Given that the Paris Agreement is unlikely to prevent dangerous climate overshoot, an alternative risk management strategy is urgently needed

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Abstract

Because the 2015 Paris Agreement will not prevent dangerous climate change, there is an urgent need to develop an alternative mitigation strategy.

Even if all national commitments are met and technological breakthroughs accelerate the transition to emission-free technologies, the 2°C target will still be overshot due to systemic inertia from existing greenhouse gases, warming oceans, and the decades required to replace existing infrastructure. Compounding factors include: (a) Most policy-makers greatly underestimate the scale, severity and duration of climate change, and the non-linear impacts of lags, feedbacks and tipping points; (b) Although all IPCC mitigation scenarios require the large-scale deployment of climate geoengineering, many methods may not be politically and/or technologically feasible; (c) While most scenarios assume climate overshoot will occur before safe climates are re-established, many human and environmental systems cannot adapt to higher temperatures. Temperatures likely to cause catastrophic and/or irreversible damage pose unacceptable risks.

Developing a viable mitigation strategy will require prioritising research both on climate overshoot risks, and on the relative effectiveness, risks, costs and timelines of potential mitigation methods. Since geoengineering is required to rapidly mitigate dangerous overshoot, the viability and risks of all potential geoengineering methods need to be investigated.

This research is a prerequisite for evaluating the comparative benefits, costs and risks of using, or not using, various forms of mitigation. A risk management plan can then be developed containing mitigation targets that are precise, measurable and attainable, with clear constraints on the magnitude and duration of both climate overshoot risks and mitigation methods.

Introduction

This paper reviews recent evidence indicating that it is highly unlikely that the 2015 Paris Agreement will prevent dangerous climate change, and argues that therefore there is an urgent need to develop an alternative, viable mitigation strategy.

Many leading scientists warn that because the world is facing an existential crisis, all potential solutions need to be examined, including solar geoengineering (e.g. Bawden 2017). However, there has been widespread resistance to even discussing the issue, in part from other experts concerned that calls to reappraise the Paris Agreement could undermine the political will to achieve existing climate targets (Honegger 2018). Opposition has also come on one side from fossil fuel supporters opposed to initiatives likely to increase “climate change alarmism” and accelerate mitigation efforts, and on the other from environmentalists concerned that any serious consideration of radical geoengineering interventions may give fossil fuel producers an excuse to delay decarbonisation.

This opposition was demonstrated at the 2019 UN Environment Assembly, when two fossil fuel producing nations (the United States and Saudi Arabia) blocked a Swiss proposal to assess potential geoengineering methods and governance frameworks (Corry and McLaren 2019).

Nevertheless, it will not be possible to manage climate risks without addressing the critical question of whether Paris Agreement targets can and will be met with current commitments and plans, and if not, what must be done to keep global temperatures from reaching levels that could cause catastrophic and irreversible damage. Ignoring the problem is not a prudent option.

The paper is organised in the following sections:

- Why it is very unlikely that the Paris Agreement targets will be met.

- Most current policy underestimates the scale, severity and duration of climate temperature overshoot risks.

- Greater insight is needed on the necessity, viability, risks and costs of all potential mitigation options.

- A comparative assessment of overshoot risks versus mitigation risks is required to enable the development of viable mitigation plans.

- Conclusion: priority needs to be given to developing a viable plan for preventing dangerous climate temperature overshoot.

Why it is very unlikely that the Paris Agreement targets will be met

The 2015 Paris Agreement succeeded in establishing a voluntary commitment by the international community for "Holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels" (UNFCCC 2015a, p. 3). However, even if all the Paris Agreement's national commitments are fulfilled, warming will probably reach between 2.9 °C and 3.4 °C by the end of the century (WMO 2019). With current mitigation efforts there is only a 5% chance that the global temperature increase will be less than 2°C and a 1% chance that it will be less than 1.5°C (Raftery, Zimmer, Frierson, Startz and Liu 2017).

The full range of Intergovernmental Panel on Climate Change (IPCC) scenarios compatible with a 50% or higher likelihood of limiting global warming to 1.5°C by 2100 assume the rapid reduction of global CO_2 emissions to net zero around 2050 (IPCC 2018). In order to do this countries must increase their commitments threefold to achieve the below 2°C goal and more than fivefold to achieve the 1.5°C goal (UNEP 2019). Regrettably, to date few countries have followed through on their commitments and instead of decreasing, global greenhouse gas emissions (GHG) have continued to rise, with the result that the emissions gap—the difference between where GHG emissions are heading and where they need to be to keep global warming within the agreed Paris Agreement goals—is greater than ever (WMO 2020a; UNEP 2020).

