The Social Value of Temporary Carbon Removals and Delayed Emissions

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May 26, 2024

Abstract

An economic approach to calculating the Social Value of Temporary Reductions (SVTR) in atmospheric carbon is discussed. The SVTR allows different carbon removals projects to be prioritised in a way that maximises welfare and establishes equivalence between temporary, risky removals with permanent ones in terms of avoided welfare losses from climate damages. The approach is compared to previous attempts in the physical and natural sciences and economics to price temporary emissions reductions, none of which successfullyintegrate economics and climate science. Applications of the SVTR exist in Life Cycle Analysis, pricing carbon debts and determining short term carbon credit and offset contracts. The paper concludes by addressing the potential criticisms of the equivalence measure and tonne-year accounting in general, that stem from concerns that temporary removals do not impact long-term temperatures. We show that these concerns are special cases of our integrated economic approach and argue that ruling out temporary removals and equivalence, and the intertemporal transfers that they imply, could unnecessarily tie the hands of policy makers.

1 Introduction

There are numerous situations in which decision-makers need guidance on whether temporary carbon removals or emissions reductions will be an effective and efficient component of their climate mitigation strategy. Governments may want to value the climate effect of forestry rotation lengthening, which increases the carbon stock of forests temporarily. Regulators of cap and trade systems may want to estimate the mitigation potential of biofuels, taking into account that biofuels reduce the carbon content of forests temporarily, whereas fossil fuels convert geological carbon to CO2 permanently. In the voluntary offset market, the question is more about reliability. A removal project may initially absorb carbon, but then re-release carbon after a few decades. The question here is, are these temporary removals of carbon valuable and in any way equivalent to permanent removals? We present a integrated economic-climate science approach to valuation that tries to answer these questions.

Interventions to mitigate climate change differ in their permanence and the risk of reversal. The risk of abated emissions being reversed or stored/sequestered carbon being re-released is a very real one, which varies from one country or technology to another. The risks associated with Nature Based Solutions (NBS) (e.g. forest fires or disease) are very different to those associated with geological storage for instance. The time profiles of sequestration of different removal technologies also differ. Contrast the time-path of carbon removals from reforestation to Direct Air Capture or peatland restoration for instance. The associated cycles of growth and decline also contain aspects of temporary storage and release. In each case policy makers need strategies to compare these different technologies systematically in order to develop the best strategic response to climate change.

Beyond these technical issues socio-economic risks also need consideration. Chief among these is the thorny issue of additionality: how much a project contributes to carbon removals compared to the counterfactual. If a project would have happened anyway, or causes emissions to take place elsewhere

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(spillovers), then it is not a credible carbon credit or offset since it will not contribute to reducing atmospheric carbon (e.g. Filewod and McCarney, 2023). With regard to tropical forests (reforestation and avoided deforestation) for instance, the evidence is rather mixed. At one extreme, West et al. (2023) show that among verified forest carbon credits in tropical forests, destined for the Voluntary Carbon Markets, only 10% of the forest credits across the world are additional to what would have arisen anyway, in the absence of the crediting system and flows of finance.[1] Albeit in a slightly different context of REDD+ rather than carbon crediting for the Voluntary Carbon Market (VCM), Guizar-Coutino et al. (2022) find moderate to poor performance with 53% additionality, while Jayachandran et al. (2017) reports 90% additionality for REDD+ projects in Uganda.[2] Yet, the lower risks associated with Carbon Capture and Storage (CCS) come at considerably higher cost.

An efficient response to climate change requires an understanding of the value of temporary and/or risky carbon removals. Without this, policy-makers run the risk of making the perfect (non-risky, permanent removals) the enemy of the good. From a welfare perspective there may be a trade off between the permanence, risk and non-additionality of some carbon removals and the cost and ease with which they can be implemented. It could be that the appropriate strategy is to start with temporary removals and then move on to more permanent ones in the future. Furthermore, with different technologies providing different time paths of carbon removal and release, a measure of equivalence is required to facilitate comparisons. Some approaches will remove carbon sooner, but in smaller amounts and at higher risk, compared to others that remove more carbon with certainty later. Decision-makers need to be able to navigate these intertemporal trade-offs systematically.

One approach frequently used to make temporary and permanent removals fungible using a concept of *equivalence*. Equivalence measure tell decision-makers how many temporary carbon removals are equivalent to a permanent one in terms of their effect on radiative forcing, temperature or welfare. Among many applications, equivalence can help to harmonise the voluntary carbon market by allowing comparisons among carbon removals, credits and offsets from different sources, thereby measuring and signalling quality. This could help unlock carbon finance and facilite efficient markets in carbon removals. Equivalence could, however, illustrate that the offerings in the VCM are of insufficient quality compared to permanent removals (too impermanent, risky or non-additional) for the market for offsets to be functional and/or effective. Either way, understanding quality is essential to make sense of temporary, time varying and risky removals in different, policy-relevant contexts. Measuring equivalence may be one way to do that.

In this paper we revisit previous studies estimating the value of temporary emissions reductions and temporary storage. After reviewing the pioneering contributions from the physical sciences the integrated economic-climate science approach of Groom and Venmans (2023) is presented. The integrated approach provides a simple pricing formula for valuing impermanent and risky projects by estimating the sum of avoided future damages that the project induces. We call this the Social Value of Temporary Removals (SVTR) and we show that it is always positive because a temporary removal leads to amore or less constant cooling throughout the duration of the project. The SVTR stems from the reduced damages associated with the cooling effect. The SVTR yields a definition of equivalence between permanent and temporary removals based on welfare: the ratio of the benefits from temporary cooling to the benefits of a permanent removal, given by the social cost of carbon (SCC).

The remainder of the paper discusses the potential applications for the Social Value of Temporary emission Reductions (SVTR) for determining equivalence, use in Life Cycle Analysis (LCA) and for charging for the rental value for storage in the atmosphere to finance removals in a world of negative emissions if emissions reductions are delayed. The paper then turns to the criticisms of 'tonne-year accounting', equivalence and the approach to economic valuation of temporary removals. The critique centres on uncertainties surrounding damage functions and the practice of social discounting, and the fact that one-off temporary removals cannot affect long-term temperatures so permanent and temporary removals can never be equivalent (Brander and Broekhoff, 2023).

The paper begins by setting out the approach to valuing temporary removals, integrating both the physics and economics of the problem (Section 2). Section 3 describes the applications of the SVTR and equivalence while Section 4) covers the potential criticisms of the economic approach to valuing temporary and risky carbon removals. Section 5 concludes.

[1] West et al. (2023) use synthetic control difference in difference methods to construct robust counterfactuals for the credited forests.

[2] Methane removals in rice farming have also been criticised along similar lines (see `https://www.climatechangenews.com/2024/02/02/shameful-shell-uses-carbon-credits-under-investigation-to-meet-climate-targets/`

2 Valuing temporary emissions removals

There is a large literature on how to evaluate whether temporary carbon removals are helpful in combating climate change. There are two key strands to the literature, one which focuses on measuring the physical changes to the climate, and another which focuses on the economic value of these reductions. Each has its own assumptions and hence pros and cons.

The physical science approach

Early answers to the question of the value of temporary storage focused on the physical units of carbon removed and either assessed the impact in terms of atmospheric concentrations of CO2 (e.g. Moura Costa and Wilson, 2000; Fearnside et al., 2000) or in terms of the cumulative radiative forcing (changes in the energy trapped by CO2 or equivalents) induced by temporary reductions in concentrations, so-called Global Warming Potential (GWP) (e.g. Matthews et al., 2009). Figure (3) shows the time path of impacts from a permanent emission of CO2 on CO2 concentrations. These approaches led to measures of *equivalence*: the ratio of the impact of a temporary carbon removal/storage to a permanent one. The family of physical measures of equivalence became broadly known as 'tonne-year accounting' methods.

To measure the equivalence between a temporary reduction of atmospheric carbon and a permanent one, permanence is typically defined as 100 years in the physical approaches. The simplest equivalence measure is simply to count the number of years the removal lasts for and divide this by 100 (e.g. Pennington et al., 2010). So if a temporary removal lasts for 50 years, equivalence is 50/100 = 50%. More complex approaches look instead at the time path of CO2 concentrations that arise from the temporary removal using an Impact Response Function (IRF) which takes into account the natural absorption of CO2 by oceans and biomass. For instance, Fearnside et al. (2000) use the Impact Response Function of atmospheric CO2 concentrations ($IRF_{CO2,t}$) over the 100 year period leading to the effect of a 'permanent' absorption of carbon at time $t = 0$ to be calculated as: $\int_0^{100} IRF_{CO2,t}dt = 52.4$. 52.4 is the so-called 'tonne-years' associated with a permanent removal. To calculate equivalence these tonne-years can be compared to the equivalent concentration response for the temporary 50 year absorption, where the impulse happens in year 50: $\int_{100-50}^{100} IRF_{CO2,t}dt$. The ratio of these two reflects the equivalence in terms of the relative effect on carbon concentrations. This is 42% for a 50 year project.[3]

The Global Warming Potential (GWP) approach is similar in form but the relevant outcome with which to compare permanent and temporary interventions is cumulative radiative forcing, that is, the cumulative effect on extra incoming energy on earth. The equivalence between permanent and temporary reductions in carbon is found by the ratio of GWP for temporary and permanent (100 year) reductions in carbon. The simple ratio of temporary to permanent years (50/100 = 50%) described above is form of GWP equivalence, but more precise approaches to measuring GWP are usually taken using impact response functions. For instance, the Moura Costa and Wilson (2000) approach is: $\int_0^{50} \alpha_t IRF_{CO2,t}dt / \int_0^{100} \alpha_t IRF_{CO2,t}dt$, where α_t is the radiative efficiency of CO2 that converts changes in concentration into radiative forcing.[4] For a 50 year project this equivalence is 59%. There are many variants on the basic premise that to evaluate temporary reductions in carbon emissions it is enough to look at relative CO2 concentrations or GWP.[5] However, there are some obvious shortcomings to these approaches.

First, by and large it is the resulting temperature arising from climate change that is the outcome of concern to society, not concentrations of CO2 or GWP.[6] Figure (1) illustrates the impact of a temporary emission reduction on both CO2 concentrations (panel b) and global temperatures (panel c). The concentration impact response function shows that after 10 years, the effect on concentration is already reduced by 30% and after 50 years, merely 40% of the effect remains. As a result, when the

[3]The Moura Costa and Wilson (2000) approach is more generous because it simply divides the duration of the temporary reduction (here 50) by the ton-years for a 100 year reduction, leading to an equivalence upwards of 90%. The Dynamic Life-Cycle Analysis approach (Levasseur et al., 2011) is similar in principle but uses the complementary integral to measure equivalence: $\int_0^{50} IRF_{CO2,t}dt / \int_0^{100} IRF_{CO2,t}dt$ which gives 58% rather than 42% equivalence.

