From: Groom, Ben <B.D.Groom@exeter.ac.uk>
Sent: Tuesday, 11 October, 2022 17:41
To: Supervisory-Body <Supervisory-Body@unfccc.int>
Cc: Venmans1,F <F.Venmans1@lse.ac.uk>
Subject: Comments

We have the following comments on the report: Document: https://unfccc.int/sites/default/files/resource/a64-sb002-aa-a06.pdf

We are very sceptical of the tonne-year approach which generates equivalence of permanent and temporary emissions reductions in a manner that ignores a) the latest climate science; b) the welfare economic aspects of the problem of temporary reductions; c) the risks associated with temporary projects. In particular Section 4.4 onwards. In the attached paper we provide an explanation as to why the approach discussed is problematic and we then offer a useful alternative that solves these shortcomings. While it could be said that our approach introduces controversial issues concerning discount rates, the previous contributions which focus on the physical measures of carbon make implicit discounting assumptions and assumptions about damages.

The paper has been presented in various places including here: https://www.college-de-france.fr/agenda/colloque/efficient-climate-policies-in-an-uncertain-world/social-value-of-offsets

Since the approach is so central to the implementation of the crediting process, we think that it is important to get the carbon equivalence right. Our approach, as discussed, is applicable to the LCA of BECCS and other nature-based solutions, carbon credit / debt pricing and other proposed carbon removal strategies, even non-nature-based ones. Our view is that it would be more appropriate to organise crediting around this more consistent framework.

We hope it is useful

Kind regards

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The social value of offsets

Ben Groom[*] and Frank Venmans[†]

9th September 2022

Abstract

How much carbon should be stored in temporary and risky offsets to compensate 1 ton of CO2 emissions? Measured in terms of economic value, rather than carbon, we cast the Social Value of an Offset (SVO) as a well-defined fraction of the Social Cost of Carbon reflecting offset duration and risk of non-additionality and failure. The SVO reflects the value of temporary storage and can be used in carbon Life-Cycle Analysis, to value payments for carbon debts, and many other climate policy applications. Estimation of the SVO yields a rule of thumb: 2.5 offsets each sequestering 1 ton for 50 years are equivalent to 1 ton permanently locked away. This equivalence offers a means of replacing perpetual offset contracts by simple and effective short-term contracts. We provide a matrix of SVOs for offsets with different risks and permanence which overcome shortcomings in the climate science and economics of previous contributions. Concrete applications to LCA of biofuels and carbon debt follow. An efficient net-zero policy will consist of offsets if their SVO-to-cost-ratio exceeds the benefit-cost ratio of alternatives. The SVO is central to this calculus and can help determine whether nature-based offsets have a role in voluntary markets and compliance mechanisms.

JEL Classification: D31, D61, H43.

Keywords: Carbon Offsets, Social Cost of Carbon, Additionality, Risk, Impermanence.

1 Introduction

To meet the target of the Paris Agreement and limit climate warming to well below 2C, 136 governments and 750 of the 2000 largest traded companies have made commitments to a net-zero programme for carbon emissions (zerotracker.net). Yet meeting these targets

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will require concerted action in the global economy and the deployment of numerous approaches to reduce carbon emissions. Absent inexpensive technological fixes, offsets, including nature-based offsets (NBS), are likely to be part of any strategy to meet net-zero commitments. Furthermore, delays in meeting net-zero targets will lead to overshoot and 'carbon debt': emissions that will have to be offset in the future (Bednar et al., 2021).

Unfortunately, there are considerable uncertainties associated with offsets due to the unregulated nature of the global offsets market, and the difficulties associated with establishing successful projects. NBS in tropical forests are seen as particularly risky due to the absence of strong institutions on the ground to monitor, enforce and account for emissions sequestered (Groom et al., 2022). Fires, either naturally occuring or as part of economic processes of land-use change, are typical risk factors, as are disease outbreaks. Perhaps more pervasive is the risk of non-additionality of credited projects: either they would have happened anway or activity is displaced (Calel et al., 2021). Empirical evidence suggests that reported emissions reductions from REDD+ projects are either vastly overstated (West et al., 2020), partial (Jayachandran et al., 2017) or minimal in relation to Nationally Defined Contributions (NDCs) (Groom et al., 2022). Over-claiming the efficacy of offsets is not confined to tropical countries either, with over-crediting occurring in Californian forest offsets (Badgley et al., 2021). Neither is overclaiming confined to NBS. Any offsetting technology can be subject to risk of failure, impermanent implementation or non-additionality (Calel et al., 2021). The uncertainties associated with offsets lead to major difficulties in evaluating the performance and comparability of different offset schemes. This leads to doubt about the functionality of offset markets to achieve net-zero. High level initiatives, such as the Taskforce for Scaling the Voluntary Carbon Markets (TSVCM) have tried to find a common standard of integrity for offsets and ensure fungibility in light of these difficulties, yet without a clear definition of the social value that offsets are eachproviding.

At the core of the offset fungibility issue is a valuation question: how many risky or temporary offsets are equivalent to a permanent removal of emissions? An emission today which is offset by a temporary project can be thought of as a postponed emission, with the same warming effect when the project ends, but with less warming during the project. The Social Value of Offsets (SVO) stems from the value of delaying emissions and this will depend on how impermanent, risky or additional they are. Estimating the SVO is imperative to harmonise the valuation of offsets and there exist no satisfactory answers to this question to date.

Using an analytical climate-economy model (Dietz and Venmans, 2019a), we derive a simple expression for the Social Value of an Offset (SVO). The SVO is shown to be positive and bounded by the value of a permanent and riskless removal of carbon from the atmosphere, measured by the Social Cost of Carbon today (SCC_0). The SVO is the SCC_0 multiplied by a correction factor reflecting macro-economic factors (e.g. growth), future temperature paths and offset-specific characteristics: Impermanence, risk of failure and additionality.

Our approach is an important departure from previous work, which has approached the problem either from a purely ‘physical’ perspective or a purely economic perspective, and so lacked a complete treatment of both perspectives. The ’physical’ strand of literature has focussed on the Global Warming Potential of a project, i.e. the total extra energy absorbed by the earth over 100 years (e.g. Kirschbaum, 2006; Korhonen et al., 2002). We include thermal inertia, staturation of carbon sinks, and an infinite time horizon allowing us to focus on temperature effects, which are the relevant driver of damages. We also add increasing marginal damages. The ’physical’ literature does not specify an explicit damage function but values projects independently of background warming, implicitly assuming constant marginal damages.

The ‘economic’ strand of studies represents a step forward in considering the economic value to society of emissions reflected in the cost of abatement embodied in the carbon price, and discounting over infinite horizons (rather than arbitrarily 100 year windows) (Herzog et al., 2003; van Kooten, 2009). Nevertheless, none specify a climate module, nor a marginal damage trajectory. We show that temporary projects are over-valued if abatement costs are constant over time and under-valued if the abatement costs follow the Hotelling rule and increase at the discount rate as they would in the Cost-Effectiveness Analysis (CEA) approach. Both are central cases in previous work. We conclude that CEA, while meaningful for climate policy in general, is misleading for valuing temporary offsets. Table S1 in the Supporting Materials (SM1) summarises previous approaches and shows the large disagreement between them. A temporary project of 50 years is valued at 0% to 90% of the value of a permanent storage depending on the method.

The SVO approach elaborated here harmonizes and updates these two strands of the literature to fully account for the most recent climate and economic science and iron out previous deficiencies. The SVO approach has the additional feature of an explicit treatment of risk in relation to the physical or economic aspects, be they at the project or broader macroeconomic scale. Despite these omissions and shortcomings, many of these approaches have been used in high-level policy, appearing in the IPCC special report on land use change, and in international guidelines for carbon footprinting and Life Cycle Analysis, as well as in guidance provided by organisations advising companies on their offsets strategies. Embodying both economic and climate science advances, the SVO should supercede these approaches.

Our SVO pricing formula overcomes the previous shortcomings and provides a theoretically sound yet practical approach to measuring the social value of offsets. The SVO is straightforward to operationalise and we provide a matrix of correction factors for different parameter values and climate scenarios. We also calibrate the formula using observed data on impermanence and offset risks. Both help answer the question of how many impermanent and risky offsets are equivalent to a permanent reduction in emissions? In the RCP2.6 emission scenario, the SVO of a project with a 0.5% likelihood of failing or becoming non-additional in each year and a maximum duration of 50 years has 40% the value of a riskless permanent project. This means that 2.5 of such offsets are equivalent to permanent carbon removal. This is our rule of thumb, providing a starting point for the harmonisation and fungibility of the offset market in pursuit of net-zero.

2 The effect of a temporary carbon offset on the climate

We embed our analysis of temporary emissions reductions in the recent climate models. Figure 1 shows the temperature effect of a temporary withdrawal of one unit of CO2 in 2020 which is released back into the atmosphere in 2070. The green bands show the deciles of 256 combinations of carbon absorption and thermal inertia models in the CMIP 5 modeling ensemble. It also shows the result for the FAIR model which adds the feedback that warmer and more acid seas will absorb less CO2. The graph shows that a CO2 withdrawal has a rapid cooling effect, which is more or less constant over time and stops rapidly after the CO2 is reinjected in the atmosphere after 50 years. These climate dynamics allow us to approximate the temperature response in Figure 1 by a step-function with a delay of period ξ between absorption and the temperature effect. From our own calculations, the best fit for ξ is $\xi = 3$ years for the SSP1-RCP2.6 scenario. The step-function with a delay of ξ is in line with the common assumption that warming ($T_{t+\xi}$) is proportional to cumulative CO2 emissions (S) between the pre-industrial period and time t: $T_{t+\xi} = \zeta S_t$, where ζ is the Transient Climate Response to cumulative Emissions (TCRE) (Dietz and Venmans, 2019b; Zickfeld et al., 2016). The Supporting Materials (SM2) show the impacts for emissions and temperatures and (SM3) for other SSP and RCP scenarios. Only one previous contribution has considered the temperature response in relation to impermanence, but only to focus on the increase in temperature at the point of CO2 re-release (here 2070), ignoring the prior reduction in temperatures and the associated economic value of reduced damages (Kirschbaum, 2006).

3 The Social Value of Offsets (SVO)

The Social Cost of Carbon (SCC) is the economic valuation of the damages caused by the marginal additional ton of CO2 to the atmosphere, or alternatively the benefit of a permanent reduction of CO2 in the atmosphere. An impermanent offset will remove CO2 from the atmosphere for a limited duration. Looking into the future, an offset that is subject to the risk of failure or non-additionality will be *expected* to have a limited duration. The Social Value of an Offset (SVO) depends on the damages prevented by, or expected to be prevented by, this temporary or risky removal of CO2 from the atmosphere. The SVO is therefore closely related to the Social Cost of Carbon (SCC) and reflects the value of delaying emissions. To characterise the SVO we use a damage function, $D(T, Y)$, which depends on the size of the economy (GDP), Y, and is convex and increasing in temperature, T, in line with recent research (e.g. Howard and Sterner, 2017; Burke et al., 2015). A unit of emissions at time τ will add a marginal damage ζD_T (subscripts denote

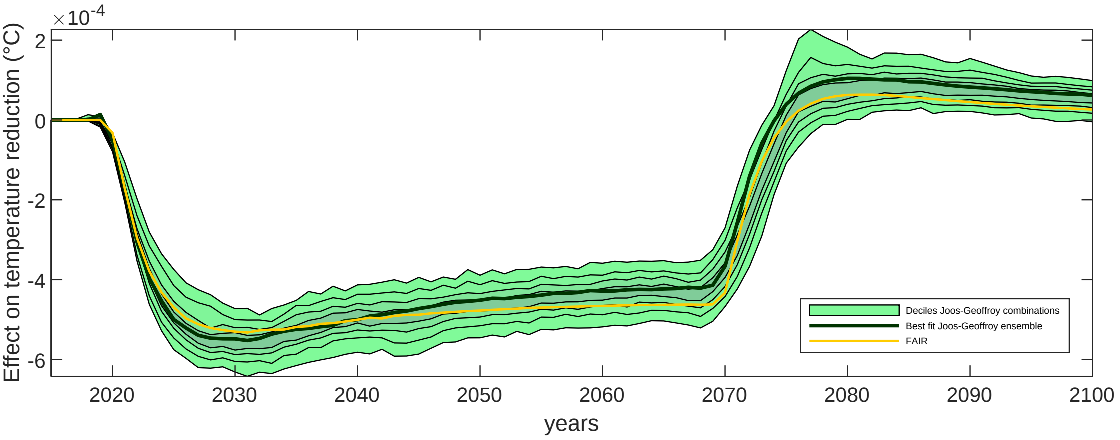

Figure 1: **The effect of an offset on warming .** The Figure shows the difference between the temperatures of the SSP1_26 background scenario and the scenario with a temporary removal project, intantaneously absorbing 1 GtCO2 in 2020 and reinjecting it in 2070. The 16 absorption models (as in Joos et al. 2013) are combined with 16 energy balance models from the CMIP 5 ensemble (as in Geoffroy et al., 2013) and the figure shows the deciles of the 256 possible combinations of models. The FAIR model uses the best fit of the CMIP5 models but adds saturation of carbon sinks. The climate sensitivity of all energy balance models has been harmonized to 3.1°C. Impact response functions for other background scenarios and atmospheric CO2 concentrations are in the Supporting Materials (SM3).

partial derivatives) with a delay ξ from time $\tau + \xi$ onwards. In a warming world, the marginal damage as a result of an emission at time τ will increase over time. The SCC at time τ, SCC_τ, is defined as the sum of the discounted marginal damages from $\tau + \xi$ into the infinite future.

$$SCC_\tau = \sum_{t=\tau}^{\infty} exp\left(-r\left(t+\xi-\tau\right)\right)\zeta D_{T_{t+\xi}} \tag{1}$$

We now characterise the relationship between the SCC and the SVO for offset projects with different characteristics. The formulae are relevant to all offset projects, but we use the example of forest offsets to make the concepts concrete. All proofs are shown in the Materials and Method section.

An impermanent offset

If an offset were to remove 1 ton of CO2 from the atmosphere permanently at time τ, its social value would be SCC_τ. However, permanence and certainty are not characterisics of the typical offset offering (Badgley et al., 2021). Assume, therefore, that an offset removes 1 ton of CO2 at time τ_1 until this 1 ton of CO2 is re-released at time, τ_2. The SVO in this case is the present value (valued at date $t = 0$) of the damages avoided for time horizon

$\tau_1 + \xi$ to $\tau_2 + \xi$:

$$SVO_{\tau_1\tau_2} = \sum_{t=\tau_1}^{\tau_2} \overbrace{e^{-r(t+\xi)}}^{Discount\ factor} \overbrace{\zeta D_{T_{t+\xi}}}^{Marginal\ damages} \tag{2}$$

The temporary project can be thought of as a permanent project at τ_1, combined with a re-release at time τ_2. Provided that marginal damages are strictly positive, the SVO is always positive. This is a departure from claims in the previous literature that the value of delaying emissions is zero or negative literature (Korhonen et al. 2002; Herzog et al. 2003; Kirschbaum 2006; van Kooten 2009. See section 6) For further intuition , note that SVO reflects the net benefit of a permanent emissions reduction at time τ_1 minus the damages caused by the re-release of emissions at time τ_2. The $SVO_{\tau_1\tau_2}$ is therefore the difference between SCC_{τ_1} and SCC_{τ_2}in present value terms. Define x_1 and x_2 as the the average growth rate of SCC_τ until τ_1 and between τ_1 to τ_2, the Materials and Methods section shows that the SVO is simply:

$$SVO_{\tau_1\tau_2} = SCC_0 \overbrace{e^{(x_1-r)\tau_1}}^{Delayed\ start} \overbrace{\left(1 - e^{(x_2-r)(\tau_2-\tau_1)}\right)}^{Impermanence} \tag{3}$$

$SVO_{\tau_1\tau_2}$ is a corrected version of the value of a permanent reduction in emissions today, SCC_0, where the correction factor reflects: i) the delay in implementation from today until τ_1 ; and, ii) the known end point and rerelease of emissions at from the project at time τ_2. The SVO formula in (3) is valid for any trajectory of marginal damages as long as $x < r$, which is proven to be the case in the Supporting Materials (SM4) for optimal and non-optimal scenarios.

An offset with failure risk

Previous contributions were silent on the matter of project risk, focussing only on impermanence. Here we extend the analysis to take into account the likelihood that at any moment the offset technology could fail, e.g. reforestation or avoided deforestation is simply destroyed by force majeure (fire or disease), property rights failure or a change in land-use policy in situ. Suppose that in principle the offset remains temporary with a known fixed end date τ_2. Suppose also that an offset project is subject to the constant instantaneous hazard rate, ϕ, which reflects the instantaneous probability of an offset failing at time τ, conditional on having already survived until that date. By definition, the probability of the project surviving for τ years or longer is given by $P(t \geq \tau) = \exp(-\phi\tau)$. This means that at any future time τ the offset project continues to provide one ton of emissions reduction with probability $P(t \geq \tau) = \exp(-\phi\tau)$, or else has failed to offset with probability $1 - \exp(-\phi\tau)$. The duration of the offset is therefore uncertain, but $\tau_2 - \tau_1$ is the maximum. The Materials and Methods section shows that if SCC_τ increases at a constant rate x, failure risk will further correct the value of an offset as follows:

$$SVO^{\phi}_{\tau_1\tau_2} = SCC_0 \; \overbrace{e^{(x-r)\tau_1}}^{\textit{Delayed start}} \; \overbrace{\left(1-e^{(x-r-\phi)(\tau_2-\tau_1)}\right)}^{\textit{Impermanence}} \overbrace{\frac{r-x}{r+\phi-x}}^{\textit{Failure risk}} \tag{4}$$

The Supporting Materials (SM5) provides closed-form solutions for the SVO assuming linear and exponential temperature paths.

