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 most countries greatly increase their commitments 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 risks are: (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 feasible 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 both carbon removal geoengineering and solar geoengineering will be required to rapidly

mitigate dangerous climate change, 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 realistic 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, feasible 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 need for a new strategy, 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 geoengineering interventions are dangerous experiments that will give fossil fuel producers excuses for delaying decarbonisation (e.g. Greenfield 2021).

This opposition was demonstrated at the 2019 UN Environment Assembly, when the United States and Saudi Arabia (two fossil fuel producing nations) blocked a Swiss proposal to assess potential geoengineering methods and governance frameworks (Reynolds 2019a), and in 2021 when a flight to test solar geoengineering was cancelled due to objections from Swedish environmentalists (Fountain and Flavelle 2021).

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 policies underestimate committed warming and the scale, severity and duration of climate temperature overshoot risks.

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

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

- Conclusion: priority needs to be given to developing a feasible 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).

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).

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, many countries have failed to follow through on their commitments, and instead of decreasing, global greenhouse gas emissions (GHG) have continued to rise. As a result 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), and without stronger policies global warming could reach 4.1°C – 4.8°C above pre-industrial levels by the end of the century (Climate Action Tracker 2021).

Stronger actions will be taken. Many countries, including the US, European Union, China, Japan, UK, and the Republic of Korea have pledged to significantly accelerate their decarbonisation programs (e.g. Harvey 2020a; Dooley, Inoue and Hida 2020; BBC News 2021; Nilsen 2021). 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, UK and Japan by 2050, and in China by 2060.

The question is whether these efforts will be enough to prevent dangerous climate change. Emissions must fall by 45% this decade for the world to meet the 1.5°C climate target (UNFCC 2021). The scale of the challenge 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). Nevertheless, 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; Le Quéré et al. 2021).

Adding to concerns that Paris targets will be missed are findings by Schwalm, Glendon and Duffy (2020) that not only are the total cumulative CO_2 emissions released to date consistent (within 1%) with the highest IPCC scenario (RCP8.5), but that this frightening trajectory is likely to continue out to mid-century. All CMIP6 models suggest that the 1.5°C temperature target will be breached around 2030 or 2035 (Climate Council 2021), and 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).

IPCC scenarios 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 (SRM – also termed solar radiation modification or solar geoengineering), this technology may have substantial risks (Royal Society 2009). However, Rockström et al. (2017) argue that to achieve the Paris goals without SRM, three extremely ambitious targets must be met:

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.

Significant progress is being made. Renewable energies are now the cheapest options in much of the world (Colthorpe 2020), and in 2020 the world committed a record $501.3 billion to decarbonization (BloombergNEF 2021). Nevertheless, no major economy has carbon pricing policies that are even remotely in line with the 1.5°C target (France 24 2021); 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, in 2018 there was still a 1 to 300 disparity between actual and necessary investment (WEF 2018).

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).

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.