[4]α_t depends on the background concentration, $CO2_t$ in the following way: $\alpha_t = 5.35 ln(CO2_t/CO2_{1850})$.

[5]See (Groom and Venmans, 2023, Table S1 in SI)

[6]Notwithstanding the fact that ocean acidification is positively affected by atmospheric CO2 concentrations, the long term effect is proportional to cumulative emissions, not cumulative forcing.

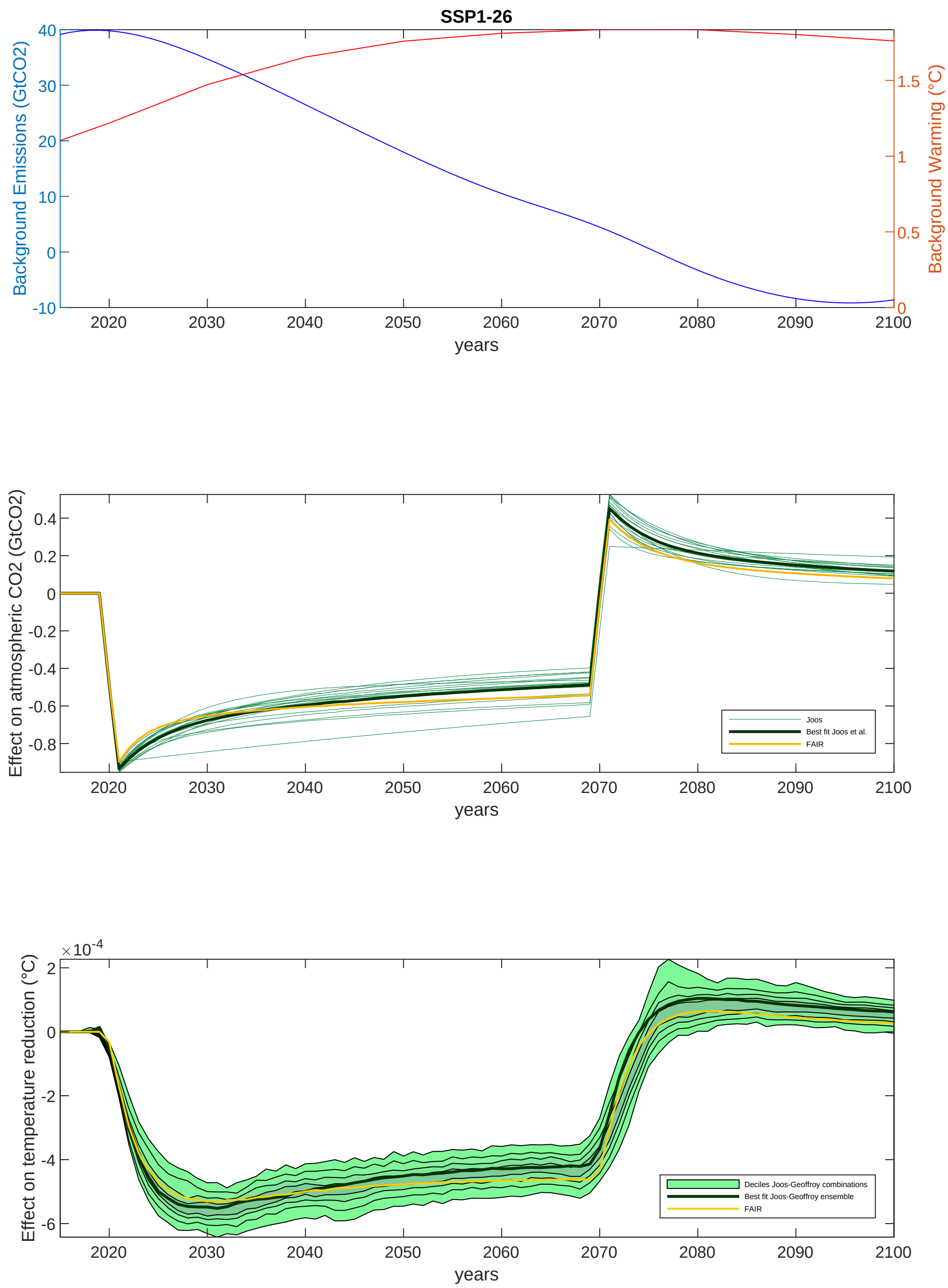

Figure 1: **The effect of a temporary emission reduction: Panel a** shows the background emissions and the temperature path of the IPCC's RCP 2.6. scenario. **Panel b** shows the effect of a temporary emission reduction (1 GtCO2 absorbed in 2020, and re-emitted in 2070) on atmospheric carbon concentrations. Each line represents a model of the CMIP 5 ensemble (as in Joos et al. (2013)). **Panel c** shows the effect of the same temporary emission reduction on temperature. The 16 absorption models are combined with 16 energy balance models from the CMIP 5 ensemble (as in Geoffroy et al. (2013)) and the figure shows the deciles of the 256 possible combinations of models. The climate sensitivity of all energy balance models has been harmonized to 3.1°C. The FAIR model uses the best fit of the CMIP5 models but adds saturation of carbon sinks.

carbon is re-injected after 50 years, the atmospheric CO2 concentration is higher than in the absence of the project.[7] By contrast, the temperature impact response function shows a relatively constant impact, with a delay of approximately 5 years. After the end of the project, when the CO2 is re-emitted, the temperature effect is close to zero after a relatively short delay. The temperature response function can be approximated by a delayed step function (a constant cooling during the project). This arises due to the effect of thermal inertia. Moreover, in a warmer world, the concentration impact response function shows less absorption due to the saturation of carbon sinks, but the temperature impact function is approximately the same, because extra CO2 leads to less extra forcing when there is already a lot of it (Matthews et al., 2009; Dietz and Venmans, 2019). Both of these factors are ignored by approaches that focus on CO2 concentrations and GWP.

Second, the definition of permanent is limited to 100 years, ignoring any impacts that either permanent or temporary emissions reductions might have in the longer term, beyond 100 years. In essence this is as if an infinite discount rate is applied to time horizons greater than 100 years. In the context of climate change, where temperature effects of CO2 emissions last for many centuries, this is a short time horizon.

Third, there is the problem of timing in the first 100 years. A project which only operates for the final 50 years of a 100 year period is often valued identically to one which spans the first 50 years. This insensitivity to timing is problematic, because the investment costs to realize emission removals include a cost of capital and are therefore discounted. By not discounting the avoided damages, the method creates an undesirable preference for later abatement compared to early abatement.

Fourth, the methods are insensitive to the background warming. An emission removal is valued in the same way, whether the earth is warmed at 1,5°C or 3°C. This is because the method does not include a damage function. In welfare terms, independence of the background temperature implies a linear damage function. By contrast, most integrated assessment models assume a convex damage function, such that the social value of an emission removal is higher in a hotter world.

An economic approach

Economic approaches are concerned with the welfare changes associated with temporary emissions removals, and how these compare with permanent removals. Groom and Venmans (2023) provide a comprehensive account of how to value temporary emissions removals from a welfare economics perspective, taking into account not only impermanence, but also the risk of failure and non-additionality, key elements of the problem associated with nature-based and other carbon-sequestration solutions. Sensibly, early economic approaches used first principles and compared the benefits of an emission removal today to the costs of an emission in the future to value temporary removals (e.g. van Kooten, 2009).

Suppose the carbon price associated with the permanent removal of carbon today is given by p_0 and the cost of emitting a ton of carbon in 50 years time is p_t. van Kooten (2009) and Herzog et al. (2003) argue that value of a temporary emissions removal, between time zero and τ, V_0 is simply:

$$V_0 = p_0 - exp(-r\tau)p_\tau, \tag{1}$$

where r is the social discount rate. Equivalence can then be estimated by the ratio of V_0 to p_0, the permanent value: V_0/p_0. Without further structure, V_0 can take on almost any value, being equal to zero if the carbon price increases at the rate of discount, r, or negative if the carbon price grows faster than the rate of interest.

The integrated approach

In this section we combine the economic insight with the climate physics of the problem and show that V_0 is always positive (Groom and Venmans, 2023). Figure (1), panel c, shows that the impact response function can be approximated by a step function with an approximately constant effect on temperature during the project, albeit with a short delay of, say, 5 years, and no effect thereafter. Moreover it has been shown that the size of this step function does not depend on the background

[7] This is because carbon absorption is slower when there is less carbon in the atmosphere. By construction, the carbon content increases by 1 unit at the time of re-emission. This observation led to claims that temporary reductions can make climate warming worse (Kirschbaum, 2006).

temperature, resulting in a model where warming is proportional to cumulative emissions S_t with a delay of ξ years (Matthews et al., 2009; Dietz and Venmans, 2019). So warming can be written as $T_{t+\xi} = \zeta S_t$, where ζ is known as the Transient Response to Cumulative Emissions (TRCE).

From a welfare perspective, the appropriate way to value emissions is to evaluate their damages. The damage function summarizes how welfare is affected by warming. Without loss of generality, [8] we will assume a quadratic damage function, where damages are proportional to production Y_t. This leads to marginal damages which are linear in temperature $MD_t = \zeta\gamma Y_t T_t$, where γ is the slope of the marginal damage function.

Knowing the climate physics and the damage function, we can define the Social Cost of Carbon (SCC) as the discounted sum of all future marginal damages,

$$SCC_0 = \int_0^\infty exp(-r(t+\xi))MD_{t+\xi}dt. \tag{2}$$

Since the emission is marginal, the SCC will also be the value of a permanent removal of a tonne of CO2: the discounted sum of all avoided marginal damages. Next, a temporary removal of carbon corresponds physically to a permanent removal combined with an emission at the end of the removal. Using the insight from Herzog et al. (2003) and van Kooten (2009) we obtain the following Social Value of Temporary Removal (SVTR) between time 0 and τ

$$SVTR_0 = SCC_0 - exp(-r\tau)SCC_\tau \tag{3}$$

Combining this with the definition of the SCC, we obtain the intuitive result that the SVTR is the value of the avoided marginal damages between time $0 + \xi$ and time $\tau + \xi$,[9]

$$SVTR_0 = \int_0^\tau exp(-r(t+\xi))MD_{t+\xi}dt \tag{5}$$

Since the marginal damages associated with the temperature change are positive, this integral is always positive. So the SVTR is never zero, and some of the possibilities proposed by the pricing formula in Equation (1) are ruled out. Indeed, given the above-mentioned climate physics, one can prove that the SCC must increase at a rate that is lower than the discount rate. [10]

[8] Our results hold for any damage function which depends on temperature, production and time. Results change slightly for a damage function which depends on the speed of warming or on the cumulative warming (temperature integrated over time), see section (4).

