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PCIC SCIENCE BRIEF: ON PARIS CLIMATE ACCORD EMISSIONS AND TEMPERATURE LIMITS

The 2015 Paris Climate Accord[1] aims to limit global warming to at most 2°C and ideally 1.5°C relative to the preindustrial climate, to limit the impacts of anthropogenic climate change. In this Science Brief, we discuss greenhouse gas emissions budgets and pathways consistent with these warming limits.

Three recent papers in *Nature Climate Change* examine different aspects of these budgets and pathways:

Tokarska and Gillett (2018) use global climate model projections to calculate a new carbon budget for future emissions, relative to the 2006-2015 period, that is consistent with keeping warming to 1.5°C. They find a median remaining carbon budget of 208 billion tonnes[2] from January 2016.

Tanaka and O'Neill (2018) use an integrated assessment model[3] to test whether the Paris temperature limits of 2°C and 1.5°C require zero greenhouse gas emissions, whether a zero net greenhouse emissions limit implies that the temperature limits will be met and what the effect of imposing both emissions and temperature limits are. Their results suggest that meeting the temperature limits doesn't require reducing net greenhouse gas emissions to zero, that reducing emissions to zero doesn't necessarily result in keeping temperatures under the Paris temperature limits by the end of the century, and that the effect of imposing both temperature and emissions limits is that temperatures decline after meeting the initial temperature limit.

Van Vuuren et al. also use an integrated assessment model[3], to develop alternative emissions scenarios that examine how the need for negative emissions[4] may be reduced through implementing other strategies, such as making large-scale lifestyle changes, shifting to renewable energy and switching to more efficient technologies for the production of energy and materials. They find that these strategies can reduce to a small degree, but not eliminate, the need for negative emissions. They also find that these measures have co-benefits such as helping to meet other United Nations sustainability goals[5].

Introduction

In order to minimize the potential impacts of anthropogenic climate change, 196 countries met in Paris, France, in the winter of 2015 for the 21st Conference of the Parties of United Nations Framework Convention on Climate Change. There they negotiated a global agreement on reducing and limiting humanity's greenhouse gas emissions. The resulting Paris Agreement aims to limit global warming to 2°C by the end of the century as compared to the preindustrial period, and ideally 1.5°C.

The contribution of Working Group 2 of the Intergovernmental Panel on Climate Change (IPCC) to the IPCC's Fifth Assessment Report outlines how risks increase as global temperatures increase. The resulting changes to climate pose risks that are too numerous and broad in scope to

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[1] The Paris Climate Accord can be accessed, here: https://unfccc.int/sites/default/files/english_paris_agreement.pdf.

[2] For comparison, annual global emissions for 2015 were about 11 billion tonnes of carbon. Note that this is distinct from carbon dioxide emissions, which were approximately 35 billion tonnes and carbon dioxide equivalent emissions (in which the emissions of other greenhouse gases are described in terms of how much carbon dioxide it would take to match their warming effect) which were roughly 55 billion tonnes.

[3] Integrated Assessment Models (IAMs) couple together a socioeconomic model to a simplified climate model in order to consider political and economic variables together with the physical climate system.

[4] Negative emissions are those processes that remove carbon dioxide and other greenhouse gases from the atmosphere. These can include forestry management, such as reforestation, in which carbon is drawn down and stored in trees, and technological solutions, such as bioenergy with carbon capture and storage, in which biomaterials are burned for energy and the resulting carbon dioxide from this combustion is captured immediately thereafter.

[5] For more information on the United Nations' 17 Sustainable Development goals, see here: https://www.un.org/sustainabledevelopment/sustainable-development-goals/.

be outlined here, but include the loss of biodiversity and ecosystem services, food insecurity and the breakdown of food systems, water scarcity, as well as impacts to infrastructure and lives from increased extreme weather events[6]. British Columbia faces potential impacts that arise both directly and indirectly from increasing temperatures. Those that arise directly includes changes to the frequency and intensity of extreme weather events, changing energy demands and increased wildfire risk. Those that arise indirectly include risks associated with rising sea levels, or changes in water availability due to glacier loss.

