Balancing a budget or running a deficit? The offset regime of carbon removal and solar geoengineering under a carbon budget

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Abstract

The idea of the carbon budget is a powerful conceptual tool to define and quantify the climate challenge. Whilst scientists present the carbon budget as the geophysical foundation for global net-zero targets, the financial metaphor of a budget implies figuratively the existence of a 'budget manager' who oversees the budget balance. Using this fictive character of budget manager as a heuristic device, the paper analyses the roles of carbon dioxide removal (CDR) and solar radiation management (SRM) under a carbon budget. We argue that both CDR and SRM can be understood as 'technologies of offset'. CDR offsets positive carbon emissions by negative emissions, whereas SRM offsets the warming from positive greenhouse gas forcing by the induced cooling from negative forcing. These offset technologies serve as flexible budgeting tools in two different strategies for budget management: they offer the promise of achieving a balanced budget, but also introduce the possibility for running a budget deficit. The lure of offsetting rests on the flexibility of keeping up an 'appearance' of delivering a given budget whilst at the same time easing budget constraints for a certain period of time. The political side-effect of offsetting is to change the stringency of budgetary constraints from being regulated by geophysics to being adjustable by human discretion. As a result, a budget deficit can be normalised as an acceptable fiscal condition. We suggest that the behavioural tendency of policymakers to avoid blame could lead them to resort to using offset technologies to circumvent the admission of failure to secure a given temperature target.

Keywords Carbon budget · Climate geoengineering · Carbon dioxide removal · Solar radiation management · Offset · Net zero

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1 Introduction

To hold global temperature rise relative to pre-industrial levels to well below 2 °C, and pursuing efforts to limit the rise to 1.5 °C, Article 4 of the 2015 Paris Agreement set a mitigation target of achieving a "balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases" in the latter half of the twenty-first century. Since then, this so-called net-zero emissions target has become a central focal point in scientific and political discussions (Rogelj et al. 2015b; Geden 2016a; Fuglestvedt et al. 2018; Tanaka and O'Neil 2018; Rogelj et al. 2019b, 2021).

The ambiguity of the text of Article 4 spurred discussions about how to interpret the meaning of net-zero emissions—or the notion of neutrality—as a target either of net-zero carbon dioxide (CO_2) emissions (carbon neutrality) or else of net-zero greenhouse gas (GHG) emissions (greenhouse gas neutrality). Because different interpretations have different implications for mitigation policy (see Rogelj et al. 2015b; Fuglestvedt et al. 2018), this may well remain the subject of continued political negotiations.

From the *geophysical* point of view, however, the scientific literature is unequivocally clear that to stop global warming at any level, global CO_2 emissions by human activities must be reduced to virtually zero (Matthews and Caldeira 2008; Rogelj et al. 2015b; Rogelj et al. 2019b). This requirement of global net-zero CO_2 emissions originates from the scientific concept of a 'carbon budget'—a finite total amount of CO_2 that can be emitted into the atmosphere to hold global warming to a given temperature level (Rogelj et al. 2019a; Matthews et al. 2020). The concept of a carbon budget is grounded in well-established scientific evidence that CO_2-induced temperature increase is near-proportional to cumulative CO_2 emissions (Allen et al. 2009a; Matthews et al. 2009; Meinshausen et al. 2009; Zickfeld et al. 2009; Gillett et al. 2013; Collins et al. 2013; Knutti and Rogelj 2015; Matthews et al. 2018; Rogelj et al. 2019a; Matthews et al. 2020).

The rise of the carbon budget concept has changed the nature and scope of climate mitigation. It reframed the mitigation challenge from a flow problem (emissions rate in a given year) to a stock problem (total cumulative emissions over time) (Allen et al. 2009b; Frame et al. 2014). The difference between "producing less CO_2" (emissions reduction) and "capturing more CO_2" (negative emissions) is made to appear marginal (Gasser et al. 2015). Any method of carbon dioxide removal (CDR) can then be normalised as an *extension* of mitigation.

The carbon budget idea changed also the debate around what might be considered 'geoengineering' (or sometimes called 'climate engineering' or 'climate intervention') technologies. Whilst the line between mitigation and CDR became blurred, CDR is now more clearly separated from solar radiation management (SRM), the two of which were previously often grouped together under a common label 'geoengineering' (Lomax et al. 2015; Cox et al. 2018; Minx et al. 2018; Bellamy and Geden 2019). For example, the Intergovernmental Panel on Climate Change (IPCC) Special Report on Global Warming of 1.5 °C (SR15) avoided using the term 'geoengineering' and referred to SRM as "remedial measures" that aim to "temporarily reduce or offset warming", distinct from mitigation, adaptation or CDR (Allen et al. 2018a). This move seems reasonable insofar that SRM aims to reduce or slow warming by reflecting solar radiation from the Earth (or increasing the Earth's albedo) and hence has nothing directly to do with CO_2.

Nonetheless, some experts consider the SRM method of stratospheric aerosol injection as part of a potential strategy to meet the Paris temperature goal (Long 2017; MacMartin et al.

2018). In overshoot scenarios where the warming temporarily exceeds and later returns to a given temperature limit through net negative CO_2 emissions, SRM could be used to shave the peak off of the warming (Smith and Rasch 2013; Tilmes et al. 2016). Such temporary or limited use of SRM is often justified as a *supplement* to—but not a *substitute* for—mitigation and CDR (Keith and MacMartin 2015; MacMartin et al. 2018).

1.1 Seeing like a fictive 'budget manager'

Carbon budgets have become a powerful conceptual tool—a "staple of climate policy discourse" (Lahn 2020)—to define and quantify the climate challenge (Matthews et al. 2020). The concept, for example, provides scientific grounds for climate justice movements such as fossil fuel divestment (Strauch et al. 2020). Activists often refer to an estimate of the carbon budget as the 'magic number' that unbiasedly informs how little amount of CO_2 can be emitted to stay below the 1.5 or 2 °C threshold. The number is deemed credible because it is calculated, through a rigorous method of quantification, by sophisticated climate models. The authority of the carbon budget is built on its impersonal appearance as a geophysical constraint with little or no room for political fudging (cf. Porter 1992).

   Whilst scientists present the carbon budget as an entity that is regulated by geophysics, their use of the financial metaphor of a budget has a hidden political implication. That is, having a finite budget suggests *figuratively* that someone has to hold the job of 'budget manager' to oversee the budget balance. The proposal by Matthews et al. (2020) of translating a global budget to national allocations implies that, if taken seriously, some kind of a 'global central planner' (cf. Keith and MacMartin 2015) might need to be in charge of such a politically difficult task of budget allocation. In this paper, we use this fictive character of a 'budget manger' as a heuristic device to analyse the role of CDR and SRM under a carbon budget. Through a lens of budget accounting, how would a budget manager see—and potentially use—the technologies of CDR and SRM as budgeting tools?