An offset with non-additionality risk

Another aspect of project risk is the risk of non-additionality: that a project adds nothing compared to the counterfactual without the project. The time profile of 'additionality risk' depends on the type of project. If a project removes CO2 from a baseline in which there was no removal, such as a reforestation project, there is a risk that in the absence of the project reforestation would have occurred anyway, e.g. if forests become more productive than barren land, due to policies that existed anyway, or due to secondary forest regrowth (Poorter et al., 2021). In this case additionality risk corresponds to an earlier end of the project, very similar to the risk of failure, as shown in panel b of Figure 2. In this context, the risk of non-additionality can be framed as a hazard rate φ, leading to the probability $P\left(t \geq \tau\right) = \exp\left(-\varphi\tau\right)$ that the project is additional (has a causal effect) at least until time τ. The expression is analogous to the case of a failure risk, leading to an adjustment factor $\frac{r-x}{r-x+\phi+\varphi}$, where both failure hazard rate and the additionality hazard rate are added up (see Materials and Methods for a proof). Note that our formula is also valid if ϕ and φ are both time dependent, but their sum is constant, which could happen in the intuitive case where degradation of a forestry project is more likely early on, whereas reforestation in the baseline is more likely further in the future.

Alternatively, conservation projects take as their baseline ongoing loss of forested land, and offsetting stems from avoided deforestation, under the assumption that in the baseline CO2 would have been emitted, but the project avoids these emissions. Here non-additionality occurs at the start of the project since the expected deforestation potentially would not have happened in the baseline, as depicted in panel (c) of Figure 2. Assume that without the preservation project, there is a hazard rate $\tilde{\varphi}$ that the forest would have disappeared, making the offset additional. The probability that the project has an additional (or causal) effect at time τ is therefore: $P\left(t \leq \tau\right) = 1 - \exp\left(-\tilde{\varphi}\tau\right)$. The correction factor now becomes $\left(\frac{r-x}{r-x+\phi} - \frac{r-x}{r-x+\phi+\tilde{\varphi}}\right)$ for sufficiently large τ_2. The Materials and Methods section provides the slightly more complex general formula.

4 A general formula for the SVO

While providing a straightforward exposition of the principles underpinning the SVO, the assumption that the SCC grows at a constant rate x does not necessarily reflect typical climate scenarios, such as the IPCC's Representative Concentration Pathways (RCP). In

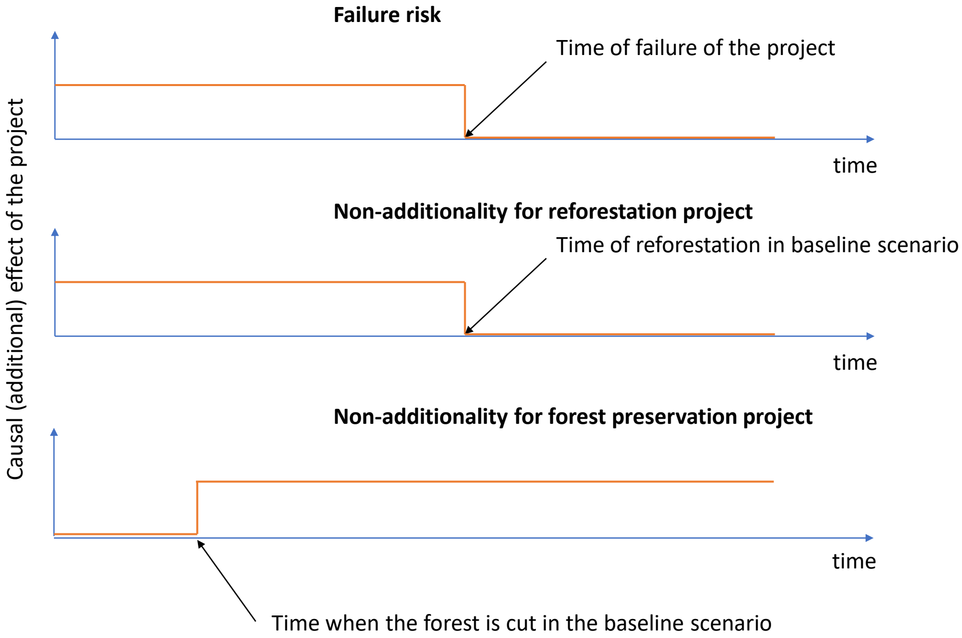

Figure 2: **The time profile of additionality risk:** The causal or additional effect of the project is the difference in carbon storage between the project and the baseline, i.e. what would have happened in the absence of the project.

this section we generalise the SVO formula to allow for any any temperature path and an explicit characterisation of climate damages, and consequently different trajectories for the SCC. The general formula also provides more detailed project specific characteristics, to account for the gradual absorption and re-release that typifies many nature-based and other solutions to climate change.

We model climate damages proportional to GDP, Y, and quadratic in temperature: $D = Y\left(1 - \exp\left(-\frac{\gamma}{2}T\right)\right)$ (Howard and Sterner, 2017), the marginal damage for a unit of CO2 emission at time t is linear: $\zeta D_T = \zeta\gamma YT$. This is a typical assumption in Integrated Assessment Models (IAM) deployed for analytical convenience here, yet does not preclude the use of other damage functions. Further, suppose that absorption and release of CO2 is reflected by a time profile q_t indicating the stock of carbon absorbed by the successful project by time t, rather than the step-function used so far. With these generalisations the formula for the SVO correction factor accounting for impermanence, failure and non-additionality risks becomes:

$$\frac{SVO^{\phi,\varphi}_{\tau_1\tau_2}}{SCC_0} = \frac{\sum_{t=\tau_1}^{\tau_2} \overbrace{e^{-r(t+\xi)}}^{Discount\ factor} \overbrace{e^{-(\phi+\varphi)(t-\tau_1)}}^{\substack{Failure\ and\ additionality \\ risk\ at\ end}} \overbrace{\left(1-e^{-\tilde{\varphi}(t-\tau_1)}\right)}^{Additionality\ risk\ at\ start} \overbrace{q_t}^{Quantity\ stored} \overbrace{\zeta\gamma Y_{t+\xi}T_{t+\xi}}^{damages}}{\sum_{t=0}^{\infty} e^{-r(t+\xi)}\zeta\gamma Y_{t+\xi}T_{t+\xi}} \tag{5}$$

This flexible generalisation brings together both physical and economic determinants of the SVO and SCC in a coherent and transparent manner, and has a number of appealing features. Firstly, the two most difficult parameters to parameterise, the TCRE, ζ, and the damage coefficient, γ, cancel and therefore do not affect the offset correction factor. Of the climate and macro-economic determinants, only the future temperature and GDP paths are needed to operationalise this formula. The Supporting Materials (SM6) extends the matrix to other RCP scenarios. Second, the formula easily accommodates further project specific factors, such as time dependence of the failure and non-additionality risks, and the Supporting Materials (SM7) provide a deeper risk analysis when growth, temperatures and individual project risks are correlated . Finally, the linear approximation of cumulative emissions, temperature and damages reflected by ζ can easily be replaced by the *exact* time profile of the temperature impact response function in Figure 1.

Table 1 summarises the adjustment factors for a subset of parameters values and temperature paths. An offset of duration of 25 years with a 0.5% annual risk of failure or non-additionality has a correction factor of 23% in RCP 2.6 (1.8C), which drops to 16% in RCP 6 (3.1C), which has higher marginal damages in the future when the project releases its carbon back in the atmosphere. Note that in high emission scenarios although the conversion factor is lower, the absolute dollar value of an offset will be higher. Table 1 allows a careful comparison of absolute and relative values.

The concept of the SVO and the general formula provide an answer to the question of how much carbon should be held in offsets compared to alternative mitigation strategies. A correction factor of z means that in order to offset the equivalent of 1 ton of carbon $1/z$ offsets would have to be purchased. Table 1 shows that this can mean anything from a near one-to-one relationship between offsets projects and permanent carbon removal, to a situation where 10 offsets, each claiming to offset 1 ton of carbon, would have to be purchased to be equivalent to a permanent emissions reduction, when duration is short and risks are high. It is important to recognise that this equivalence is in welfare terms and in the aggregate. Given uncertainty, some projects will end up reducing emission by more than 1 ton in the end, others by less, but on average the overall impact would be a 1 ton emissions reduction. Table 1 makes the rate of conversion explicit. The SVO essentially values the social benefit of temporary carbon storage and delayed emissions. As such, the efficiency of offsets compared to alternatives can also be gauged by comparing offsets in terms of their benefit-cost ratios.

5 Applications of the SVO

The benefit of delaying emissions via temporary and risky storage of carbon can be estimated using calibration, and this leads to many important applications. Supplementary Materials (SM8 and SM9) provide details.

1 ton of CO2 emitted is equivalent to 2.5 tons of CO2 stored for 50 years

Calibration of the SVO for duration τ_2, hazard risk of failure, ϕ, and additionality, φ, leads to a simple rule-of-thumb for the SVO correction factor. The chief failure risks concern fires and disease at the project level, and political risk (e.g. risk of property rights appropriation) at the macroeconomic level. In the absence of a comprehensive dataset of offset failure rates exists we draw inference from these sources of failure risk to shed light on failure risk. The Supplementary Materials (SM8) shows that observed and recommended buffers for offsets imply values of $\phi = [0.001, 0.002, 0.01]$ for $\tau_2 = 50$, a reasonable period for regrowth, based on buffers ranging from 5 - 40% (Badgley et al., 2022; FCPF, 2020). Estimated business risks (termination of contracts and political risks) imply $\phi = [0.01, 0.04]$, with higher rates in Asia, Latin America and Central and Eastern Europe compared to Europe and North America (Meschi and Metais, 2015; Bekaert et al., 2016).

Additionality risk is difficult to estimate precisely. Jayachandran et al. (2017) estimate 90% additionality (10% leakage) in their randomised control trial of REDD+ projects in East Africa. Elsewhere, 40% of REDD+ projects were estimated to overlap with protected areas (Simonet et al., 2015), or generally non-additional (West et al., 2020), meaning 60% additionality. Guizar-Coutino et al. (2022) estimate 53% additionality (a 47% reduction in deforestation), also from REDD+ projects, Using 80 - 75% additionality as a central approximation implies $\varphi = [0.004, 0.006]$. $\varphi = 0.005$ can be read from Table 1 Non-forest offsets tend to have historically lower levels of additionality (e.g. Cames et al., 2016; Calel et al., 2021) (See SM8). While 75-80% additionality is potentially optimistic, lower levels of additionality, once identified, are unlikely to be acceptable for future offsets.

Although not perfect (see Badgley et al. 2021), buffer stocks can help manage the physical risks of individual nature-based projects, leaving political and additionality risks as the chief concerns for the SVO. RCP 2.6 in combination with a $\tau_2 = 50$ year horizon, $\phi = 0$ and $\varphi = 0.005$ leads to an SVO correction factor of 40%. This means that 2.5 one-ton offsets would be equivalent to one ton of CO2 emitted. This constitutes a practical rule-of-thumb for the implementation of the SVO for forest-based offsets.

Contracts of 50 years are better than eternal contracts: With a 1:2.5 equivalence between emitted tons and forestry offset storage over 50 years, contracts for 2.5 tons sequestered for 50 years can replace eternal contracts for individual tons. The current practice in the voluntary market is to assume that each ton is stored eternally, with the responsibility to uphold this commitment lying with the forest manager. A 50 year commitment is more realistic to administer, being analogous to 50 year Treasury Bonds for instance. With the correction factor reflecting impermanence and additionality risk the forest managers' responsibility to society is complete after 50 years. At this point the same forest can receive credits again for a new cycle of 50 years if additionality can be proven based on past experience and current trends in deforestation and policy. The approach improves on current CDM practice, where an emission leads to an implicitly eternal liability: a ton emitted today requires a new CDM forestry project of one ton every 20 years. Additionality risks and the eternal liability structure have precluded forest-based offsets from being included in compliance mechanisms such as the EU ETS, and led to only a small proportion of CDM projects being nature-based. Shorter contracts organised around the SVO could reduce these uncertainties, increase eligibility and potentially increase the supply of nature-based offsets.

Life Cycle Analysis (LCA): LCA of carbon compares the carbon emissions of different activities (energy production, agriculture, etc.) to guide climate policy. Take burning wood pellets for home heating. Here one ton of CO2 is emitted, reducing a forest carbon sink by one ton, which is gradually replenished thereafter. The SVO and correction factor help gauge whether pellets are better than burning fossil fuels over their lifetimes. In terms of the SVO formula q_t is now the reduced stock of forest biomass, when pellets are burnt, which gradually tends to zero over time as the forest regrows. The Supporting Material (SM8) reviews the contributions of Fearnside et al. (2000) and Brandão et al. (2019) and shows if biomass production starts with old growth forest, wood pellets only have a 7% advantage compared to fossil fuels using the SVO approach, compared to 50% when typical LCA methods such as Global Warming Potential are used. This difference arises from the accurate treatment of the physical and economic aspects of the dynamic cycle of delay and growth that determines the emissions path, temperature and climate damages. The SVO approach suggests a wholesale change to way in which LCA of carbon is undertaken in general.

The value temporary atmospheric storage and carbon liabilities: The SVO approach values the temporary storage of carbon, but can be adapted to value the cost of temporary storage in the atmosphere and 'carbon debt': the cost of emitting now and reducing emissions later. A carbon liability or 'debt' is an important financing mechanism in a net-zero world where revenues from carbon taxes are insufficient to fund the massive (10% of world GDP) investment in climate mitigation required to hit 1.5C Bednar et al. (2021). If companies emit today under the agreement that they remove the carbon at some future date, there are two elements to the liability: the cost of the future emissions reduction and the damages caused until the debt matures. The SVO formula can value the damages of this temporary atmospheric storage by interpreting q_t in Equation 4 as the additional carbon stored in the atmosphere and using the temperature response function for a temporary release of carbon. Figure SM9a in SM9 shows the impact of temporary emissions on temperatures. The resulting Social Cost of Atmospheric Storage (SCAS) is anchored more in Cost Benefit Analysis and defines the rental cost of atmospheric storage in terms of the damages caused, rather than using arbitrary interest payments as in Bednar et al. (2021). Yet, the fundamental difficulties with carbon debt are: i) the commitment periods are much longer than the standard commitment periods of financial debt; and, ii) debt holders going bankrupt before the debt matures leading to carbon default. These issues are limited if the SCAS is paid in full up front. Given our 1:2.5 rule of thumb, a company which emits a ton today and commits to a permanent removal in 50 years time, would pay 40% of the carbon price to cover the damages of the the temporary atmospheric storage. Up front payment of the SCAS provides finance and proper incentives to abate emissions rather like a carbon tax (See Supporting Material, SM8).

6 Cost effectiveness analysis does not value the timing of damages

Climate change mitigation is frequently viewed in terms of Cost-Effectiveness Analysis (CEA), which minimizes abatement costs to keep warming below a target level. For instance, the carbon price in the UK reflects the marginal abatement cost of meeting a net zero target by 2050. CEA is often seen as a useful climate policy tool because it is easier to agree on a temperature target than to agree on the size of damages and the discount rate (Aldy et al., 2021). However, in the evaluation of temporary removal of carbon, CEA is problematic.

Technically, a feature of a cost-minimising abatement strategy is that the price of carbon increases at the discount rate, a manifestation of the Hotelling Rule. Using $x = r$ in Equation (3) yields a zero value for a temporary removal, in line with older literature (e.g. Herzog et al., 2003). By contrast, our Equation 2 and SM4 show that the SVO cannot be zero. The discrepancy stems from the fact that in a cost-effectiveness setting the carbon price is not equal to the SCC, so equation 3 cannot be used: x in Equation 3 is the growth rate of the SCC, not the growth rate of any carbon price path or marginal abatement cost. The zero-valuation result should not be interpreted as an indication that offsets have no value, but rather as a failure to value carbon emissions properly. CEA minimises costs and does not maximize welfare, it therefore disregards the welfare value of delaying damages, as measured by the SVO. In the Supporting Materials (SM4) we show that the SCC always increases at a rate that is lower than the discount rate: $r > x$. The Supporting Material (SM10) further shows that CEA can also overvalue projects if they extend beyond the point at which the target is met, or if reforestation costs are constant over time, since from this point onwards the carbon price remains constant ($r > x = 0$). This too gives misleading results for the valuation of offsets. Ultimately, it is important to consider the welfare effects of delayed emissions, not their target-compatible cost-effectiveness.