These risks exist on a continuum and are smaller with less warming. To minimize risks, global warming should itself be minimized, to whatever extent it is possible to do so. Though the temperature limits set by the Paris Agreement are 2°C and 1.5°C, these are round figures chosen in part for their feasibility and in part as figures to organize international action around. While risks don't increase sharply at 2.1°C, of the Paris Agreement temperature limits, substantial benefits are likely for 1.5°C compared to 2°C. Such benefits include slower sea level rise, less damage to ecosystems and coral, decreased water scarcity[7] and less risk of economic damages[8].

With the Paris Agreement goals in place, we are left with the question of how to reach them. With the acceptance deadline for papers that may be cited in an upcoming IPCC special report[9] on the 1.5°C Paris Agreement temperature limit having just passed, a large volume of research has recently been published in the peer reviewed literature on this topic. Here we discuss three papers, taken from *Nature Climate Change*. These papers examine three related areas: (1) the cumulative remaining carbon budget that is consistent with a warming of under 1.5°C by the end of the century as compared to the preindustrial period, (2) whether a zero emissions goal is necessary to meet the Paris Agreement's temperature limits and (3) whether there are potential mitigation pathways that reduce the need for carbon dioxide removal[10] from the atmosphere.

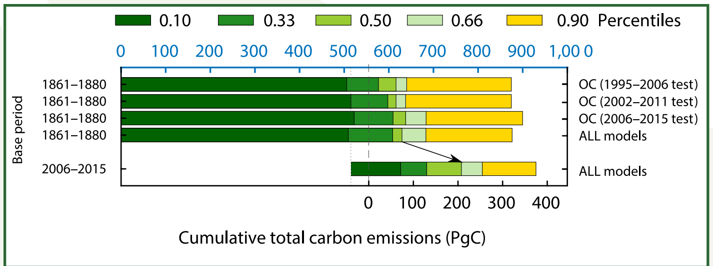

Figure 1: Carbon budgets consistent with a global warming of less than 1.5°C, from Tokarska and Gillett (2018). This figure shows the cumulative frequency distribution of carbon budgets that are consistent with keeping global warming to less than 1.5°C for all 16 models used by the authors (two lower bars) and the subsets of those models that are consistent with observations over three periods (three upper bars, periods as noted on right). The blue horizontal axis corresponds to the carbon budget relative to 1861-1880, for measuring the four upper bars. The black horizontal axis corresponds to the carbon budget since January 2016 and is used for measuring the lower bar. The light grey dotted line shows carbon emissions to the end of 2010 and the dark grey dashed line indicates total cumulative carbon emissions over 1870-2015.

Remaining Carbon Budgets Consistent With 1.5°C Warming

The Earth's average temperature has already increased by about 0.89°C for the decade of 2006-2015 relative to the 1861-1880 period. In order to keep global warming to under 1.5°C, we first need an estimate of the remaining carbon budget. That is, how much we can still emit while having a good chance of remaining under 1.5°C.

Prior attempts to estimate the remaining carbon budget were determined, in part, by looking at past atmospheric carbon dioxide concentrations and using carbon cycle models to calculate what emissions must have been in order to allow for those atmospheric concentrations. Going by these calculations, a budget of about 55 billion tonnes of carbon remains, or about five years of emissions at the current global rate.

However, climate model simulations from models driven with carbon emissions tend to show an overall greater concentration of carbon dioxide than is actually observed,

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6. For an overview of the main findings of Working Group II in the IPCC's *Fifth Assessment Report*, see IPCC (2014).
7. For more information on how physical climate change impacts may vary between 1.5°C and 2°C, see Schleussner, C.F., et al., (2016).
8. For a discussion of the potential economic risks associated with 1.5°C, 2°C and 3°C, see Burke, Davis and Diffenbaugh (2018).
9. The IPCC *Special Report Global Warming of 1.5°C* is still in development as of the writing of this Science Brief. For more information on this report, see here: http://www.ipcc.ch/report/sr15/.
10. Carbon dioxide removal methods vary greatly. They include using chemical reactions to capture the emissions directly at power plants, afforestation and reforestation, fertilizing the ocean, increasing the weathering of rocks that bind carbon and using machines to capture carbon directly from the air. For an overview of methods that remove carbon dioxide from the atmosphere and how they may fit into larger mitigation efforts, see section 6.5.1 of Ciais et al. (2013) and section 6.9.1 of Clarke et al. (2014).

owing to uncertainties in emissions from land use change in the past, and the uptake of carbon from the ocean and land[11]. This may, in turn, lead to an overestimate of total cumulative emissions in the past and an underestimate of the remaining budget for future emissions.