[9] To see this note that Equation (5) can be reframed as the difference between two infinite integrals:

$$SVTR_0 = \int_0^\infty exp(-r(t+\xi))MD_{t+\xi}dt - exp(-r\tau)\int_\tau^\infty exp(-r(t+\xi)MD_{t+\xi}dt \tag{4}$$

[10] Write Equation (2) for any time τ

$$SCC_\tau = \int_\tau^\infty exp(-r(t+\xi-\tau))MD_{t+\xi}dt. \tag{6}$$

Apply the Leibniz integral rule for differentiation (taking the derivative of the lower bound as well as the expression inside the integral),

$$\frac{\partial SCC_\tau}{\partial \tau} = -exp(\xi)MD_{\tau+\xi} + rSCC_\tau. \tag{7}$$

Reorganise

$$\frac{\partial SCC_\tau/\partial\tau}{SCC_\tau} = r - exp(\xi)MD_{\tau+\xi}/SCC_\tau. \tag{8}$$

The intuition is the following. Consider the SCC at time t and time t+1. From t+1 onwards all the future marginal damages are the same. Yet, in the SCC at time t+1 all these damages are discounted for a period less. This increases their value by the discount rate. The exception is the marginal damage at time t, which is included in SCC_t, but not in SCC_{t+1}. This increases SCC_t and leaves SCC_{t+1} unaffected, decreasing its growth rate between the two periods. In other words, emissions are less costly in present value terms if they happen in the future rather than in the present because a flow of damages is avoided in the interim. (see also (Groom and Venmans, 2023, Methods Section)).

There are some instances when the *carbon price* will rise precisely at the rate of discount, r. The key situation is when a cost effectiveness approach (Cost Effectiveness Analysis or CEA) is taken to determine the carbon price, rather than the Cost Benefit Analysis (CBA) approach taken for the SVTR in Equation (4). A CEA approach to pricing carbon stems from a target-based approach to climate policy, e.g. net zero by 2050, and derives the carbon price from the marginal abatement cost (MAC) at the targeted level of carbon.[11] The intuition for this carbon price is that a project or intervention that adds to carbon makes the target more costly to achieve by exactly the marginal abatement cost, and a project that reduces carbon makes hitting the target cheaper by the same amount. In this way the cost effectiveness of alternative mitigation strategies can be tested to see whether they are socially valuable in the sense of reducing or raising the costs of meeting the proposed target. A key aspect of the CEA approach is that the efficient carbon price will rise at the rate of discount. This is a manifestation of Hotelling's Rule for the optimal extraction of a non-renewable resource, where in this case the non-renewable resource is the carbon budget associated with the policy target.

Looking at Equation (1) it is easy to see that the value of a temporary removal (V_0) will be precisely zero in the CEA case where the carbon price rises at the rate of discount, r. The intuition here is straightforward. If the price rises at the rate of discount, the present value of the carbon price is identical for any time horizon prior to the target being met. Valued this way, there is no gain to be had in temporarily removing carbon now only to release it later on. Another interpretation is that, other things equal, a removal does nothing to improve the cost effectiveness of achieving the carbon policy target if it is re-released before the target is met.[12]

Nevertheless, the zero valuation under a CEA approach does not mean that there is no *social* value to temporary removals. We have already shown that the SVTR is always positive in Equation (4). The distinction stems from CEA disregarding damages and focusing soley on finding the lowest total abatement cost to stay below a given temperature target. By contrast, the objective of CBA is to maximize welfare by making trade-offs between both abatement costs and climate damages. The CEA approach has implications for the timing of emissions reductions which reduce welfare due to its indifference to the timing of damages. The cost effective emissions abatement path will abate later than the welfare optimal given by CBA, even for the same policy target. This delay in abatement translates into a carbon price trajectory that starts too low and rises too fast: at the rate of discount, compared to the optimal carbon price with CBA: the SCC (Coppens et al., 2024). Ultimately, the zero valuation of temporary removals in the CEA pricing framework arises because damages have been left out of the model. Even when a CBA approach is taken in the context of a climate target, Groom and Venmans (2023) show that Equation (5) is still valid and temporary removals remain valuable.[13]

To conclude, the welfare gains of temporary storage of carbon stem from the flow of avoided damages. Yet, with overall temperatures and the long term damages depending on cumulative emissions, questions arise as to just how temporary emissions reductions fit into a long-term strategy for climate change mitigation given that after re-release, cumulative emissions return to their previous level. These conundrums are discussed in the following sections. In Section 3 we discuss the applications of the economic approach and how the pricing formula should be augmented to account not only for impermanence but also project failure and additionality risk. A key, although controversial, application is the calculation of *Equivalence* to permanent removals by dividing the SVTR by the Social Cost of Carbon. The idea being that equivalence of 20% would imply that 5 such tons of carbon from such a project would be required to be equivalent to a permanent removal or to offset an emission of 1 ton. In Section 4 we discuss some criticism of equivalence measures, alongside some other concerns about the economic approach.

3 Applications of the Social Value of Temporary Reductions

Four applications of the SVTR are discussed: the use of the SVTR in CBA of different projects, the calculation of equivalence; life cycle valuation (LCA) of biofuels; Rental value of atmospheric storage.

[11] This approach to carbon pricing is taken by the French and UK governments.

[12] In France the carbon price rises faster than the discount rate for reasons of political economy (Gollier, 2021). Here, temporary emissions removals would have a negative value.

[13] Note that Cost Effectiveness analysis may also overvalue temporary projects instead of finding zero value. This is when temporary removal projects end after reaching the temperature target, when the carbon price raises slower than on a Cost Benefit path.

3.1 Selecting projects using the SVTR

The SVTR is an estimation of the social benefits of a temporary emissions reduction, which says nothing about the costs of any given project. The elements of cost associated with temporary emissions reductions vary from project to project and with the technology deployed. With nature based solutions, such as forest carbon, the costs range from the basic restoration costs associated with reforestation to the potential welfare costs of excluded communities and the opportunity costs of other forgone land uses, such as arable agriculture or livestock. Technical solutions, such as direct air capture, have their own distinct capital and running costs. Choosing among these projects and other permanent removals projects (e.g. emissions reductions) can be aided by the use of the SVTR in a welfare framework by using the benefit cost ratios (BCR) of the set of projects under consideration.

If each project or technology i has an $SVTR_i$ and cost c_i (broadly defined), the BCR is simply: $BCR_i = SVTR_i/c_i$. With a fixed budget an agency can maximise the welfare associated with carbon removals if one implements the projects in order of their BCRs, starting with the highest. Removals can also be compared to abatement opportunities, whose BCR is the SCC over the marginal abatement cost.

The SVTR can also be used to indicate whether carbon credits or offets traded in the voluntary carbon market (or indeed any market) are socially valuable. Note that for any project i, the difference between $SVTR_i$ and its cost c_i (rather than the equivalence ratio) measures the net social welfare generated by a removal project i. This can be a useful guide when an agency wants to understand the social value of a program of removals, or the value of the market for removals, carbon credits or offsets. One possibility, however, is that the market for offsets and credits exists but the $SVTR_i < c_i$ for some of the carbon removal technologies/projects deployed. That is, investors are willing to pay for the appearance of good Corporate Social Responsibility (CSR), but the social value of the projects deployed is negative.

So, on the one hand the prospect of impermanence, failure risk and non-additionality risk does not mean that carbon removal technologies with these qualities are valueless. In many cases we should not let the perfect need be enemy of the good since markets for carbon removals may have social value in mitigating climate change. On the other hand, where $SVTR_i - c_i < 0$ actors need to be more discerning. The perfect should definitely be the enemy of the *bad* in cases where the social value of the market is negative. To say more than this requires a rigorous analysis of the functioning of the voluntary carbon markets, the impact of asymmetric information and the source of CSR values in those markets (McWilliams and Siegel, 2001; MacKenzie et al., 2011; Mason and Plantinga, 2013).

By using welfare as the metric of comparison both of these uses of the SVTR (ranking projects using BCRs and measuring the welfare value of actions in the market place) make implicit assumptions about the equivalence and fungibility of permanent and temporary carbon removals when evaluating the technologies. Calculating equivalence is another potentially useful application of the SVTR covered in the next section.

3.2 Equivalence and fungibility

In the physical sciences literature on accounting for temporary emissions reductions, the comparison to permanent emissions reductions has generally been referred to as 'tonne-year' accounting. The idea is that there is an equivalence drawn between temporary solutions and permanent ones so that credits in the VCM or for Certified Emissions Reductions are comparable. Loosely speaking, if a permanent solution lasts for 100 years and a temporary one lasts for 50 years, then two of the latter solutions are seen as *equivalent* to one of the former. In sum the inverse of the equivalence factor indicates the number of temporary (1-tonne) projects are needed to be equivalent in terms of GWP, radiative forcing etc.

A similar equivalence idea was proposed by Groom and Venmans (2023) where equivalence is measured in welfare terms. In this framework equivalence is the ratio of the welfare gain associated with the temporary project with the welfare gain associated with a permanent carbon removal today: SCC_0:

$$Equivalence_{\tau_1\tau_2} = \frac{SVTR_{\tau_1\tau_2}}{SCC_0} \tag{9}$$

This definition is somewhat similar to tonne-year approaches in providing a simple summary statistic to compare temporary and permanent carbon removals. In general, the idea of equivalence introduces fungibility into the credit market or into public policy, in principle allowing temporary and permanent solutions to be compared and combined for policy purposes. With welfare as the underlying metric, rather than physical measures such as GWP or tonnes of carbon, this definition of equivalence is rather like comparing the Net Present Values of two investment projects. In each case the actual schedule of costs and benefits is summarised into a single number via discounting. We discuss objections to and concerns about the concept of equivalence per se, and this definition of equivalence in particular, in Section 4.