IPCC Scenario	Risk at start	Risk at end	SVO Correction factors (max.duration, v)				SCC ($\$/tCO_2$) Damages ($\gamma$)	
(Temp in 2100)	$\tilde{\varphi}$	$\phi + \varphi$	25	50	100	∞	γ=0.0077	γ=0.0025
RCP 2.6	1000(low risk)	0	24%	44%	70%	100%	109	35
(1.8°C)		0.0025	23%	42%	63%	83%	109	35
		0.005	23%	40%	58%	71%	109	35
	0.5	0	23%	43%	69%	99%	109	35
		0.0025	22%	40%	62%	82%	109	35
		0.005	21%	38%	56%	69%	109	35
	0.25(high risk)	0	21%	41%	67%	97%	109	35
		0.0025	20%	39%	60%	80%	109	35
		0.005	20%	36%	54%	68%	109	35
RCP 6.0	1000	0	17%	34%	64%	100%	161	52
(3.1°C)		0.0025	17%	32%	57%	81%	161	52
		0.005	16%	31%	51%	67%	161	52
	0.5	0	16%	33%	63%	99%	161	52
		0.0025	16%	31%	56%	80%	161	52
		0.005	15%	30%	50%	66%	161	52
	0.25	0	15%	32%	61%	98%	161	52
		0.0025	14%	30%	55%	78%	161	52
		0.005	14%	28%	49%	65%	161	52
Uncertain RCP	1000	0	20%	38%	66%	100%	138	45
		0.0025	19%	35%	58%	79%	138	45
		0.005	18%	33%	51%	64%	138	45
	0.5	0	19%	38%	66%	100%	138	45
		0.0025	19%	35%	58%	78%	138	45
		0.005	18%	33%	51%	64%	138	45
	0.25	0	18%	37%	65%	99%	138	45
		0.0025	18%	34%	57%	77%	138	45
		0.005	17%	32%	50%	63%	138	45

Table 1: Adjustment factors for non-permanence and risk. We assume a quadratic damages proportional to GDP $exp\left(-\frac{\gamma}{2}T^2\right)$ with damage parameters of Howard and Sterner (2017) (Column 8) as well as Nordhaus (2017) (Column 9). Temperature pathways evolve according to SSP1-RCP2.6; SSP4-RCP6.0 and an uncertain temperature path (Riahi et al. 2017, www.https://tntcat.iiasa.ac.at). Other parameters are $r = 3.2\%; \tau_1 = 1year; \zeta = 0.0006°C/GtCO_2; GDPgrowth = 2\%; T_0 = 1.2°C$. We use Equation (5) . For $\tilde{\varphi} = [0.5\ 0.25]$ the likelihood that the project is additional after 5 years is 92% and 71% respectively. For $\varphi + \phi = [0.0025\ 0.005]$ the likelihood that the project is additional after 50 years is 78% and 88% respectively.Under uncertainty, we assume a temperature path following one of 3 RCP's (2.6, 3.4 or 6.0) with equal probability and a hazard rate with the same mean but increasing in temperature $\varphi_{uncertain} = \varphi_{certain}\left(0.5 + 0.5T/\bar{T}\right)$, where $\bar{T} = 2.01°C$,i.e. mean warming of the next 80 years in the 3 RCP's. Results for SSP4-RCP3.4 and SSP5-RCP8.5 are shown in SM7.

7 Conclusion

A simple expression has been developed that provides the social value of an offset capturing its duration, likelihood of failure and its potential for non-additionality. While these factors do conspire to reduce the value of a ton of carbon sequestered via an offset, offsets are not valueless. Offsets have a role to play as long as they provide value for money and a sufficient benefit from their delaying of emissions. From the perspective of public sector appraisal, offsets may well have an important role to play where their Benefit-Cost Ratio is higher than other alternatives. Despite the fact that SVO is less than the SCC, offsets may still be competitive with other technologies where their costs of provision are low. Careful valuation of the SVO is required to make this decision, and offset suppliers should provide information on the risks and expected time-horizons for each of their offerings, nature-based or otherwise. With such information, our formula could provide a mechanism to harmonise, make fungible and regulate offsets, and help gauge the extent to which they should contribute to the targets of the Paris Agreement and related net-zero commitments. A preliminary calibration of the SVO shows that 2.5 1-ton, 50 year offsets are equivalent 1 ton of emissions. Due to its more accurate representation of both the physical and economic aspects of carbon storage, the SVO can also improve the application of Life Cycle Analysis (e.g. of biofuels) and the valuation of carbon debts, or indeed any activity that involves the temporary storage of carbon or the rescheduling of its emissions. Of course the social value of nature-based carbon offsets may well be much higher because of the co-benefits of biodiversity and ecosystem service provision. These need to be weighed against the advantages on the other side of learning by doing in the pursuit of new technological solutions, not forgetting that learning by doing also occurs in the implementation of nature-based solutions. With those caveats, the SVO should be a central organising concept for the appraisal of net-zero climate policy.

Materials and Methods

Proof of Equation (3)

Assume that the social cost of carbon is finite. Adding and subtracting the same sum over $[\tau_2, \infty]$ in Equation (2) and multiplying by $exp\left(-r\tau\right)$outside the sum and by $exp\left(r\tau\right)$ inside the sum, we obtain:

$$SVO_{\tau_1\tau_2} = exp\left(-r\tau_1\right) * \sum_{t=\tau_1}^{\infty} exp\left(-r\left(t+\xi-\tau_1\right)\right)\zeta D_{T_{t+\xi}} - exp\left(-r\tau_2\right)\sum_{t=\tau_2}^{\infty} exp\left(-r\left(t+\xi-\tau_2\right)\right)\zeta D_{T_{t+\xi}} \tag{6}$$

Given the definition of SCC_τ in (1), $SVO_{\tau_1\tau_2}$ simplifies to:

$$SVO_{\tau_1\tau_2} = exp\left(-r\tau_1\right)SCC_{\tau_1} - exp\left(-r\tau_2\right)SCC_{\tau_2} \tag{7}$$

$SVO_{\tau_1\tau_2}$ is simply the difference between the present values of SCC_{τ_1} and SCC_{τ_2}. Define x_2 as the mean growth rate of the SCC between time τ_1 and τ_2 x: $SCC_{\tau_2} = SCC_{\tau_1}exp(x(\tau_2 - \tau_1))$, and $x_1$as the mean growth rate of the SCC between τ_0 and τ_1. Substituting out SCC_{τ_1} and SCC_{τ_2}in Equation (7) results in Equation (3).

Note that if marginal damages increase faster than the discount rate in the long run, equation 1 shows that the social cost of carbon is infinite. As a result, Equation (3) cannot be used but equation 2 is valid. Equation 2 shows that the SVO is positive, unlike van Kooten's claim that the value of an offset is zero when marginal damages increase faster than the discount rate (p 459).

Proof that if marginal damages increase at a constant rate x, the SCC increases at the same rate.

For notational convenience we will switch to continuous time.If the marginal damages increase exponentially at rate x, the SCC at time τ is:

$$SCC_\tau = \int\limits_{t=\tau}^{\infty} \exp\left(-r\left(t+\xi-\tau\right)\right)\zeta D_{T_{\tau+\xi}} \exp\left(x\left(t-\tau\right)\right)dt$$

where $D_{T_\tau}$is the marginal damage at time τ. The SCC at time τ can then be re-written as:

$$SCC_\tau = \frac{\exp\left(-r\xi\right)}{r-x}\zeta D_{T_{\tau+\xi}} \tag{8}$$

from which it follows that:

$$SCC_\tau = \frac{\exp\left(-r\xi\right)}{r-x}\zeta D_{T_{0+\xi}}e^{x\tau} = SCC_0 e^{x\tau} \tag{9}$$

In the case of the seminal model by Golosov et al. (2014) model or Traeger (2021), x corresponds to the growth rate of GDP. When climate damages are quadratic and are proportional to GDP, x corresponds to the growth rate of GDP plus the growth rate of temperature.

Derivation of SVO with failure risk

By multiplying each time period with the probability that the project has not failed $e^{-\phi(t-\tau_1)}$ Equation (5) becomes:

$$SVO^{\phi}_{\tau_1\tau_2} = \exp\left(-r\tau_1\right) \int\limits_{t=\tau_1}^{\tau_2} \exp\left(-\left(r+\phi\right)\left(t-\tau_1\right) - r\xi\right) \zeta D_{T_{t+\xi}} dt$$

In the case of exponentially increasing marginal damages $D_{T_{t+\xi}} = D_{T_{\tau+\xi}} e^{x(t-\tau)}$ we obtain an exponential function in the integral, which we can solve

$$SVO^{\phi}_{\tau_1\tau_2} = \exp\left(-r(\tau_1+\xi)\right) \zeta D_{T_{\tau_1+\xi}} \int\limits_{t=\tau_1}^{\tau_2} \exp\left(-\left(r+\phi-x\right)\left(t-\tau_1\right)\right) dt \tag{10}$$

$$= \exp\left(-r(\tau_1+\xi)\right) \zeta D_{T_{\tau_1+\xi}} \left[\frac{1-\exp\left(-\left(r+\phi-x\right)\left(\tau_2-\tau_1\right)\right)}{r+\phi-x}\right]. \tag{11}$$

We can now write the result as a function of the SCC using Equation (8)

$$SVO^{\phi}_{\tau_1\tau_2} = SCC_{\tau} \exp\left(-r\tau_1\right)\left[1-\exp\left(-\left(r+\phi-x\right)\left(\tau_2-\tau_1\right)\right)\right] \frac{r-x}{r+\phi-x}. \tag{12}$$

From here the formula in the text follows assuming that the SCC grows at a rate x. It is straightforward to see that this results also holds for constant marginal damages, i.e. for $x = 0$. The Supporting Material (SM7) derives formulas for other paths of marginal damages.

Derivation of SVO with additionality risk

Additionality risk is taken into acount by multiplying each period by the probability $\left(1-e^{\tilde{\varphi}(t-\tau_1)}\right) e^{-\phi(t-\tau_1)}$ where ϕ is the hazard rate for both project failure and non-additionality at the end and $\tilde{\varphi}$ governs the risk of non-aditionality at the start. Equation **??** now becomes

$$SVO^{\phi}_{\tau_1\tau_2} = \exp\left(-r(\tau_1+\xi)\right) \zeta D_{T_{\tau_1+\xi}} * \tag{13}$$

$$\int\limits_{t=\tau_1}^{\tau_2} \exp\left(-\left(r+\phi-x\right)\left(t-\tau_1\right)\right) - \exp\left(-\left(r+\phi+\tilde{\varphi}-x\right)\left(t-\tau_1\right)\right) dt$$

$$
\begin{aligned}
&= \exp\left(-r(\tau_1+\xi)\right)\zeta D_{T_{\tau_1+\xi}} \quad * \qquad (14)\\
&\left[\frac{1-\exp\left(-\left(r+\phi-x\right)\left(\tau_2-\tau_1\right)\right)}{r+\phi-x} - \frac{1-\exp\left(-\left(r+\phi+\tilde{\varphi}-x\right)\left(\tau_2-\tau_1\right)\right)}{r+\phi+\tilde{\varphi}-x}\right]
\end{aligned}
$$

We can now write the result as a function of the SCC using Equations 8 and 9

$$
\begin{aligned}
SVO^{\phi}_{\tau_1\tau_2} &= SCC_0 \overbrace{\exp\left(-(r-x)\tau_1\right)}^{Delayed\ start}\overbrace{\left(1-\exp\left(-\left(r+\phi-x\right)\left(\tau_2-\tau_1\right)\right)\right)}^{Impermanence} \quad * \qquad (15)\\
&\left[\overbrace{\frac{r-x}{r+\phi-x}}^{\substack{Failure\ risk\ or\\ Additionality\ at\ end}} - \overbrace{\frac{r-x}{r+\phi+\tilde{\varphi}-x}\,\frac{1-\exp\left(-\left(r+\phi+\tilde{\varphi}-x\right)\left(\tau_2-\tau_1\right)\right)}{1-\exp\left(-\left(r+\phi-x\right)\left(\tau_2-\tau_1\right)\right)}}^{Additionality\ risk\ at\ start}\right]
\end{aligned}
$$

Note that ϕ slightly increases our 'early end' factor, because the project may fail before time τ_2 in which case the impermanence becomes irrelevant. Similarly, the second factor in the 'additionality risk at start' term reduces the effect of impermanence (τ_2), taking into account that if the project does not start before τ_2, the impermanence is irrelevant. Therefore, for combinations of τ_2 and $\tilde{\varphi}$ which make it unlikely that the project never starts, the correction factor for additionality risk will converge to $\frac{r-x}{r+\phi-x} - \frac{r-x}{r+\phi+\varphi-x}$.

Data and Code Availability Statement

The code and data used to create Figure 1-8, and the Excel spreadsheet that leads to Table 1 and 2 will be made available in a public repository on publication.

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Supporting Material

SM1. Extended literature overview on valuing temporary offsets

Table SM1 shows 11 methods to value temporary storage or temoporary emissions of CO2, applicable to both valuing offsets or life cycle analysis of products such as biofuels. Different methods give widely diverging results. A temporary offset project is of 50 years is valued between 0% and 90% of a permanent project (column 4).

Methods based in climate physics

The simplest approach (not in Table SM1) is to add up all carbon emissions and absorptions over the lifecycle of a product. This results in zero value for a temporary offset. In 2000, the IPCC special report on LULUCF in proposed two new methods, both based on the CO2 concentration impact response function of a pulse of CO2 emission shown in Figure 7. These methods gave a higher weight to early emissions, because CO2 is absorbed over time. Note that in the future, a larger quantity of carbon absorbed in carbon sinks and hotter oceans will reduce the speed of carbon absorption, a.k.a. saturation of carbon sinks. Early studies do not take into account this feedback on carbon sinks.

Next, climate forcing, i.e.the extra flow of energy that is trapped by greenhouse gases, is a logarithmic function of the CO2 concentration, due to saturation of radiative forcing. As a result, the marginal forcing of a pulse of atmospheric CO2 is lower when the CO2 concentration is already large. To take that into account, several methods are based on the cumulative radiative forcing by a project, assessing the total energy added or avoided over its lifetime. This is known as the Global Warming Potential and was popularized by the IPCC, because the relative value of different greenhouse gases is evaluated in the same way. Note that the saturation of carbon sinks approximately compensates the saturation of radiative forcing (Matthews, Gillet, Stott, Nature 2009) which is not taken into account in these studies.

Finally, there is a substantial delay between forcing and temperature, due to thermal inertia. Therefore, instead of evaluating forcing, it is more precise to focus on the temperature effect of a pulse of emissions or a project. Our Figure 7c shows a very different temperature impact response function compared to the concentration impact response function in our F 7b. Note that a temporary project leads to a higher concentration just after the project, which (mis)lead early studies to conclude that temporary offsets can have detrimental effects for the climate (Meinhausen & Hare 2000, Korhonen et al. 2002, Kirschbaum et al. 2006, Thamo & Pannell 2016). This is unwarranted because the temperature impact response function does not show this large overshoot. Nevertheless, F 1 shows that a temporary project can lead to a tiny increase in peak warming after carbon is released back into the atmosphere. This was the mechanism for Kirschbaum et al. (2006) to conclude that temporary offsets can increase climate damages. However, as shown by Dornburg & Marland (2008) this is misleading because Kirschbaum (2006) disregards the much larger reduction of temperature during the project.

Compared to the this literature focussing on climate physics, we are the first to take into account the entire temperature impact response function, taking into account carbon absorption, saturation of wavelengths, saturation of carbon sinks and thermal inertia.

None of the above studies specifies a damage function, but the absence of background concentrations or temperatures implies a constant marginal damage function and a linear total damage function. We are the firtst to use the more standard assumption of a convex total damage function with increasing marginal damages. Using a constant (or gradually declining) discount rate, we also avoid the jump in the implicit discount rate from 0 to infinity at the end of the time horizon, which is very common in older methods.

Cost-effectiveness / cost minimization

Unlike the preceding studies which focus on physical measures, Herzog et al. (2003) develop early-on a clear economic concept, i.e. a cost-effectiveness approach. On page 299 they state:

> "More critical to our formulation is the assumption of cost-effectiveness – i.e., that however the goal of a carbon mitigation policy is developed, it is achieved cost-effectively by equilibrating carbon price across options and comparing options across time by considering the time value of funds – i.e., using a discount rate."

Unsurprisingly, they obtain the equivalent of our equation 3 and and go on to show that the value of a project is zero if the carbon price increases at the discount rate. As a second example of a possible future carbon price path, they assume a constant carbon price and obtain a high value for temporary carbon sequestration. Note that a constant carbon price is compatible with a cost-benefit approach with constant marginal damages, both independent of the size or the economy and independent of temperature. Although some empirical studies find constant marginal damages at currently observed temperature ranges, we are not aware of any cost-benefit analysis using constant marginal damages. Constant marginal damages are unlikely because: 1) because extreme weather events tend to lead to larger damages in a future society with more assets; 2) climate tipping points are possible in the future; and, 3) beneficial side-effects of increasing CO2 at low levels of warming (CO2 fertilization) will be saturated in the future. Constant marginal damages in a cost-benefit analysis also give counter-intuitive results. In general, optimal temperature continues to increase until the carbon price equals the marginal abatement costs of zero emissions, typically several hundreds of dollars per ton. Models with constant marginal damages would find extremely high optimal peak temperature or an extremely high initial carbon price, not in line with current observed damages.

We build on these insights and validate their result for the special case where the carbon price equals the social cost of carbon and show that their formula does not give meaningful results for other carbon price paths. This is because a cost-effective approach replaces damages by an exogenous climate target. Therefore, the carbon price path is indifferent to the timing of climate damages. The Social Value of an Offset estimates exactly that, the value of the timing of emissions (see SM10). Kim et al. (2008) add maintenance costs to the formula of Herzog et al. (2003), and find the same results: zero value if the carbon price increases at the discount rate and a large value if the carbon price is constant.

Cost-benefit / welfare maximization

van Kooten (2009) defines the price of carbon as the shadow value of CO2 in the atmosphere, to be understood as marginal damages of atmospheric CO2, abstracting from carbon absorption and thermal inertia. He compares the value of an offset with an avoided emissions for the special case where marginal damages increase at a constant rate. van Kooten (2009) argues that an avoided emission can also be considered to be temporary because will be emitted later anyway due to intertemporal leakage (a green paradox). This alleviates the problem that marginal damages cannot increase exponentially in the very long run. We generalise his formula for arbitrary paths of marginal damages, we correct for CO2 absorption and thermal inertia, and we connect the SVO to the social cost of carbon. van Kooten (2009), following Herzog et al. (2003) and Korhonen et al. (2002), assume that the value of a temporary project can be zero if marginal damages increase faster than the discount rate (p 459). That is an invalid conclusion because the SCC is infinite in this case. Our equation 2 shows that the SVO is always positive and finite. Note that there are also other dimensions of damages that should be considered (Kirschbaum, 2006). Not only the level of warming matters. Firstly, some damages depend on the speed of warming. For example, slowly migrating species are more likely to get extinct if the same warming happens rapidly rather than slowly. Since warming is proportional to cumulative emissions, the speed of warming is proportional to emissions $\dot{T} = \zeta E$. This increases the value of a temporary offset if future emissions are lower. In an optimist scenario where countries comply with their current commitments, we have higher emissions today than in the future and are currently warming the earth at the highest speed. This is an argument in favour of temporary offsetting. Note that if emissions are expected to increase over a long period (a reasonable assumption in earlier decades) the damage related to warming speed reduces the value of an offset. Secondly, some damages depend on cumulative warming, i.e. $\int_{1850}^{\tau_2} T dt$. For example, ice melting is approximately proportional to cumulative warming rather than instantaneous warming. A temporary offsetting project will unambiguously reduce cumulative warming and add social value.