   Of course, a carbon budget manager is a fictional character; they do not exist in reality. Our use of the fictive budget manager does not directly parallel policy decisions in the real world. But it does allow us to explore more nuanced political implications *if* a carbon budget were adopted not merely as a scientific concept but as a 'real' policy tool.

   At the same time, the carbon budget could shape, if not determine, policy in more subtle ways. Scientists often believe that greater clarity of science leads to more consistent—and hence better—policy. The carbon budget is seen as a conceptual device to bring consistency between science and policy (Frame et al. 2014; Knutti and Rogelj 2015). But policymakers' behaviours do not necessarily follow the logic of scientists. Their primary concern is more to avoid blame for failure than to strive for consistency (Hood 2007; Howlett 2014; Geden 2016b; 2018). As shall be argued below, policymakers may find both kinds of 'geoengineering' technology useful to escape from the admission of failure.

   In the next two sections, we review the geoscience literature to spell out the geophysical base of the carbon budget concept (Section 2) and the ambiguous role of non-CO_2 forcing in estimating carbon budgets (Section 3). These reviews lay out how the carbon budget imposes a geophysical constraint, whilst leaving a grey area created by non-CO_2 forcing. In the following two sections, we argue that a fictive budget manager (used here as a heuristic device) could see both CDR and SRM as 'technologies of offset' under a carbon budget (Section 4) and that these offset technologies might serve as flexible budgeting tools with regard to two different strategies for budget management (Section 5): they can both help sustain a balanced budget

(fiscal prudence) and run a budget deficit (fiscal profligacy). The paper ends (Section 6) with concluding discussions about how blame-avoidance behaviour might lead policymakers to use both offset technologies as ways to circumvent admitting policy failure.

2 Science behind a carbon budget: linearity and irreversibility

A history of the carbon budget reveals that the term has been used from the 1980s to suggest different meanings (Lahn 2020). One example is the annual update of the 'global carbon budget' by the Global Carbon Project, published regularly since 2005. This is referred to as the historical trend in CO_2 fluxes between the atmosphere, land and ocean (Friedlingstein et al. 2019). Its focus is on estimating the global carbon cycle over the historical period and would be better phrased as the 'historical carbon cycle budget'. This would avoid confusion with the concept of 'remaining carbon (emissions) budget', that is, a total amount of future allowable CO_2 emissions consistent with a given temperature level (Rogelj et al. 2019a; Matthews et al. 2020). This paper uses the term 'carbon budget' solely in this latter sense.

The scientific concept of a carbon budget is established by discovering the near-linear relationship between CO_2-induced global warming and cumulative CO_2 emissions, defined as the 'transient climate response to cumulative carbon emissions' or TCRE (Gillett et al. 2013; Collins et al. 2013; MacDougall 2016). The TCRE is arguably the most significant geophysical foundation of the carbon budget concept (Rogelj et al. 2019a). In essence, a carbon budget can be understood as the inverse of the TCRE—choosing a given temperature limit is directly linked to cumulative CO_2 emissions (see Fig. 1a).

The linearity of TCRE arises from the physical and biogeochemical processes of the coupled climate and carbon-cycle system (Millar et al. 2016; MacDougall 2016). Currently, about half of the annual anthropogenic CO_2 emissions is taken up by natural carbon sinks, the other half remaining in the atmosphere (known as the airborne fraction of CO_2 emissions) which leads to the annual increase in atmospheric CO_2 concentration (Friedlingstein et al. 2019). However, this CO_2 uptake by the ocean and land sinks weakens with increasing cumulative emissions, leading to a higher airborne fraction of CO_2 emissions (Matthews et al. 2009). On the other hand, a higher CO_2 concentration causes a reduction in radiative forcing per unit increase in atmospheric CO_2. That is, a smaller increase in CO_2-induced warming occurs at higher CO_2 concentrations. This cancels out a higher CO_2 concentration at larger cumulative emissions (due to the above saturation effect of carbon sinks). Together,
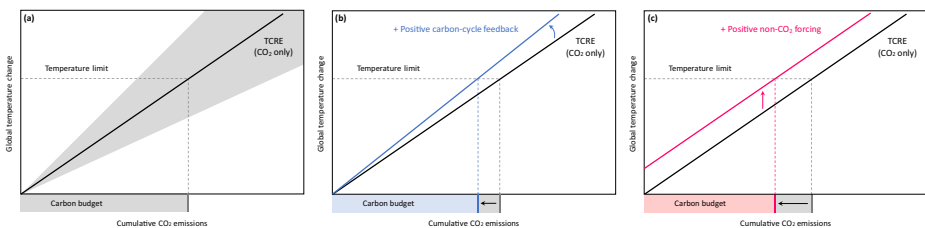

Fig. 1 Schematic of estimating the carbon budget based on transient climate response to cumulative carbon emissions (TCRE) (adapted from Knutti and Rogelj 2015; Rogelj et al. 2019a). **a** Linearity of CO_2-induced global temperature change to cumulative CO_2 emissions. Grey shades indicate the uncertainty range for the TCRE estimated by models. **b** Positive carbon-cycle feedback (e.g. permafrost thawing) that is currently unrepresented in models reduces the allowed carbon budget for a given temperature limit. **c** Positive non-CO_2 forcing at the time that CO_2 emissions reach net-zero levels also reduces the budget at a future point in time

these two effects give rise to the near-linear relationship between CO_2-induced warming and cumulative CO_2 emissions.

This near-linear response of global temperature to cumulative carbon emissions is found to be remarkably robust across climate models and independent of emission scenarios (Gillett et al. 2013; Collins et al. 2013). The TCRE is thus considered a geophysical property inherent in the coupled climate-carbon system (Matthews et al. 2017).

Another important geophysical feature that underlies the carbon budget concept is the additional warming that occurs after a complete cessation of CO_2 emissions, often called the 'zero emissions commitment' or ZEC (Gillett et al. 2011; Ehlert and Zickfeld 2017). Whilst the TCRE postulates the instantaneous temperature response to cumulative CO_2 emissions, the ZEC is the long-term future warming caused by past CO_2 emissions. If there were a substantial increase in temperature *after* CO_2 emissions ceased, the allowable amount of cumulative emissions would have to be smaller in order to secure the desired temperature level.