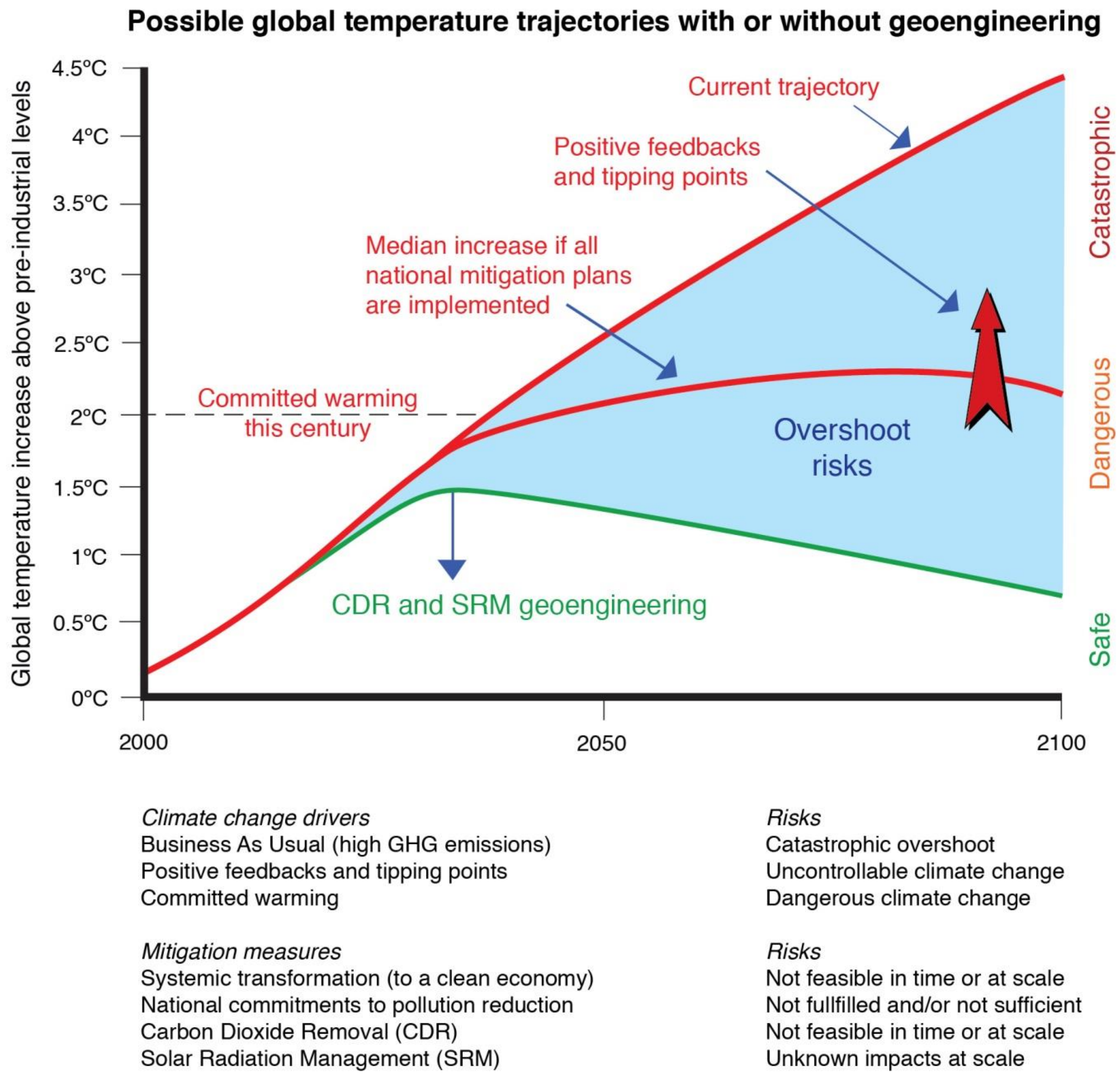

Figure 1. Possible global temperature trajectories with or without geoengineering.

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

Most current policies underestimate committed warming and the scale, severity and duration of climate temperature 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. Mean annual temperatures are already higher than annual levels over the past 12,000 years (Bova et al. 2021), and there is a high chance that current committed warming will raise global average temperatures to 2.0°C or more above pre-industrial levels by the end of the century (Huntingford, Williamson and Nijsse 2020; von Schuckmann et al. 2020; Zhou, Zelinka, Dessler and Wang 2021).

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?

Von Schuckmann et al. (2020) point out that to prevent further warming and bring the Earth back into an energy balance, the amount of CO_2 in the atmosphere will need to be reduced back to 353 ppm, a level passed in 1990. Because climate stabilization—the goal of the 1992 United Nations Framework Convention on Climate Change (UNFCCC) and the 2015 Paris Agreement—requires that the Earth energy imbalance (EEI) be reduced to approximately zero to achieve Earth's system quasi-equilibrium, they argue that EEI is the most fundamental metric for determining success or failure in climate change mitigation.

Once net zero emissions are achieved, carbon uptake by natural carbon sinks and human carbon removal technologies will gradually lower CO_2 concentrations. This will counter atmospheric warming from the oceans and help stabilise global temperatures (MacDougall et al. 2020). However, 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 project that even if all emissions stopped today, 74% of the world will be exposed to deadly heat waves by 2100 (Mora et al. 2017).

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 will average 416 ppm in 2021 (Met Office 2021), and the CO_2 equivalence of all greenhouse gases are now over 500 ppm (Butler and Montzka 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).

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. methane released by melting permafrost (Gasser et al. 2018), nitrous oxide (Tian et al. 2020), and the impacts of carbon-cycle feedbacks (Hausfather and Betts 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, global warming above 1.5°C will make much of the tropics unliveable (Zhang, Held and Fueglistaler 2021); 20% to 30% of the world's land surface will experience aridification at less than a 2°C temperature rise (Park et al. 2018); and conflicts over increasing shortages of food and water are forecast to increase (e.g. Farinosi 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.