To summarize, we build on an extensive existing literature and we are the first to take into account the decreasing absorptive capacity of carbon sinks, thermal inertia, a convex damage function, a constant discount rate and the cumulative sum of all marginal damages avoided by the project.

SM2. Climate dynamics of a temporary withdrawal of CO2

Consider the simple case of a temporary offset that removes a single ton of CO2 at time $t_1 = 0$, only to release it again at time t_2. Figure 7 uses 16 climate models from the CIMP 5 ensemble (Joos et al., 2013; Geoffroy et al., 2013) to illustrate the complex impact on the climate system on emissions and temperatures of a 1GtCO2 reduction in 2020 for a period of 50 years: after 50 years the offset ends and the emissions are re-released, compared to a no-offset world. Figure 7 shows the temperature effect over time of a temporary withdrawal of 1 GtCO2 in 2020

Firstly, Figure 7a reflects the baseline against which the offset's impact is evaluated: the pre-offset emissions and temperature (warming) path. Figure 7b shows the impact of the offset on CO2 concentration: i.e. the difference between offset and baseline scenarios. The shape of the response curves can be understood as follows. In the case of a positive pulse, the extra atmospheric CO2 is gradually absorbed by oceans and plants, because CO2 absorption happens faster under higher CO2 concentration. The opposite is true for a negative pulse. In both cases, any difference in CO2 concentration between scenarios will fade out over time. In Figure 7b the immediate effect of 1GtCO2 removed in 2020 reduces over time, and the net effect is reduced over time. After 50 years, the effect is 60% of the initially absorbed quantity of CO2. Next, 1 GtCO2 is re-released into the atmosphere as the offset ends, and atmospheric CO2 concentration is at first higher than the original concentration, but again this difference fades over time. Figure 7c shows the impact on temperature, where the dynamics reflect recent findings that temperature responses

Study	Driver of value/ Objective function	Formula relative value SVO/SCC	SVO/SCC for project of 50 y	Discount rate	Time horizon	Feedback on sinks	Thermal inertia	Damage function	Applications
Climate physics									
Moura-Costa & Wilson (2000) Moura-Costa Method	Cumulative concentration	$\frac{\tau_2}{\int_0^{100} IRF_{CO2}dt} = \frac{\tau_2}{55}$	90%	$0\ \forall t < 100$ $\infty\ \forall t > 100$	100 years (1)	no	no	Linear in concentration	IPCC special report on LULUCF (2000)
Fearnside, Lashof, Moura-Costa (2000) Lashof Method	Cumulative concentration	$\frac{\int_{100-\tau_2}^{100} IRF_{CO2}dt}{\int_0^{100} IRF_{CO2}dt}$	42%	$0/\infty$	100 years	no	no	Linear in concentration	IPCC special report on LULUCF (2000)
Clift & Brandao (2008) Levasseur et al. (2010) Dynamic LCA	Cumulative concentration	$\frac{\int_0^{\tau_2} IRF_{CO2}dt}{\int_0^{100} IRF_{CO2}dt}$	58%	$0/\infty$	100 years	no	no	Linear in concentration	BSI/Carbon Trust PAS 2050 carbon footprint
O'Hare et al. (2009)	Cumulative concentration	$1 - \frac{\int_0^{100} e^{-r(\tau_2+t)} IRF_{CO2_t}dt}{\int_0^{100} e^{-rt} IRF_{CO2_t}dt}$	80%	Constant	$100 + \tau_2$	no	no	Linear in concentration	
Cherubini et al. (2011) Global Warming Potential	Cumulative radiative forcing	$\frac{\int_0^{\tau_2} \alpha_t IRF_{CO2}\ dt}{\int_0^{100} \alpha_t IRF_{CO2}\ dt}$	59%	$0/\infty$	100 years (2)	no	no	Linear in radiative forcing	International Organisation of Standardization (2013) on carbon footprint
International Reference Life Cycle Data System (ILCD)	Cumulative radiative forcing	$\frac{\tau_2}{100}$ (3)	50%	$0/\infty$	100 years	no	no	Linear in radiative forcing	European Commission (2010)
Kendall (2012) Time Adjusted Warming Potential	Cumulative radiative forcing	1-$\frac{\int_0^{100-\tau_2} \alpha IRF_{CO2}\ dt}{\int_0^{100} \alpha IRF_{CO2}\ dt}$	41%	$0/\infty$	100 years	no	no	Linear in radiative forcing	
Kirschbaum (2006)	Minimize temp in 2100	$\frac{T^{Peak\ w\ project}}{T^{Peak\ w/o\ project}}$ (4) and $\frac{\int_{2000}^{2100} T^{w\ project}dt}{\int_{2000}^{2100} T^{w/o\ project}dt}$	n.a.	$0/\infty$	100 years	yes	yes	Linear in peak warming or cumulative warming	
Cost minimization									
Herzog, Caldeira, Reilly (2003), Kim, McCarl, Murray (2008)	Cost-minimization, Carbon price	$\frac{p_0 - e^{-r\tau_2} p_{\tau_2}}{p_0}$	between 80% (constant p) and 0% (Hotelling)	Constant	∞	n/a	n/a	Absent in the case of a carbon price with constant growth rate. Linear in the special case of a constant carbon price.	
Welfare maximization									
van Kooten (2009)	Marginal damages of atmospheric CO2	$\frac{1-\left(\frac{1+\gamma}{1+r}\right)^{\tau_2}}{1-\left(\frac{1+\gamma}{1+r}\right)^{N}}$ (6)	64%	Constant	100-500 years	no	no	Marginal damages increase exponentially over time at rate γ	
This study	Welfare maximization, Marginal damages of Temperature	$\frac{\int_\xi^{\tau_2+\xi} e^{-rt} T * IRF_T dt}{\int_\xi^{\infty} e^{-rt} T * IRF_T dt}$ (7)	43%	Constant	∞	yes	yes	Quadratic in temperature	

Table SM1: Overview of methods to evaluate a temporary project absorbing one ton of CO2 at time 0 and releasing it back to the atmosphere at time τ_2. IRF_{conc} is the atmospheric CO2 impulse response function for a pulse of emissions, shown in Figure 3b. The impulse response function shows that an inital emission of one unit of tCO2 is gradually absorbed over time by the biosphere and the oceans. $\int_0^{100} IRF_{conc}dt$ is 52.4 year-tCO2 in Joos et al. (2013) for a scenario with constant background concentration at 389ppm. $\alpha_t = 5.35ln\left(\frac{CO2_t}{CO2_{1850}}\right)$ is the radiative efficiency of CO2 and depends on the background concentration $CO2_t$. $\int_0^{100} \alpha_t IRF_{conc}dt$ is the extra energy (forcing) in the first 100 years as a result of an emission pulse. IRF_T is the temperature impulse response function, shown in Figure 1c, p is the carbon price, and T is temperature. Discount rate $0/\infty$ indicates absence of discounting before the 'Time horizon' and disregarding of effects thereafter. Models with zero discount rate have an implied infinite disount rate after the time horiz on.

Notes:

(1) In the case of a 100 year horizon, the denominator is 52.4 ton-years of CO2. Müller-Wenk & Brandão 2010 use a 500 year period, in which case the denominator is 183.6 ton-years CO2.

(2) Time horizons of 20 and 500 years are also considered in the IPCC.

(3) In general the ILCD method is based on the GWP for emissions and permanent absorptions. For projects where the delay is the focus of the analysis, it recommends to subtract 1/100 of the emission for each year of delay.

(4) Kirschbaum does not calculate the SVO/SCC, but compares a project to a baseline scenario without the project. He distinguishes 2 types of peak warming, $max\left\{T_{2000}, T_{2001}, ...T_{2100}\right\}$ for damages related to warming speed, or $max\left\{\frac{T_{2000}}{100}, \frac{T_{2001}}{101}, ..., \frac{T_{2100}}{200}\right\}$ for damages related to the level of warming. The second formula is meant to measure damages from cumulative warming such as ice melting.

(6) Marginal damages are assumed to increase at a constant rate γ. An abated emission is assumed to be emitted N years later due to supply side effects (green paradox). We use $\gamma = 2\%; N = 100$.

(7) The IRF_Tfunction is shown in Figure 1c.

to emissions pulses are relatively rapid and persistent (Ricke and Caldeira, 2014). The cooling effect occurs with a delay of 5 years due to the thermal inertia, after which the effect on temperature is more or less constant, reflecting the balance of the countervailing effects of thermal inertia and absorption dynamics. After 50 years, when the GtCO2 is re-released, these dynamics are reversed. The overshoot of CO2 concentration leads to a rapid energy forcing and curtails the offset's cooling effect within 5 years without a large temperature overshoot. The overall effect of the offset on temperature resembles a step function. Indeed, when we compare the SVO of an offset of 50 years using the exact temperature response function and the approximate step function with 3 years of delay, the approximation error is only 0.02%. Zickfeld et al. (2021) describe differences between positive and negative emissions, which are very small for small emission pulses.

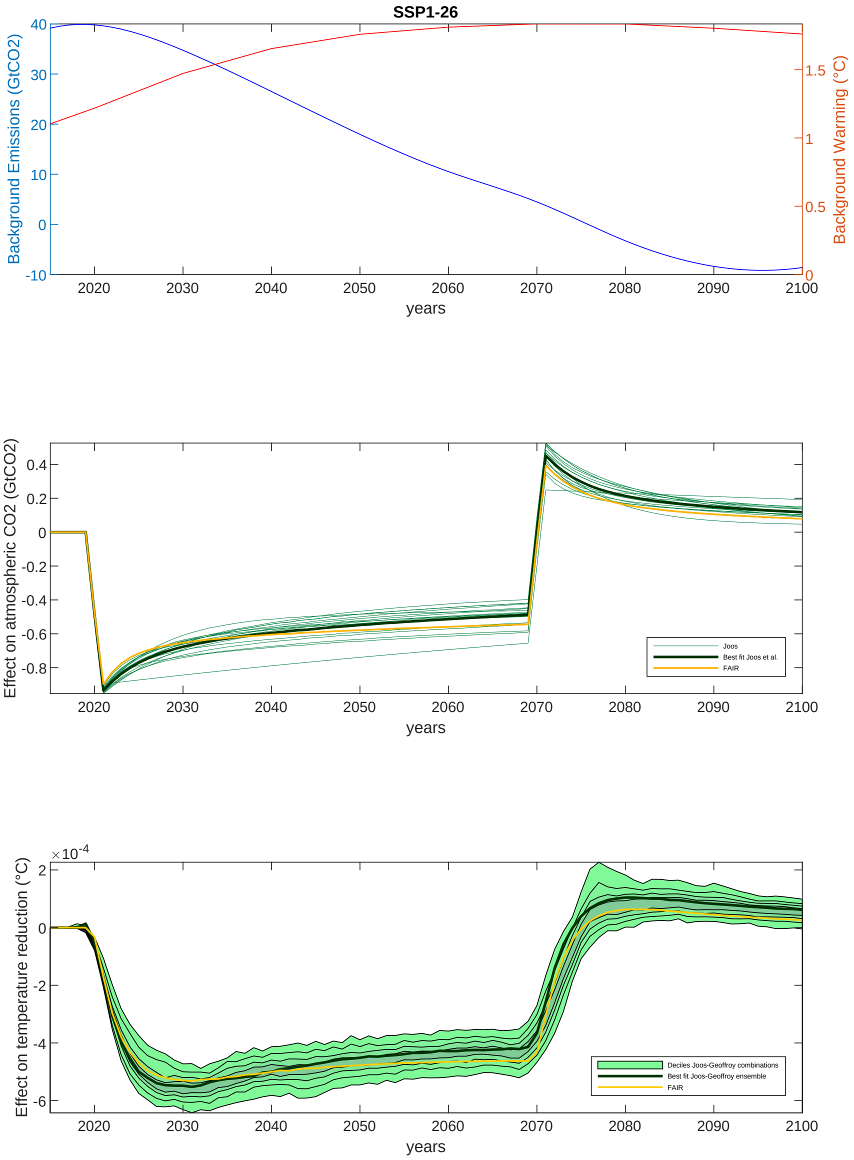

Figure SM2: The effect of an offset on atmospheric CO2 concentrations and on warming for the SSP1_26 background scenario. Figure a shows the background emissions and temperature, following the SSP1-26 scenario. Figure b shows the difference between CO2 concentration of the background scenario and the scenario with a temporary removal project, instantaneously absorbing 1 GtCO2 in 2020 and reinjecting it in 2070. The 16 green lines correspond to 16 carbon absorption models in the CMIP 5 modeling ensemble described by Joos et al. (2013). The yellow line is the FAIR model, which is based on the the best fit of the CMIP 5 ensemble, but adds a carbon sink saturation feedback. Figure c shows the difference between the temperatures of the background scenario and the scenario with the removal project. 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 FAIR model uses the best fit of the CMIP5 energy balance models. The climate sensitivity of all energy balance models has been harmonized to 3.1°C.

SM3. Climate dynamics under other background emissions

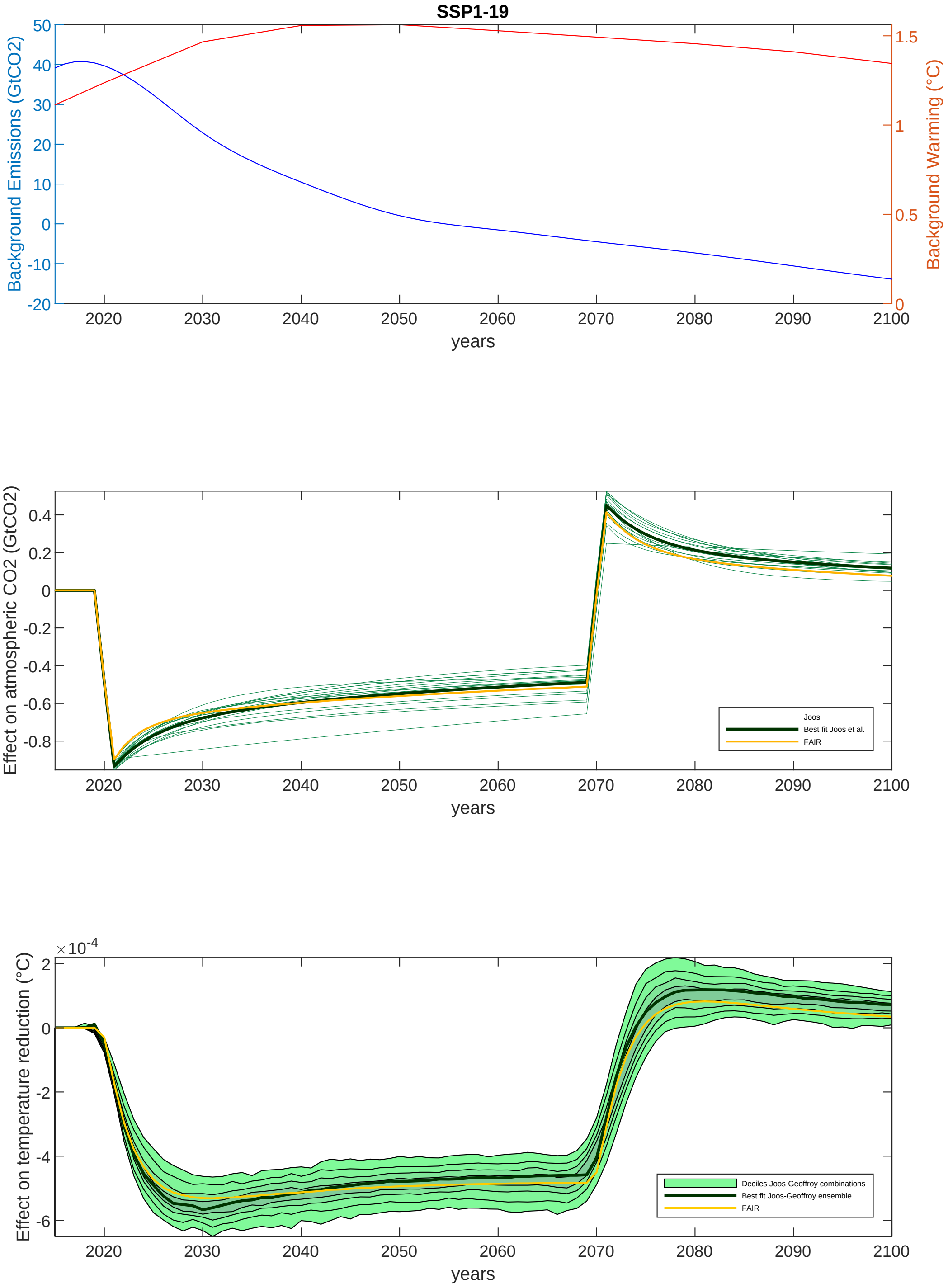

Figure SM3a: The SSP1-19 background scenario (a), the effect of an offset on CO2 concentrations (b) and on warming (c).