Tokarska and Gillett (2018) develop a new method that uses the output of global climate models to estimate the remaining carbon budget consistent with keeping warming to under 1.5°C by 2100 while reducing the uncertainty associated with land-use change emissions. But, before applying their new method, the authors first test whether repeating the older analysis over the whole time period using only those climate models whose simulated temperatures most closely match observations results in a substantial change to the resulting carbon budgets. They screen the ensemble of 16 models that they have selected and from these pick out only those models that are consistent with observations over three periods. This amounts to 14 models for 1995-2006, 12 models for 2002-2011 and eight models for 2006-2015 (Figure 1). They find that doing so increases the median budget to 74.5 billion tonnes of carbon, larger than the prior estimate of 55 billion tonnes.

In order to come up with a new estimate, Tokarska and Gillett take climate projections starting from the 2006-2015 period, determine when the projections show an additional warming of 0.61°C—which, when added to the 0.89°C warming already experienced, matches the 1.5°C Paris temperature limit—and note the fossil fuel emissions up to that point. This reduces the uncertainty that arises from trying to calculate emissions from land-use change in the past.

Using this method, Tokarska and Gillett arrive at an estimate of about 208 billion tonnes of carbon for the remaining carbon budget (Figure 1), or about 20 years of emissions at the current rate, with a 33-66% uncertainty range of 130-255 billion tonnes of carbon. The authors also test their method using five different choices of observational data sets and arrive at resulting best estimates that range from 174 billion tonnes of carbon to 226 billion tonnes of carbon remaining, depending on the choice of observational data set.

The Consistency of the Paris Agreement's Temperature Limits and Zero-Emissions Goal

In addition to its temperature goals of 2°C and 1.5°C, the Paris Agreement sets the goal of bringing net anthropogenic greenhouse gas emissions down to zero by the second half of this century. This emissions goal is suggested in service of the temperature goals. This raises questions about the consistency of the temperature limits and the zero emissions goal.

Tanaka and O'Neill (2018) break this issue into three questions: Do the temperature goals imply the need for greenhouse gas emissions to fall to zero? Does reducing net greenhouse gas emissions to zero imply that the temperature goals will be met? And, finally, would meeting the temperature limits together with the emissions goals result in a different outcome than meeting only one or the other?

In order to answer these questions, the authors use an integrated assessment model[3,12] and explore three test cases. In the first case, they impose the temperature limits without the zero emissions constraint by calculating emissions pathways that meet the 2°C and 1.5°C temperature limits with the least cost. In the second case, they impose the net zero emissions target at different points in time over the second half of the 21st century, without the temperature constraints, in order to determine the effect that the net zero emissions constraint has on global temperatures. Finally, in the third case, they apply both limits together, to see how this differs from applying each limit individually.

In the first case, Tanaka and O'Neill find that temperatures can be stabilized at 2°C or 1.5°C by dramatic cuts in greenhouse gas emissions that, nonetheless, do not fall to zero. To allow this, emissions would need to drop by nearly 80% relative to 2010 by 2033 to meet the 1.5°C limit, and by nearly 66% by 2060 to meet the 2°C limit. Allowing for an overshoot, in which temperatures briefly rise above the temperature limits before falling below them again, large negative emissions are required for a portion of the century. For the 1.5°C limit, emissions must go to zero by 2070 and remain negative until after 2090. To meet the 2°C limit, they must fall to zero by 2085 and remain negative until just after the end of the century. These results suggest that timing is key if substantial negative emissions are to be avoided. It is also worth noting that, though greenhouse gas emissions don't remain at zero in these cases, the mix of greenhouse gases changes, with carbon dioxide decreasing at all points while emissions of methane and nitrous oxide first decrease and then increase slightly.

In the second case, the authors examine the effect of a zero emissions limit on global temperature. Again, they find that the timing of greenhouse gas emissions reductions is important. If emissions peak by 2030 and are brought to zero by 2060, global temperature peaks at just

[11] For a discussion of these uncertainties, see: Friedlingstein, P., et al. (2014).

[12] For more information on the Integrated Assessment Model used, see Tanaka et al. (2007).