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. These feedback loops have not yet been modelled in net zero emissions scenarios (Climate Council, 2021).

Earth is now losing at least 1.2 trillion tons of ice each year (Mooney and Freedman 2021). 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). 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.

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; Klose, Karle, Winkelmann and Donges 2020). 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.

Although these multiple interacting threats create systemic risks (i.e. threaten the functionality of natural and social systems), their complex, nonlinear dynamics are not adequately understood by conventional risk analysis (Renn et al. 2020). 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; Lear et al. 2020). 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°C–2.6°C warming by 2050 and 4.1°C–5°C warming by 2100, with a 5% probability of catastrophic climate change occurring within three decades. On the positive side, although the probability of staying below staying below 2°C of warming by 2100 is currently only 5%, it rises to 26% if all countries follow through on their pledges (Liu and Raftery 2021).

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

Mitigation efforts need to stay focused on accelerating the global transition to a net-zero carbon emissions economy. 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 2019); 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); using buildings as a global carbon sink (Churkina et al. 2020); reducing bottom trawling (Sala et al. 2021); and developing less-polluting agricultural and industrial processes (e.g. Loboguerrero et al. 2019; Boyle 2021; Mazengarb 2021).

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).

Otto et al. (2019) suggest that a rapid global transformation to carbon-neutral societies will require activating contagious and fast-spreading processes of social and technological change. Positive social tipping dynamics can be induced in many ways: e.g. through strengthening climate education and engagement, disclosing greenhouse gas emissions information, revealing the moral implications of fossil fuels, removing fossil-fuel subsidies, divesting from assets linked to fossil fuels, incentivizing decentralized energy generation, and building carbon-neutral cities.

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.

To achieve the 1.5°C target, IPCC pathways have to assume the large-scale removal of CO_2 from the atmosphere (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; direct CO_2 capture; carbon capture and storage; bioenergy with carbon capture and storage; and carbon capture, use and storage—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). A complicating factor is that rising temperatures reduce photosynthesis, so under business-as-usual emissions, declining rates of photosynthesis will almost halve the carbon land sink as early as 2040 (Duffy et al. 2021). 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.

Although CDR costs are likely to fall as technologies are developed and scaled up (e.g. Plumer and Flavelle 2021), 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 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). Modelling also indicates that a moderate and carefully targeted application of solar aerosols could shave peak temperatures with reduced side effects (Tilmes et al. 2020).

SRM also introduces complex problems of global-scale governance, including risks of unequal distribution of benefits and costs (Reynolds 2019b), and an increased risk of international conflicts (Corry 2017). On the other hand, econometric models indicate that solar geoengineering would reduce inter-country income inequality (Harding, Ricke, Heyen, MacMartin and Moreno-Cruz 2020).

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). Moreover, if greenhouse gas concentrations are allowed to increase there may be a point at which solar geoengineering will not be able to prevent global warming due to stratocumulus clouds thinning (Schneider, Kaul and Pressel 2020). At the same time, a solar radiation management intervention may serve as an "awful action alert" and spur additional emission mitigation (Aldy and Zeckhauser 2020).

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).

Another technology, Iron Salt Aerosols (ISA), may be able to simultaneously decrease both solar radiation and levels of greenhouse gases. This method mimics the climate cooling produced by iron-rich dust storms. ISA first helps to produce clouds, and then falls with the rain to provide a safe micronutrient that will increase the growth of continental plants and marine plankton, greatly enhancing ocean biological productivity. Oeste, de Richter, Ming, and Caillol (2017) estimate that using ISA to double the current level of iron in the air could potentially remove up to twelve gigatons of CO_2 equivalent per year at an estimated cost below one dollar a tonne.

Alarmed by potential risks, many environmental organisations are opposed to even researching many types of geoengineering. However, interest in geoengineering is growing (Flavelle 2020), and whether geoengineering is or is not a good idea, the genie is already out of the bottle. It will not be possible to stop countries from researching and deploying geoengineering: e.g. the US government has approved modest funding for geoengineering research (Temple, 2019), and China is planning to modify weather over an area greater than 5.5 million square kilometers (Griffiths 2020).