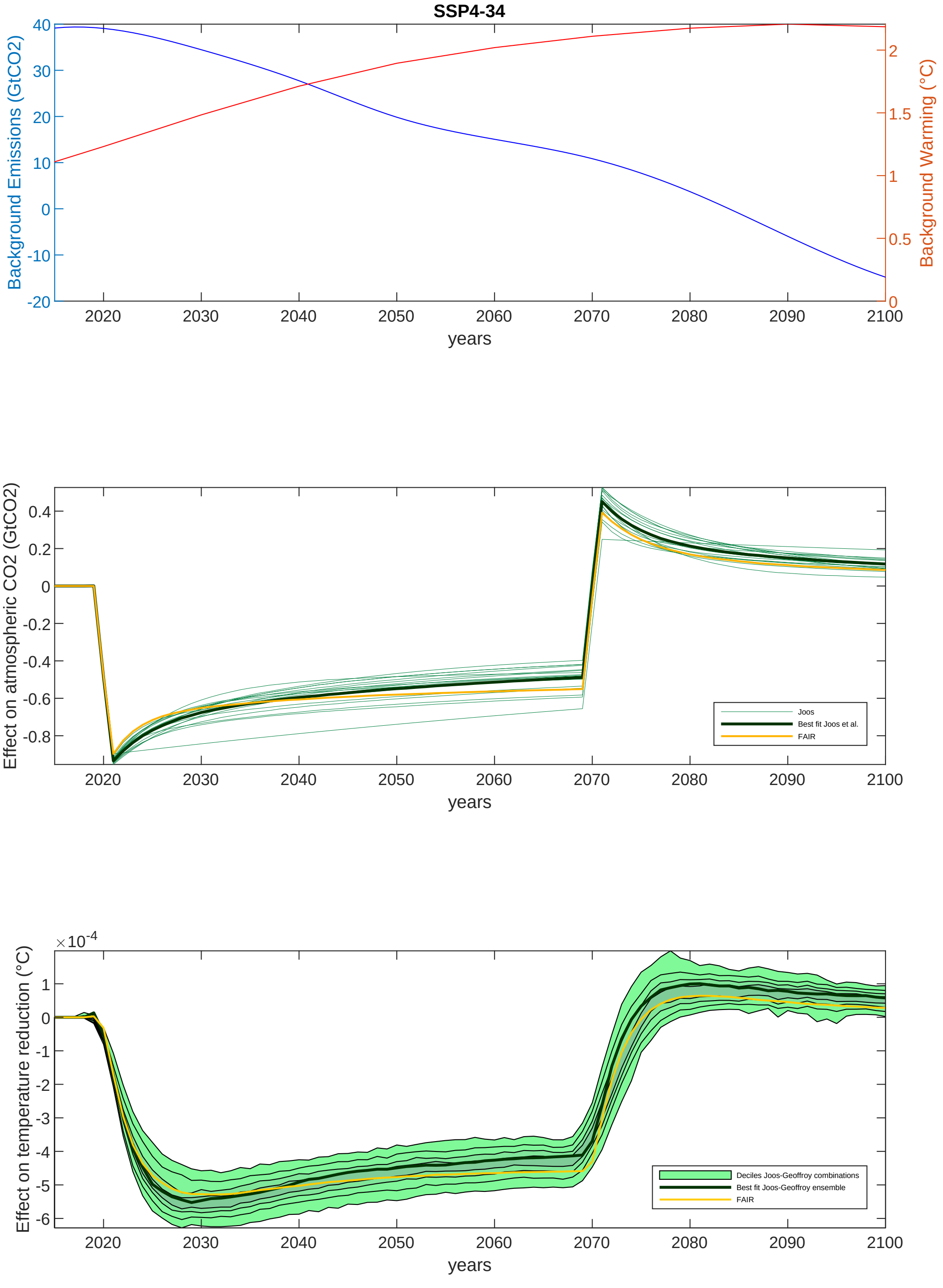

Figure SM3b: The SSP4-34 background scenario (a), the effect of an offset on CO2 concentrations (b) and on warming (c).

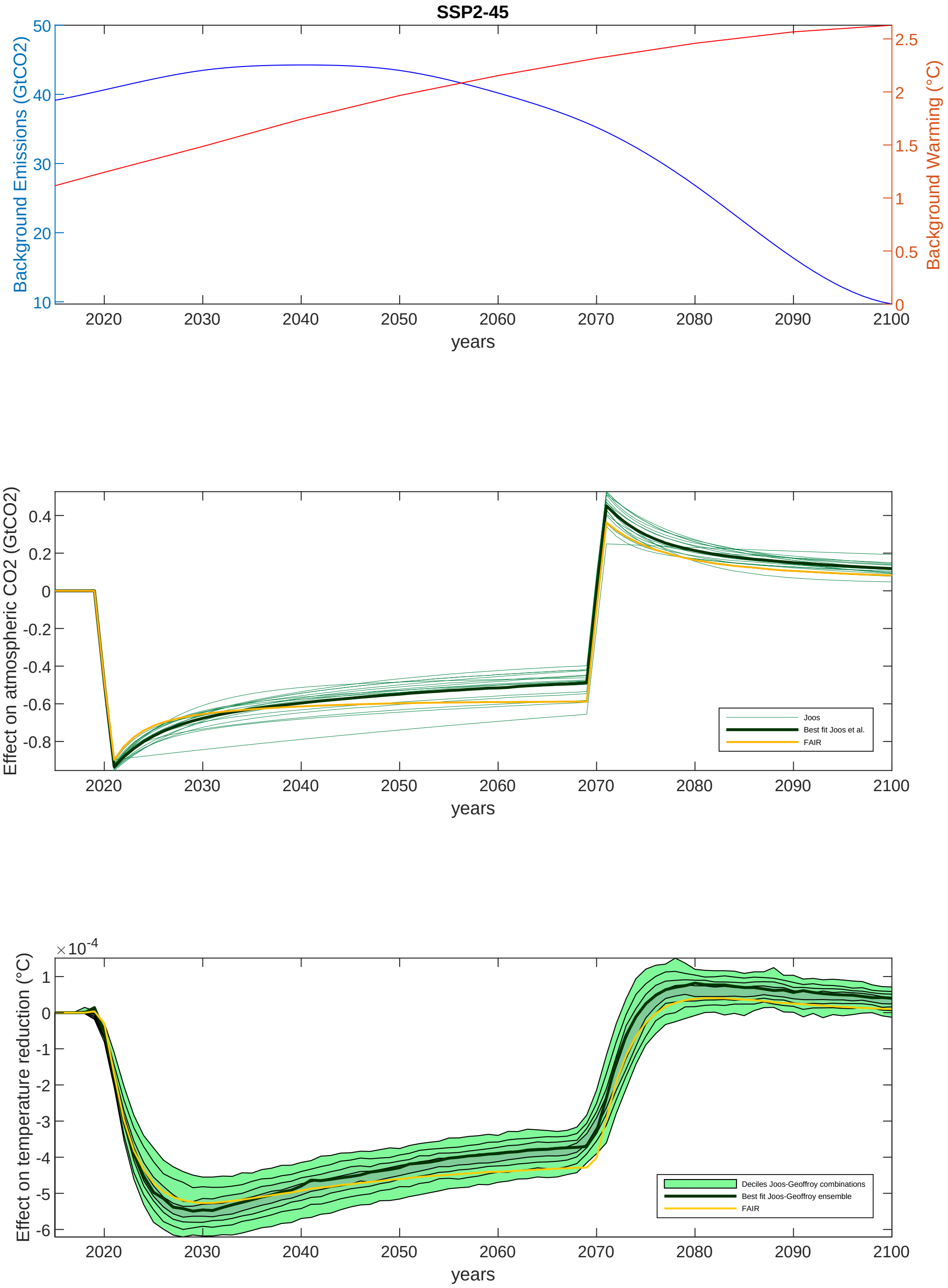

Figure SM3c: The SSP1-45 background scenario (a), the effect of an offset on CO2 concentrations (b) and on warming (c).

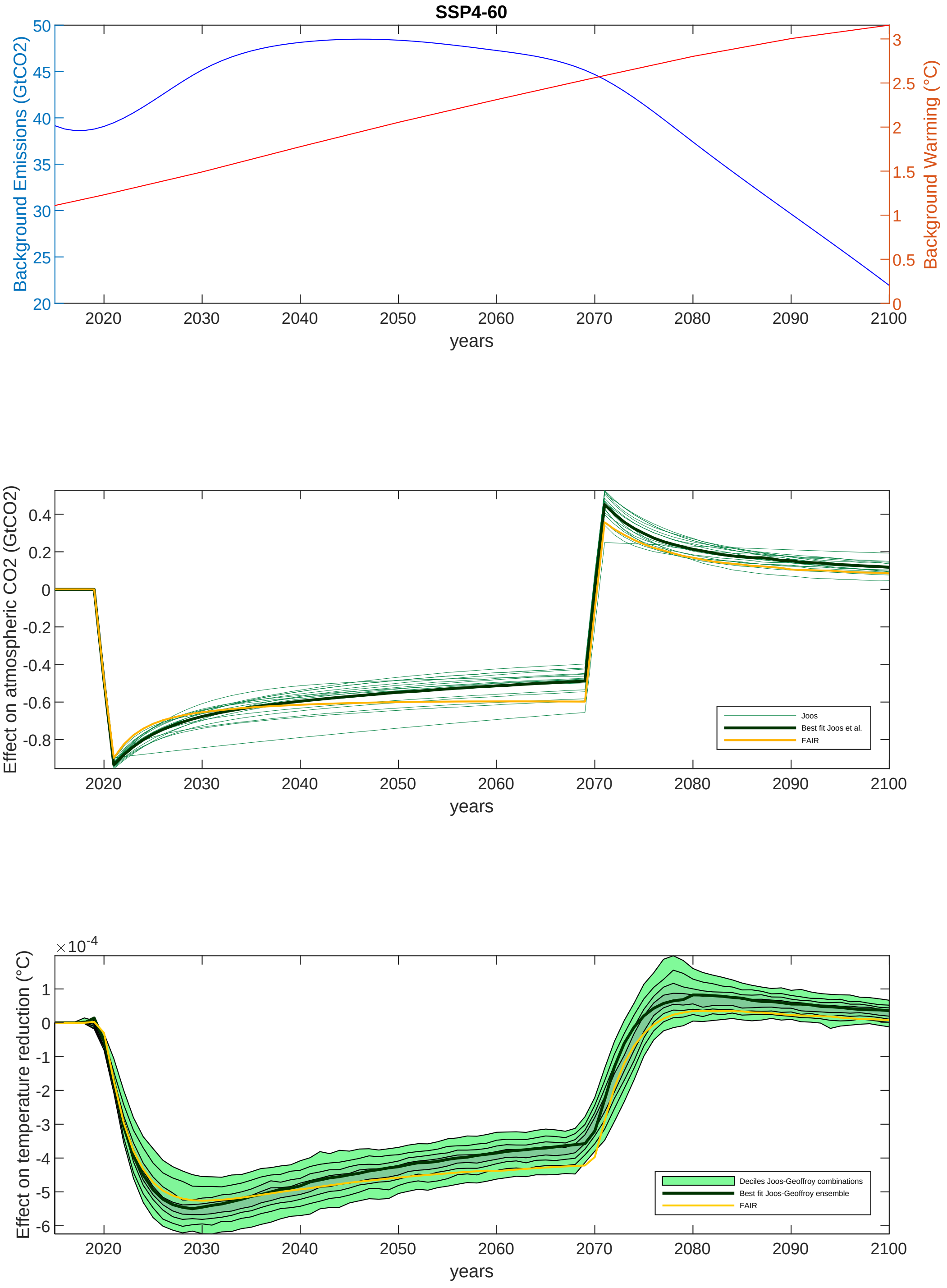

Figure SM3d: The SSP4-60 background scenario (a), the effect of an offset on CO2 concentrations (b) and on warming (c).

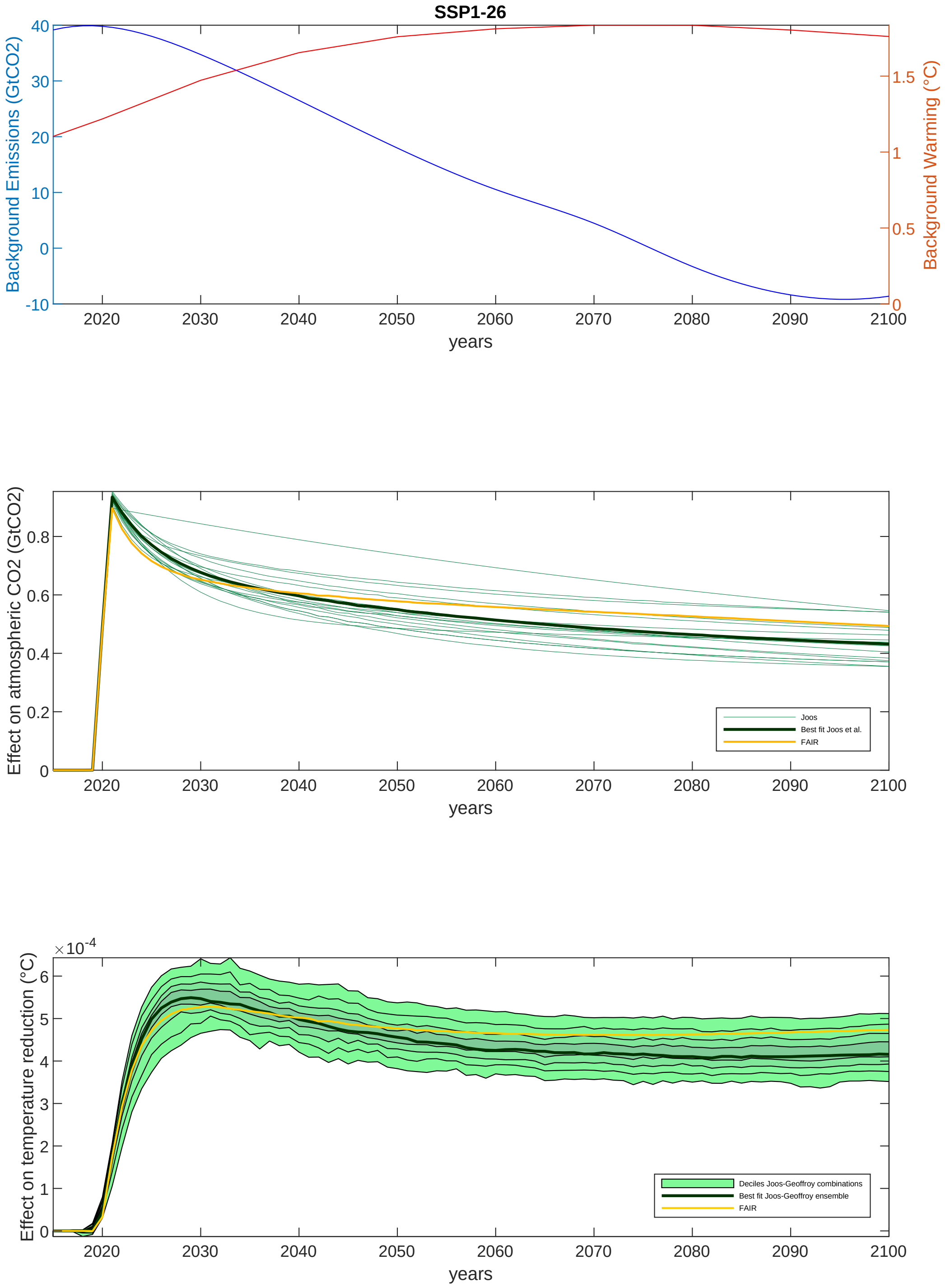

Figure SM3e: A permanent increase in carbon: SSP 1-2.6.

SM4. Formula and growth rate of the SCC on optimal and non-optimal trajectories

The dynamics of the social cost of carbon are explained in the context of a simple control problem of a stock pollutant. We assume that warming T is proportional to cumulative emissions S, $T = \zeta S$, with ζ the Transient Climate Response to Cumulative Emissions. This means that we abstract from the short delay between emissions and warming ($\xi = 0$). From the definition of cumulative emissions we have $\dot{S} = E$. The damages associated with the pollutant (e.g. CO2 equivalents) are given by the function $D\left(T\right)$, where T is and $\frac{\partial D(T)}{\partial T} = D_T \geq 0$ and $\frac{\partial^2 D(T)}{\partial T^2} = D_T \geq 0 D > 0$. Since temperature is a linear function of cumulative emissions, applying the chain rule gives $D_S = \zeta D_T$ The economic benefits of emitting the pollutant are given by $B\left(E\right)$where E are emissions at any given point of time, and $\frac{\partial B(E)}{\partial E} = B_E\left(E\right) \geq 0$ and $\frac{\partial^2 B(E)}{(\partial E)^2} = B_{EE}\left(E\right) \leq 0$. The net benefits of economic activity that requires the emission of CO2e is therefore: $B\left(E\right) - D\left(S\right)$. Given this simple set-up, the control problem is to maximize the present value of the net benefits from emitting the stock pollutant taking into account the constraints on the stock dynamics, the technology associated with extraction of fossil fuels, the net benefits function, and the discount rate r. The net benefits are measured in cash equivalents and so the appropriate discount rate is the consumption rate of discount, and for the purposes of the exposition, the discount rate is assumed to be invariant to the time horizon being evaluated. The control problem therefore takes the following form:

$$V = \max_{E} \int_{t=\tau}^{\infty} \exp\left(-r\left(t-\tau\right)\right)\left(B\left(E\left(t\right)\right) - D\left(S\left(t\right)\right)\right) dt \tag{16}$$

$$s.t.$$

$$\dot{S} = E$$

$$S\left(0\right) = S_0$$

The optimum path of extraction and stock accumulations can be solved using optimal control methods. We have assumed the that limit on fossil fuel is not binding, that it is optimal not to burn all reserves.The solution stems from the Maximum Principle associated with the current value Hamiltonian:

$$H\left(E, S, \mu\right) = \left(B\left(E\left(t\right)\right) - D\left(S\left(t\right)\right)\right) + \mu\left(E\right) \tag{17}$$

where μ is the shadow value of the stock: the change in the value of the maximand in Equation (16) as a result of a marginal change in the stock, S. The interior solution for this problem is given by:

$$\frac{\partial H}{\partial E} = B_E + \mu = 0 \tag{18}$$

$$-\frac{\partial H}{\partial S} = \dot{\mu} - r\mu = D_S \tag{19}$$

$$\lim_{t \to \infty} \mu(t) \exp(-rt) S(t) = 0 \tag{20}$$

From 18 we know that the shadow price of the stock is negative because $B_E > 0$. This makes sense because the stock in this case is a pollutant, and so additional units of the stock are detrimental to net benefits, other things equal. Combining 18 and 19 leads to the following expression for the dynamics of the shadow price μ:

$$\frac{\dot{\mu}}{\mu} = \frac{D_S(S)}{\mu} + r \tag{21}$$

which shows that the shadow price of the stock pollutant increases at a rate which is lower than the rate of discount, r, because $\mu < 0$. It remains to be shown that μ has the interpretation of the Social Cost of Carbon as presented in the main text in Equation (1). Defining $\theta = -\mu$ and solving out the differential Equation on (21) shows that (See Hoel 2016, p8-11):

$$\theta(\tau) = \int_{t=\tau}^{\infty} exp\left(-r(t-\tau)\right) D_S\left(S(t)\right) dt \tag{22}$$

which is identical to Equation (22). In an optimal control problem, the shadow price on the stock of cumulative emissions is the Social Cost of Carbon, which is also the benefit of reducing this stock by a marginal ton.