Fortunately, stronger actions will be taken. The European Union, China, Japan, the UK, the Republic of Korea, South Africa, Mexico and Argentina have recently pledged to significantly accelerate their decarbonisation programs (e.g. Harvey 2020a; Hida 2020), and in the United States the Biden administration intends to introduce a $2 trillion plan to fight global warming (Davenport 2020). These initiatives aspire to reduce the carbon emissions of the largest emitters to net zero over the next 30 to 40 years—in the EU, US and Japan by 2050, and in China by 2060. If fully implemented, these new goals will reduce the temperature increase by the end of the century from around 3°C to 2.5°C (UNEP 2020)—important progress but still not enough to prevent dangerous warming.

The scale of the problem is illustrated by the International Energy Agency's warnings that despite growing energy demand there is no carbon budget left for building any more CO_2 emitting power stations, vehicles and industrial facilities (IEA 2019).

The 1.5°C - 2°C goal is intended to conform to the United Nations Framework Convention on Climate Change (UNFCCC) aim of preventing 'dangerous anthropogenic interference' with Earth's climate (UNFCCC 1992). Major impacts are already occurring with 1°C of warming (IPCC 2018; WEF 2019), and there are serious risks associated with exceeding the Agreement's temperature targets (IPCC 2018).

While 90% of IPCC scenarios predict that average global temperatures will rise above the 1.5°C limit, they assume that if overshoot occurs, temperatures can be returned to safe levels by 2100 through large-scale carbon dioxide removal (CDR) (Anderson 2015). The caveat is that these geoengineering measures may not be politically and/or technologically feasible (IPCC 2018). Many policy makers also assume that most human and environmental systems will be able to adapt to a few degrees of higher temperatures without serious consequences. Unfortunately, both assumptions are questionable and don't match available evidence (IPCC 2018).

Although global temperatures could be rapidly reduced with solar radiation management (also termed solar radiation modification or solar geoengineering), this technology may have substantial risks (The Royal Society 2009). However, to achieve the Paris goals without SRM, three extremely ambitious targets must be met (Rockström et al. 2017):

1) Global CO_2 emissions should decline by 50% per decade.

2) Net emissions from agriculture and deforestation must be cut to zero by 2050 (at the same time as more food is required to meet the needs of a growing global population).

3) Carbon dioxide removal technologies will have to be rapidly developed and scaled up to remove 5 gigatons of CO_2 per year from the atmosphere by 2050.

A number of strategies have been advanced for achieving the IPCC target of net-zero GHG emissions by mid-century. For example, the Energy Transitions Commission, a coalition of global energy leaders, suggests that it should be technologically and economically feasible for the developed world to reach this target by 2050 and the developing world by 2060, even without the significant use of offsets from afforestation (ETC 2020). The costs of achieving this are relatively small when compared to the large adverse impacts that would be triggered by unmitigated climate change—1% to 2% of global GDP per annum. However, they also caution that in order to achieve these theoretically possible emissions reductions, numerous technical, economic and institutional barriers will have to be overcome, including developing ways to capture and store 6 to 9.5 Gt of CO_2 per year.

The principal problems with the Paris Agreement are that all modelled scenarios capable of achieving its goals are predicated on two assumptions: first, that the global political will exists to make a rapid switch away from our current dependence on fossil fuels; and second, that the sequestration of carbon will be feasible at sufficient scale to reduce overshoot to safe levels. But at this time there is little indication that the international community is willing to engage in the massive decarbonisation needed to avoid global temperatures rising to extremely dangerous levels, and no plans have been made to develop and deploy the required CDR technologies (COMMIT & CD-LINKS 2018).

For example: in 2020, G20 countries spent 50% more in their pandemic stimulus packages on sectors linked to fossil fuels than on low-carbon energy (Harvey 2020b); only 6 out of 46 clean energy technologies and sectors are currently on track to help hit international emissions reduction targets (IEA 2020a); and although many mitigation plans rely on the widespread deployment of carbon capture and storage (CCS); in 2018 there was still a 300 to 1 disparity between actual and necessary investment (WEF 2018). As Geden and Löschel point out (2017, p. 881), "The inclusion of carbon dioxide removal from the atmosphere — 'negative emissions' — in integrated assessment models allow for emissions pathways compatible with low stabilization targets… But policymakers refrain from any political commitment to developing and deploying negative emissions technologies at the assumed scale of 670–810 gigatonnes by 2100".