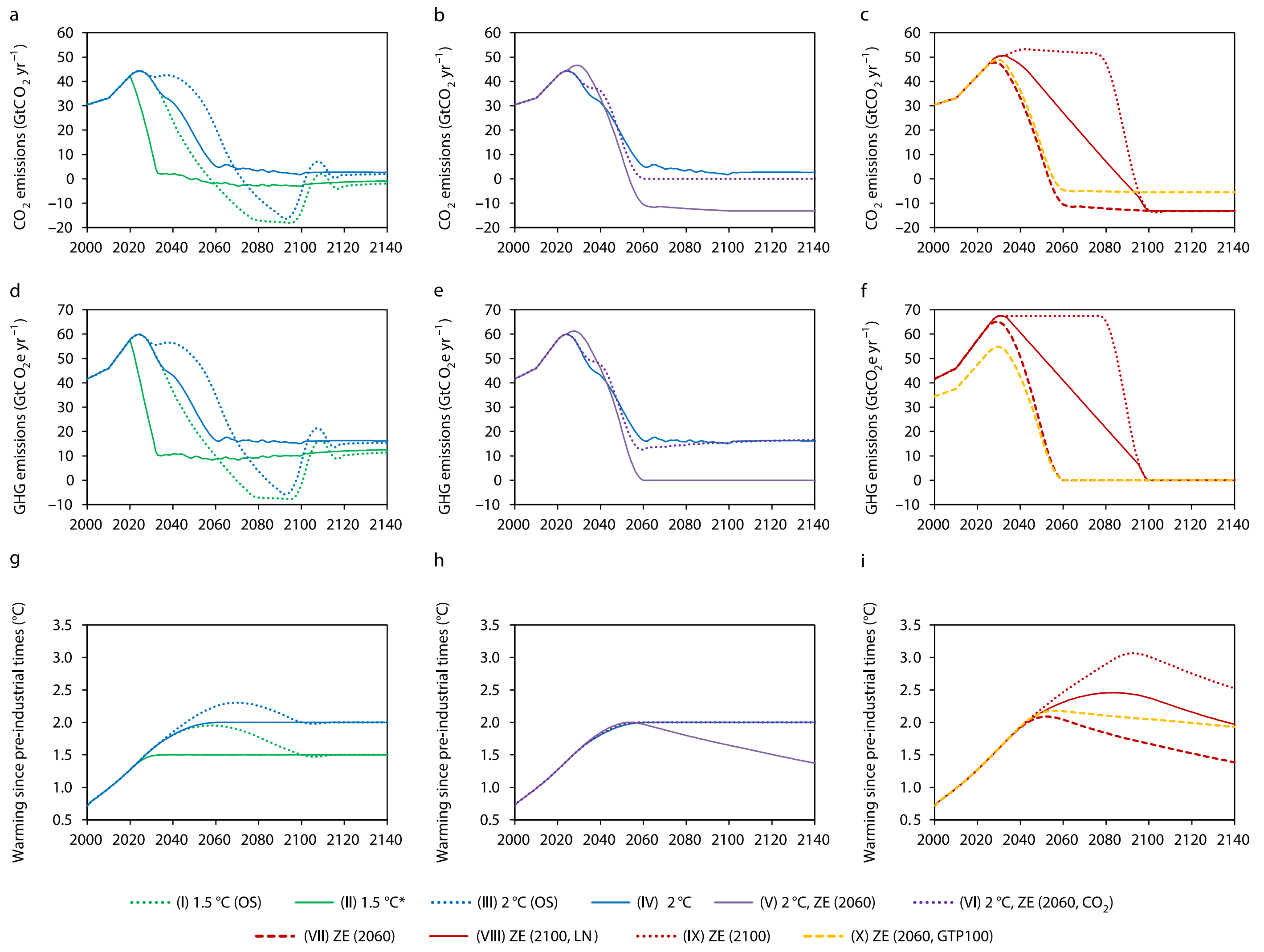

Figure 2: Global Greenhouse Gas Emissions and Warming, from Tanaka and O'Neill (2018).
This figure shows global anthropogenic carbon dioxide emissions (a-c), greenhouse gas emissions (d-f) and warming since the pre-industrial period, for years 2000-2140. OS refers to runs where overshooting the target was allowed, ZE refers to zero emissions and LN refers to a linear decrease in emissions. In the labelling of runs, temperatures refer to temperature targets and years refer to the year at which the goal (e.g. zero emissions) is achieved. Colours and line styles for runs are as marked.

over 2°C in the 2050s and declines thereafter. If a similar approach is taken, but emissions are not reduced to zero until 2100, temperature rises above 2°C in the early 2040s, peaks at about 2.5°C in the 2080s and then slowly lowers, coming down to 2°C in the middle of the 22nd century. If emissions don't start declining after 2030, but are allowed to continue at a constant level until late in the century and then reduced to zero over the period of 2080-2100, when it is cheap to do so, temperatures peak at 3.1°C in the early 2090s and remain above 2.5°C well into the 22nd century.

