COMMENTARY:

Solar geoengineering reduces atmospheric carbon burden

David W. Keith, Gernot Wagner and Claire L. Zabel

Solar geoengineering is no substitute for cutting emissions, but could nevertheless help reduce the atmospheric carbon burden. In the extreme, if solar geoengineering were used to hold radiative forcing constant under RCP8.5, the carbon burden may be reduced by ~100 GTC, equivalent to 12–26% of twenty-first-century emissions at a cost of under US$0.5 per tCO$_2$.

Failure to address the accumulation of atmospheric carbon is among the most frequently noted disadvantages of solar geoengineering[1–3], an attempt to reflect a small fraction of radiation back into space to cool the planet. The latest US National Academy of Science solar geoengineering report[1] states it "does nothing to reduce the build-up of atmospheric CO$_2$".

This is not so. Solar geoengineering reduces the carbon burden, and therefore ocean acidification, due to the three pathways explored here: carbon-cycle feedback[4–8], reduced permafrost melting, and reduced energy-sector emissions.

While it is appropriate to treat solar geoengineering as distinct from carbon mitigation or geoengineering approaches that tackle carbon directly[9], the impact of solar geoengineering on the carbon cycle calls for more integrated research. Solar geoengineering or solar radiation management (SRM) is, in this sense alone, arguably a form of carbon dioxide removal (CDR).

Carbon impacts of solar geoengineering

We calculate the total carbon burden in 2100 and carbon emissions impacts during the twenty-first century by estimating, based on diverse prior literature, the difference between a Representative Concentration Pathway (RCP) 8.5 scenario and one in which solar geoengineering is used to hold radiative forcing at current levels. This is not a complete analysis, but rather a call for further research. It is also a call for assessing solar geoengineering scenarios that go well beyond oft-modelled extreme scenarios that offset total anthropogenic radiative forcing[10]. These rough estimates alone, however, provide suggestive evidence of the potentially large impact of solar geoengineering on the carbon burden and emissions.

Warming can increase the atmospheric carbon burden by increasing ecosystem respiration, decreasing primary productivity, and decreasing oceanic carbon uptake. These carbon cycle feedbacks amplify climate responses to anthropogenic emissions. Point estimates differ widely (see Supplementary Table 1).

We derive an overall range in two steps. First we take estimates of 31 GtC (ref. 5) and 251 GtC (ref. 4) from the only two models that directly simulate the carbon cycle response to RCP8.5 and solar geoengineering, and combine them with the full range of results from a study[11] estimating the carbon response with and without CO$_2$ impact on climate: 42–420 GtC. The latter provides systematic sampling of the uncertainty in the carbon cycle feedback under assumptions that are similar — though not equal — to those that would be used to simulate solar geoengineering to stabilize radiative forcing under an RCP8.5 scenario. We then combine the two ranges using equal weights and uncorrelated error propagation to yield an overall estimate of the contribution of the terrestrial biosphere and ocean of 89–283 GtC (Table 1).

The direct impact of solar geoengineering on the loss of carbon from permafrost soils is unexplored. We instead include estimates from recent intercomparisons of dynamic permafrost models that estimate a decrease in cumulative emissions under RCP8.5 to range from 27 to 122 GtC (ref. 6).

These rough estimates should be interpreted with caution. Caveats include: neglecting the differences between the Special Report on Emissions Scenarios (SRES)-A2 (ref. 11) and RCP8.5 (refs 4–6) scenarios; neglecting the fact that simulating carbon-cycle feedback by eliminating all climate change[11] is, at best, a rough proxy for solar geoengineering; and ignoring more speculative carbon feedbacks such as sea-bed methane hydrates[7]. Moreover, our subsequent rough translation of carbon burden to emissions, and vice versa, does not account for changes in ocean buffering[12].

Table 1 | Reduction in twenty-first-century emissions and in 2100 atmospheric carbon burden in GtC.

Source	Reduction in twenty-first-century emissions (GtC)	Reduction in 2100 burden (GtC)
Carbon cycle (burden)	127–404	**89–283**
Permafrost (emissions)	**27–122**	19–85
Energy sector (emissions)	**24–54**	17–38
Total	232–527	162–369

Estimates show the range of the difference between RCP8.5 and a solar geoengineering scenario with constant twenty-first-century radiative forcing. We derive a primary estimate of either burden or emissions (shown in bold) and then convert it using a fixed airborne fraction of 0.7, based on the RCP8.5 CMIP5 multi-model mean[25]. See Supplementary Materials for details on the calculations.

For a given energy demand and fuel mix, carbon emissions will rise with temperature, as the efficiency of heat engines declines with rising ambient temperature. Warming will also decrease energy demand for heating and increase energy demand for cooling. We use a global estimate of energy demand response to warming in the residential sector[13], roughly scaled to cover the commercial sector as well as transport, along with various estimates of the impact of climate changes on energy use, to yield a rough estimate that avoiding the warming in an RCP8.5 emissions scenario decreases cumulative emission by 24–54 GtC (see Supplementary Materials).