In reality, the world is still many decades away from ending net greenhouse gas emissions, let alone deploying viable negative-emission technologies. These problems lead to the following logical conclusions: (a) dangerous climate target overshoot is almost inevitable; and (b) SRM will probably be required to constrain temperature overshoot until greenhouse gas concentrations are stabilized at safe levels (Figure 1). However, not only are SRM technologies not ready for large-scale deployment, but they cannot be used until their risks are understood and mitigated.

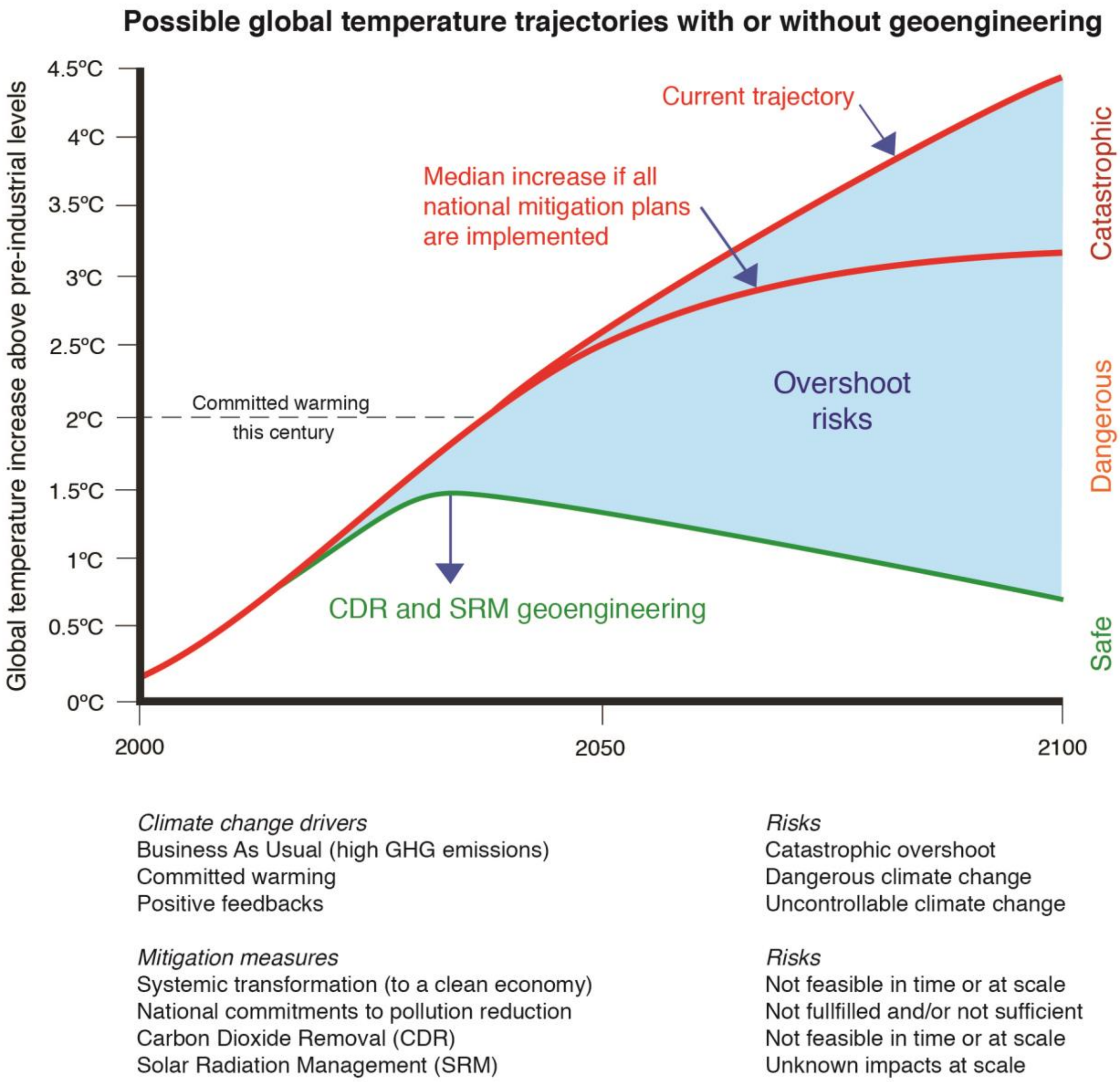

Figure 1. Possible global temperature trajectories with or without geoengineering.

Given the highly likely scenario that the Paris Agreement (the only existing international plan to restrict greenhouse gases) will fail to prevent dangerous climate change, humanity must now urgently develop and reach agreement on a viable back-up strategy—a realistic "Plan B".