Note that Equation (22) has a straightforward interpretation: the social cost of carbon is the discounted sum of all marginal damages and it is easy to see that this also applies to marginal projects on non-optimal temperature paths. Hence, Equation (21), which is just the time derivative of Equation (22), shows that the SCC on non-optimal temperature paths also increases at a lower rate than the discount rate (as long as marginal damages are positive).

SM5. The SVO with different assumed temperature, emission and marginal damage paths

Marginal damages grow at a constant rate, x

The exposition of SVO in Section 3 has assumed for simplicity that the SCC and marginal damages grow at a constant rate x. In this appendix, we look at conditions which are

	RCP2.6	RCP4	RCP6	RCP8.5
2020-2040	2.2%	2.4%	2.5%	2.8%
2020-2060	2.1%	2.3%	2.4%	2.7%
2020-2080	2.0%	2.3%	2.4%	2.6%
2020-2100	2.0%	2.2%	2.3%	2.5%

Table SM5: Mean growth rates of the SCC for different temperature paths and time frames. We assume a quadratic damage function, proportional to GDP, which increase at 2%. For a stable temperature, the SCC will increase at the growth rate of GDP. The discount rate is 3.2%. Since RCP scenarios are only defined until 2100 we assume a linear trend between 2095 and 2120 and constant temperatures thereafter.

compatible with this assumption.

Consider the quadratic damage function in section 4 $D_T = \gamma YT$. Assume income grows at a constant rate g and temperature grows at constant rate y. As a result, marginal damages are $D_T = \gamma Y_0 T_0 e^{(g+y)t}$ and will grow at a constant rate $x = g + y$.

What if the damage function would not be quadratic? Assume that the damage function is a general power function of power θ, $D = \gamma YT^{\theta}$, that temperature raises at rate y and the economy at rate g. Then $D_T = -\gamma\theta YT^{(\theta-1)} = \theta\gamma\zeta Y_0 S_0 e^{(g+(\theta-1)y)t}$ and the growth rate of marginal damages is again constant and equal to $x = g + (\theta - 1)y$. With these assumptions, the SVO pricing formulas in Section 3 are appropriate.

Which emission paths will lead to a temperature path with a constant growth rate? Since emissions are the time derivative of cumulative emissions and using the approximation $T = \zeta S$, we can write $S_t = S_0 e^{yt} \Leftrightarrow E_t = \dot{S}_t = \underbrace{yS_0}_{E_0} e^{yt}$. Therefore, a temperature increasing at rate y requires emissions to increase at the same rate, with initial ($t = 0$) emissions $E_0 = yS_0$. With emissions in 2020 in the order of magnitude of 40GtCO2/y and cumulative emissions around 2000GtCO2, this is valid for y=2%.

Temperature paths are rising at a constant rate of more or less 2% until 2070 for the RCP8.5% scenario. For other RCP scenario's 2.6, 3.4 and 6.0 the growth rate of temperature starts at 2% but approaches 1% in 2030 2040 and 2045 respectively. If there is no risk involved, our formula 3 only requires a mean growth rate of the SCC, which are shown in Table 7.

Concave increasing marginal damages

On very long time horizons, marginal damages do not increase at constant rate. At some point in the future, be it because fossil fuels are exhaused, temperatures will stabilize. Therefore we consider a trajectory of marginal damages converging over time towards a maximum. For the sake of brevity, from here on, we will use the shorter notation for the marginal damage per unit of CO2 $D_S = \zeta D_T$ and assume that there is no lag between emissions and marginal damages ($\xi = 0$). Assume marginal damages approach a steady state D_S^* at a constant rate x. $D_S = D_S^* - (D_S^* - D_S^0)\, exp(-xt)$.

$$SVO_{\tau_1,\tau_2} = \int_{\tau_1}^{\tau_2} e^{-rt-\phi(t-\tau_1)} \left(D_S^* - \left(D_S^* - D_S^0\right) e^{-xt}\right) dt \tag{23}$$

$$= e^{\phi\tau_1} \left[\left[\frac{D_S^* e^{-(\phi+r)t}}{\phi + r} \right]_{\tau_1}^{\tau_2} - \left[\frac{\left(D_S^* - D_S^0\right) e^{-(\phi+r+x)t}}{\phi + r + x} \right]_{\tau_1}^{\tau_2} \right] \tag{24}$$

$$= e^{-r\tau_1} \left\{ \left[\frac{D_S^*}{\phi + r} \left(e^{-(\phi+r)(\tau_2-\tau_1)} - 1\right) \right] - e^{-x\tau_1} \left[\frac{\left(D_S^* - D_S^0\right)}{\phi + r + x} \left(e^{-(\phi+r+x)(\tau_2-\tau_1)} - 1\right) \right] \right\} \tag{25}$$

The above path for marginal damages can be compatible with several cumulative emissions paths. For example, marginal damages can be proportional to production $D_S = -\gamma Y S$ and cumulative emissions follow the path $S_t = \frac{D_S^* exp(-gt) - \left(D_S^* - D_S^0\right) exp(-(x+g)t)}{\gamma Y_0}$. As a result, emissions in the long run are negative and decrease at rate g, to offset the effect of increasing production on marginal damages $E_t = \frac{-gD_S^* exp(-gt) + (x+g)\left(D_S^* - D_S^0\right) exp(-(x+g)t)}{\gamma Y_0}$. For a simpler case, we can assume that marginal damages are γS and that cumulative emissions follow the path $S_t = S^* - (S^* - S_0)\, exp(-xt)$. As a result, emissions are exponentially decreasing $E = E_0 e^{-xt}$ with initial condition $E_0 = x(S^* - S_0)$. This leads to the following formula for the social value of the offset

$$SVO_{\tau_1,\tau_2} = \gamma e^{-r\tau_1} \left\{ \left[\frac{S^*}{\phi + r} \left(e^{-(\phi+r)(\tau_2-\tau_1)} - 1\right) \right] - e^{-x\tau_1} \left[\frac{(S^* - S_0)}{\phi + r + x} \left(e^{-(\phi+r+x)(\tau_2-\tau_1)} - 1\right) \right] \right\}. \tag{26}$$

A linear emissions path and quadratic marginal damages

Assume a linear decreasing emissions path $E_t = E_0 - xt$. This implies a quadratic cumulative emissions path $S_t = S_0 + E_0 t - \frac{x}{2} t^2$. Temperature peaks at time E_0/x, when emissions are zero. To make notation easier, we assume that marginal damages are γS. For damages proportional to production, marginal damages are $Y_0 e^{gt} \gamma S$ The solution is the same provided that γ is replace by γY_0 and r is replaced by $r - g$. As a result, marginal damages follow a quadratic time path $D_{S_t} = D_{S_0} + \gamma E_0 t - \frac{\gamma x}{2} t^2$.An extension to another damage function that would also lead to quadratic marginal damages is straightforward.

The value of the project writes

$$SVO_{\tau_1,\tau_2} = \int_{\tau_1}^{\tau_2} e^{-rt-\phi(t-\tau_1)} \gamma \left(S_0 + E_0 t - \frac{x}{2} t^2\right) dt \tag{27}$$

Integrate by parts

$$SVO_{\tau_1,\tau_2} = e^{\phi\tau_1}\left[\left[\gamma\left(S_0 + E_0 t - \frac{x}{2}t^2\right)\frac{e^{-(\phi+r)t}}{\phi+r}\right]_{\tau_1}^{\tau_2} - \int_{\tau_1}^{\tau_2} e^{-(r+\phi)t}\gamma\left(E_0 - xt\right)dt\right] \tag{28}$$

Integrate by parts a second time

$$SVO_{\tau_1,\tau_2} = e^{\phi\tau_1}\gamma\left\{\left[\frac{e^{-(\phi+r)t}}{\phi+r}\left(\overbrace{S_0 + E_0 t - \frac{x}{2}t^2}^{S_t} - \frac{\overbrace{E_0 - xt}^{E_t}}{\phi+r} - \frac{x}{(\phi+r)^2}\right)\right]_{\tau_1}^{\tau_2}\right\} \tag{29}$$

The social cost of carbon (the above formula for period $0, \infty$) is not really meaningful because emissions on a linear path become ever more negative (and warming becomes negative in the very long run). Therefore, we will now assume that when emissions reach zero at time $t^* = E_0/x$,they remain zero. As a result, temperature peaks at $S^* = S_0 + \frac{E_0^2}{2x}$ and is stable thereafter. This gives the following social cost of carbon (using Equation (29) between time zero and t^* and adding the present value cost of constant damages $\frac{e^{-rt^*}}{r}\gamma S^*$ thereafter)

$$SCC_0 = \gamma\frac{e^{-rt^*}}{r}\left(2S^* - \frac{x}{r^2}\right). \tag{30}$$

Substituting out γ allows to calculate the adjustment factor for impermanence and risk. In case the project stops before emissions are zero $\tau_2 \leq \frac{E_0}{x}$ this yields the following formula

$$SVO_{\tau_1,\tau_2} = SCC_0 e^{\phi\tau_1}\left[\frac{e^{-rt^*}}{r}\left(2S^* - \frac{x}{r^2}\right)\right]^{-1} \quad * \tag{31}$$

$$\left[\frac{e^{-(\phi+r)t}}{\phi+r}\left(\overbrace{S_0 + E_0 t - \frac{x}{2}t^2}^{S_t} - \frac{\overbrace{E_0 - xt}^{E_t}}{\phi+r} - \frac{x}{(\phi+r)^2}\right)\right]_{\tau_1}^{-\tau_2} \tag{32}$$

SM6. Extended matrix of correction factors

IPCC Scenario	Risk at start	Risk at end	SVO Correction factors (max.duration, v)				SCC ($\$/tCO_2$) Damages ($\gamma$)	
(Temp in 2100)	$\tilde{\varphi}$	$\phi + \varphi$	25	50	100	∞	γ=0.0077	γ=0.0025
RCP 2.6	1000(low risk)	0	24%	44%	70%	100%	109	35
(1.8°C)		0.25	23%	42%	63%	83%	109	35
		0.5	23%	40%	58%	71%	109	35
	0.5	0	23%	43%	69%	99%	109	35
		0.25	22%	40%	62%	82%	109	35
		0.5	21%	38%	56%	69%	109	35
	0.25(high risk)	0	21%	41%	67%	97%	109	35
		0.25	20%	39%	60%	80%	109	35
		0.5	20%	36%	54%	68%	109	35
RCP 3.4	1000	0	19%	37%	66%	100%	142	46
(2.6°)		0.25	19%	35%	59%	81%	142	46
		0.5	18%	33%	53%	68%	142	46
	0.5	0	18%	36%	65%	99%	142	46
		0.25	18%	34%	58%	80%	142	46
		0.5	17%	32%	52%	67%	142	46
	0.25	0	17%	35%	63%	97%	142	46
		0.25	16%	33%	56%	79%	142	46
		0.5	16%	31%	51%	66%	142	46
RCP 6.0	1000	0	17%	34%	64%	100%	161	52
(3.1°C)		0.25	17%	32%	57%	81%	161	52
		0.5	16%	31%	51%	67%	161	52
	0.5	0	16%	33%	63%	99%	161	52
		0.25	16%	31%	56%	80%	161	52
		0.5	15%	30%	50%	66%	161	52
	0.25	0	15%	32%	61%	98%	161	52
		0.25	14%	30%	55%	78%	161	52
		0.5	14%	28%	49%	65%	161	52
RCP 8.5	1000	0	13%	29%	60%	100%	233	76
(5.1°C)		0.25	13%	27%	53%	79%	233	76
		0.5	12%	25%	47%	64%	233	76
	0.5	0	12%	28%	59%	99%	233	76
		0.25	12%	26%	52%	78%	233	76
		0.5	12%	24%	46%	64%	233	76
	0.25	0	11%	27%	58%	98%	233	76
		0.25	11%	25%	51%	77%	233	76
		0.5	11%	24%	45%	63%	233	76

Table SM6: Adjustment factors for non-permanence and risk. We assume a quadratic damages proportional to GDP $exp\left(-\frac{\gamma}{2}T^2\right)$ with damage parameters of Howard and Sterner (2017) (Column 8) as well as Nordhaus (2017) (Column 9). Temperature pathways evolve according to SSP1-RCP2.6; SSP4-RCP3.4; SSP4-RCP6.0 and SSP5-RCP8.5 (Riahi et al. 2017, www.https://tntcat.iiasa.ac.at). Other parameters are $r = 3.2\%; \tau_1 = 3year; \zeta = 0.0006°C/GtCO_2; GDPgrowth = 2\%; T_0 = 1.2°C$. We use Equation (5) . For $\tilde{\varphi} = [0.5\ 0.25]$ the likelihood that the project is additional after 5 years is 92% and 71% respectively. For $\varphi + \phi = [0.0025\ 0.005]$ the likelihood that the project is additional after 50 years is 78% and 88% respectively.

An Excel spreadsheet to calculate the correction factors for any scenario is available from the authors.

SM7. The social value of an offset under multiple sources of risk

A general formula for the SVO under uncertainty

Here we add risk from uncertain consumption (macroeconomic risk) and temperature (climate risk) in an expected utility framework. We calculate the expected utility of the project by multiplying future damages by future marginal utility in Equation (5) and discounting at the pure time preference rate, δ. Dividing this outcome by marginal utility today will result in the SVO expressed in monetary terms. Assuming a time separable utility function with constant elasticity of substitution: $u = \frac{c^{1-\eta}}{1-\eta}$, a constant savings rate s (so that $c = (1-s)Y$), and initial time zero, the numerator in Equation (5) now becomes:[1]

$$SVO^{utils}_{\tau_1,\tau_2} = \zeta\gamma \sum_{t=\tau_1}^{\tau_2} e^{-\delta(t+\xi)} E\left[\underbrace{\frac{c^{1-\eta}_{t+\xi}}{1-s}}_{Marg.\ Utility*Y} Q_t T_{t+\xi}\right] dt, \tag{33}$$

where Q_t is the stock of carbon. In case of failure or non-additionality $Q_t = 0$, unlike q_t in equation 5, which is defined as the carbon stored in the successful project. We now consider the impact of uncorrelated and correlated risks on the SCC, SVO and the correction factor.

Uncorrelated risks

Let's start by assuming that consumption c, the stock of carbon stored by the project q and temperature T are stochastic, but independent from each other. Equation (33) now becomes

$$SVO^{utils}_{\tau_1,\tau_2} = \frac{\zeta\gamma}{1-s} \sum_{t=\tau_1}^{\tau_2} e^{-\delta(t+\xi)} E\left[c^{1-\eta}_{t+\xi}\right] E\left[Q_t\right] E\left[T_{t+\xi}\right] dt, \tag{34}$$

Equation (34) shows that that there is no risk premium for temperature uncertainty. This follows from our assumption of a quadratic damage function, which results in a linear marginal damage. For convex marginal damages (power of total damages larger

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[1] We assume a so-called 'open loop' optimization and abstract from Bayesian updating and policy learning over time, where optimal policy adapts to observed damages. Under Bayesian updating our expectations are conditional on the information set of the period before. See van den Bremer and van der Ploeg (2021) for thorough insights on uncertainty in a 'closed loop' optimization.

than 2), Jensen's inequality implies a positive risk premium increasing the SVO. Similarly, there is no risk premium for the uncertainty regarding the stock of carbon in the project. In case the expected size of the stored stock is 1 and the hazard rate, ϕ, is constant, we have $E\left[Q_t\right] = e^{-\phi t} q_t$ as in the main text.

The effect of uncertainty on consumption depends on the choice of the inter-generational inequality aversion η. Some models (Golosov et al. 2014, Hambel, van der Ploeg 2021) use $\eta = 1$. In that case, consumption disappears from the Equation 34 and the social value of the offsetting project is independent of future consumption. Higher consumption decreases marginal utility and increases damages in a proportional way, exactly compensating each other. In the case of $\eta > 1$, the discounting effect dominates, $c^{1-\eta}$ is convex and Jensen's inequality implies that the expected value increases with uncertainty, increasing the value of the project. It can be shown that this boils down to a decrease of the risk-free discount rate (van den Bremer & van der Ploeg 2021). More specifically, the future economic uncertainty increases the value of the project if $\eta > \beta$,where β is the climate beta, which is 1 in our model, i.e. damages are proportional to production. The opposite is true for $\eta < 1$, but in what follows we will assume that $\eta > 1$.