China's massive unilateral experiment highlights the urgent need to address the issue of governance in advance of large-scale testing and deployment. While a number of important studies are exploring these issues, research in this area needs to be prioritised and expanded (e.g. National Academies of Sciences, Engineering, and Medicine 2021).

The Special Report on the Governance of Marine Geoengineering (Brent, Burns and McGee 2019) points out that international treaties should be structured to improve governance without being so restrictive as to hinder responsible research and development. Distinctions also need to be made between the likely risks and impacts of diverse CDR and SRM techniques (Florin, Rouse, Hubert, Honegger and Reynolds 2020)—for this reason it will be helpful to separate negotiations on CDR and SRM governance.

Because there are still many unresolved questions about climate geoengineering, research is urgently needed on the relative feasibility, risks and costs of all potential mitigation measures. A useful initial strategy might be to target zero GHG emissions, while deploying portfolios of different CDR technologies, each at modest scales (Minx et al. 2018).

Despite the problems associated with various forms of geoengineering, a diverse range of technologies will be needed to keep warming within safe limits (i.e. an 'all hands on deck' approach is required). The critical problem that must be addressed is that although CDR methods are safer than SRM, they will act too slowly to prevent dangerous overshoot. For example, most coral reefs will die from heat stress by 2040 (e.g. Heron et al. 2017), unless solar geoengineering is used to prevent ocean temperatures from rising.

A comparative assessment of overshoot risks versus mitigation risks is required to enable the development of realistic 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.

While it could be very dangerous to deploy untested methods that are either ineffective or do more damage than good, the consequences could be catastrophic if geoengineering was not deployed in time to avert commitment to significant overshoot. 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).

Opponents of climate geoengineering need to recognise that the alternative to researching and deploying geoengineering is to leave all efforts to limit temperature increases to reducing emissions, a strategy that would be almost certain to fail (Aldy and Zeckhauser 2020). Reynolds (2020) argues that IPCC reports contain many claims about solar geoengineering that are speculative or contrary to existing evidence, and suggests that an IPCC Special Report is needed to accurately assess the advantages and disadvantages of SRM.

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; Buck, Geden, Sugiyama and Corry 2020) 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).

A feasible 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).