Most current policy underestimates the scale, severity and duration of climate overshoot risks

Many policy makers—and most current policy—seriously underestimate the scale, severity and duration of climate change. The global flux imbalance means that oceans are now warming at the equivalent of five Hiroshima-sized atomic bombs every second (Lubben 2020; Cheng et al 2020). More than 93% of the extra heat is being absorbed by the oceans (Cheng, Abraham, Hausfather and Trenberth 2019). The long life of CO_2 and the large thermal inertia of the oceans make long-term future warming inevitable. There is a high chance that current committed warming will raise global average temperatures to 2.0 °C+ above pre-industrial levels by the end of the century (Huntingford, Williamson and Nijsse 2020).

Solomon, Plattner, Knutti and Friedlingstein (2009) estimate that climate change resulting from increases in carbon dioxide concentrations will be largely irreversible for 1,000 years, and many anthropogenic climate change impacts, including ocean acidification will be irreversible on at least a multi-century to millennial timescale (UNFCC 2015b). It will take several centuries to millennia for equilibrium to be reached in temperature and sea level.

Even if CO_2 is stabilized at 400 to 450 parts per million the long-term consequences are likely to be devastating. Carbon dioxide levels are now over 410 ppm (NOAA 2020): the last time atmospheric CO_2 levels were above 400 ppm was 3 million years ago in the Pliocene era. Then sea levels were 15 metres higher than now, Arctic summer temperatures were 14 degrees higher and there were trees growing in Antarctica (Galey and Hood 2019; Carrington 2019).

Rising temperatures are already having serious impacts including degrading terrestrial and marine ecosystems, rising sea levels, regional desertification, intensifying forest fires, increasingly extreme weather, increasing soil erosion and decreasing crop yields (IPCC 2019a; IPCC 2019b). Logical inferences from this are: If the global climate is neither safe nor stable now, how could it be safely stabilized at a higher temperature? Is the 1.5°C climate target too high?

Even under the most optimistic scenarios, decarbonisation is not likely to occur quickly enough to prevent dangerous climate change due to systemic inertia and lags caused by a wide range of factors. These factors include committed warming from previous emissions and existing infrastructure, the delayed impacts of existing warming, the time required to develop and deploy new technologies, and cultural and political inertia and resistance (e.g. Brown, Alexander, Arneth, Holman and Rounsevell 2019). For instance, since global warming will continue due to the greenhouse gases that have already been emitted, researchers estimate that even if all emissions stopped today, 74% of the world will be exposed to deadly heat waves by 2100 (Mora et al. 2017).

Rogelj et al. (2015) point out that "No scenarios that have a high probability of limiting warming to below the 1.5°C limit during the entire twenty-first century exist in the literature." The IPCC consensus is that average temperatures are on track to increase to 1.5°C by the 2040s (IPCC 2018); Henley and King (2017) argue that global mean temperatures are likely to pass 1.5°C by 2029. The World Meteorological Organisation now estimates that there is a ~70% chance that one or more months during the next 5 years will be at least 1.5°C warmer than preindustrial levels (WMO 2020b).

An additional problem is that the masking effect of anthropogenic air pollution lowers global mean surface temperatures by 0.7°C (Lelieveld, Klingmüller, Pozzer, Burnett, Haines and Ramanathan 2019). While the warming resulting from removing aerosols could be reduced in the near term by the simultaneous reduction of short-lived greenhouse gases such as O_3, temperatures will inevitably rise above the 1.5°C limit once the world stops burning fossil fuels. Some of the latest-generation models also suggest that the scenarios currently used by the IPCC may underestimate the sensitivity of climate to CO_2 (Sherwood et al. 2020). In addition the scenarios may have underestimated the emissions and impacts of other greenhouse gases e.g. nitrous oxide (Tian et al. 2020).

The scientific consensus is that climate change is likely to push most natural and human systems into increasingly dangerous and irreversible states (IPCC 2018). For example, 20% to 30% of the world's land surface will experience aridification at less than a 2°C temperature rise (Park et al. 2018). In financial terms the 2.5°C–3°C of global warming implied by current national commitments may reduce per capita output by 15%–25% by 2100 (Burke, Davis and Diffenbaugh 2018), with output reduced by more than 30% if warming reaches 4 °C. Each one degree rise above the current baseline will place approximately 1 billion people in "near-unliveable" temperatures, which may cause mass migration (Xu, Kohler, Lenton, Svenning and Scheffer 2020). Conflicts over increasing shortages of food and water are also forecast to increase (e.g. Farinosi et al. 2018).