The risk adjustment to the discount rate will increase both the SVO and SCC. To see which effect dominates in the correction factor SVO/SCC, we combine Equation 1 and 2 and write the offset correction factor as:

$$\frac{SVO_{0,\tau_2}}{SCC_0} = \frac{SVO_{0,\tau_2}}{SVO_{0,\tau_2} + e^{-r\tau_2} SCC_{\tau_2}}. \tag{35}$$

An adjustment of the discount rate has a larger effect on the SCC in the long run, i.e. a larger effect on the second term of the denominator $e^{-r\tau_2} SCC_{\tau_2}$ compared to the first term. Therefore, the correction factor decreases.

Correlated risks

Here we consider how the SVO is affected when there is uncertainty in future emissions paths/temperature, economic growth and the project level storage of carbon, and when each is correlated with other aspects of the project, like the failure rate. Consumption and temperature can be positively correlated because larger production increases business-as-usual emissions, and leads to more emissions for a given effort of abatement. By contrast, a negative correlation is also possible. Good institutional design, political stability and international cooperation can both increase consumption and decrease emissions. Also, the damages from higher temperature will decrease consumption. Most studies find that correlation is small, but positive (Dietz et al., 2018).[2] Temperature and the quantity of

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[2] The elasticity of marginal damages with respect to consumption is known as the climate beta. If temperature is uncorrelated with temperature, our assumption of damages being proportional to consumption gives a climate beta of 1. Positive correlation between temperature and consumption will increase the climate beta beyond 1. Dietz et al. (2018) find a climate beta of 1.06 for damages proportional to production and around 5% of production. They also assume that the expected marginal damages increase

carbon stored by the project can also be correlated. They can be negatively correlated if project failure rates are more likely under high temperatures because future temperatures and failure rates of projects may be driven by common factors such as government quality, the quality of property rights regime, wars, or high temperature may reduce the carbon storage through forest fires, droughts and floods. How do these correlations affect the SVO, the SCC and the correction factor? Table 7 summarises the possibilities.

With variances given by $\sigma_i > 0$ and correlatons given by $\rho_{i,j} = 0$, Table 7 shows that when there is uncertainty over the future temperature path, $\sigma_T > 0$, but this is independent of consumption growth, $\rho_{c,T} = 0$, and the success of the project, $\rho_{q,T} = 0$ (q_t in Equation 5), the expected (mean) temperature path of those shown in Equation (5) is appropriate to calculate the SVO. The SVO is therefore unaffected. This is also the case as when there is uncorrelated uncertainty over the quantity of carbon stored by the project. $\sigma_q > 0$. By contrast, when future consumption is uncertain $\sigma_c > 0$, but uncorrelated to future temperatures and failure rates, it is appropriate to decrease the discount rate to reflect the demand for precautionary savings (Arrow et al., 2013). This increases the SVO. However, since the SCC includes damages that are further in the future, the reuction in the discount rate affects the SCC more than the SVO, and the correction factor in Equation (5) will decrease. If, however, there is a positive correlation between future temperature and consumption, $\rho_{c,T} > 0$, because higher production leads to higher business as usual emissions, the precautionary effect of uncertainty may be reduced or even reversed. In such cases a positive systematic risk premium could enter the social discount rate because the benefits of emissions reductions are more likely to occur in richer future states of the world, where they are valued less in terms of marginal utility (van den Bremer and van der Ploeg, 2021). Also at the project level, if the likelihood of failure or non-additionality is larger in a warming world, $\rho_{q,T} < 0$, the SVO and the correction factor decrease. This could be the case if institutional capacity in the future affects both the ambition of future climate policy and enforcement of projects. The size of this effect is shown in Table 1. Care is needed, therefore, in evaluating the effect of uncertainty on the SVO.

	Uncertain temperature*	Uncertain carbon stock	Uncertain consumption**	Consumption and temp positively correlated**	Offset failure more likely in a hotter world
	$\sigma_T > 0; \rho_{q,c} = \rho_{T,c} = 0$	$\sigma_q > 0; \rho_{q,c} = \rho_{q,T} = 0$	$\sigma_c > 0; \rho_{c,T} = \rho_{c,q} = 0$	$\rho_{c,T} > 0$	$\rho_{q,T} < 0$
SVO	0	0	↗	↘	↘
SVO/SCC	0	0	↘	↗	↘

*SVO increases and SVO/SCC decreases if total damage function is a power function with a power beyond 2.
** Effects are zero for $\eta = 1$ and reversed for $\eta < 1$

Table SM7: Overview of uncertainty effects: Quadratic total damage function and $\eta > 1$ assum. We consider mean-preserving spreads for an increase in uncertainty and

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with the climate beta, such that the SCC increases with beta. Our analysis does not have this valuation effect since it focusses on mean-preserving correlation, so the SCC decreases with beta.

Private risk aversion vs socially optimal risk aversion

Finally, it is important to consider risk aversion and whether individual offset buyers apply a risk premium that differs from the social risk premium? Investors may fear reputational damage from failed projects or may price diversifiable risk. Diversifiable risk does not come with a social risk premium. Only the mean success rate matters for the climate since in aggregate and on average underperforming offsets are themselves offset by over-performing ones. Nevertheless, investors are unlikely to have a diversified portfolio of projects, and consequently individual buyers may have higher risk-aversion compared to socially optimal risk-aversion, and then value a risky project below its expected social value in Equation (33). This higher risk aversion would be socially sub-optimal. Consider 2 projects with the same cost, but project A has a higher social risk-adjusted value (avoids more climate suffering on average, in expectation) despite being more risky. It would be socially optimal to do project A, while the private investor with an extra individual risk premium would finance project B and achieve lower climate mitigation on average than is optimal, despite the lower risk.Pratically speaking though, individual risk-aversion is difficult to calculate because motivations for buying offsets are much more complex compared to standard financial assets. Motivations include altruism, green reputation, political reputation, strategic signals in international negotiations and ethical perceptions. These motivations will differ between buyers and are much harder to model for standard financial markets where agents are assumed to maximize a standard consumption-dependent utility function.

SM8. Estimates of failure and additionality risk

Failure risk

Project certifiers develop a buffer credits to allow certain projects in their portfolio to fail. We can estimate the implied failure rate from this information purely to shed light on the likely scale of the risks. The requirement for offsets to hold buffer stocks of x% implies a failure hazard rate of $\phi = \frac{-ln(100\%-x\%)}{\tau_2}$. Buffer pools are typically 5-25% of project size. For example, Verra, the largest certifier of carbon credits has today a global buffer pool of approximately 58 million credits out of ˜130 million AFOLU issuances. In 2019 for instance, 4.5-6 million credits were wiped out from a buffer pool due to the Brazilian Amazon fires (see: https://verra.org/fires-in-the-brazilian-amazon-a-case-in-point-for-forest-carbon-projects/). Note that buffer contributions can be viewed on the online database https://registry.verra.org/app/search/VCS and ECT (2022). Furthermore, guidelines for World Bank projects recommend buffer values that vary with institutional and other risks associated with the host country. (FCPF, 2020). Finally, the Forest Carbon Partnerships Facility developed buffer guidelines for projects funded by the World Bank. They propose a buffer that is of 10% minimum up to 40% depending on the presence of 4 types of risks[3] :

- Lack of broad and sustained stakeholder support? Are stakeholders aware of, and/or have positive experience with Feedback & Grievance Redress Mechanism, benefit sharing plans etc. or similar instruments in other contexts? Have occurrences of conflicts over land and resources been addressed? (max 10% extra)
- Lack of institutional capacities and/or ineffective vertical/cross sectoral coordination. Is there a track record of key institutions in implementing programs and policies? Is there experience of cross-sectoral cooperation? Is there experience of collaboration between different levels of government? (max 10% extra)
- Lack of long term effectiveness in addressing underlying drivers. Is there experience in decoupling deforestation and degradation from economic activities? Is relevant legal and regulatory environment conducive to REDD+ objectives? (max 5% extra)
- Exposure and vulnerability to natural disturbances. Is the Accounting Area vulnerable to fire, storms, droughts, etc? Are there capacities and experiences in effectively preventing natural disturbances or mitigating their impacts? (max 5% extra)

These buffer recommendations are the source of the calculations in the text using the formular above, assuming the buffer pool is designed to cover the expected failure over the first 50 years. This time horizon is chosen because when a forest burns, the regrowth over the next 50 years can replenish the buffer pool to its initial value. In this sense the buffer can be interpreted as covering an expected loss over 50 years, i.e. the time for a forest to return to an average carbon stock. In that case, a buffer of 5%, 10% and 40% corresponds to a failure risk of $\phi = [0.001, 0.002, 0.01]$ respectively, as discussed in the main text. Further evidence of this kind can be found in Badgley et al. (2022). The California-Quebec carbon market allows for carbon offsetting from increased carbon sinks in forests. Badgley et al. (2022) show that between 5.7 and 6.8M tCO2 have been lost due to fire in the first 10 years of the program. This represents 2.6% of the total certified credits and between 95% and 114% of the buffer set aside for wildfires (the total buffer is 31M credits and also contains contributions covering other risks). 2.6% loss over 10 years corresponds to $\phi = 0.0026$. The Californian program sets aside 3% for diseases and insects, but Badgley et al. (2022) argue that this is again a minimum, because a single disease on a single species (Tanaok affected by *P. ramorum*) would use up the entire buffer. The total buffer in California is 31M, representing 12% of the stored carbon. Note that the total buffer covers wildfire (19%), disease and insects (18%), Other natural risks (18%), financial and management risks (44%). Using the same calculation as above, this corresponds to a value of $\phi = 0.0025$ if the buffer is believed to protect for hazards occurring during the first 50 years.

Finally, offsets may fail as a result of broader political and institutional risks associated with the country or regions in which they are located. Changes in political dispensations,

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[3] Forest Carbon Partnership Facility, Buffer Guidelines, version 2, April 2020.

property rights expropriation, and abrupt policy changes concerning Foreign Direct Investment or economic development more broadly, are all elements of what we now refer to as 'political risk'. In the absence of project specific measures of political risk we look at the risks associated with sovereign debt and business relationships to obtain a proxy for the hazard rate of failure, ϕ. Bekaert et al. (2016) consider the contribution of political risk to the spread of returns to sovereign debt using the country by country ICRG (International Country Risk Guide) ratings on political risk. Reflected as an adjustment to the discount rate, and assumed to be a rough proxy for country aggregate failure risk of offsets, Bekaert et al. (2016) provide estimates of ϕ in the order of $\phi = [0.02, 0.04]$ depending on the whether the country is considered a high or low political risk. On business risks estimates the hazard rates of contract termination between local and international partners imply $\phi = [0.01, 0.04]$, with higher rates in Asia, Latin America and Central and Eastern Europe compared to Europe and North America: an additional 1.7% for Asia, 1.6% Latin America and 0.66% for Central and Eastern Europe compared to Europe and North America (Meschi and Metais, 2015).

There are obvious questions as to the extent to which some of these measures of failure risk are overlapping. There is a clear need to direct future empirical work to auditing the success rates of nature based offsets over time ex post, and obtaining good ex ante measures of risk to assess the Social Value of Offsets. Further avenues for investigation can be found in assessing the risk of failure arising from the tree species (compatibility with the natural environment), soil, climate etc.

Additionality risk

What is the likely additional period of a reforestation project? In other words, after how many years, the forest would have been reforested in the absence of the project? This is a question that is very difficult to answer because it depends on the assumed baseline scenario, which is not observed. Also, there are currently no data available to estimate the likely additional period for Nature Based Solutions (NBS) from observed projects, because most projects are less than 2 decades old.

Roe et al. (2021) create a feasibility score per country based on 19 feasibility dimensions along economic, institutional, geophysical, technological, socio-cultural, environmental-ecological dimensions. However, mapping these scores into likelihoods of failures is not possible at present.

As discussed in the main text, additionality risk is otherwise difficult to estimate precisely. Jayachandran et al. (2017) estimate 90% additionality (10% leakage) in their randomised control trial of REDD+ projects in East Africa. Elsewhere, 40% of REDD+ projects were estimated to overlap with protected areas, suggesting 60% additionality (Simonet et al., 2015). Other contributions using quasi-experimental evidence to evaluate the policy impact of interventions like REDD+ provide an optimistic picture in the sense that REDD+ is demonstrated to have had a positive effect (e.g. West et al., 2020), sometimes large in percentage terms: 47% reduction in deforestation in Guizar-Coutino et al. (2022), but show that the positive effect is small against a backdrop of continued deforestation (Groom et al., 2022). Nevertheless, focussing on additionality of forest-offsets we find 80 - 75% additionality as a central approximation to be plausible when looking ahead at the implementation of forest based offsets: higher levels of non-additionality would not be acceptable for future offsets. From this approximation we obtain the estimate of $\varphi = [0.004, 0.006]$ that was presented in the main text, and the SVO entry of $\varphi = 0.005$ which can be read from Table 1.

Outside of forest projects, the CDM has delivered the largest pool of offsetting credits to date. Less than 1% was related to NBS: By August 2021, the CDM had issued 2157M credits, of which 20,7M were related to Land Use and Land Use Change and Forestry (LULUCF), 19.9M temporary Certified Emissions reductions (tCER) and 0.8M long-term CER (lCER) credits (See UNFCCC, 2021). Cames et al. (2016) find that the additionality of most CDM projects is problematic. "We estimate that 85% of the covered projects and 73% of the potential 2013-2020 CER supply have a low likelihood of ensuring environmental integrity (i.e. ensuring that emission reductions are additional and not over-estimated). Only 2% of the projects and 7% of potential CER supply have a high likelihood of ensuring environmental integrity." However, there were no LULUCF projects in their study. Similarly, Calel et al. (2021) calculate that at least 52% of the Indian wind power projects under the CDM would very likely have been built anyway. Schneider and Kollmuss (2015) show that "all projects abating HFC-23 and SF6 under the Kyoto Protocol's Joint Implementation mechanism in Russia increased waste gas generation to unprecedented levels once they could generate credits from producing more waste gas.", a perverse outcome of the crediting system.

Haya et al. (2020) assess the additionality of the California's standardized approach for 2 types of projects: Methane in mining and rice cultivation. In the standardized approach, additionality is established with precise rules that apply to all projects. Additionality is established for the whole group of projects, not for each project individually as in the CDM. That makes the additionality easier to measure and reduces transaction costs. They conclude that "We find that the standardized approach offers the ability to reduce, but not eliminate, the risk of over-crediting. This requires careful protocol-scale analysis, conservative methods for estimating reductions, ongoing monitoring of programme outcomes, and restricting participation to project types with manageable levels of uncertainty in emission reductions. However, several of these elements are missing from California's regime, and even best practices result in significant uncertainty in true emission reductions."

To conclude, if one were to assume that all offsets were as successful as the CDM projects according to Cames et al. (2016) and Calel et al. (2021) there may be a good argument for not using this instrument to achieve carbon mitigation. However, for forestry projects, while additionality remains an issue, it remains a reasonable risk to take according the the best estimates that are available given the values of the SVO that emerge and the likely cost advantage that forestry projects have over other technologies.

SM9. Policy applications

One ton emitted=2.5 tons stored for 50 years

Current practice of certifying nature based solutions takes two radically opposing stances: either forestry projects have no value after a relatively short time and are therefore ineligible (e.g. in the Clean Development Mechanism of the Kyoto Protocol (CDM)), or forestry projects are assumed to be eternally additional (current voluntary offset market). Our formula allows an intermediary stance to be taken.

Under the CDM forestry projects can only deliver temporary Certified Emission Reductions (tCER) which are only valid for the duration of a compliance period (2008-2012 or 2013-2020). Alternatively, forestry project can yield so-called 'long term Certified Emission Reductions' (lCER), for the duration of 20 years (twice extendable to 60 years). After this period, the stored carbon is assumed to be reinjected in the atmosphere. In other words, each use of a tCER reduces the emission budget in the next Kyoto period by one allowance. The temporary value is a major barrier to the development of projects, which explains in part why less than 1% of CDM projects are based on forestry. As a result of their temporary value, tCER's and lCER's were always excluded for compliance in the EU ETS.

In contrast to the low success in the CDM, forestry projects are very popular and correspond to up to 50% of the voluntary carbon markets (Berkeley Carbon Trading Project). This is because instead of having a temporary value, the voluntary market offsets one ton of emission by one ton stored in a forest, which assumes an infinite additional effect. This is overly optimistic, because although most certifiers have a reserve of offsetting credits to cover observable project failure, the remaining problems with additionality are generally unobservable and ill-accounted for in the buffer stock. The most straightforward way to take the temporary nature of projects into account is to estimate each project's individual duration. However, the duration over which the project is additional is notoriously difficult to estimate. This is because the counterfactual is never observed and needs to be inferred from similar plots of land who are identical to the land of the project in all relevant regards, except that the project is absent. This requires ex-ante experimental or ex-post quasi-experimental approaches which are few and far between (Jayachandran et al. (2017), West et al. (2020) and Groom et al. (2022) being examples of exceptions in the literature in relation to REDD+).

Given the issues with perpetuity and additionality, our formula can be used to reduce the commitment period of offsetting projects and internalise the risk of additionality. For example, our formula shows that one emitted ton can be compensated by 2.5 tons of CO2 in a forestry project storing carbon for 50 years with an additionality risk of $\varphi = 0.005$ per year as discussed in SM8, and assuming RCP 2.6. With this short-term contract of 2.5 tons of CO2, after 50 years there is no more liability by the emitter because the emission and the offsetting project are equivalent according to the SVO, that is, in welfare terms. Furthermore, at the end of the contracted period the same forest, which is likely to be still storing carbon, can get credited for a new cycle of 50 years, provided that it can prove additionality over the following decades based on past performance and trends at the time. This type of contract would be an improvement upon current practise because instead of an implicit eternal commitment by the forestry manager, we now have a much more realistic commitment of 50 years. It is also an improvement over the current CDM practice, where an an offset project needs to be replaced by another offset project after the end of the commitment period, which is an implicit eternal liability: a ton emitted today requires a new validation of a CDM forestry project of one ton every 20 years (which can be three times be the same plot of land). Such eternal commitments are unlikely to be honored over many decades or centuries. Better to sharpen the commitment to shorter time periods.