It is worth noting that the potential impacts of such a warming are widespread and nontrivial[6]. The resulting risks posed by raising global temperatures by even 2°C are defined as high for extreme weather events and impacts to unique and threatened ecosystems (such as Arctic sea ice and coral reef ecosystems), moderate-to-high for unevenly distributed impacts that disproportionately affect the disadvantaged, and moderate for global aggregate impacts and large-scale singular events (such as irreversible shifts in ecosystems and ice sheet collapse).

Turning to the third case, Tanaka and O'Neill apply both the temperature and emissions limits in concert. They find that the addition of the net zero greenhouse gas emissions constraint (which the authors impose at different points in time after emissions peak) causes a decline in temperature after it peaks. However, if only carbon dioxide emissions are brought to zero and the emission of methane and nitrous oxide are allowed to continue, albeit at a reduced level, the result is temperature stabilization at the temperature limit. This is worth noting, because the reduction of carbon dioxide is easier than the elimination of methane and nitrous oxide.

Emissions Pathways That Reduce the Need for Negative Emissions

The Paris Agreement temperature limits of 2°C or 1.5°C may reduce the potential impacts of anthropogenic climate change, but as we have seen, it requires substantial emissions reductions. One way to lessen the need for direct emissions reductions is to require negative emissions. Such negative emissions solutions include Bioenergy with Carbon Capture and Storage (BECCS), aforestation and reforestation, and Carbon Dioxide Removal (CDR) technologies[10].

While scenarios that meet the 1.5°C temperature limit have been made for the report that was mentioned at the start of this Science Brief, this report has not yet been released. However, the IPCC did assess a set of 114 scenarios that led to a median warming of about 1°C—and a likely range that is under 2°C—in its Fifth Assessment Report[13]. Of the 114 scenarios assessed that met this goal, 104 required net negative emissions in the second half of this century.

However, the implementation of negative emissions solutions faces a set of challenges: they are generally expensive; some of the technologies, such as BECCS and CDR are nascent or still under development; some of the options, such as BECCS, require very large amounts of land, and those technologies that capture carbon dioxide directly from the air require large storage areas.

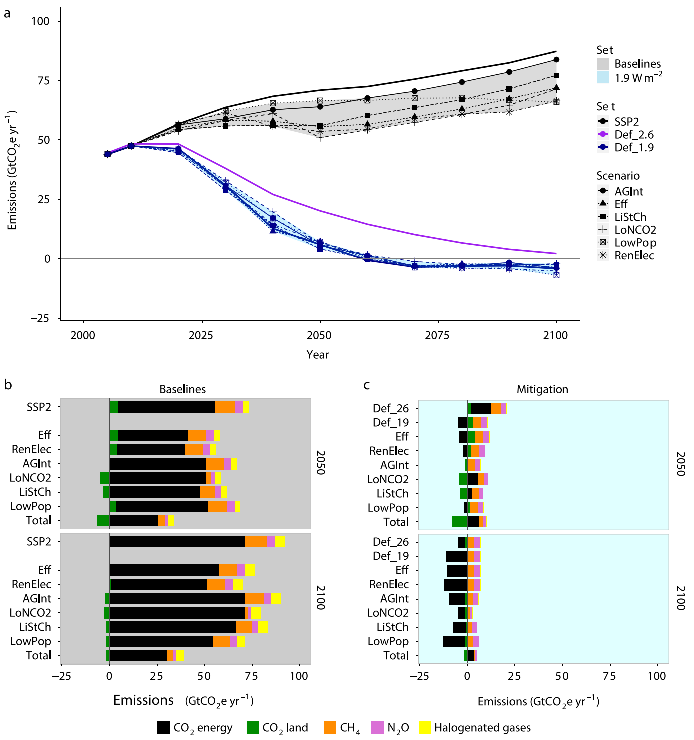

Figure 3: Greenhouse Gas Emissions, from van Vuuren et al. (2018).
This figure shows total emissions over the 2000-2100 period (a) and for baseline (b) and mitigation (c) scenarios (mitigation includes both carbon tax and negative emissions, primarily from BECCS) at 2050 and 2100. Light grey shading indicates baselines and light blue shading indicates scenarios with mitigation. Emissions sources and sinks are indicated by colours as marked.