Additionally, the possible triggering of uncontrollable feedback loops poses substantial risks. Global warming is already producing feedback effects from warming oceans and drying land sectors, including releasing methane from permafrost (Anthony et al. 2018) and releasing CO_2 from forest fires. It should be noted that there are no credible technological solutions for many climate change problems: for example, the Arctic and boreal permafrost contain 1460 to 1600 Gt of organic carbon, almost twice the carbon in the atmosphere (WMO 2020a), and if gigatonnes of methane are released from melting permafrost and warming oceans, the process cannot be reversed.

An International Cryosphere Climate Initiative report (ICCI 2015, p. v) warns that the Paris commitments will not prevent crossing irreversible thresholds: e.g. melting glaciers that will result in the loss of reliable water resources for millions of people; melting polar ice sheets that will eventually flood coastal cities; the release of additional greenhouse gases from melting permafrost; and the loss of fisheries from ocean acidification. Cryosphere climate change is slow to manifest but once triggered "inevitably forces the Earth's climate system into a new state, one that most scientists believe has not existed for 35–50 million years."

The ICCI report points out that while a global mean temperature increase of 1.6 °C will melt most of the Greenland Ice Sheet (which would eventually raise sea levels by seven meters), it will take another ice age to replace the lost ice. Every degree of warming up to 2°C will also add another 1.3 metres to sea levels from accelerated ice flow into the ocean and melting from the Antarctic Ice Sheet, while warming between 2°C and 6 °C will add 2.4 metres per degree (Garbe, Albrecht, Levermann, Donges and Winkelmann 2020).

Since tipping elements have been identified in all earth systems including cryosphere, ocean circulation systems and the biosphere, a growing risk is that even if the Paris Agreement targets are met, a cascade of positive feedbacks could push the Earth System irreversibly onto a "Hothouse Earth" pathway (Steffen et al. 2018). During the last glacial period abrupt climate changes sometimes occurred within decades, with temperatures over the Greenland ice-sheet warming by 8°C to 16°C at each event (Corrick et al. 2020).

Lenton et al. (2019) warn that there may already be no time left to prevent tipping since it will probably take at least 30 years to achieve net zero emissions. Nevertheless, interventions may reduce damage.

Tipping elements of the climate system into a different state will probably cause irreversible economic losses. Cai, Lenton and Lontzek (2016) argue that because these interacting factors multiply risks, the social cost of carbon pollution should be appraised at US$116 per tCO_2. Some models produce much higher values: e.g. the IPCC estimates that keeping temperatures below the 1.5°C pathway may require carbon taxes in 2030 of US$135–$5,500 per tCO_2e (IPCC 2018).

Climate conditions are increasingly entering 'no-analogue' state that cannot be readily modelled, given that the present anthropogenic carbon release rate has no precedent since the Paleocene–Eocene Thermal Maximum 66 million years ago (Zeebe, Ridgwell and Zachos 2016). Rapid global warming and accompanying ocean oxygen loss led to the Permian-Triassic mass extinctions (Penn, Deutsch, Payne and Sperling 2018), and Rothman (2017) estimates that carbon emissions are likely to reach the tipping point for the next catastrophic mass extinction event by 2100.

Given that severe impacts are occurring with only 1°C of global warming, the following categories of climate change risk have been proposed: (1) warming greater than 1.5 °C as “dangerous”; (2) warming greater than 3 °C as “catastrophic”; and (3) warming in excess of 5 °C as “unknown,” as changes of this magnitude pose existential threats (Xu and Ramanathan 2017).

If the world fails to rapidly reduce emissions, Brown and Caldeira (2017) estimate that there is a 93% probability that global warming will exceed 4°C by the end of the century. Xu and Ramanathan (2017) estimate a 50% probability of 2.4–2.6 °C warming by 2050 and 4.1–5 °C warming by 2100, with a 5% probability of catastrophic climate change occurring within three decades.

Greater insight is needed on the necessity, viability, risks and costs of all potential mitigation options

Mitigation efforts need to stay focused on accelerating the transition from fossil fuels to renewable energy sources. Many proposals have been developed on how this can be done (e.g. Jacobson et al 2019; Ram et al. 2019). For example the International Energy Agency has a post-pandemic economic plan to force greenhouse gas emissions into permanent decline and boost global economic growth by 1.1 per cent at a cost of US$3 trillion spent over three years (IEA 2020b). Methods that will support decarbonisation include lowering energy demand (Grubler et al. 2018); effective carbon taxes (IPCC 2018; IMF 2019; Bauer et al. 2020); introducing a global price signal based on risk assessments (Chen, van der Beek and Cloud 2017); supply-side carbon constraints (e.g. removing subsidies; production bans) (Le Billon and Kristoffersen 2019); ecosystem restoration (Strassburg et al. 2020); supporting natural climate solutions (Griscom et al. 2017); changing diets (Harwatt 2018); developing new energy sources (e.g. Shen 2019); gene editing plants and animals (Giddings, Rozansky and Hart 2020); and developing less-polluting agricultural and industrial processes (e.g. Loboguerrero et al. 2019; Bates 2017).

