], but adds saturation of carbon sinks, i.e. warmer and more acid oceans absorb CO2 more slowly. As is visible on the graph, this effect is mild, but it leads to a more constant temperature impact over time.

To make Table 1, we use the result in Groom Venmans[13], showing that the impact response function of a temporary carbon removal is very well approximated by a step function with a delay of 3 years (this can be seen in Figure 1 and 2). The magnitude of this step function is known as the Transient Climate Response to CO_2 Emissions (TCRE). To estimate the TCRE, we use the mean of the temperature impact response function over the first 100 years in Azar et al.[19]. This ensures that we use same parameters for the energy balance model for both CO_2 and CH_4.

Figure 3 shows the marginal damages (unlike the temperature effects in Fig 1b) of a pulse of methane emission (in blue), compensated by a 20-year carbon removal (in yellow), with a net effect in red.

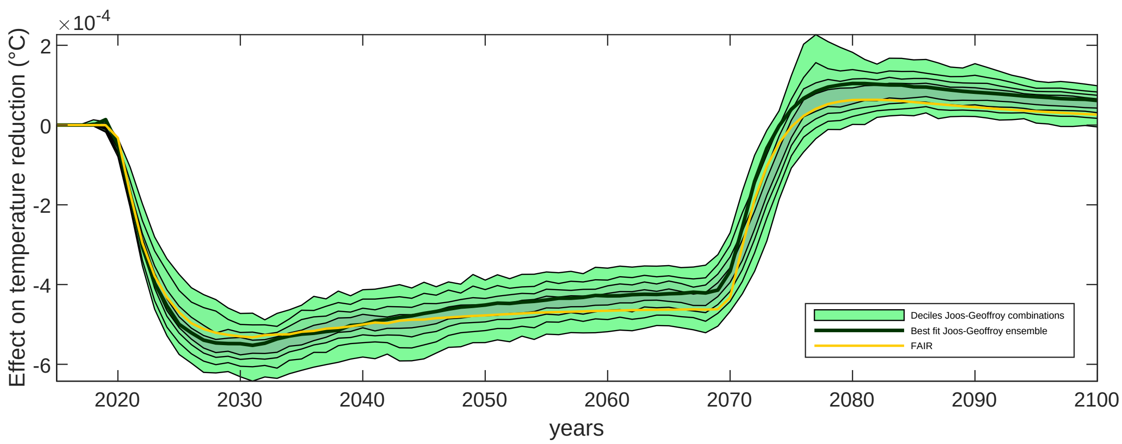

Figure 2. The effect of a 50 year offset on warming. The Figure shows the difference between the temperatures of the SSP1_26 background scenario and the scenario with a temporary removal project, instantaneously absorbing 1 GtCO2 in 2020 and reinjecting it in 2070. The 16 absorption models (as in Joos et al. 2013) are combined with 16 energy balance models from the CMIP 5 ensemble (as in[15]) and the figure shows the deciles of the 256 possible combinations of models. The FAIR model uses the best fit of the CMIP5 models but adds saturation of carbon sinks. The climate sensitivity of all energy balance models has been harmonized to 3.1°C.

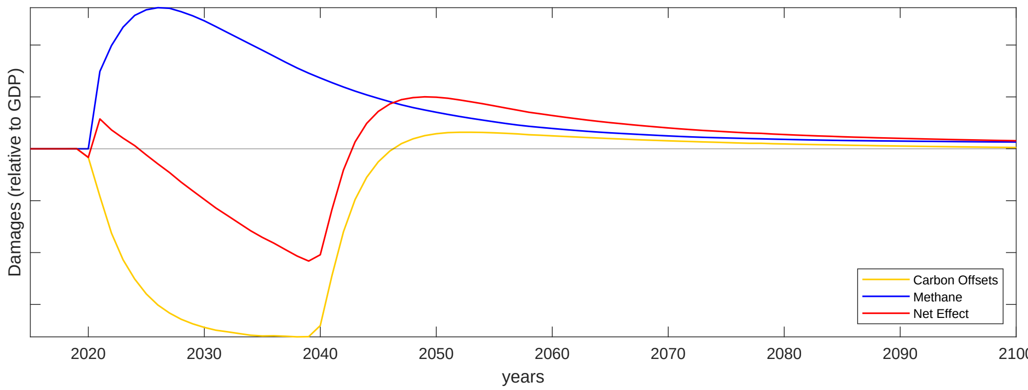

Figure 3. The net economic damage effect of an emitted tonne of CH_4 offset by a temporary carbon removal 136 tonnes of CO_2. The Figure shows the marginal damages caused by the methane emission (in blue), the avoided marginal damages caused by the carbon removal (in yellow) and the net effect in red. Background temperatures of the SSP1_26 scenario, quadratic damages, discount rate of 2.5%, no failure risk, that is, first line in Table 1.

Data Availability Statement

The data used to create the Figures, and the Excel spreadsheet that underpins the Tables is available at the following github repository: https://github.com/FVenmans/OffsetMethane.

Code Availability Statement

The code used to create the Figures, and the Excel spreadsheet that underpins the Tables is available at the following github repository: https://github.com/FVenmans/OffsetMethane.

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Competing Interests Statement

The authors declare no competing interests

Author Contribution Statement