Yet, any calculation of equivalence must also take into account the risks associated with each proposed carbon removal project or intervention. For instance, one of the key factors that has prevented Nature-Based Solutions (NBS) to climate change, such as avoided deforestation or reforestation, being used is the fear that they will be impermanent, or risk failure (technology fails) and/or non-additionality (the project would have happened anyway) (West et al., 2023; Delacote et al., 2024). Claims of equivalence need to take these factors into account, not just for NBS but for all removal technologies. An augmented formula for the SVTR which takes these risk factors into account is:

$$SVTR^{\phi,\varphi}_{\tau_1\tau_2} = SCC_0 \overbrace{\exp\left(-(r-x_1)\tau_1\right)}^{\textit{Delayed start}} \overbrace{\left(1-\exp\left(-\left(r+\phi+\varphi-x_2\right)\left(\tau_2-\tau_1\right)\right)\right)}^{\textit{Impermanence}} \left[\overbrace{\frac{r-x_2}{r+\phi+\varphi-x_2}}^{\textit{Failure and Additionality risk}}\right] \tag{10}$$

where risks that a project fails or becomes non-additional at any give time is given by ϕ and φ respectively. These parameters are hazard rates and act in a similar way to discount rates on future benefits, such that the probability that a project survives until time t is given by $exp(-(\phi+\varphi)t)$. To make Equation (10) more concrete, consider a carbon credit associated with a reforestation project. This project may be known to be impermanent, lasting only from time t_1 to time t_2. This means that we have to wait for forest growth from today $t = 0$ until τ_1 until any carbon removal benefits arrive. Throughout the duration of the project (τ_1 to τ_2), the forest is subject to the annual risk of *failure* from, e.g. forest fires, pests or property rights expropriation. The parameter ϕ reflects the annual risk and the term $exp(-\phi * t)$ reflects the probability due to failure that the forest will remain standing at time t. The higher is ϕ the lower the probability that a forest will be standing at time t. The parameter φ reflects in a similar way the concept of additionality risk. That is, it reflects the annual risk that a given reforestation project would have happened anyway, irrespective of the financing provided. The term $exp(-\varphi * t)$ reflects the probability that the project is non-additional at time t. These hazard rates (ϕ and φ) combine to raise the effective discount rate for the project's carbon removal benefits to $r+\phi+\varphi-x_2$ from $r-x_2$ in the absence of these risks. The higher discount rate actually increases the value of the *impermanence* correction because the project benefits that are truncated upon re-release at τ_2 are worth less in present value terms due to the higher effective discount rate: future benefits would be much less likely to accrue in the long-run. However, failure and additionality risks ultimately lower the value of the SVTR because of the higher effective discount rate compared to a riskless project. This is reflected in the final term in square brackets which is the ratio of discount rates without and with failure and additionality risks.[14]

A simple parametric expression for equivalence in Equation (9) flows from the augmented definition of the SVTR in Equation (10). Here, the $SVTR^{\phi,\varphi}_{\tau_1\tau_2}$ is related to the social cost of carbon today: SCC_0. Rather than explicitly using SCCs in the future, Equation (10) assumes that the SCC grows from a starting point of SCC_0 at a rate x_1 from time $t = 0$ to t_1 and at rate x_2 for the duration of the project between t_1 and t_2. Given the definition of equivalence Equation (9) equivalence is given by the combination of the *delayed start*, *impermanence* and *failure and additionality risk* terms in Equation

[14] Additionality risk also applies to conservation projects. They could be modelled as being subject to a hazard rate $\widetilde{\varphi}$ reflecting the likelihood that the conserved forest may not have been cut down, and that this deforestation event has a hazard of $\widetilde{\varphi}$ of happening at any moment of time. In this case, $\widetilde{\varphi}$ is the hazard rate that the project becomes additional. (Groom and Venmans, 2023, pp 771) provide an alternative formula for this case.

(10).[15]

Once estimated, equivalence can be used to compare temporary removals to permanent ones. The idea is that, if equivalence turns out to be 20% for a risky, temporary project providing a tonne of carbon removals during its life, then this project provides only a fifth of the benefits of cooling that a permanent removal would provide. To be equivalent in policy terms, or for offsetting an emission of carbon, we would need 5 of this type of project to be equivalent in welfare terms. On average, so the argument goes, conditional on impermanence, failure and additionality risks, 5 of these projects would be expected to provide the same welfare benefits from cooling as a permanent removal. If equivalence were 50% then only two of these projects would be required for welfare equivalence.[16]

Equivalence in practice

Estimating equivalence requires estimates of the project level risk parameters ϕ and φ, as well as the trajectory of the SCC over time given by x_1 and x_2, which are more economy-wide phenomena and depend on emissions pathways, climate damages and the discount rate r. Obtaining estimates of project level risk parameters is not straightforward for many projects, particularly NBS, due to lack of transparency in reporting and in evaluating additionality (Delacote et al., 2024; West et al., 2023). However, recent studies suggest various degrees of failure and additionality. West et al. (2023) analyse certified carbon credits in tropical forests areas of the world and find only 10% additionality. This translates into an additionality hazard rate of $\varphi = .0.046$ or 4.6% risk of non-additionality per year.[17] At the other extreme for Nature Based Solutions, Jayachandran et al. (2017) finds additionality of around 90% in the context of REDD+ in Uganda ($\varphi = 0.2\%$). In between Guizar-Coutino et al. (2022) find additionality of around 50% for a range of REDD+ projects ($\varphi = 1.4\%$). Non NBS approaches to emissions reduction or removal (e.g. CCS) are expected to be more reliable and may lie towards the more optimistic end of additionality for NBS, between $\varphi = 0\%$ and $\varphi = 0.2\%$. As for failure risk, studies in the Acre Region of Brazil and in California suggest, for different reasons, a 50% failure rate for forest carbon credits (e.g. Badgley et al., 2022). This means that the failure hazard calibrates to $\phi = 1.4\%$.

Table (1) reports the equivalence rates associated with different levels of failure and additionality risks calibrated from the studies cited above. Returning to the forest example, imagine a tropcial forest offset project that has the non-additionality risk of 4.6% and a failure risk of 1.4% as suggested by West et al. (2023) and Badgley et al. (2022) respectively. This is the worst case scenario where $\phi + \varphi = 6\%$ and is reflected in the bottom row of Table (1). Even if this project were to last forever, equivalence suggests that such a carbon credit would only be worth 14% of a permanent carbon removal, and hence at least 8 of these 1-tonne projects would be required to be equivalent in welfare terms to a permanent removal. If the project was also temporary, lasting only 10 years, equivalence falls to 7% and at least 15 such projects would be required. The survival / additionality probability declines rapidly as $\phi + \varphi$ increases. The final column illustrates this sensitivity, with there being a 1 in 20 chance of survival beyond 50 years when the risks sum to 6%. To reiterate though, the data to calibrate the SVTR and equivalence are rather scarce. Previous work proposed more modest risks, stemming from estimates of country-level political risk (risk of property appropriation and the like), leading to a failure risk (from force majeure) of 0.5%.[18] While Table (1) updates the estimation of risk terms based on the latest literature, there is still a need for more transparency in project level data, particularly in the realm of

[15] As shown in Equation (11):

$$Equivalence^{\phi,\varphi}_{\tau_1\tau_2} = \frac{SVTR^{\phi,\varphi}_{\tau_1\tau_2}}{SCC_0}$$

$$= \overbrace{\exp\left(-(r-x_1)\tau_1\right)}^{Delayed\ start}\overbrace{\left(1-\exp\left(-\left(r+\phi+\varphi-x_2\right)\left(\tau_2-\tau_1\right)\right)\right)}^{Impermanence}\left[\overbrace{\frac{r-x_2}{r+\phi+\varphi-x_2}}^{Failure\ and\ Additionality\ risk}\right] \tag{11}$$

[16] We discuss the potential criticisms of equivalence in Section 4.

[17] This stems from imagining the probability of survival until time t is given by $exp(-\varphi * t)$.

[18] The updated equivalence values in Table (1) are more pessimistic than those found in Groom and Venmans (2023), who suggested as a rule of thumb that 2-3 risky and potentially non-additional offsets would be equivalent in welfare terms to a permanent emissions reduction.

nature based solutions in order to establish the contribution of different technologies to the reduction of climate damages via the calibration of the SVTR (e.g. Delacote et al., 2024).

Failure and Additionality Risk (ϕ+φ) resp.	Permanence (Years) 10	25	50	100	∞	Survival Probability $P(t > 50)$
0%	10%	24%	44%	70%	100%	100%
0.2%[a]	10%	23%	42%	64%	85%	90%
0.5%[b]	10%	22%	39%	57%	70%	78%
1.4%[c]	9%	20%	31%	41%	44%	50%
4.6%[d]	7%	13%	17%	18%	18%	10%
6.0%[e]	7%	11%	13%	14%	14%	5%

Table 1: **Equivalence of Temporary and Permanent Emissions Reductions ($SVTR/SCC$):** Column 1 shows the sum of failure (ϕ) and additionality risk (φ): a: additionality risk from Jayachandran et al. (2017); b: additionality risk from Guizar-Coutino et al. (2022); c: additionality risk from Acre study (see Groom and Venmans (2023)); d: additionality risk from West et al. (2023); e: sum of additionality risk of 4.6% and failure risk of 1.4%. Columns 2-6 reflect the equivalence measure for different levels of permanence from 10 years to forever (∞). Note that the Social Cost of Carbon in the scenarios considered is \$109/tCO2 using damages from Howard and Sterner (2017) and \$36/tCO2 using damages from Nordhaus (2017). The final column reports the probability that a project will exist in 50 years given the hazard rates on failure and additionality.

The economic implications of reduced equivalence on the market for offsets and carbon credits, supposing that this measure is used to underpin fungibility in that market, are somewhat unclear and the analysis of these implications remains for future work. However, it seems reasonable to assume that low levels of equivalence will raise the cost of meeting a particular target level of offsetting or crediting of carbon, since multiple offsets would be required. The supply side response will depend on the extent to which expansion of the technology (e.g. forest area) is a binding constraint on a voluntary market, how the costs compare to other removal technologies or emissions reductions, and whether commitments formerly announced (e.g. net zero by 2050 of the GFANZ at COP 26) are sustained. Certainly some NBS with low equivalence could become defunct in the VCM due to the growing cost of equivalence.

With temperatures in the long run determined by cumulative emissions, care is required in making the claim that several contemporaneous short-run projects are equivalent to permanent ones in relation to the overall objective of limiting temperature change. We discuss these issues in Section (4). With this in mind, perhaps the most useful application of the equivalence measured in Table (1) is to in the construction of shorter-term commitments, and hence contracts for carbon credits that are more easily monitored and enforced. The idea works as follows.

Consider a project with a 50 year horizon and a 1.4% annual hazard rate of failure and zero additionality risk (it definitely would not have happened anyway or have been undone elsewhere). According to Table (1) this project has an equivalence rate of 31%, meaning approximately 3 of these solutions is equivalent in welfare terms to a permanent solution. That is, that one emitted tonne of CO2 can be compensated by 3 tons of CO2 removed by a project that stores carbon for 50 years with a failure risk of $\phi = 0.014$ per year. This suggests a short run equivalence contract which, rather than making commitments in perpetuity, is valid for 50 years and requires 3 tons of CO2 to be sequestered. After the contract expires, 50 years later, the provider would have fulfilled their liability to the credit holder based on this equivalence. At the end of the project the option of re-crediting the existing forest would be available, using all the information that has arrived in the interim concerning the likelihood of additionality and the risk of failure, and proof that continuation would be additional. This approach to contracting will be more manageable than the perpetual contracts found elsewhere, e.g. in the Clean Development Mechanism (Cames et al., 2016). The economics of such contracts given the potential for asymmetric information and uncertain quality remains an area for future research. Nevertheless, similar proposals already exist in the literature (Balmford et al., 2023).