Equity issues also need to be addressed since the responsibilities and costs of emissions are not equally shared. For example, the richest 1 per cent of the global population produce more than twice the carbon pollution of the poorest 50 per cent (UNEP 2020); more than one-third of all global carbon emissions since 1965 can be attributed to the 20 largest fossil fuel companies (Taylor and Watts 2019); and many of the populations facing the highest risks from climate change live in developing countries (e.g. low lying island states) that produce few emissions per capita (IPCC 2018).

By itself, rapidly reducing emissions of carbon dioxide, methane, nitrous oxide and other greenhouse gases will not prevent temperatures exceeding safe limits. The response to mitigation will also be delayed by the inertia and internal variability of the climate system (Samset, Fuglestvedt and Lund 2020). As a consequence climate geoengineering is currently the only technology with the potential to prevent global warming from causing massive damage during the long period that it will take to transition to an emissions-free global economy, remove carbon dioxide from the atmosphere, and re-establish a safe and stable climate.

The question of whether or not humanity should engage in geoengineering is moot. The increases in global temperatures since the Industrial Revolution demonstrate humanity’s ability to geoengineer the earth’s atmosphere through the release of massive quantities of greenhouse gases. Earth’s climate must now be re-engineered toward stable conditions similar to the last 10,000 years of the Holocene, during which natural and human systems assumed their current form.

IPCC pathways have to assume the large-scale removal of CO_2 from the atmosphere if the 1.5°C target is to be achieved (IPCC 2018). Carbon dioxide removal methods (also known as negative emissions technologies) involve activities such as terrestrial afforestation/reforestation; ocean afforestation with macro-algae; ocean fertilisation; ocean upwelling; biochar; soil carbon management; enhanced silicate rock weathering (ERW); direct CO_2 capture; CCS; bioenergy with carbon capture and storage (BECCS); and carbon capture, use and storage (CCUS)—capturing carbon and using it to manufacture a wide range of useful products.

However, in order to remove sufficient CO_2 from the atmosphere to meet the Paris targets it will be necessary to create a new carbon sink on the scale of the ocean sink (Rockström et al. 2016). The potential capacity of many CDR measures is also constrained by available land, water and nutrients and by environmental concerns (e.g. Anderson and Peters 2016; Heck, Gerten, Lucht and Popp 2018). Another major obstacle is cost (IPCC 2018), and no plans currently exist to develop and deploy the CDR technologies needed to reduce the overshoot to safe levels.

Dooley and Kartha (2018, p. 94) point out that it is dangerous to assume that CDR measures can and will be deployed on time and at scale. "If the promise of future negative emissions leads policy makers to grossly underestimate the effort needed in the near term to meet these targets, the results would be disastrous." Additionally, since CO_2 would only be removed slowly, CDR methods will not have an appreciable effect on the global climate for decades. Nevertheless, both decarbonisation and CO_2 removal measures will have to be ambitiously deployed to limit the duration of climate temperature overshoot to less than two centuries (Ricke, Millar and MacMartin 2017).

Other potential geoengineering approaches include cirrus cloud thinning (Kristjánsson, Muri and Schmidt 2015), and solar radiation management. Leading SRM methods are stratospheric aerosol injection (Keith and Irvine 2016), marine cloud brightening (Wood, Ackerman, Rasch and Wanser 2017) and changes to land surface albedo.

While injecting sulphate aerosols into the stratosphere may be a rapid, effective and relatively inexpensive way to cool global temperatures (Smith and Wagner 2018), it poses new risks, including reduced photosynthesis (Proctor, Hsiang, Burney, Burke and Schlenker 2018) and possible negative impacts on precipitation and ozone loss (Irvine, Kravitz, Lawrence and Muri 2016). Using iron salts (Oeste, de Richter, Ming, and Caillol 2017) or other mineral aerosols may overcome some of these problems: e.g. using calcite would also result in cooling but also potentially help repair ozone levels (Keith, Weisenstein, Dykema and Keutsch 2016). It is also argued that in comparison with no solar reduction, a moderate amount of solar reduction may produce temperature and precipitation values in all regions that are closer to the preindustrial climate (Irvine, Emanuel, He, Horowitz, Vecchi and Keith 2019).