Although the value of ZEC seems to vary—from negative to positive—among climate models, the current evidence suggests that there is little or no additional long-term warming committed from past CO_2 emissions (Matthews and Caldeira 2008; Gillett et al. 2011; MacDougall et al. 2020). Global temperature remains approximately constant over several centuries after CO_2 emissions reach zero (Solomon et al. 2009). This arises from a near-cancellation of the two opposing—warming and cooling—effects of heat (through physical processes) and carbon (through biogeochemical processes) uptake by the ocean (Matthews and Solomon 2013; Goodwin et al. 2015; Williams et al. 2016).

These two effects can be explained thus. The ocean acts like a 'huge heat sink' for the Earth, absorbing about 90% of the heat trapped by an increase in greenhouse gases in the atmosphere (Knutti and Rogelj 2015; von Schuckmann et al. 2020). The ocean has a very long timescale to adjust to a new thermal equilibrium with the atmosphere. When atmospheric CO_2 concentration is kept constant, ocean heat uptake declines over time to approach an equilibrium, which leads to continued warming for centuries. On the other hand, when CO_2 emissions are zeroed, atmospheric CO_2 concentration declines due to the continued uptake of CO_2 by the ocean. This cooling effect of ocean carbon uptake largely cancels out the warming effect of ocean thermal inertia, hence the near-constant global temperature over time. The eventual warming caused by past CO_2 emissions is mostly irreversible and continues to persist for centuries to a millennium (Solomon et al. 2009; Matthews and Solomon 2013)—unless actively and permanently removing CO_2 from the atmosphere.

In summary, the TCRE shows the *linear* relationship of CO_2-induced temperature change to cumulative CO_2 emissions, whereas the ZEC presents the *irreversible* temperature change caused by CO_2 emissions. These two geophysical features provide a robust scientific basis for the idea of carbon budget. Importantly, however, these geophysical features of linearity and irreversibility are specific *only* to CO_2. They are not applicable to other non-CO_2 greenhouse gases (see Section 3). This is why the concept of emissions budget is named using 'carbon' instead of 'greenhouse gas'.

There are two sources of uncertainty when estimating a carbon budget: geophysical and socioeconomic uncertainty (Matthews et al. 2017, 2020). Much of the geophysical uncertainty is reflected by the uncertainty range for the TCRE (grey shade in Fig. 1a). This uncertainty can be taken into account by specifying a likelihood (e.g. a 50% or 66% probability) of keeping warming below a given temperature level. However, there remain additional carbon-cycle feedbacks that are currently unrepresented in the TCRE range. For example, the effect of permafrost thawing on additional CO_2 release can substantially reduce the remaining carbon

budget (MacDougall et al. 2015; Comyn-Platt et al. 2018; Gasser et al. 2018; see Fig. 1b). It is worth noting here that different methodological definitions of the 'global mean temperature' metric and the 'reference period' have non-trivial influences on estimates of carbon budgets (see Rogelj et al. 2017; Tokarska et al. 2019a).

In addition to geophysical uncertainty, carbon budget estimates are also influenced by socioeconomic uncertainty associated with the effect of non-CO_2 forcing on future warming (Rogelj et al. 2015a). As shall be discussed below, if there remained positive non-CO_2 forcing at the time global CO_2 emissions reach net zero, this would reduce the allowable budget (MacDougall et al. 2015; Tokarska et al. 2018; Mengis and Matthews 2020; see Fig. 1c).

3 The complication of non-CO_2 forcing in estimating a carbon budget

The carbon budget concept makes it clear that peak temperature is largely determined by cumulative CO_2 emissions. But global temperature is also influenced by anthropogenic emissions of non-CO_2 GHGs and aerosols. The emissions of non-CO_2 GHGs such as methane (CH_4) and nitrous oxide (N_2O) have positive radiative forcing; on the other hand, the emissions of aerosol particles like sulphur dioxide (SO_2) cause negative radiative forcing by increasing—directly and indirectly—the reflection of solar radiation (Ramanathan et al. 2001). Currently, non-CO_2 forcing has a net warming effect because positive non-CO_2 GHG forcing is balanced only in part by negative aerosol forcing (Mengis and Matthews 2020).

Any change in non-CO_2 forcing has an impact on the near-term change of global temperature. Model studies find that changes in global temperature after a cessation of non-CO_2 emissions vary considerably from immediate warming to gradual cooling (Matthews and Zickfeld 2012; Allen et al. 2018a; see Fig. 2). This is due to the short atmospheric lifetimes of some non-CO_2 GHGs and aerosols (Pierrehumbert 2014). For example, methane remains in the atmosphere for about a decade, tropospheric ozone for several weeks, and aerosols for just a few days (although nitrous oxide has a long atmospheric lifetime of more than a hundred years). Whilst CO_2 emissions cause an *irreversible* warming that will persist over the centuries, the warming caused by non-CO_2 forcing in aggregate is largely *transient* and hence reversible over time.

It is well-founded in the geoscience literature that due to their short atmospheric lifetimes, the warming from non-CO_2 forcing species depends more on their *emission rates* than on their cumulative emissions (Smith et al. 2012; Bowerman et al. 2013; Rogelj et al. 2014; Allen et al. 2016, 2018b). This suggests climate mitigation policy to be divided into "two separate baskets" of CO_2 and non-CO_2 emissions (Smith et al. 2012).

According to geoscientists, CO_2 mitigation should focus on limiting total cumulative emissions, whilst on the other hand non-CO_2 mitigation is to reduce emission rates by the time that net-zero CO_2 emissions are reached. The *timing* of reducing non-CO_2 emissions is crucial. Non-CO_2 mitigation can slow the rate of near-term warming but contributes to limiting peak warming *only* when CO_2 emissions are close to net zero (Bowerman et al. 2013; Rogelj et al. 2014; Allen et al. 2016). Non-CO_2 mitigation cannot therefore 'buy time' for delaying CO_2 mitigation; it only serves as a complementary strategy for the *simultaneous* reduction in CO_2 emissions.