Cost-effectiveness

Risks, uncertainties, and inter-temporal trade-offs make simple cost-effectiveness estimates a poor measure of the overall utility of solar geoengineering. Narrow calculations of costs make solar geoengineering, in particular using stratospheric aerosols, appear 'too cheap'. Our analysis does not claim completeness. There are clearly unquantified and perhaps unquantifiable risks of solar geoengineering. Those may imply that the only relevant decision criterion for solar geoengineering deployment is one based on risk–risk tradeoffs, not one based on cost–benefit analysis. Increased albedo is not anti-CO_2. But when considering solar geoengineering as a means of reducing carbon burdens, cost-effectiveness is relevant because the comparison is to other means of achieving the same result.

We estimate the cost-effectiveness of solar geoengineering's carbon cycle impact using our estimate of the equivalent twenty-first-century emissions reductions of 232–527 GtC (Table 1) converted roughly into 850–1,900 $GtCO_2$. We assume a radiative forcing efficacy[14] of 0.55 Wm^{-2}, triple a prior engineering estimate of aircraft lofting costs[15] for a cost of US$2 billion per Mt per year, use monitoring costs equal to the totality of the current annual US Global Change Research Program budget, rounded up to US$3 billion per year[16], and use a central discount rate of 3% (Supplementary Materials).

Total costs come to approximately US$300 billion for the twenty-first century. That roughly equals estimated equivalent mitigation costs of US$0.2–0.4 per tCO_2, dipping to US$0.1–0.2 per tCO_2 for a 5% discount rate, and increasing slightly to US$0.2–0.5 per tCO_2 for a 2.5% rate. Regardless of the specific range used, these numbers are far below current estimates of the costs of CDR[9], which can go into the hundreds of dollars per tCO_2.

SRM as CDR

If used to offset changes in twenty-first-century radiative forcing under an RCP8.5 emissions scenario, our rough estimates suggest that solar geoengineering could reduce the carbon burden in 2100 by around 160–370 GtC, roughly equivalent to reducing twenty-first-century emissions by 850–1,900 $GtCO_2$ at a mitigation cost of US$0.2–0.4 per tCO_2. Rather than having no impact on carbon, solar geoengineering may be among the most cost-effective methods of limiting the rise in CO_2 concentrations and, therefore, the rise in ocean acidification.

Even with these carbon benefits, solar geoengineering cannot substitute for cutting emissions. For one, our rough estimates, using an extreme scenario, show a total emissions impact of 'only' around 12–26% of total twenty-first-century emissions under RCP8.5 (ref. 17).

Second, the two primary factors we identify here, carbon-cycle feedback and permafrost release, merely move carbon within the biosphere. Only the smaller third factor, via the energy sector, prevents moving carbon from the geosphere. Unlike some forms of CDR, no mechanism here removes carbon from the biosphere and puts it back into the geosphere. Thus, terminating solar geoengineering efforts would lead to a significant adverse carbon impact.

Third, none of this addresses an oft-cited, indirect link via societal responses, often under the heading of 'moral hazard'[18]. Solar geoengineering may have direct implications on nations' and jurisdictions' willingness to cut emissions. The phenomenon is important and empirically still understudied[18,19]. But there is a sharp distinction between political questions about the response to possible or actual deployment of solar geoengineering and technical questions about carbon cycle response. Both questions matter. Policy-relevant analysis must not confuse them.

The need for integrated research

We intend our rough estimate of solar geoengineering's potential to reduce carbon burden not as an answer, but as a spur for further research. That begins with a more detailed look at direct carbon burden and emissions impacts of solar geoengineering scenarios. RCP8.5 is but one such scenario. It must not end there, for a number of reasons.

First, if solar geoengineering is used to stabilize radiative forcing under a scenario with stronger climate policy and lower carbon emissions, then the reduction in carbon burden will be correspondingly smaller.

Second, the amount of solar geoengineering is a policy choice. While climate-modelling studies often assume that solar geoengineering will be used to offset all warming, a moderate scenario with less solar geoengineering is likely a better policy[10]. For example, using solar geoengineering to halve the rate of radiative forcing growth might better balance the risks and benefits[4,10]. Under such a scenario, everything else staying equal, the reduction in carbon burden would likely be roughly halved as well relative to the calculations here. Some carbon impacts also depend on the type of solar geoengineering and specific materials used. Our rough cost calculation, in particular, assumes using sulfate aerosols. Resulting stratospheric ozone depletion may lead to small increases in ocean acidification[20]. Using different compounds[21,22] may have lower effects or even the opposite effect. Marine cloud brightening similarly has direct implications on emissions, carbon burden[23], and, thus, also ocean acidification[24].