SRM also introduces complex problems of global-scale governance, including the unequal distribution of benefits and costs (Reynolds 2019), and an increased risk of international conflicts (Corry 2017). Moral hazard is another risk—that the promise of cheap, quick geoengineering fixes to global warming will reduce political pressure for decarbonisation (Tilmes et al. 2013). This is a serious issue as SRM will not prevent rising levels of atmospheric CO_2 from acidifying the oceans with catastrophic impacts on marine life (Eyre et al. 2018).

Increasing the moral hazard are risks that it may not be possible to use climate engineering methods at scale, and/or it may be decades before they can be safely deployed (Lawrence et al. 2018). Even so there may be few objections to using some technologies to address localised problems: e.g. using marine cloud brightening to prevent coral reefs from bleaching (Temple 2017).

A useful initial strategy might be to deploy portfolios of different CDR technologies, each at modest scales (Minx et al. 2018). The critical problem is that although CDR methods are safer than SRM, they will act too slowly to prevent dangerous overshoot. Nonetheless, these technologies are among the many tools that will be needed to keep warming within safe limits (i.e. an 'all hands on deck' approach is required).

Because there are still many unresolved questions about climate geoengineering, research is urgently needed on the relative viability, risks and costs of all potential mitigation measures.

A comparative assessment of overshoot risks versus mitigation risks is required to enable the development of viable mitigation plans

Most scenarios allow climate target overshoot because they focus on reaching climate goals by 2100. To avoid this Rogelj et al. (2019) propose that researchers instead focus on capping peak warming at safe levels. This will require exploring all potentially viable methods for reducing climate risks (Rockström et al. 2016). As the Scientific Advisory Board of the UN Secretary-General (2016) emphasizes, policy-makers need to understand climate change as an issue of risk management: since all options involve risks, the challenge is to develop strategies that minimize likely risks and costs while maximizing benefits.

On one hand the consequences could be catastrophic if geoengineering was not deployed in time to avert commitment to significant overshoot, while on the other hand it could be very dangerous to deploy untested methods that are either ineffective or do more damage than good. The precautionary principle requires more research before any geoengineering methods can be deployed at climate-altering scales (e.g. Committee on Geoengineering Climate 2015a; Committee on Geoengineering Climate 2015b). The precautionary principle also means, however, that the risks of dangerous and potentially catastrophic climate change justify action rather than inaction (King, Schrag, Dadi, Ye and Ghosh 2015).

Research is urgently needed on the comparative risks of safe temperature overshoot versus the risks of various mitigation approaches (Climate Institute 2018). The evaluation of climate risks needs to take into account not only linear developments and their impacts, but also likely non-linear developments since climatic tipping elements, climatically sensitive social tipping elements, and climate–economic shocks may be the largest contributors to the costs of climate change (Kopp, Shwom, Wagner and Yuan 2016). The economist Nicholas Stern (2016) argues that while these hard-to-predict estimates are difficult to estimate, future IPCC reports need to take them into account as they have the most troubling potential consequences. Another area that deserves more attention is the higher-risk scenarios, which are less predictable but also hold more devastating implications.

The research should support public dialogue on the relative costs and risks of using or not using various types of climate engineering (Honegger et al. 2017; Lawrence et al. 2018) and lead either to the development of a much stronger, viable Paris Agreement [i.e. Plan A, version 2], or an alternative, internationally agreed on "Plan B" (Figure 2).