Nonetheless, the effect of non-CO_2 forcing on future warming has significant implications for estimating the carbon budget. The role of negative aerosol forcing is of particular importance—though it is often overlooked in carbon budget estimates (see Mengis and Matthews 2020). Given that aerosols *mask*—but do not erase—some of the warming caused
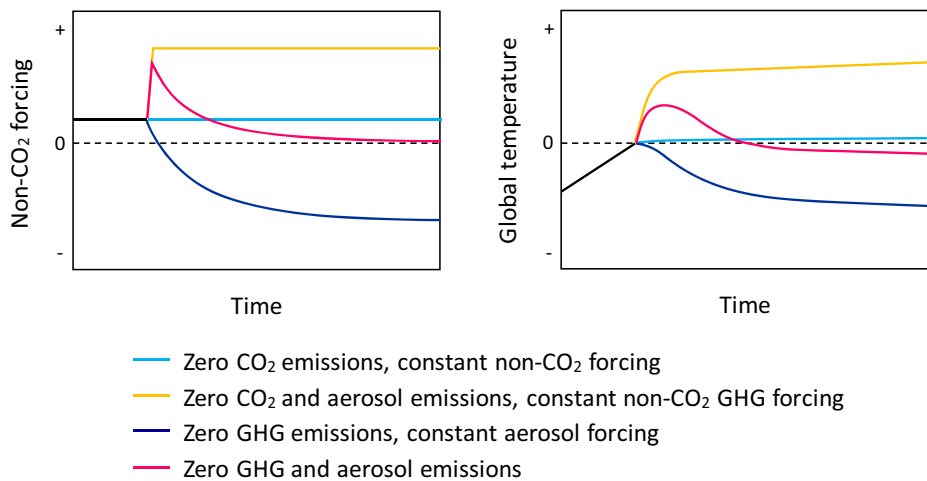
Fig. 2 Schematic of the warming commitment of past emissions of greenhouse gases and aerosols (adapted from Matthews and Zickfeld 2012; Allen et al. 2018a). Radiative forcing (left) and global temperature change (right) with different combinations of GHG and aerosol emissions reduced to zero. A large immediate warming is caused after elimination of CO_2 and aerosol emissions (yellow line), whilst elimination of all GHG emissions leads to a gradual cooling (dark blue line). Elimination of all GHG *and* aerosol emissions leads to a sharp near-term increase, then a subsequent gradual decline in temperature, returning to below the current level (magenta line). The difference in temperature between constant non-CO_2 forcing (light blue line) and zeroed non-CO_2 emissions (magenta line) reflects the magnitude of non-CO_2 warming at current levels

by GHG emissions, the removal of aerosols (for example by reducing air pollution) could cause a spike in near-future warming, known as the 'climate penalty' (Shindell and Smith 2019; see magenta line in Fig. 2). The magnitude of the eventual warming from the elimination of anthropogenic aerosols is estimated to be about 0.5 °C or possibly more (Ramanathan and Feng 2008; Hienola et al. 2018; Samset et al. 2018; Lelieveld et al. 2019).

Currently, most anthropogenic aerosols are emitted alongside CO_2 by burning fossil fuels. Phasing out fossil fuels—the cardinal rule of mitigation policy—reduces *both* CO_2 and aerosol emissions. This means that reducing CO_2 emissions would eventually be accompanied by the unavoidable warming (~0.5 °C) from the removal of aerosol cooling (Lelieveld et al. 2019; Shindell and Smith 2019). For this reason, taking into account the effect of eliminated aerosols reduces the allowable carbon budget for a given temperature target (Mengis and Matthews 2020).

All of this leads to the reduction of non-CO_2 GHG emissions taking on an increased importance. However, it is highly unlikely that non-CO_2 GHG emissions will be eliminated *completely*. In particular, methane and nitrous oxide emissions from agriculture and livestock will likely continue owing to their low technical mitigation potentials (Gernaat et al. 2015). There will always remain *some* volume of non-CO_2 GHG emissions even after substantial reduction efforts have been made (Rogelj et al. 2015b). Putting these two non-CO_2 elements together—the effects of *declining* emissions of aerosols and *residual* emissions of non-CO_2 GHGs—means that future non-CO_2 forcing will mostly likely continue to have a non-trivial net warming effect. In estimating carbon budgets, non-CO_2 forcing is often assumed to be constant or declining (Rogelj et al. 2019a). But this assumption could be wrong: net non-CO_2 forcing might increase over the course of the twenty-first century (Feijoo et al. 2019; Mengis and Matthews 2020).

The important point from the above discussion is that the uncertainty over how net non-CO_2 forcing (a total of positive and negative forcing from non-CO_2 GHGs and aerosols) will evolve over time complicates the work of estimating a carbon budget. The carbon budget concept puts the central focus on limiting cumulative CO_2 emissions within an allowable budget. But the question about to what extent non-CO_2 forcing will reduce the allowable budget can hardly be ignored. And if the remaining non-CO_2 warming could somehow be offset by an opposing cooling effect, then the complication of future non-CO_2 forcing could be neutralised. This is where SRM might possibly find a potential role in carbon budget management.

4 Technologies of offset: CDR and SRM under a carbon budget

As seen above, the carbon budget is constructed on a firm geophysical base and its size estimate is deducible from climate model simulations. The calculative logic of modelling facilitates a translation from an aggregate index of global temperature into a metric of tonnes of CO_2. An important underlying assumption of the budget concept is *path independence*. That is, every tonne of CO_2 adds to the same amount of warming, no matter when and where it is emitted (Matthews et al. 2009; Knutti and Rogelj 2015; Tokarska et al. 2019b). Emissions pathways do not matter since the cumulative emissions are identical.

Path independence is key to understanding the role of CDR and SRM through a lens of budget accounting. Estimating carbon budgets is essentially a form of quantification. Quantification entails the process of *commensuration*—i.e. making things that are qualitatively different to be quantitatively equivalent (Espeland and Stevens 1998; Mennicken and Espeland 2019). Commensuration works to simplify different entities into numbers that can easily be compared through a common metric (Espeland and Stevens 1998). For example, by measuring the quantity of CO_2 emissions, different social activities from burning trees to driving cars are accounted for numerically as equivalent acts of emitting CO_2 into the atmosphere.

In estimating a carbon budget, there are two processes of commensuration involved. First is a commensuration of CO_2 emissions in time and space. The path independence of the carbon budget suggests that CO_2 emissions at one place and time are climatically equivalent to emissions of the same magnitude at a different time and place. This leads to a second commensuration: an equivalence of *reducing* anthropogenic CO_2 emissions from sources to *removing* CO_2 by anthropogenic sinks (Gasser et al. 2015). Stopping the net flow of anthropogenic CO_2 into the atmosphere can be done either by eliminating an emission directly at source (zero emission) or by balancing this emission by sucking out the corresponding amount of CO_2 from the atmosphere (net-zero emission).