3.3 Life Cycle Analysis

Just as the time profile of forest carbon storage varies over time with periods of temporary storage and release, the production and consumption of different products, or different methods of energy production have different time profiles of carbon emissions throughout their lifetimes.[19] In order to answer questions like: is and EV more or less carbon intensive than one with an internal combustion engine?; or, is a vegetarian diet is more or less carbon intensive than an omnivorous one?, we need to have a way of accounting for the carbon emissions throughout the lifetime of these products and processes. The broad field of Life Cycle Analysis (LCA) is oriented to these questions. When it comes to evaluating carbon emissions a typical LCA approach will add up the tonnes of carbon associated with products and processes throughout their lifetimes, from production to disposal. However, just like the *physical* approaches described above, since LCA is concerned with physical quantities of carbon it has difficulties handling the time dimension of emissions and storage pathways: an emission of carbon in 10 years time is usually counted the same as an emission in 100 years time (e.g. O'Hare et al., 2009).[20] As a consequence, by explicitly taking into consideration the point in time at which carbon removals or emissions take place over the lifetime of a product or process, the SVTR and its associated equivalence measure can have major advantages as a means of undertaking LCA, and hence in answering these important policy questions. In this section we illustrate how the SVTR can be used in LCA to answer the question of whether biofuels in the form of wood pellets are more or less carbon intensive than fossil fuels in producing electricity. The conclusions arising from the SVTR approach rather than the standard LCA approach are very different as a result of the different treatments of time in the evaluation.

The example builds on the pioneering work of Brandão et al. (2019) who undertook LCA of carbon for biofuels using the profiles of carbon emissions and sequestration shown in Figure (2), which accounts for different initial land-use changes in the first instance. This comparison is important in the assessment of performance-based regulations on transport fuel, the biofuels mandates in the US, the low carbon fuel standards in California (California Air Resources Board, 2009) and the comparison of wood pellets to fossil fuels for electricity generation. The approach we take uses a generalisation of the expression in Equation (10) where, instead of using the stepped path of temperatures associated with the marginal carbon removal shown in Figure (1), we use the explicit pathway of carbon emissions, q_t associated with the technologies in question: biofuels and fossil fuels. This generalised version of the SVTR is shown in the Appendix and admits any path of carbon removals and re-release over time via the term q_t, while remaining flexible on the emissions pathways used to calculate the value of a permanent removal: SCC_0.

Using the economic equivalence approach in Equation (13) we re-evaluate the project discussed in Brandão et al. (2019), that compares 15 LCA methods for carbon life cycle analysis for the use of wood pellets for home heating. The specific assumptions that are used concerning the timing and time horizons for carbon emissions and sequestration are outlined in Appendix 5. A key issue in the case of this biofuel is the assumed baseline/initial conditions against which alternatives such as fossil fuels are compared. Three possibilities are considered for the starting land use for biomass production:

1. Cutting a young forest of 25 years old (not analysed in Brandão et al. (2019));
2. Cutting an old forest, which has reached steady state carbon stock of 200 tC/ha (first example in Brandão et al. (2019)), and
3. Biomass production starting from barren land, which has no initial carbon stock (second example in Brandão et al. (2019)).

The cumulative emissions from the three scenarios are presented in Figure (2). The plotted values are the input q_t to Equation (13) in the Appendix. The cycles of forest growth are similar in each case, but the level of cumulative emissions clearly depends on the initial baseline, with the old growth forest baseline (the orange line in Figure (2)) yielding the highest increase cumulative emissions in the first instance and having a higher level throughout the 100 years evaluation horizon. Barren land baseline has a negative change in cumulative emissions in the first instance and the lowest level cumulative

[19] This section expands on the Supplementary Information contained in Groom and Venmans (2023).

[20] Relatedly, LCA often mixes up greenhouse gases with different lifecycles in the atmosphere when calculating the CO2 equivalence (O'Hare et al., 2009).

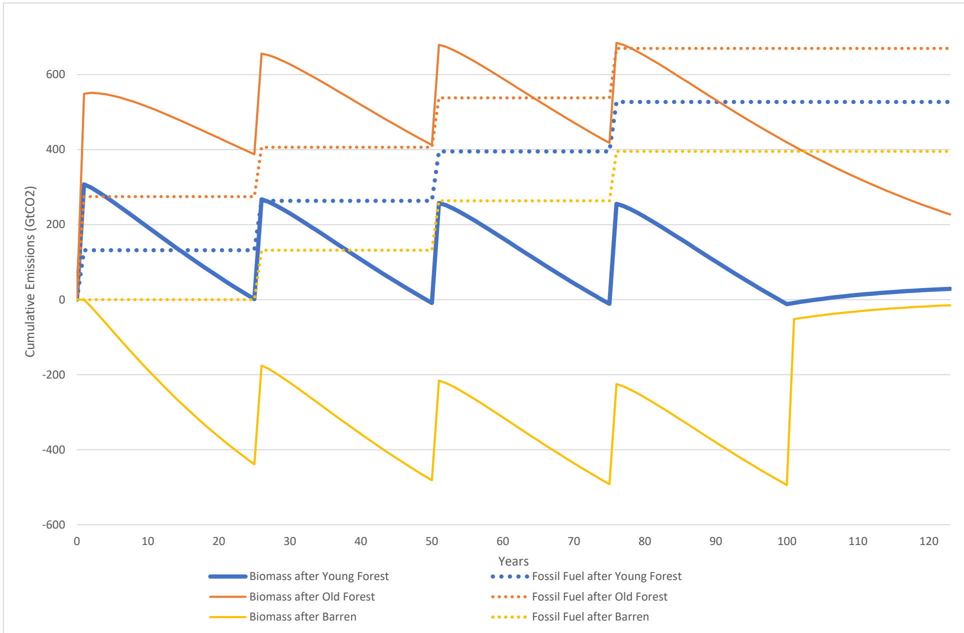

Figure 2: **Cumulative emissions for biomass (solid line) and fossil fuel (dotted line) for three initial conditions**: 1) Cutting a young forest of 25 years old, 2) Cutting an old forest, which has reached steady state carbon stock of 200 tC/ha, 3), Biomass production starting from barren land, which has no initial carbon stock. Note: Brandão et al. (2019) assume that only 50% of the heat content of wood pellets is converted to energy, compared to 100% for fossil fuels.

emissions thereafter. In each case the cycle of sequestration is similar, with cumulative emissions going down over the 50 year cycle as biomass regrows. Note that the cumulative emissions of fossil fuels are also plotted. To close the analysis temporally, in each scenario the initial baseline: young forest; old forest; or barren land, re-emerges after 100 years.

Table (2) shows the outcome of the comparison between the economic approaches using the SVTR and the Global Warming Potential approaches used in Brandão et al. (2019). Column 2 shows the value of the pathway of cumulative emissions for biofuels using the SVTR approach for each of the 3 scenarios. Column 3 undertakes the equivalent evaluation for fossil fuels. Typically in LCA, the comparison between one technology and another is presented in terms of the so-called Carbon Neutrality Factor (CNF). In our case the CNF measures the extent to which biofuels (wood pellets) improve upon the alternative (fossil fuels) in terms of the effect of their carbon emissions on GWP, welfare or whichever measure of social cost and equivalence is being used. The formula for the CNF is:

$$CNF = \frac{SocialCost_{Fossil} - SocialCost_{Biomass}}{SocialCost_{Fossil}} \tag{12}$$

We use the CNF in Table (2) to compare the results using SVTR (column 4) and GWP (column 5) as in Brandão et al. (2019). Columns 2 and 3 are inputs into Equation (12) the outcome of which is shown in column 4.

Using the economic SVTR approach gives rise to a crucial distinction in the case of baseline scenario 2, in which the starting point of the life cycle is old growth forest cleared for wood pellets. In this case the carbon cost of biomass is highest and the SVTR approach is suggests that it is only 7% better than fossil fuels (column 4). On the other hand, the GWP approach suggests that biomass is 50% better than fossil fuels in this context (column 5). This distinct conclusion is precisely because of

Baseline Scenario	Social Cost of Biomass ($/ha)	Social Cost of Fossil Fuels ($/ha)	Carbon Neutrality Factor (CNF) Groom and Venmans (2023)	Carbon Neutrality Factor (CNF) Brandão et al. (2019)
Young Forest (1)	7894	11291	30%	NA
Old Forest (2)	43532	46803	7%	50%
Barren land (3)	-19725	20294	197%	210%

Table 2: **Economic equivalence of biofuels and fossil fuels using the SVTR:** The Table re-evaluates the examples assessed by Brandão et al. (2019). Column 2 reports the social cost of temporary emissions from burning biomass (emissions which are gradually reabsorbed by the forest). Column 3 reports the social cost of burning methane with the same heat content as the harvested biomass. The final 2 columns show Carbon Neutrality Factor (CNF) using our method (SVTR) and the GWP methods respectively.

the problematic treatment of the timing of cumulative emissions when using GWP to compare energy sources. In particular, the absence of a discount rate for cumulative emissions for the GWP approach means that it underweighs cumulative emissions that happen earlier and overweighs those that happen later. Qualitatively, since the emissions from pellets happen early on, particularly for old growth forest, the GWP approaches will tend to make wood pellets look much better than when the SVTR approach is used. Quantitatively, a 7% improvement is far less compelling than a 50% improvement, signalling that wood pellets produced from old growth forests are probably to be avoided. Scenarios 1 and 3 are more aligned between economic and physical estimates of equivalence because the particular flow of emissions and releases are more closely matched over time between biomass and fossil fuels. Note that Brandão et al. (2019) assume that fossil fuels deliver 2 times more useful energy per unit of CO2. Under the assumption that a unit of heat from oil and biomass are equally efficient,that applies to natural gas. However, oil is more carbon intensive, which increases column 3 by 50%. In this case biomass is much more attractive, bringing the CNF to 114% for young forest.[21]

These results show the range of applicability of the SVTR and the economic approach to equivalence and how it can take into account the timing of emissions and removals. Arguably, the economic approach is preferable because it handles the long-term dynamics more completely and transparently than physical approaches, which make implicit assumptions about the importance of outcomes at different points in time.

The value of temporary atmospheric storage

Most IPCC scenarios that stay below 1.5°C by 2100 overshoot 1.5°C in the interim and required significant negative emissions in the second half of this century.[22] Financing carbon dioxide removals in a world of negative emissions will therefore become a major challenge beyond 2050, when net zero pledges are presumably to be attained. The problem arises because, unlike emission reductions induced by revenue raising carbon taxes, the net carbon removals required for reducing cumulative emissions are likely to require substantial government budgets to be deployed. Bednar et al. (2021) argue that up to 10% of world GDP will be required. One way to bridge that funding gap could be through carbon debt financing whereby emitting companies' emissions are recorded against a carbon budget with a view to the company being liable to pay back (removing carbon) later with a permanent project. The SVTR is also useful in this context since, by measuring the damages associated with the temporary overshoot of emissions it provides a monetary measure of the carbon debt and the appropriate payments due on that debt.[23] In essence, the SVTR can be used to set the rental price that companies should pay for the temporary storage of their carbon emissions in the atmosphere. Charging for temporary storage thereby provides a source of revenues to finance negative emissions in a world of zero carbon tax revenues. In practive the scheme could work as follows: 1) a central bank responsible for carbon sells

[21]Assuming 50% carbon and 19MJ/kg for wood, 85% carbon and 43MJ/kg for oil and 75% carbon and 55MJ/kg for methane.