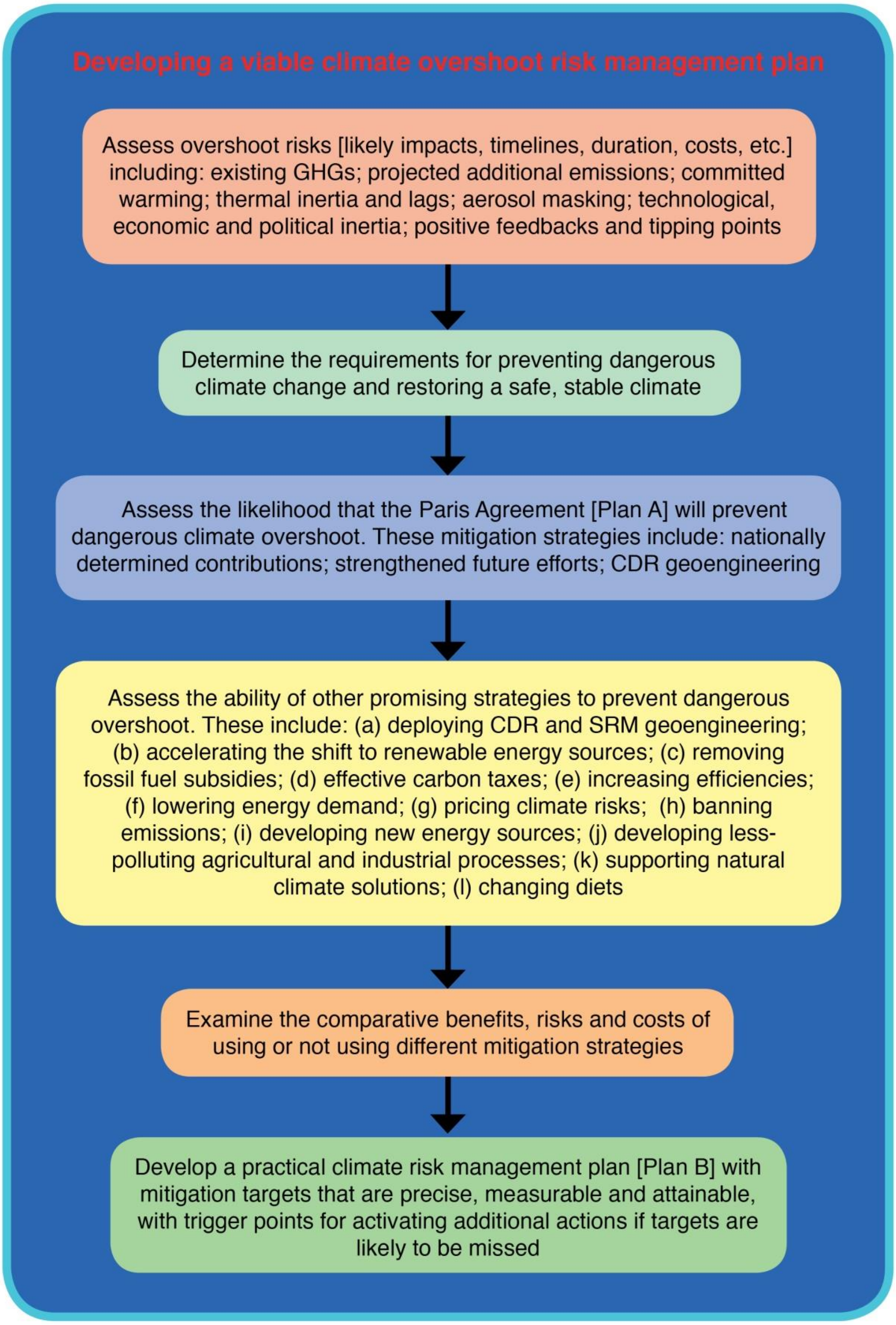

Figure 2. A proposal for developing a viable climate overshoot risk management plan.

A viable risk management plan will need to contain three main elements: metrics, timelines and trigger points for initiating actions. A starting point will be to establish a scientifically credible plan for decarbonization (Rockström et al. 2016). In order to challenge policy-makers and hold them accountable, mitigation targets must be precise, evaluable and attainable, with clear constraints on the magnitude and duration of overshoot and the feasibility of mitigation methods (Geden and Löschel 2017).

Conclusion: priority needs to be given to developing a viable plan for preventing dangerous climate temperature overshoot

To summarise:

1. Given that mitigation efforts under the existing Paris Agreement are unlikely to prevent dangerous climate change, priority must be given to developing and reaching international agreement on a viable alternative strategy—either a much stronger Paris Agreement or a "Plan B".

2. Climate change is a risk management problem. It requires a comparative assessment of the likely risks and costs of acting or not acting to prevent undesirable impacts.

3. Overshoot risks have been seriously underestimated. Research is urgently required on climate inertia, lags, feedbacks, tipping points and timelines.

4. Greater insights are needed on the necessity, viability, risks, costs and timelines of the full range of mitigation options.

5. Because climate overshoot cannot be prevented without large-scale geoengineering, knowledge gaps need to be urgently filled on all potential geoengineering methods.

The world faces a key juncture. Not moving off the current trajectory—an increase of at least 3°C - 4°C—will result in a world that is unstable and dangerous for life as we know it. Moving, however, will require a reconsideration of where solutions are likely to exist. To help reduce further obstruction and delays, a broad scientific consensus needs to be established on the need for a comparative assessment of all significant overshoot and mitigation risks and options well in advance of the IPCC's Sixth Assessment Report (to be published in 2021 and 2022).

At this critical time scientists and decision-makers must prioritise the investigation and development of a realistic, viable plan for preventing dangerous climate temperature overshoot or risk irreversible, catastrophic damage to the biophysical and physiochemical systems that support human civilization.

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