Life Cycle Analysis

Many methods in valuing temporary storage of carbon have been developed to be applied in life cycle analysis. Figure SM9a shows that an extra unit of emissions results in a similar step-function as the scenarios where CO2 is absorbed shown in SM3. Take for example pellets for home heating. Assume that burning pellets emits one ton of CO2 and that it reduces a forest carbon sink by the equivalent amount. Assume further that the forest gradually replenishes the carbon sink. Call q_t the effect on the carbon sink, starting at -1 when pellets are burnt and gradually evolving to zero as the forest regrows. The social cost of this temporary reduction in the carbon sink can be calculated with our formula and compared to the social cost of carbon which applies to fossil fuels. Similarly, to value the use of colza oil in diesel cars, one can assume that in the absence of the colza, the field would have been forest. The harvest of a colza field entails the cost of a lower carbon sink during one year. q_t is now the difference between carbon content in the colza field and the hypothetical forest in the baseline and switches to zero after one year ($\tau_2 = 1$). As argued in the literature review, our formula takes into account many more features than current practice.

Application to Biomass production: In this section we compare the social cost of biomass production (pellets) with the social cost of using fossil fuels for the same useful energy. We use the same project as in Brandão et al. (2019) who compare 15 methods for carbon lifecycle analysis. They use the following scenario: 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 decays at 6.67% per year. Rotation length for biomass production is 25 years. 1 ton of CO2 from biomass delivers the same useful energy as 0.5 ton of fossil fuel CO2. The result of the analysis depends on the assumed baseline/intial conditions. Three possibilities are considered in which biomass production starts with:

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 GtC/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).

In each scenario the initial baseline reemerges after 100 years. The cumulative emissions from the three scenarios are presented in Figure SM9b.

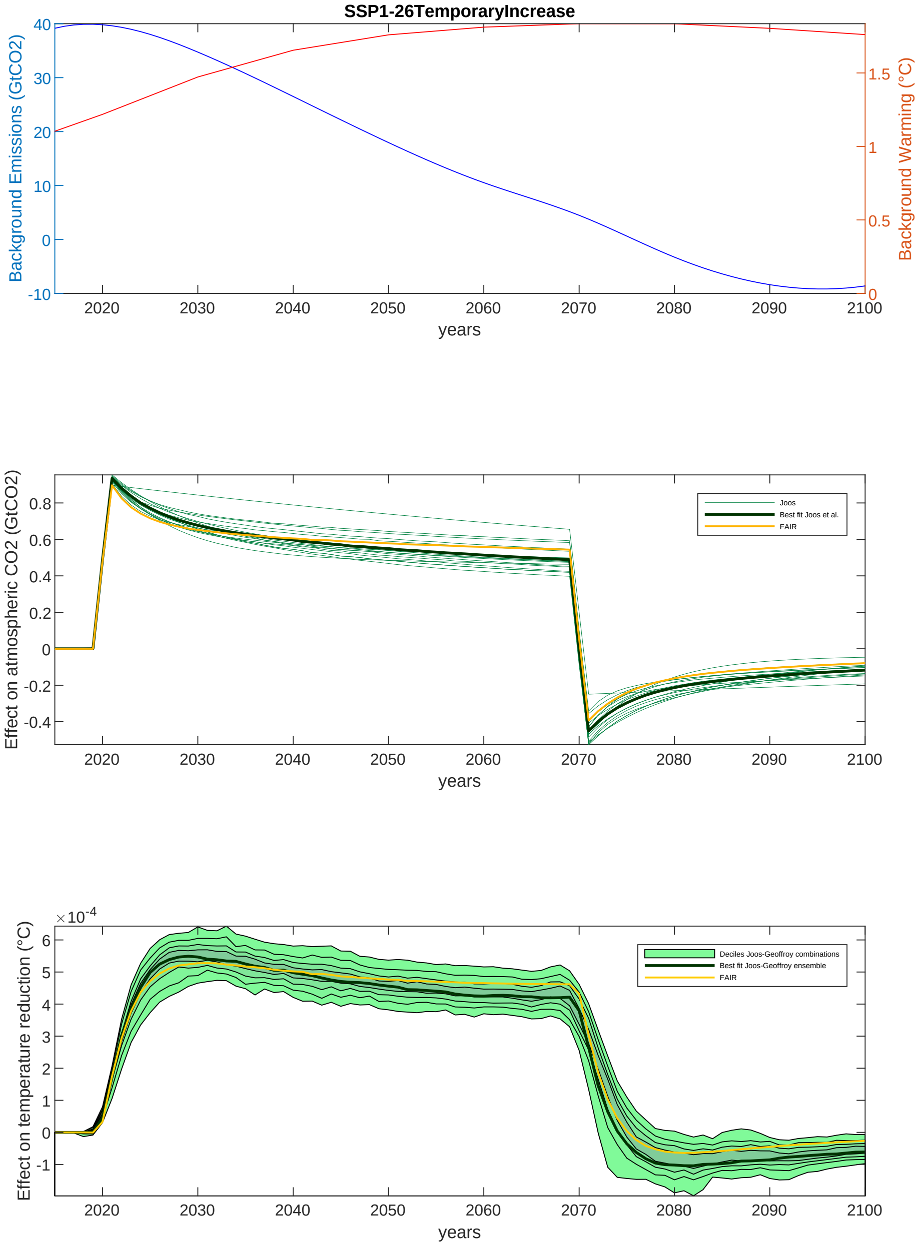

Figure SM9a: A temporary increase in carbon: SSP 1-2.6.

We calculate the social cost of biomass per hectare by inserting the cumulative emissions q in our Equation 5. In Scenario 1 the social cost of biomass per hectare is 7894$/ha and the social benefit of avoided fossil fuel is 11,291$/ha.[4] So switching from fossil fuels to biomass reduces the social cost by 29%. This ratio is known as the Carbon Neutrality Factor $CNF = \frac{SocialCostFossil - SocialCostBiomass}{SocialCostFossil}$.

In Scenario 2, biomass grown after old forest, the social cost of biomass is 43,532$/ha, very similar to the social cost of the avoided emissions, which is 46,803$/ha. Biomass reduces the social cost by merely 7%. This is much lower than older methods such as Global Warming Potential and Global Temperature Potential (e.g. Fearnside et al., 2000), which yield a CNF in the neighborhood of 50% (Brandão et al., 2019, Figure 2). Our results differ because we treat the economics and climate science in a more up to date and accurate way. For instance, methods like Brandão et al. (2019) put insufficient weight to the early emissions from biomass because damages are not properly discounted. For the same reason, later emissions are given less weight due to the arbitrary time horizon of 100 years, after which emissions receive zero weight. Other methods, such as O'Hare et al. (2009) find a larger cost for biomass than for fossil fuels. These methods put excessive weight on early emissions because they ignore thermal inertia and increasing marginal damages, which are included in our approach.

In Scenario 3, starting with barren land the social *gain* from reforestation is 19,725$/ha. This gain comes on top of the avoided social cost of fossil fuels of 20,294$/ha. Since Biomass has a gain instead of a cost, the total gain is 197% of the avoided fossil fuel cost. Compared to the methods proposed in this paper, most of the approaches taken in Brandão et al. (2019) have a slightly higher gain in this scenario, slightly more than 200%.

Ultimately, these results illustrate the applicability of the SVO formula for evaluating biofuels and their relative contribution to climate change mitigation. The results differ in important ways due to the updated economic and climate science deployed in the SVO formula. The comparisons provided here more accurately reflect the physical and economic aspects of valuing the delay of emissions, the cycles of growth and harvest and the avoided emissions of nature based solutions.

The value of temporary atmospheric storage

Our formula is also useful to calculate the cost of atmospheric CO2 storage in case companies would become liable to offset their emissions permanently in future decades. The carbon budget to stay below 1.5°C will be crossed in the coming decade (IPCC 2021), therefore, most IPCC scenarios that stay below 1.5°C, overshoot in temperature and show significant net zero emissions in the second half of this century. Financing carbon dioxide removals will be a major challenge after 2050, because unlike emission reductions which

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[4] We assume the damage function of Howard and Sterner. This assumption does not affect the ratio of costs. We use a discount rate of 3.2% and no hazard risk.

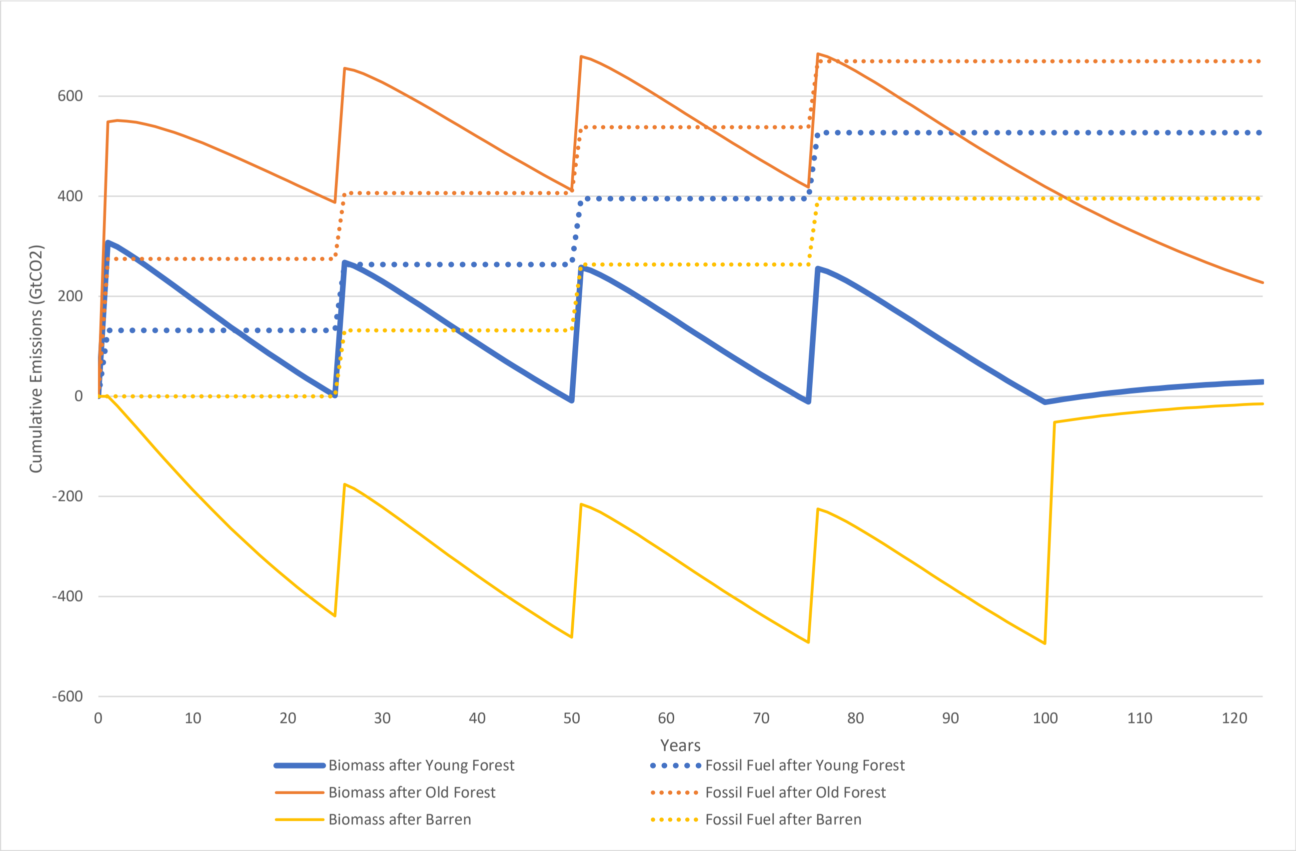

Figure SM9b: Cumulative emissions for biomass (solid line) and fossil fuel (dotted line) for three initial conditions: 1) Cutting a young forest of 25 years old, 2) Cutting an old forest, which has reached steady state carbon stock of 200 GtC/ha, 3), Biomass production starting from barren land, which has no initial carbon stock.

can be obtained by a carbon tax with government income, net carbon removals require substantial government budgets, more than 10% of world GDP according to Bednar et al. (2021). Part of the carbon removals can be financed by making emitting companies liable for financing the carbon dioxide removals in the following decades. In other words, emitting companies take on 'carbon debt'. A (carbon) central bank could sell carbon debt to commercial banks, who in turn sell carbon debt to CO2 emitters, adding a risk premium to cover solvency risk of borrowers. CO2 emitters pay back their carbon debt by a permanent carbon removal project at the end of the debt contract. Bednar et al. (2021) also propose an interest rate on carbon debt, which corresponds to the 'price the temporary storage of CO2 in the atmosphere', which they pick to be somewhere between 0% and 8%. The price of temporary storage form a welfare perspective[5] is the marginal damage from a ton, the undiscounted expression inside our equation 2 . This would be the welfare maximizing risk-free interest rate to be charged by the central bank (an intrest rate that increases with increasing temperatures). However, again, a fundamental difficulty with the notion of carbon debt is that the commitment periods are much longer than the standard commitment periods of financial debt. [6] To limit the problem of long time horizons, emitters could pay the atmospheric storage cost upfront, a cost which corresponds to our formula of the SVO. For example, a company which emits a ton today and commits to a permanent removal in 50 years time, still has to pay 40% of the carbon price to cover the damages of the the temporary atmospheric storage. Paying storage cost upfront is preferrable in the presence of bankruptcy risk and it maintains the correct incentive to abate its emissions if the company's private discount rate is lower than the social discount rate.

SM10. Cost effectiveness framing

Climate change mitigation is frequently viewed in terms of cost-effectiveness. For instance, the carbon price in the UK reflects the marginal abatement cost of meeting a net zero target by 2050. Offsets can also be viewed as contributing to this target, with some caveats. Consider two approaches: 1) a project absorbing a ton permanently; 2) a temporary project combined with a permanent project which starts immediately after the temporary projects ends, each absorbing a ton of carbon. These approaches are equally effective in reducing emissions in the long-run. This yields a decision rule that favours approach 2) with the temporary project if it costs less:

$$C^P_{\tau_1,\infty} \geq C_{\tau_1,\tau_2} + e^{-r(\tau_2-\tau_1)} C^P_{\tau_2,\infty} \tag{36}$$

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[5] Bednar et al. apply a cost-effectiveness approach, which is indifferent to timing of marginal damages.

[6] Some companies have an incentive to take on a lot of carbon credit and file for bankruptcy after. Commercial banks may anticipate such moral hazard and refuse to lend to risky firms. However this brings inefficiency problems of it's own. Similar to financial debt, worthwhile risky startups, may not be viable because nobody wants to issue them carbon debt.

where $C^P_{\tau_1,\infty}$ is the cost of a permanent project at time τ_1. Assuming that we know the rate at which the cost of permanent projects increases over time, x, we have the equivalent of Equation (3) in the cost-effectiveness context, and the decision rule becomes:

$$C_{\tau_1,\tau_2} \leq \left(1 - e^{(x-r)(\tau_2-\tau_1)}\right) C^P_{\tau_1,\infty} \tag{37}$$

On an optimal trajectory, the cost of a project equals the social value: $C^P_{\tau_1,\infty} = SCC_{\tau_1,\infty}$, making the right hand side of Equation (37) the same as Equation (3).

However, in a non-optimal world, this approach is problematic. If abatment costs are not equal to the SCC, prices are not intertemporally optimized, projects are ranked on the basis of prices that do not reflect their social value, and the decision rule in Equation (37) will not maximise welfare over time.

To illustrate, consider a carbon price that follows a cost-effectiveness approach, i.e. it yields the lowest discounted cost to stay within a given temperature target. In this case the carbon price follows a Hotelling path, increasing at the rate of discount so that $x = r$. Cost-effectiveness, by its very nature, is indifferent to the timing of damages and this leads to a carbon price that starts too low today and ends up too high in the future compared to a welfare-maximising optimal reaching the same long term temperature, but takes into account both the timing of the costs and benefits of mitigation. With $x = r$, Equation (37) indicates that a temporary project should only be realized if the cost is zero or negative. This criterion reflects the intuition that in a cost-effectiveness framework any temporary project that stops before the temperature constraint is met makes no contribution to staying below that temperature. Yet, it is impossible to value the delay of damages with a model that is indifferent to the timing of damages. Indeed, the expression for SVO_{τ_1,τ_2}in Equation (3) shows that delaying emissions through offsetting will have a positive social value.

This incompatibility of a cost-based approach with welfare maximisation in the context of offsets has important implications for some conventional approaches to valuing offsets. For instance, the formula of Carbon Plan (https://carbonplan.org/research/permanence-calculator-explainer) emerges after applying iterative substitution to Equation (36), and allows a comparison of the cost of a permanent project, $C_{\tau_1,\infty}$, with an infinite stream of temporary projects, C_{τ_s,τ_t}:

$$e^{-r\tau_1} C_{\tau_1,\infty} \geq e^{-r\tau_1} C_{\tau_1,\tau_2} + e^{-r\tau_2} C_{\tau_2,\tau_3} + e^{-r\tau_3} C_{\tau_3,\tau_4} + ... \tag{38}$$

The Carbon Plan formula assumes that all temporary projects have the same duration and the cost of a forestry project does not change through time. We obtain

$$C_{0,\tau_1} = \frac{C_{0,\infty}}{\sum_{i=0}^{\infty} e^{-r\tau_i}} \tag{39}$$

The previous discussion of cost-effectiveness explains why this formula is problematic. On a welfare maximizing path, the cheapest offsetting projects are realized first and as the SCC rises, more expensive projects are realized. Therefore, a world were there are offsetting opportunities in the future at the same cost as today is a world where cost prices are not intertemporally optimized. This intertemporal inefficiency will lead to non-welfare-maximizing decision rules. Concretely, the hypothesis of cheap future offsetting opportunity is too optimistic, leads to the adjustment factor being too high, and offsets being overvalued.