[22]This section expands on the Supplementary Information contained in Groom and Venmans (2023).

[23]With overshoot there is additional atmospheric residence time of emissions in the atmosphere. The SVTR formula also applies if temperature is continuously rising despite negative emission of some companies.

carbon debt to commercial banks; 2) commercial banks sell carbon debt to CO2 emitters[24], where the debt contract specifies the amount of repayment (in terms of carbon) required in the future; 3) The price of the debt should reflect the cost to society of temporary storage of CO2 in the atmosphere. The purchase of this debt would generate climate finance for carbon removals. the question remains of how to price this debt and its interest payments. In a pioneering proposal, Bednar et al. (2021) propose to charge a carbon interest rate between 0 and 8%. However, from an economic welfare perspective, the price of this debt should be governed by its social costs. The social cost of permanently storing CO2 in the atmosphere is simply the sum of marginal damages from a tonne of emitted carbon: the social cost of carbon. The appropriate (risk-free) period to period interest payment on permanent storage would be the marginal damage in each period. This price would be charged by the central bank and would rise with increasing temperatures if damages are increasing with temperature.

However, one difficulty with the notion of carbon debt is that the commitment periods even for temporary storage in the atmosphere are much longer than the standard commitment periods of financial debt. Some companies will have an incentive to take on a lot of carbon credit and file for bankruptcy after. The latter asymmetry in information could easily collapse the market on the supply side, destroying socially valuable contributions to carbon mitigation. To limit this problem, emitters could commit to pay the fixed atmospheric storage cost upfront. This is where the SVTR could play an important role since the asset price associated with atmospheric storage and carbon debt is simply the SVTR in Equation (4) from Section (2). Equivalence then has an important interpretation in this context because it indicates the proportion of the SCC that needs to be paid to hold particular types of debt. According to Table (1) in Section 3, and when there is no doubt that emissions will occur ($\phi = \varphi = 0$, as is likely), then a ton emitted today and paid back in 25 (50) years time would be worth 24% (44%) of the social cost of carbon, since this is the value of the flow of damages associated with the temporary atmospheric storage. Paid up front, this would provide a safe source of carbon finance. While the measures of equivalence in Table (1) do not depend on the controversial parameters that determine the social cost of carbon (e.g. marginal damages and the transitory climate response to emissions (TCRE), to be discussed in the following section), the SCC *is* determined by these parameters. This means that the asset price and interest payments for temporary storage are also dependent on these parameters.

4 Potential shortcomings of the integrated economic approach to valuing of temporary reductions

The SVTR approach to temporary emissions reductions relies on cost benefit analysis and the economics of climate change, and so similar criticisms as apply to these disciplines can be levelled at the SVTR and its associated equivalence measure (e.g. Pindyck, 2017). In relation to the economics of climate change several issues arise: the damage function is unknowable or poorly calibrated (Pindyck, 2017, 2013); the social discount rate is too high or too low (Groom et al., 2022; Drupp et al., 2018); discounted Utilitarianism is inappropriate Nesje et al. (2023); or, damages to ecosystem services are absent from typical Integrated Assessment Models (IAM) and analytical expressions for the Social Cost of Carbon (Drupp and Haensel, 2018; Hoel and Sterner, 2007; Sterner and Persson, 2008). Each of these criticisms can be brought to bear on the issue of valuing temporary removals in addition to concerns about the mixing of temporary and permanent removals . We now discuss some of the main potential shortcomings of the economic approach and tonne-year accounting in general.

4.1 The damage function

There is a great deal of uncertainty surrounding the nature of damages arising from climate change (Pindyck, 2017, 2013). One concern is with the quadratic functional form of damages, with some preferring higher order terms to capture more rapidly increasing effects of temperature change on GDP via or potentially capturing catastrophic risks (e.g. Weitzman, 2009). Others worry that the damage function ignores tipping points (e.g. Howard and Sterner, 2017; Pindyck, 2017; Cai et al., 2016). Others are less concerned about the functional form but more concerned about the calibration and the source of information from which damages are derived (Pindyck, 2019; Howard and Sterner,

[24] Adding a risk premium to cover solvency risk of borrowers.

2017). Finally, there is uncertainty about the climate science which manifests in the estimate of the TCRE parameter (ζ). The Social Cost of Carbon can vary quite considerably with different positions on these (and other) issues relating to damages (Hänsel et al., 2020). However, when it comes to estimating the SVTR and particularly equivalence, some of these concerns disappear.

The general form for economic equivalence is shown in Equation (13) in the Appendix. Here the damage function is quadratic and so marginal damages are linear: $MD_t = \zeta\gamma Y_t T_t$, where γ is the slope of the marginal damage function, ζ is the TCRE, Y_t is GDP and T_t is degrees centigrade above pre-indutrial temperatures. This means that two of the most difficult to estimate and uncertain parameters that determine the Social Cost of Carbon: ζ and γ (both highlighted in red in Equation (13)) cancel out in the ratio $SVTR_{\tau_1,\tau_2}/SCC_0$.[25] Calculating economic equivalence is therefore rather straightforward requiring easily available data: income and growth (from national accounts); temperature (from RPC scenarios); the discount rate (from the literature). As discussed, estimating failure and additionality risks (ϕ and φ) is only slightly more problematic. Ultimately, the key question is how well the economic approach to evaluating temporary emissions reductions performs compared to the alternatives. Viewed in terms of damages the alternatives make less acceptable assumptions concerning the damage function, sometimes implicitly. The implicit assumption in the physical approaches is that the marginal damages from an extra degree of warming do not depend on temperature (e.g. Moura Costa and Wilson, 2000; Levasseur et al., 2011), i.e. that total damages are linear in temperature. This is an unattractive quality. One advantage of the economic approach is that it is explicit in its theoretical assumptions concerning the damage function. Indeed any damage function can be included in Equation (13) to calculate equivalence or the SVTR. On the omission of aspects like tipping points, extensions to the framework show that the SVTR is always larger because of the ability of temporary removals avoid tipping points, as discussed below.

4.2 The discount rate

The arguments surrounding the determination of the social discount rate (SDR) have been well rehearsed elsewhere (Drupp et al., 2018; Groom et al., 2022; Gollier, 2013; Cropper et al., 2014). For our purposes it is enough to state that the SCC and hence the SVTR are sensitive and negatively related to the Social Discount Rate (SDR). Objections to using a positive SDR are usually concerned with the apparent unfairness of less weight being put on costs and benefits in the future, possibly accruing to currently unborn and distant future generations. Zero discount rates are often proposed as the solution. Suppose that this recommendation is applied to the discount rate appropriate for consumption (r in Equation (4)), rather than solely the utility discount rate (sometimes called the pure rate of time preference), as famously recommended by the Stern Review and Frank Ramsey years before (Drupp et al., 2018; Stern, 2007; Ramsey, 1928). What happens to the SVTR, SCC and equivalance, and what are the implications for policy of zero discount rates when applied to the cost-benefit framework of the SVTR?

The first thing to recognise is that in our thought experiment applies to the calculation of the SVTR in Equation (4) so that a zero discount rate means that $r = 0$. In this case, the SVTR remains positive when a zero discount rate is applied, becoming the undiscounted sum of avoided damages between emissions reduction and re-release. While this seems like a straightforward result it was not recognised prior to Groom and Venmans (2023) for the following reason. With a zero discount rate the SCC becomes infinite, leaving previous conceptions of the SVTR undefined because they were calculated by taking the difference between two SCCs both valued at infinity, as in Equation (3) (e.g. van Kooten, 2009). The integral version of the SVTR in Equation (4) shows that the SVTR is always positive irrespective of the discount rate.[26]

However, using a zero discount rate does introduce problems for the calculation of equivalence. In this integrated framework a zero discount rate means the SCC becomes infinite as discussed, which means that since equivalence is the ratio $SVTR_t/SCC_0$, it becomes zero. The intuition here is clear and reasonable though. Even though the SVTR is always positive, it is infinitesimally small compared to the value of a permanent emissions reduction/carbon removal (the SCC), so temporary reductions have *zero* equivalence to permanent ones. The problem becomes worse in the context of the *physical*

[25] The principle of canceling damage parameters can also apply to more complex damage functions. For example, if the damage function is cubic, the damage slope parameters will again cancel and T should be replaced by T^2.

[26] See Section (2) for more on this topic. The proof relies on the linearity of temperature changes in cumulative emissions, which allows us to model the SVTR as a step function. See footnote 9.

estimates of the value of temporary emissions removals discussed in Section (2). Here, emissions reductions at each point in time between 0 and 100 years are treated identically so in general there is no distinction between a carbon removals project that removes carbon from the atmosphere tomorrow and for 10 years, and the same project starting in 50 years time. This is problematic from the economic perspective in which the main value of temporary storage stems from delaying emissions. To handle the temporal ambiguity that arises in the absence of a positive discount rate, the physical approaches use an arbitrary time horizon of 100 years to define permanent emissions reductions, with shorter duration emissions reductions treated as 'temporary'. This approach implicitly applies a zero discount rate to physical units in the period zero to 100 years, and an infinite discount rate to emissions reductions beyond 100 years. This means that temporary emissions reductions beyond 100 years are worthless. O'Hare et al. (2009) and van Kooten (2009) discuss the issue. O'Hare et al. (2009) note that while it might be tempting to apply a market or social discount rate to physical units of carbon as a way around this problem, such discount rates are only appropriate for units of consumption. We simply do not know what the discount rate is for physical units of carbon unless we are willing to make the assuption that the relationship between physical changes (e.g. GWP or forcing) and well-being is linear.[27] Ultimately, framing temporary emissions reductions in terms of economic damages, connecting these to climate scenarios and then using a discount rate to compare and weigh the impact of projects that provide benefits and costs at different points in time, avoids the need for arbitrary cut-offs to the time-horizon. The approach avoids unusual implied discounting regimes and allows a less ad hoc calculation of the equivalence of temporary emissions reductions that takes into account their different effects over time.

Finally, economists have very good reasons for discounting. First note that if the social discount rate is organised around the Ramsey Rule it can be decomposed into two components: a pure time preference rate applicable to utility[28], and an inequality aversion component. Setting the discount rate r to zero means that the analysis is insensitive to inter-temporal inequality and implies that additional income to a rich generation is treated the same as additional income to a poorer generation. Economists see this as unacceptable in general, philosophers more so (Nesje et al., 2023).Moreover, using a zero discount rate can have unintended consequences, because it ignores the typically positive opportunity cost of capital. If avoided damages are equally valued whenever they arrive (not discounted), but the government issues interest-bearing debt, the benefit-cost ratio of a given abatement project can always be improved by postponing the project, because postponed costs reduce interest payments before the start of the project, while benefits are not discounted. A government that is concerned with public finance would delay action on climate change if this asymmetry in the treatment of costs and benefits were to be imposed.