The third reason is moral hazard: the need to consider social and societal responses beyond the technical calculations.

Sensible policy decisions about both emissions mitigation and solar geoengineering will be aided by better estimates of the carbon-cycle benefits of solar geoengineering and of the way the reduction in carbon burden scales with the amount of solar geoengineering and mitigation. A coordinated research effort should aim to understand the coupling between solar geoengineering, CDR, the energy system, and the 'natural' carbon cycle. Policymakers cannot make sound choices without a sustained, integrated research programme. ❐

David W. Keith and Gernot Wagner are at the Harvard John A. Paulson School of Engineering and Applied Sciences, 12 Oxford Street, Cambridge, Massachusetts 02138, USA, and Harvard Kennedy School, 79 John F. Kennedy Street, Cambridge, Massachusetts 02138, USA. Claire L. Zabel is at The Open Philanthropy Project, 182 Howard Street #225, San Francisco, California 94105, USA.*

**e-mail: david_keith@harvard.edu*

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Additional information

Supplementary information is available in the online version of the paper.

Competing financial interests

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COMMENTARY:

Catalysing a political shift from low to negative carbon

Glen P. Peters* and Oliver Geden

Policymakers are beginning to understand the scale of carbon dioxide removal that is required to keep global warming "well below 2 °C". This understanding must now be translated into policies that give business the incentive to research, develop and deploy the required technologies.

Following the publication of the IPCC's Fifth Assessment Report, 'negative emissions' came under intense scrutiny. The criticism mainly focused on the conceptual use of immature carbon dioxide removal (CDR) technologies to meet the 2 °C target in Integrated Assessment Models (IAMs), and on the potential risks of deploying CDR technologies at scale[1–5]. Most attention has been placed on bioenergy combined with carbon capture and storage (BECCS), a technology that both produces energy and removes carbon, and which is the CDR technology dominant in most IAMs.

The political implications of large-scale CDR have remained largely out of the debate. In principle, the governments that signed and ratified the Paris Agreement accept the IPCC consensus that CDR cannot be avoided if ambitious climate targets like 1.5 °C or 2 °C are to be met. But so far, there is no debate on the one issue that usually dominates UN climate negotiations — differentiation and burden sharing. Which countries are going to start CDR first? Which countries will deliver the bulk of the CDR? Currently, no countries have mentioned BECCS in their Nationally Determined Contributions, and only about a dozen even mention the key ingredient of carbon capture and storage.

Entering negative territory

In Paris, governments not only agreed on limiting temperature increase to "well below 2 °C" and possibly even to 1.5 °C, they also set a target of reaching a balance between emission sources and sinks in the second half of the century[6]. Officials are now learning that even if they only strive for a balance between sources and sinks, they need CDR to counteract residual emissions in hard-to-mitigate sectors, such as industrial and transport subsectors and CH_4 from agriculture. Since we have emitted so much already, CDR is also required to offset some earlier or ongoing carbon emissions. According to IAMs, CDR starts as early as 2020, reaches 10–20 $GtCO_2$ per year in 2100 (25–50% of current annual emissions), and cumulatively removes 400–800 $GtCO_2$ by 2100, a size comparable to the remaining carbon budget[7]. Most policymakers, heads of state and governments seem to be unaware of the broader political implications[8].

In policymaking, mitigation efforts are often referenced to the percentage reductions from a given base year. The (net) zero line — or reducing emissions by 100% — has been the conceptual reference point. Because UN climate negotiations are generally based on the principle of 'common but differentiated responsibilities' (CBDR), it could be expected that industrialized countries will reach the zero line earlier than emerging economies and developing countries. Aiming at net negative emissions — emission reductions of more than 100% — would probably perpetuate CBDR, both in the timing of net zero and the scale of negative emissions. New or prolonged conflicts about global burden sharing would be inevitable. Emerging and developing countries are likely to demand that industrialized countries invest more in CDR, whilst they themselves might not even reduce their own emissions to zero.

Country and sectoral distribution

Most, if not all, discussions of CDR have been at the global level. This is an unhelpful abstraction, as individual actors must deliver CDR. The next simplest form of abstraction, useful for climate policy negotiations, is the country level. To assess the potential political conflicts, we compared the output from four cost-optimal IAMs[9,10] (Fig. 1). China, the USA, the EU28 and India take the lead in ramping-up BECCS until 2050, with cumulative values of 5–10 $GtCO_2$ up until 2050 (median outcomes: China, 10 $GtCO_2$; the US and EU, 7.5 $GtCO_2$; and India, 6 $GtCO_2$). These countries also provide the largest cumulative contributions over the twenty-first century (median outcomes: China, 80 $GtCO_2$; the US, 60 $GtCO_2$; India and the EU, 50 $GtCO_2$; Brazil, 40 $GtCO_2$; and Russia, 30 $GtCO_2$), but they still represent less than half of the cumulative global CDR total.