These two processes of commensuration are based on the assumption that 'a ton of CO_2' is functionally equivalent irrespective of how, where and when CO_2 is emitted, removed or stored. And thereby any other—social, political, ethical or environmental—considerations implicated in CO_2 emissions or removals get overlooked (Carton et al. 2021). This is not specific to carbon budget estimates but actually has been a long-standing issue pertaining to carbon accounting in general (Lohmann 2005; MacKenzie 2009). The carbon budget just renders the quantitative equivalence of CO_2 across time and space a more central aspect of climate science-policy discourse.

There is however another, more ambiguous, process of (in)commensuration. That is, the separation of CO_2-induced warming from non-CO_2 warming. Due to the short atmospheric

lifetimes of non-CO_2 forcing agents, a reduction of non-CO_2 emissions cannot generally replace the need for reducing CO_2 emissions to net zero. And yet, if future non-CO_2 forcing has a warming effect at the time of reaching net-zero CO_2 emissions, this will then reduce the remaining carbon budget. In the accounting of the carbon budget, therefore, transient non-CO_2 warming is generally *temporally incommensurate*—even if *temporarily commensurate*—with irreversible CO_2-induced warming.

These processes of (in)commensuration provide the geophysical basis for the general accounting rules of the carbon budget, based on which a fictive budget manger might see the CDR and SRM methods as potential budgeting tools.

4.1 The logic of offset—CDR and SRM as budgeting tools

From a budget manager's perspective, a carbon budget appears not as a geophysical constraint but as an accounting system. This means that the mitigation challenge is seen as analogous to the 'managerial accounting problem' of controlling the balance of revenues and expenses within a given financial budget. Quantification and commensuration are fundamental to carbon budget management. And the process of commensuration enables the act of *substitution*—i.e. replacing things with those that are quantitatively equivalent (cf. Markusson et al. 2018). Like money, the commensurable things are, by definition, substitutable according to a common metric.

In terms of the budget accounting, CO_2 removal is considered (almost) synonymous with CO_2 mitigation. A carbon budget manager is indifferent to *how* anthropogenic CO_2 emissions are reduced to zero, whether by eliminating CO_2 emissions from all sources entirely (absolute zero) or by offsetting them with anthropogenic removals of CO_2 from the atmosphere (net zero). All that matters is that the net amount of CO_2 emitted to and removed from the atmosphere is confined within geophysical limits. This view is reflected by a widespread use of 'net emissions' (the sum of emissions minus removals) rather than 'gross emissions' (a total amount of emissions, before subtracting removals) in emission scenarios (Anderson and Peters 2016; Holz et al. 2018).

A key characteristic of CDR in this context is to decouple the nature and cost of emissions reductions from emissions *sources* in time and space (Kriegler et al. 2013; Lomax et al. 2015). Instead of reducing directly emissions from specific activities, CDR offers alternative routes to creating equivalent results through delivering negative emissions elsewhere. CDR is a means to *offset* positive CO_2 emissions by negative emissions (cf. Meadowcroft 2013). In the eyes of a budget manager, CO_2 removal is analogous to raising 'additional revenues' that allow for greater expenditure. Taking more CO_2 *out* of the atmosphere allows for more CO_2 to be pumped *into* the atmosphere.

What about SRM? Unlike CDR, SRM has nothing to do directly with CO_2. The focus of SRM is on inducing negative radiative forcing in the climate system, for example, through releasing sulphate aerosols into the stratosphere (Lawrence et al. 2018). A key effect of SRM is to decouple global temperature from CO_2 emissions and hence from atmospheric CO_2 concentrations (Matthews and Caldeira 2007). SRM could slow or stop the warming regardless of the amount of CO_2 emitted to, or removed from, the atmosphere. A problem is that the cooling induced by SRM has only a *temporary* effect: any abrupt termination of SRM would necessarily lead to a subsequent spike in warming (Matthews and Caldeira 2007).

SRM is *not* substitutable with mitigation precisely because it does not reduce CO_2 emitted to the atmosphere. Neither does it remove CO_2 from the atmosphere. Just as transient non-CO_2

warming is distinguished from irreversible CO_2 warming, the *masked* warming created by stratospheric aerosols is not equivalent, in a temporal sense, to the *avoided* CO_2-induced warming by mitigation or CDR. Despite this non-equivalence, it is clear that the intended purpose of SRM *is* to offset the warming resulting from positive GHG forcing (including both CO_2 and non-CO_2) by inducing negative radiative forcing. By masking GHG warming, SRM thus provides a *temporary* 'breathing space' that allows more emissions of CO_2 and non-CO_2 GHGs. In financial terms, SRM can be regarded as analogous to borrowing 'stop-gap funds' to temporarily extend a given budget limit. Under tight budgetary conditions, a budget manager might find such temporary borrowing a useful financial tool. It must however be noted that this stop-gap measure offers only *borrowed* funds, a debt which will have to be repaid eventually through later CO_2 removal—or otherwise additional borrowing will be needed to extend the budget limit indefinitely (cf. Asayama and Hulme 2019).

We can thus see that both CDR and SRM are built upon the same logic of *offsetting*—i.e. balancing out a positive effect by an opposing negative effect, the result being no net difference. The two 'geoengineering' technologies are therefore 'technologies of offset'. A crucial difference between them however concerns *what* they are actually offsetting. CDR is offsetting positive CO_2 *emissions* by inducing negative emissions ('emissions offset'), whereas SRM is about offsetting the *warming* from anthropogenic greenhouse gases with the cooling caused by injected stratospheric aerosols ('warming offset').

Importantly, commensuration—or inventing quantitative equivalence—is the central premise of offsetting. This is because, in principle, we cannot offset things that are not commensurable. Offsetting is also a particular form of substitution. Because the purpose of offsetting is to neutralise an effect by creating an opposite effect, what offsetting substitutes for is the effort to directly remove the former effect. For example, if it were made mandatory that CO_2 resulting from fossil fuel extraction had to be sequestered in geological carbon storage (Allen et al. 2009b), then this policy might be considered a substitute for keeping fossil fuel in the ground.

But why might offsetting by CDR and SRM become useful for a fictive budget manager? It is because these offset technologies can be used *independently* of efforts to reduce CO_2 emissions. In the eyes of a budget manager, both CDR and SRM would appear as additional tools to increase the flexibility for managing the budget balance, either by, respectively, raising 'new revenues' or borrowing 'stop-gap funds'. The lure of offset technologies rests in their ability to place greater *flexibility* in the hands of a budget manager who is in charge of delivering a given carbon budget. But the flexibility of offset could also become the source for a perverse incentive to circumvent the geophysical constraint of a budget.