4.3 It's not just about the average temperature...

The integrated (economic-physical) approach frames the problem of temporary emissions removals in terms of the impact on temperature change and associated economic damages. There are two related motivations for this. First, the temperature level is the main variable of interest when it comes to estimating economic damages, making temperature change the economically relevant physical quantity to measure (e.g. Burke et al., 2015). This contrasts with concentrations, GWP and forcing which are less interesting from an economic, not to mention biological perspective. Second, given this, the dynamics of temperature capture more physical science processes than those that govern CO2 concentrations, such as the satiation of carbon sinks and thermal inertia, each of which play a role in determining the time profile of temperature change (contrast the middle and lower panels of Figure (1)). However, there are other features of climate change that are of interest economically that are not well captured by temperature change alone.

First, as raised by Kirschbaum (2006), the rate of change of temperature is important from the perspective of adaptation. It is more difficult for humans and particularly nature to adapt when temperatures are changing quickly. This suggests another potential value for temporary emissions reductions: the slowing of temperature change to allow for adaptation. Since temperature is propor-

[27] O'Hare et al. (2009) offer a careful discussion of this matter, in the end opting for linear marginal damages as a means of valuing damages in a GWP inspired framework.

[28] Expert elicitation among prominent economists shows that the median value for the pure time preference rate is 0.5% and the modal value is 0%, in line with Stern (2007), for very long-time projects of public interest (Drupp et al., 2018).

tional to cumulative emissions, the change in temperature is proportional to emissions. This gives rise to damages which are an increasing function of emissions rather than temperature. A temporary removal boils down to a negative emissions at the start and a positive emission at the end (as in Figure (1)). Provided that the re-release of emissions does not happen at a point in the future in which emissions are higher than when the removal took place, the rate of change of temperature will be reduced by a temporary removals project. This smoothing of the temperature path over time may avoid biodiversity loss with permanent effects. So even if in the long run temperature is not affected by temporary removals, some permanent damages may be avoided.

Second, certain outcomes may be dependent on the duration at a particular temperature, rather than a temperature level per se. For example, tipping points such as melting Antarctic ice and permafrost are mainly driven by persistence of warming, rather than warming at a given point in time. Here again, temporary removals may reduce the likelihood of triggering these tipping points, even if these removals end before peak warming. Extensions of the basic model to embody the economic consequences of these different dimensions of climate change are relatively straightforward. Venmans and Groom (2024) illustrate how temporary removals can be valuable for different critical measures of temperature in the context of tipping points.

4.4 After re-emission, nothing has changed...

Since temperature change depends approximately linearly on cumulative emissions, when a temporary carbon removal is re-released temperatures return to what they would have been in the absence of the removal. If one is solely concerned with the long-run (meaning after the end of the temporary removal) a problem then arises: one-off, temporary removals do not necessarily reduce temperatures in the long-run. This is a powerful point, and from it flows some justifiable scepticism about the use of equivalence and tonne-year accounting, and the fungibility between permanent and temporary removals that they facilitate (Brander and Broekhoff, 2023).[29]

At best, so the argument goes, temporary removals simply rearrange the chairs on the deck of the Titanic before the inevitable long-run disaster. At worst, the *rearrangement* distracts from other actions that could have stopped the ship from sinking. One comment to the UNFCCC public consultation on the treatment of temporary removals in article 6.4 of the convention, states clearly:[30]

> The Paris Agreement does not say "...hold the increase to well below 2°C, but only for the next 100 years" or "only until the present value costs appear negligible."

These arguments state that there cannot be any equivalence between temporary removals and permanent ones and that temporary removals are essentially valueless from the long-run perspective. The essential claim is that the intertemporal trade-offs embodied in calculating equivalence (i.e. the cooling from X number of 20 year removals today is equivalent the cooling from a permanent tonne removed) are unacceptable through this physical lens. The only thing that matters is the long-run temperature.

There are two cases discussed already in which the integrated framework of the SVTR agrees with this view: i) when Cost Effectiveness Analysis is used to evaluate removals; ii) where a zero discount rate is used in a Cost Benefit Analysis. CEA is used to analyse climate policy when the difficulties in measuring climate damages are seen as insurmountable and abatement is organised around a policy target such as net-zero by 2050 or keeping below 1.5C. In this case pricing of carbon is set by the marginal abatement cost (See Section 2). In this framework, any one-off, temporary removal will not contribute to meeting the target prior to the target being met, and a cost effectiveness analysis will attribute zero value a temporary removal. This valuation approach embodies the emphasis on the long-run target that is central to the criticism of equivalence above. With a value of zero, there is no equivalence.

A similar result emerges when a zero discount rate is applied to calculate the SVTR. In this case however, it is not the value of a temporary removal that becomes zero. We have already shown that

[29] Kirschbaum (2006) takes the argument further and suggests that temporary removals actually make things *worse* in the long-run because of the overshoot of CO2 and (to a lesser extent) temperatures that occurs after re-release of the stored carbon.Figure (1) shows indeed a small increase in temperature after release, but this is temporary and negligible compared to the cooling effect during the removal.

[30] A very succinct comment can be found in the response to the UNFCCC public consultation in document A6.4-SB004-AA-A04 on the issue of temporary emissions removals: Broekhoff et al. https://tinyurl.com/yw3ud4cr

the SVTR is always positive. Rather, the value of the permanent removal becomes infinite, making the relative value a temporary removal, its equivalence, zero. In the absence of discounting, long-run well-being is valued positively for an infinite time horizon, so any short-term welfare that could be obtained from a temporary removal becomes valueless by comparison. In sum, zero equivalence emerges as two special cases of economic analysis. Yet, these are not general cases within the integrated framework of the SVTR described above, and each case comes with its own difficulties for decision-making.

In defense of temporary removals and equivalence

When looked at from the perspective of intertemporal welfare the conclusions drawn from the dismissal of one-off temporary removals may lead us to rule out some efficient approaches to mitigating climate change. For instance, it is important to recognise that a series of temporary removals, each starting whenever the preceding project ends, will be equivalent in terms of their effect on temperatures as a single permanent removal. Indeed, we have argued above that contracting over a series of short term removal contracts may be more straightforward and effective than a single perpetual contract. It would be problematic and lead to inconsistent policy to rule out temporary projects per se just because when analysed as a one-off removal they may not on their own reduce long-run temperature. Using the SVTR in Equation (4) to guide mitigation policy is time-consistent in the sense that it gives the same value to a permanent removal as to a series of temporary projects, but we only know this if we value both the short and the long run.This matters for cost-effective policy because a series of temporary removals could well be cheaper than a permanent one from, e.g. Direct Air Carbon Capture (DACC).[31]

Beyond this divisibility and consistency issue, even one-off removals may have some important benefits to society. The preceding arguments against temporary removals ignore the flow of benefits arising from reduced temperatures and reduced damages during the life of the project: the stepped dip in temperature visualised in Figure (1). It is true that these benefits accrue only to a particular group of people who are alive at that time, with future generations no better off in climate terms than without the temporary emissions reductions.[32] However, this does not mean that the temporary cooling was not worthwhile and should be written-off entirely.

In welfare terms, focusing solely on the long-run (the point at which the target has been met) leads to indifference to temporary carbon removals in the short-run. However, if policy is organised around these principles, then one is also indifferent to methane emissions, which dissipate in the short run over a period of around 20 years, because these have no long-run effect on temperatures. Practically speaking, ignoring short-run effects would lead to a tendency to treat methane as equivalent to the future addition to CO_2, since methane is converted to atmospheric CO_2 in the long-run. Yet there is a large scientific consensus that methane is a big problem because of its immense warming effect during the two decades of residence in the atmosphere. The scientific concern about methane can be framed as a concern about the short-term pathway towards the long-run goal, which is ignored if one focuses on the long-run objective only. The SVTR approach would provide a clear signal on how to trade-off short-run versus long-run effects based on society's valuation of well-being at different points in time and the best estimates of damages that occur through time. It is a small extension from measuring these intertemporal trade offs to expressing the equivalence of CO_2 and methane emissions in welfare terms as proposed.

If concerns remain about the inter-temporal trade-offs of welfare that are implicit in the welfare related equivalence measure (e.g. the idea that X temporary removals that improve well-being today can never be equivalent to a single permanent removal that improves well-being in the distant future), these trade-offs can be circumvented themselves with careful application of temporary carbon removals to counter temporary temperature effects. For instance, if temporary carbon removals of, say, 20 years are directed towards compensation of methane emissions, which have an atmospheric lifetime of 20 years, the temperature effects of a methane emission can be smoothed out and approximately nullified. Provided the temporary carbon removal projects can be arranged to have an approximately equal and opposite effect on temperature in 'real time' then the inter-temporal welfare transfers can be

[31] A related point is that temporary interventions that are seen as successful often do not come to an abrupt end when the contract ends, and so become perpetual.

[32] In fact they could be worse off if the investment was not efficient and money could have been put to better uses (the costs outweigh the benefits), if some crowding out of emissions reductions takes place, or where re-release happens at hotter temperatures.

considerably reduced.[33] Groom et al. (2024) show how temporary carbon removals projects can be deployed to closely match the time profile of temperature changes from methane emissions, e.g. from agriculture. The lesson is that temporary removals projects could be contracted to offset specific types of emissions that have less durable effects on the climate, removing concerns about intertemporal trade-offs and long-term efficacy, as well as the difficulties associated with perpetual contracts.

Nevertheless, ruling out any transfer of well-being from future generations to present ones, e.g. by disallowing temporary emissions reductions on the basis that in the end (the long-run) the overall objective of limiting climate change to 2C is not met, also rules out some welfare enhancing interventions. Overlooking the short-term impact of methane is a good example, but other examples exist. Imagine that society could invest in a technology that lasts only for 100 years and which reduces mortality for humans and other species while operative. After 100 years mortality rates increase back to where they would have been without the technology, or possibly slightly higher as all species get used to returning to the old situation. Certainly, this technology would not meet any target that read 'we must reduce mortality rates to X% for all time', but this failure would not necessarily rule out this technology altogether just because there is another technology that can reduce mortality risk permanently.[34] The criticism of Kirschbaum (2006) can be criticised for the same reason: it ignores the cooling effect of the temporary removal which in welfare terms could outweigh the costs of any overshoot.

The overall point is that comparing permanent and temporary solutions requires an assessment of the acceptable intergenerational transfer of well-being.[35] To make sense of these trade-offs a framework for weighing the present against the future is required rather than ruling out particular transfers altogether. The SVTR analysis helps guide such decisions towards the efficient intertemporal response, while equivalence assumes that some trade-offs between permanent and temporary responses are eligible according to societal preferences. The integrated approach proposed here makes explicit the assumptions underpinning the allowable trade-offs at least.[36] Finally, even if a welfare maximization is undertaken in the presence of a temperature constraint, (which boils down to adding damages in the CEA approach) Groom and Venmans (2023) show that removals ought to be scheduled according to the SVTR (Equations (3) and (4) remain the same).