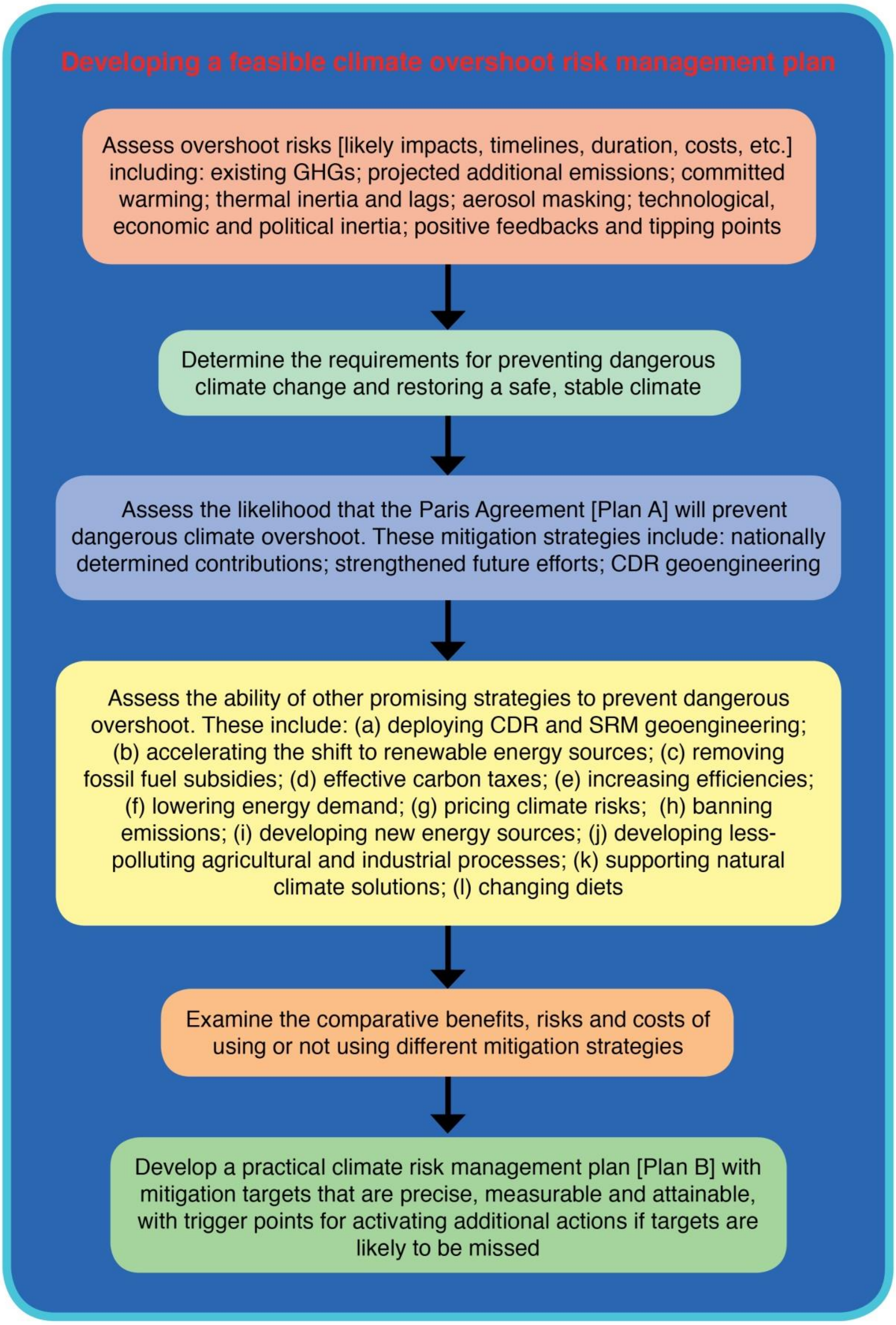

Figure 2. A proposal for developing a feasible climate overshoot risk management plan.

A major obstacle to ambitious action is the United Nations Framework Convention on Climate Change's requirement for consensus—for example fossil fuels are not even mentioned in the Paris Agreement due to the opposition of fossil fuel producing nations to any measures likely to curtail production and sales (Verkuijl and Lazarus 2020). To accelerate change, it will be useful to use a two-track approach, with UNFCC agreements supplemented by climate "coalitions of the willing" (Jayaram 2020) or a "climate club" (Nordhaus 2020): e.g. agreements among nations willing to impose meaningful internal carbon taxes matched by tariffs on all imported goods and services. (A number of these coalitions already exist at state, sub-state and non-state levels, e.g. the Climate Ambition Alliance.) This approach will allow the simultaneous application of both the Paris Agreement ("Plan A") and a realistic risk management plan ("Plan B").

Conclusion: priority needs to be given to developing a feasible 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 alternative feasible strategy—a much stronger Paris Agreement and/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, feasibility, 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. A critical issue is that although CDR methods are safer than SRM, they will act too slowly to prevent dangerous overshoot.

6. Even if met, the Paris Agreement targets would not result in a safe, stable climate since climate stabilization requires reducing the Earth energy imbalance to approximately zero. For this reason EEI needs to be used as the basic metric for measuring the effectiveness of climate change mitigation.

7. To be feasible, a climate change mitigation plan must be based both on what must be done and what can be done to ensure a safe climate, rather than on what is politically expedient.

8. A realistic plan will need to combine three approaches: (a) rapidly reducing GHG emissions; (b) deploying CDR geoengineering to draw down atmospheric carbon; and (c) using solar geoengineering to keep temperatures within safe limits until CO_2e levels have been reduced to a level that stabilizes the climate.

9. A two-track approach utilising "coalitions of the willing" will allow the simultaneous application of both a strengthened Paris Agreement and a realistic "Plan B".

The world faces a key juncture. Not moving off the current trajectory—a likely increase of 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. As the climatologist Hans Joachim

Schellnhuber said, “Political reality must be grounded in physical reality or it’s completely useless.” (Silk 2015)

Despite decades of warnings of the need to cut emissions, emissions have steadily increased. Aldy and Zeckhauser believe that the current crisis is the result of “the considerable heterogeneity among economic analyses of the likely damages associated with climate change; the willingness of environmental experts to focus on unachievable means to reach unachievable goals as a political measure to motivate action; and the intentional inattention of such experts to adaptation and amelioration for fears of moral hazard. A summary assessment of these failings is that policy preferences led analyses, rather than the reverse.” (2020 p. 6)

To improve analysis and policy making, 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, feasible 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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