In order to explore to what extent the need for negative emissions can be reduced, van Vuuren et al. (2018) use an integrated assessment model to develop a number of alternative scenarios in which other measures are taken to reduce anthropogenic greenhouse gas emissions. These are: two different scenarios with carbon taxes of varying stringency; a scenario in which the most efficient energy and material technologies are rapidly deployed; a scenario with rapid deployment of renewable energy; a scenario with increased agricultural yields and intensified animal husbandry; a scenario with implementation of cultured meat in 2050 and the best technologies for reducing greenhouse gases other than carbon dioxide; a scenario involving lifestyle choices that reduce greenhouse gas emissions, such as moderately reducing meat consumption, reducing demand for heating and cooling, reducing energy demand for household appliances and using less carbon intensive personal transportation; a reduced pop-

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13. These scenarios fall under the IPCC's Representative Concentration Pathway (RCP) 2.6. The IPCC uses four trajectories of atmospheric greenhouse gas concentration, known as RCPs for its Fifth Assessment Report. The four trajectories are denoted by the change to radiative forcings that would result from each concentration, e.g. RCP 2.6 would result in an increase of 2.6 Watts per square meter as compared to the preindustrial period (taken to be the year 1750). For more information on the RCPs, see: van Vuuren et al. (2011).
14. This scenario is known as Shared Socioeconomic Pathway 1 (SSP1), part of the scenario framework for the IPCC's FIfth Assessment Report. For an updated overview of the Shared Socioeconomic Pathways, see Riahi et al., (2017).
15. This scenario is known as Shared Socioeconomic Pathway 2 (SSP2), see footnote 14.

ulation grown scenario[14] in which, in addition to reduced inequality and reduced energy intensity, population is limited to 6.9 billion by the year 2100; and a scenario in which all of these solutions are employed. These are compared against a middle of the road control scenario[15] in which social, economic and technological trends follow historical patterns, with inequality, modest population growth and slow adoption of sustainable development goals. The authors then add a stringent carbon tax to the scenarios that didn't involve a carbon tax, to examine how they work with mitigation.

The authors find that even the combination of all of the proposed interventions is insufficient to meet the emissions goals of the Paris Agreement without some form of negative emissions, such as reforestation or BECCS. While negative emissions options are still required to meet the 1.5°C temperature limit, the interventions that the authors explore can be used to reduce the need for negative emissions. The authors also find that, regardless of scenario, a rapid shift in energy consumption and land use is required. Prior to considering any sort of mitigation the scenarios with the greatest impact by 2100 are, in order: the scenario in which of renewable electricity generation is implemented, the scenario in which energy intensity, population and inequality are reduced, and the scenario in which use of efficient technologies for energy and material production are implemented.

Summary

The work of these authors furthers our knowledge of the emissions budgets and pathways that could allow us to meet the 1.5°C and 2°C Paris Agreement temperature limits. While substantial emissions reductions are still required to stay under these temperature limits, the remaining carbon budget may be larger than previously estimated, meaning that these goals may still be reached. In addition, assuming that temperature stabilization at the Paris temperature limits is acceptable, meeting the Paris temperature limits alone may not require reducing all greenhouse gas emissions to zero, though it does require that carbon dioxide emissions be eliminated. This is important, because eliminating carbon dioxide emissions will likely be easier than eliminating all greenhouse gas emissions.

The timing of emissions reduction is also highlighted here, because reducing emissions to zero doesn't necessarily result in meeting the Paris temperature limits by the end of the century if the reduction occurs too late. Finally, the need for negative emissions may be reduced slightly by the implementation of other measures, such as using more renewable energy, implementing more efficient technology in energy and manufacturing and making large-scale lifestyle changes. And importantly, we now have quantitative estimates of to what extent these alternative measures may be helpful.

Though these results may provide for some level of optimism, the underlying message remains: though carbon budgets may be larger than previously estimated, stabilization at the Paris temperature limits may be possible without reducing all greenhouse gas emissions to zero and alternatives to negative emissions may be useful, making substantial cuts in greenhouse gas emissions as soon as possible remains necessary to stay under these temperature limits.

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