Temporary removals lead to permanent benefits

Moving beyond the arguments pitting temporary flows of well-being against long-run concerns, it is worth asking whether or not temporary carbon removals can induce *permanent* reductions in damages, or whether they are more appropriately characterised as rearranging the chairs on the deck of the Titanic. It turns out that there are at least two reasons why temporary removals could generate permanent benefits: 1) learning by doing; 2) the avoidance of tipping points. Learning by doing can be induced by implementing a removal technology, which adds to the public stock of knowledge for technology in general, and reduces the cost of implementation for all parties henceforth. Venmans and Groom (2024) show that the value of the technical change brought about by abatement with early-stage technologies can cover 25 to 50% of the cost of the abatement project.[37] The benefits from avoiding tipping points are more complicated, but if tipping points are related to the level of temperatures, temporary emissions reductions that straddle the period at which peak temperatures are reached will reduce the likelihood of tipping points being triggered. Yet, if one-off temporary removals end prior to peak warming, they may not reduce tipping point risks in this context, which echoes the long-run concerns about temporary projects. However, if triggering tipping points depends on the duration at a higher temperature rather than peak warming (such as melting ice caps), temporary removals can also be beneficial in reducing the likelihood of a tipping point being triggered, even if

[33]Note that when a methane emission is compensated with a welfare-equivalent permanent CO2 emission we obtain the opposite welfare transfer: the short term becomes warmer whereas the long run becomes cooler.

[34]Perhaps a better analogy would be if mortality rates were rising in the background and the policy objective were to limit this rise to some agreed percentage. The point holds in each case.

[35]Indeed, all investment opportunities, public or private, in education, health, transport, face similar trade-offs over time and require a similarly systematic treatment.

[36]It is worth reiterating that a positive social discount rate embodies concepts of inter-temporal fairness through the inequality aversion component of the Ramsey Rule. This captures the fact that of growth is positive and future generations are richer, the benefits of temporary cooling accrue to the poorer, current generation at the expense of the richer future one. Putting less weight on changes in richer future generations well-being is a central reason for discounting the future, and another reason for considering temporary carbon removals (Groom et al., 2022).

[37]Note that a removal without learning could offset an emission which would have led to learning if it was abated. This points to the more general point that technological change should be valued when ranking green projects.

they end before the peak temperature is reached. Venmans and Groom (2024) also show that the number of tipping points triggered can also be reduced by temporary removals. In sum there are important cases where temporary removals provide permanent benefits, irrespective of when they happen.

To conclude, while there are justifiable concerns about temporary removals and their fungibility with permanent ones, we have argued here that there are many reasons why temporary solutions could be the cost effective or efficient approach to climate change mitigation (Brander and Broekhoff, 2023). They may improve well-being via temporary cooling even in the face of a temperature constraint, or be the starting point for a mitigation strategy that is followed by further temporary solutions or a permanent one. It is even possible that temporary removals have permanent effects on temperature and well-being through the avoidance of tipping points. What is needed is a means of evaluating when these potential benefits outweigh the costs.

5 Conclusion

Temporary emissions reductions are potentially valuable additions to climate policy. Whether they are known for sure to be temporary or have some positive probability of being curtailed or non-additional (like tropical forest offsets for instance), the extent to which such solutions can form part of a climate strategy hinges not on the fact that there may be impermanence and risk, but rather on the extent to which they are efficient. We conclude that there are several benefits that temporary emissions reductions provide that need to be taken into account in determining an efficient strategy, and that these need to be weighed against the costs.

Temporary emissions reductions provide temporary cooling and lower climate damages. These are valuable as a flow irrespective of whether in the long-run temperatures return to where they would have been without the temporary project. Objections to this on the basis of the long-run objectives require discussion but most likely reflect a clash of welfarist versus physical perspectives on what makes for good policy. From a welfarist perspective the social value of temporary reductions (SVTR) is always positive.

Irrespective of the temporary flow of lower damages provided, temporary emissions reductions may provide permanent benefits. Firstly, the simple application of abatement can ratchet up technological change through a learning by doing effect. Secondly, temporary removals could also reduce the likelihood of tipping points. This is especially the case for temporary removals which span the period of peak warming and for tipping points which depend on the duration of warming rather than peak warming, such as ice melting. Thirdly, temporary removals may reduce the speed of warming and thereby avoid a permanent loss of biodiversity.

These results stem from a economic/welfarist approach to valuation rather than a purely physical approach. Objections are still possible, either of the internal workings of the framework itself, e.g. the process of discounting or the level of the discount rate, or of the framework as a whole. Nevertheless, we have argued here that there are some inevitable trade-offs that need to be addressed in the context of these dynamic and long-run policy questions and that that flows of well-being are important. In many ways the economic approach might be more transparent in its assumptions about allowable intertemporal trade-offs than the physical strand of the tonne-year literature, for example in calculating the equivalence between temporary and permanent emissions reductions. Yet, even outside of the economic framework, some important physical processes are dependent not just on the level of temperature (and hence cumulative emissions) but on the rate of change of temperature, e.g. migration and adaptation of species (including humans) and on the duration of warming (melting). So even in physical terms temporary emissions reductions can ameliorate these otherwise worrying processes by slowing down the rate of temperature change.

From an economic/welfarist perpective, all removal technologies should be evaluated in terms of the well-being they provide compared to alternative approaches. Recent work on the additionality suggests that certain Nature Based Solutions have very low levels of additionality, e.g. 10% of forests are additional (West et al., 2023). The equivalence to permanent solutions of such risky, non-additional solutions is around 7% for 10 year projects, meaning that 14 tonnes of such reductions would be equivalent in welfare terms to 1 permanent emissions reduction. How this affects the market for carbon credits remains to be seen, but it may be that once these risks are taken into account and the quality of projects is properly and transparently considered, several temporary solutions will not be economically worthwhile (Delacote et al., 2024).

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A A permanent emissions increase

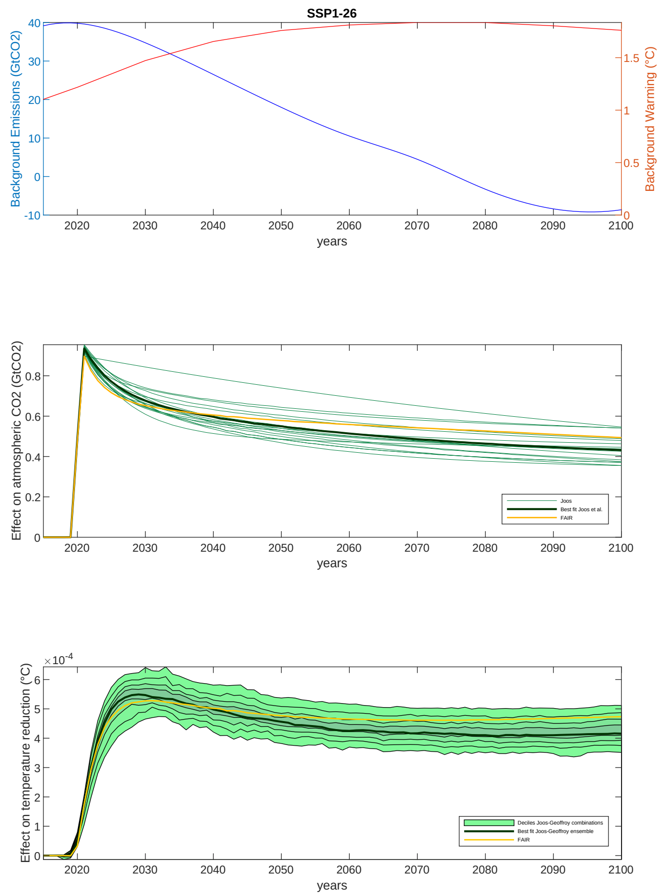

Figure 3: **The effect of a permanent emissions increase: Panel a** shows the background emissions and the temperature path of the IPCC's RCP 2.6. scenario. **Panel b** shows the effect of a permanent emission pulse of 1 GtCO2 in 2020 on atmospheric carbon concentrations. Each line represents a model of the CMIP 5 ensemble (as in Joos et al. (2013)). **Panel c** shows the effect of the same permanent emissions pulse on temperature. The 16 absorption models are combined with 16 energy balance models from the CMIP 5 ensemble (as in Geoffroy et al. (2013)) and the figure shows the deciles of the 256 possible combinations of models. The climate sensitivity of all energy balance models has been harmonized to 3.1°C. The FAIR model uses the best fit of the CMIP5 models but adds saturation of carbon sinks.

B Generalized expression for the SVTR

Equation (13) shows the generalised version of the equivalence measure used in Section 3 to undertake the LCA of biofuels.

$$Eq_{SVTR_0} = \frac{SVTR^{\phi,\varphi}_{\tau_1\tau_2}}{SCC_0} = \frac{\sum_{t=\tau_1}^{\tau_2} \overbrace{e^{-r(t+\xi)}}^{Discount\ factor} \overbrace{e^{-(\phi+\varphi)(t-\tau_1)}}^{\substack{Failure\ +Additionality \\ risk\ at\ end}} \overbrace{\left(1-e^{-\tilde{\varphi}(t-\tau_1)}\right)}^{Additionality\ risk\ at\ start} \overbrace{q_t}^{Quantity\ stored} \overbrace{\zeta\gamma Y_{t+\xi}T_{t+\xi}}^{damages}}{\sum_{t=0}^{\infty} e^{-r(t+\xi)}\zeta\gamma Y_{t+\xi}T_{t+\xi}}, \tag{13}$$

Groom and Venmans (2023) have a repository for their paper which can be found here: https://github.com/BenGroom/socialvalueofoffsets/releases/tag/SVO1, which contains en excel spreadsheet that allows this formula to be calibrated to any proposed removals technology and for any emissions RCP pathway. Risk and discounting parameters can also be freely calibrated there.

The assumptions made in the analysis of biofuels for energy production are as follows:

Firstly we assume that when burning pellets that emit one ton of CO2 the forest carbon sink is reduced by the equivalent amount. The forest then gradually replenishes the carbon sink.[38] When land use change occurs in the production of the alternative biofuel, such as the clearance of forest, the pathway of carbon emissions and sequnestration reflects this in q_t. In the case of annual biofuel crops such as colza, this stock of carbon held in the current land use is converted to emissions in one year.[39]

Further, above ground biomass (GtC/ha) of the forest grows according to a standard growth function $200\big(1-e^{-0.03Age}\big)^{1.1}$, which results in a biomass of 97GtC/ha after 25 years and a steady state of 200GtC/ha. Below ground biomass (roots) is 25% of above ground biomass. Dead roots decay at 5% per year. 75% of above ground biomass is harvested. Any remaining biomass above ground decays at 6.67% per year. Rotation length for biomass production is 25 years. Then we assume that that 1 ton of CO2 from biomass delivers the same useful energy as 0.5 ton of fossil fuel CO2.

[38] q_t in Equation (13) reflects the effect on the carbon sink, starting at -1 when pellets are burnt and gradually evolving to zero as the forest regrows.

[39] This implies that $\tau_2 = 1$.