5 Prudence or profligacy: two strategies for managing a carbon budget

Whilst CDR and SRM could be seen as flexible budgeting tools, *how* a budget manager might use these offset technologies for controlling the budgetary balance has yet to be fully realised. In this section, we explore two different scenarios in which a budget manager could possibly use the two offsetting methods (CDR and SRM) for managing a carbon budget. First, a *fiscal prudence* scenario in which a budget manager will stick to keeping a balanced budget with moderate reliance on offset technologies. A second scenario is *fiscal profligacy,* where a budget manager will resort to excessive offsetting and hence run into a budget deficit. An important point here is that the flexibility that offset technologies provide for budget

management can enable, in principle, both scenarios to be equally plausible. In other words, not only do CDR and SRM offer the promise of balancing a budget, they also open up the possibility of running a budget deficit.

5.1 Fiscal prudence—the promise of keeping a balanced budget

As discussed above, a carbon budget is constrained by the geophysical value of TCRE. The linearity of TCRE suggests that a given temperature target has a 'static budget' of cumulative CO_2 emissions. The budget size is fixed by a chosen temperature target. Continued or increased spending eats away fast at the remaining budget funds, so that the most direct option is to cut 'expenditures' (i.e. reduce CO_2 emissions). That said, as the budget tightens with the imposition of a lower temperature target like 1.5 °C, it becomes more difficult to meet the budget constraint through emissions reductions alone. It therefore becomes increasingly attractive, and perhaps necessary, for a budget manager to create new 'revenue streams' (i.e. CO_2 removal by enhancing sinks) to ease the restraint on expenditures.

CDR is at the heart of the net-zero strategy for balancing a budget, that is, for achieving a balance between sources ('expenditures') and sinks ('revenues') of CO_2. It is widely recognised that there will remain some amount of CO_2 emissions that are either prohibitively expensive or technically infeasible to eliminate directly at source, such as steel and cement manufacturing, long-distance freight, shipping or aviation. CDR is likely needed, at a minimum, for offsetting the so-called residual CO_2 emissions from such hard-to-abate sectors (Davis et al. 2018; Luderer et al. 2018).

Meanwhile, the role of SRM in this context is somewhat ambiguous. SRM may be required to achieve a balanced budget, but the scope for that depends on the future evolution of non-CO_2 forcing. Any future non-CO_2 warming at the time of net-zero CO_2 emissions will reduce the remaining budget funds that could otherwise be saved for accommodating hard-to-eradicate CO_2 emissions. As argued above, future non-CO_2 forcing would likely cause a net warming effect due to the declining aerosol emissions and the residual non-CO_2 GHG emissions. Analogously, this warming effect of non-CO_2 forcing could be seen as a 'financial penalty' that would reduce the allowable CO_2 budget.

Emission scenarios often assume that net-negative CO_2 emissions would compensate for residual non-CO_2 GHG emissions to achieve net-zero GHG emissions (Rogelj et al. 2015b; Fuglestvedt et al. 2018). However, a contrasting scenario in which *SRM* would be deployed to offset the 'residual non-CO_2 warming' is not implausible. Given that non-CO_2 warming is accounted separately from CO_2 warming in carbon budget estimates, using SRM for this purpose does not replace CO_2 mitigation. SRM-induced cooling in this case is more like borrowing 'stop-gap funds' to neutralise the 'financial penalty' of residual non-CO_2 warming, thereby keeping intact the geophysical limits of the 'budgeted funds' for CO_2 emissions.

This offset of non-CO_2 warming by SRM cooling will however be done *outside* the general accounting of CO_2 budget funds. In financial terms, this is akin to 'debt leverage' by a shadow bank which acts *like* a bank but which operates outside normal banking regulations. Crucially, the leverage offered by SRM cooling releases only 'stop-gap funds' for neutralising non-CO_2 warming. The borrowed funds would have to be paid back at some point in the future, either by eliminating non-CO_2 emissions or else by an increase in CO_2 removal. This supplementary use of SRM is only a *partial* financial tool for retaining a balanced budget, not a stand-alone measure.

In sum, both CDR and SRM could, in principle, serve as budgeting tools to help achieve a net balanced budget by cancelling out, respectively, the 'residual expenditures' (residual CO_2 emissions) and the 'financial penalty' (residual non-CO_2 warming). Whilst CDR assumes a vital role in the net-zero budget scheme, the role of SRM is not essential but more *supplemental*—its usage largely depends on the magnitude of future non-CO_2 warming. Nonetheless, the purpose, and hence the value, of offsetting in this scenario is to maintain adherence to the budget constraints—of a given temperature target—imposed by the geophysics. A budget manger could rely on the offsetting tools for securing the fiscal discipline of a balanced budget.

5.2 Fiscal profligacy—the peril of running a budget deficit

In contrast to maintaining a balanced budget, it is equally possible to conjecture that a fictive budget manager would use (or abuse) offset technologies for relaxing geophysical budget constraints and thereby raising a budget deficit. Budget deficit means that more CO_2 is emitted—either temporarily or indefinitely—than the originally designated budget by the geophysics. This arguably seems like a reckless choice for a budget manager. However, the flexibility offered by CDR and SRM can actually incentivise a budget manager to have recourse to 'excessive offsetting' that risks running a sustained budget deficit. The lure of excessive offset lies in the fact that it allows a budget manger to keep up an 'appearance' of delivering a given budget whilst at the same time easing budget constraints for a certain period of time.

In this case, CDR would serve as a financial scheme for running a temporary budget deficit—or incurring a 'carbon debt'—by promising that large-scale CDR deployment will eliminate a deficit later on in the future (cf. Carton 2019; Asayama and Hulme 2019). This is called an 'overshoot' scenario in which global temperature temporarily exceeds a given threshold, but later returns to the target level by delivering net-negative CO_2 emissions (Huntingford and Lowe 2007; Rogelj et al. 2018; Tokarska et al. 2019b). Overshoot thus creates a temporal gap in offset—possibly lasting decades—between emissions and removals. To reverse an overshoot, what CDR is presumed to offset in large part is not current emissions but past emissions that have up to that time been accumulated in the atmosphere.

However, the elimination of such a budget deficit requires raising more 'revenues' than what was being spent. That is, CDR will have to deliver *more* removal of CO_2 from the atmosphere than the excess amount of CO_2 emissions over the budgetary limit ('excess emissions'). According to climate model simulations, an 'overshoot budget' (the cumulative amount of CO_2 that is emitted and removed *after* exceeding and then returning to a given temperature target) is generally smaller than an 'exceedance budget' (the cumulative amount of CO_2 that is emitted *before* exceeding a given temperature target) (MacDougall et al. 2015; Zickfeld et al. 2016; Gasser et al. 2018; Tokarska et al. 2019b; see Fig. 3a). This means that a debt incurred by exceeding a budget must be repaid with interest, the amount of which depends on the magnitude of overshoot (cf. Asayama and Hulme 2019).

Temporary overshoot gives a budget manager considerable leeway to meet budgetary requirements. As a fiscal management scheme, overshooting is basically about easing a demand of near-term mitigation by shifting the burden to the future. A key point here is that overshoot effectively changes the 'meaning' (or 'weight') of geophysical budget constraints. As overshoot is being allowed, even if temporarily, the budget ceiling loses any sense of a 'strict upper limit' that must not be exceeded. It instead becomes a mere 'benchmark' that can
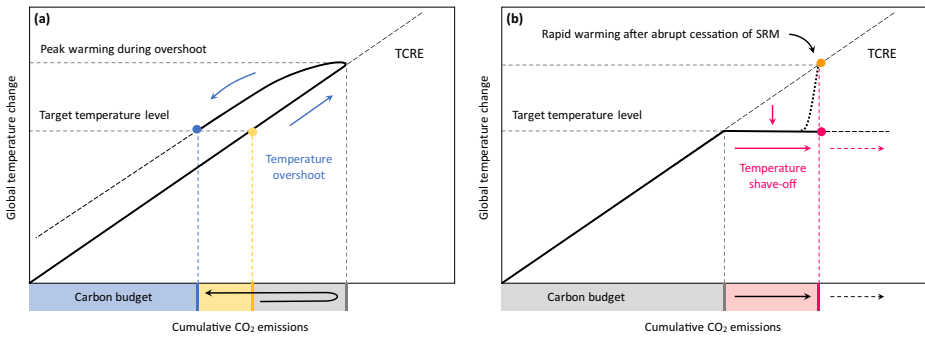
Fig. 3 Schematic of the transition of carbon budgets in temperature overshoot and shave-off scenarios. **a** The amount of CO_2 emissions exceeds the budget for a given temperature level ('exceedance budget', a yellow dot), but later declines to the budget consistent with the same temperature level ('overshoot budget', a blue dot) by CDR. Due to the hysteresis during the period of peak warming, the overshoot budget contracts below the size of the initial exceedance budget. **b** The amount of CO_2 emissions continues to grow beyond the original budget, whilst the temperature is kept constant at a given level by SRM (a magenta dot). A sudden termination of SRM causes a rapid warming to the temperature level consistent with cumulative emissions estimated from the TCRE (an orange dot)

be crossed, if needed, for an indeterminate period of time (Geden and Löschel 2017). As a result, the financial discipline of adhering to a given budget would be eroded; political expediency takes its place.

In the fiscal profligacy scenario, this risk of budget discipline erosion is even greater if a budget manager also resorted to using SRM as a budgeting tool. SRM can prevent temperature overshoot by shaving off 'excess warming' that occurs above the temperature threshold even whilst CO_2 emissions continue to rise. As continued CO_2 emissions are allowed without remission, the budget ceiling loses its power to restrain CO_2 emissions. More and more CO_2 emissions can be accumulated over the original budget limit for so long as SRM keeps cancelling out the excess warming (see Fig. 3b). Thus, the offsetting of excess warming by SRM cooling breaks the linear relationship between CO_2-induced global warming and cumulative CO_2 emissions—the geophysical foundation of the carbon budget concept is eroded.

In financial terms, as SRM shaves off the warming from excess CO_2 emissions without reducing those emissions, this work of shaving off temperature is analogous to 'monetising a debt'—i.e. financing a government deficit through debt monetisation by the central bank. Though debt monetisation is convenient for a government who can borrow funds without needing to repay a debt, it is a highly dangerous operation. Not only does it erode the fiscal discipline of a government, but it may also cause runaway inflation which is detrimental to the nation's economy.

Likewise, SRM is merely *masking* the warming caused by excess CO_2 emissions. SRM cannot pay back 'borrowed funds' on its own terms without a massive rollout of CDR. The act of borrowing through SRM ('temperature shave-off') should be combined with the promise of repayment by CDR ('temperature overshoot'), which is often called temperature 'overshoot and peak-shaving' (Asayama and Hulme 2019). This is just like a debt of any kind that must be paid back at some point. Otherwise, 'debt monetisation' by SRM will have to be operated for a prolonged—potentially indefinite—period of time, since a sudden cessation of SRM would cause a dangerous spike in warming and associated severe impacts, losses and damage (Matthews and Caldeira 2007; Jones et al. 2013; McCusker et al. 2014; see Fig. 3b).

Taken together, under a severe budget constraint, the financial flexibility that CDR and SRM offer as budgeting tools may well look attractive in the eyes of a budget manager. It is no surprise that a fictive budget manger might have recourse to excessive offsetting by CDR and SRM despite knowing the danger involved in such a reckless decision. In a temporal sense, this means extending a budget deadline by creating a deficit (cf. Asayama et al. 2019). Crucially, as a budget deficit is normalised as a not uncommon fiscal condition, the budget ceiling that was imposed as a geophysical constraint becomes adjustable—either significantly eased or completely eliminated—at the discretion of a budget manager. The result is unmitigated carbon emissions greatly exceeding the original budgetary limit.

6 Discussion and conclusions

Using the fictive budget manager as a heuristic device, we have explored how CDR and SRM could come to play a role as budgeting tools to manage a carbon budget. We show that they can be understood as 'technologies of offset'. CDR offsets positive CO_2 emissions by delivering negative emissions ('emissions offset'), whereas SRM offsets warming from positive GHG forcing by inducing cooling from negative forcing ('warming offset'). In financial terms, CDR and SRM could be thought of being analogous to, respectively, raising 'new revenues' and borrowing 'stop-gap funds'. The flexibility of offset technologies could lead to two different strategies for budget management emerging as equally plausible scenarios: either prudence or profligacy. CDR and SRM offer a budget manager the promise of achieving a balanced budget, but at the same time introduce the possibility of running a budget deficit. Put another way, the promise of budget flexibility through offsetting goes hand-in-hand with the danger of eroding budget discipline.

The logic of offset is to neutralise an effect of an action by creating an opposite effect, instead of removing directly the effect of the first action. Whilst CDR and SRM offset different things, both technologies are based on the same offsetting logic. Due to this nature of offset, their usage is physically *independent* of—or *decoupled* from—the effort on reducing CO_2 emissions. This gives offset technologies greater flexibility as budgeting tools *and* creates a deep ambivalence about their use—offset is both alluring and dangerous. CDR and SRM might be potentially useful to retain a balanced budget, but they could easily turn into a scheme to accept a budget deficit, that is, justify *delayed* action on near-term mitigation. In this sense, offset technologies are potential 'technologies of prevarication' (McLaren and Markusson 2020).

Crucially, having flexible budgeting tools, even (or perhaps especially) speculative tools, can affect political *perceptions* of the stringency of budgetary constraints. Under the offset regime, the budget constraints regulated by the geophysics become malleable by pragmatic human discretion. Temporary exceedance of a budget ceiling could be seen as tolerable because CDR promises to eliminate later an incurred deficit. Or else, a budget ceiling might seem of no importance because SRM allows the growing deficit by monetising debt for an indefinite period of time. This is the political side-effect of offset technologies: they normalise running a budget deficit as an acceptable fiscal condition. The risk is that the promise of these two offset technologies will lure the world into the fiscal quicksand of carbon debt. This risk should not be underestimated.

6.1 Offsetting as an escape from admitting policy failure

The fictive character of a budget manager is useful to delineate hypothetical scenarios in which a carbon budget is adopted as if it were a 'real' policy framework. But this is of course fiction. No such figure as a 'global central planner' who is in charge of managing a carbon budget exists in the real world. So, what can we say about the implications for real policymaking from our analysis based on the fictive character? Here, it is worth revisiting the view of scientists and others, who propose the carbon budget concept as a policy tool, about the relationship between science and policy.

Scientists often claim that the significance of the carbon budget as a guide for climate policy rests on its conceptual simplicity (Knutti and Rogelj 2015; Lahn 2020). The carbon budget greatly simplifies the complex relationships between CO_2 emissions, atmospheric CO_2 concentrations and temperature change into a single chart (Frame et al. 2014). On this chart, the primary cause of climate change (i.e. cumulative CO_2 emissions) is directly linked to the most favoured indicator for climate policy (i.e. global average temperature). Carbon budget is seen as "the simplest and most transparent means" (Rogelj et al. 2019a) of connecting the geoscience to climate policy. In their view, greater scientific clarity brought about by the carbon budget should translate into more consistent mitigation policy.

We argue that such a view of the science-policy interface is a common misconception about how *actual* policymaking takes place in reality. As Geden (2016b) points out, inconsistency is the inherent feature—the modus operandi—of policymaking. Instead of striving for consistency, policymakers are more likely to keep alive uncertainty and ambiguity as a source of political flexibility (Geden 2018). This is because the policymaker's behaviour is driven by a strong tendency of avoiding blame for policy failure rather than a desire to claim credit for policy success (Hood 2007; Howlett 2014).

What does this behavioural tendency of policymakers towards blame avoidance suggest for how they approach a carbon budget? Think about policymakers who are under a tight budget constraint but with fewer policy options to meet the requirement for balanced budget. Policymakers may seek to raise the budget ceiling by shifting a politically agreed temperature target (well below 2 °C) to higher levels (for example to 2.5 °C). But this would appear to public audiences as a clear and obvious failure. This means that policymakers are more likely to quietly move a goalpost—or shift the blame—than to openly admit their failure.

In this context, a policy choice to accept 'temporarily' a budget deficit by promising to eliminate it later seems politically tempting. This is because it can help policymakers maintain the 'appearance' of sticking to the original budget plan. A combined use of CDR and SRM for temperature 'overshoot and peak-shaving' is more palatable than simply conceding the exceedance of a targeted temperature threshold. This does not mean that the offsetting strategy for shaving an overshoot off is not politically problematic. Such recourse to 'debt financing' may possibly result in attracting—not shifting—more blame. Even so, insomuch as the original temperature target is being met through a recourse to offset technologies, it could offer policymakers an 'escape route' from having to admit failure. In other words, offset technologies create "constructive ambiguity" (Geden 2018) for policymakers to avoid blame for failure.

The paradox of adopting a carbon budget as a policy tool is that the more transparency science brings into politics, the greater the political risk of failure becomes. The very idea of a finite carbon budget suggests a decisive focus on controlling carbon emissions to stop global warming, thereby relegating SRM to a marginal policy option. But at same time, the more precise calculation of the remaining budget creates the political condition in which missing a temperature target will be a high-stakes political failure. Under such political circumstances, SRM can emerge as a last resort

to avoid an abysmal failure. The irony is that pressing for more science-based policy clarity might actually lead to the opposite of what scientists wish to achieve.

So what might be a solution to this political paradox of the carbon budget? Perhaps, what is needed for making better policy is *less* attention paid to finding 'single numbers' to summarise the global climate challenge (cf. Asayama et al. 2019; Hulme 2020). Estimating carbon budgets is a form of quantification and commensuration—a means to reduce social complexities into mere numbers (Porter 1992; Espeland and Stevens 1998; Mennicken and Espeland 2019). Through the process of commensuration by mathematical models, the concept of a carbon budget transforms the complex challenge of climate change into the managerial accounting problem of controlling net carbon emissions in balance.

However, the quantity of tonnes of CO_2 in account books says nothing about the human practices involved in emitting CO_2. The carbon budget is ignorant of the social and ethical difference between reducing CO_2 emissions from sources and removing CO_2 by enhanced sinks (Shue 2019; McLaren et al. 2019) and opens the door for the risks associated with SRM. The simplicity of the carbon budget thus comes at a high cost—of narrowing the gaze of policymakers and of removing people and their values from policy discourse. This is the fundamental problem of 'epistemological reductionism' associated with climate modelling (Hulme 2011; Heymann 2019).

The logic of offsetting is premised on the process of commensuration by reducing qualitative difference into quantitative equivalence. A resistance to commensuration—or the 'undoing' of equivalence (Carton et al. 2021)—is thus the best way to prevent the abuse of offsetting. In policy terms, this suggests a need for governance from the 'ground up' (Bellamy and Geden 2019)—a stronger focus on concrete policy actions to reduce emissions or remove carbon at specific sources and sinks. In line with the proposal by McLaren et al. (2019), this also requires a clear separation of policy targets between CO_2 mitigation, CO_2 removal *and* non-CO_2 mitigation. Climate policy should be designed using a broad set of social welfare goals rather than being tied to delivering a single, global net-zero target. Such policy design would be better able to appreciate *incommensurable* human values that cannot be reduced to a mere number in the climate policy debate.

Data availability No new data or model outputs were generated as part of this study.

Declarations

Conflict of interest The authors declare no competing interests.

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