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Crutzen +10: Reflecting upon 10 years of geoengineering research

Research for assessment, not deployment, of Climate Engineering: The German Research Foundation's Priority Program SPP 1689

Andreas Oschlies[1] and **Gernot Klepper**[2]

[1]GEOMAR Helmholtz Centre for Ocean Research Kiel, Kiel, Germany, [2]Kiel Institute for the World Economy, Kiel, Germany

Abstract The historical developments are reviewed that have led from a bottom–up responsibility initiative of concerned scientists to the emergence of a nationwide interdisciplinary Priority Program on the assessment of Climate Engineering (CE) funded by the German Research Foundation (DFG). Given the perceived lack of comprehensive and comparative appraisals of different CE methods, the Priority Program was designed to encompass both solar radiation management (SRM) and carbon dioxide removal (CDR) ideas and to cover the atmospheric, terrestrial, and oceanic realm. First, key findings obtained by the ongoing Priority Program are summarized and reveal that, compared to earlier assessments such as the 2009 Royal Society report, more detailed investigations tend to indicate less efficiency, lower effectiveness, and often lower safety. Emerging research trends are discussed in the context of the recent Paris agreement to limit global warming to less than two degrees and the associated increasing reliance on negative emission technologies. Our results show then when deployed at scales large enough to have a significant impact on atmospheric CO_2, even CDR methods such as afforestation—often perceived as "benign"—can have substantial side effects and may raise severe ethical, legal, and governance issues. We suppose that before being deployed at climatically relevant scales, any negative emission or CE method will require careful analysis of efficiency, effectiveness, and undesired side effects.

Key Points:
- The bottom–up approach of concerned scientists has developed into an interdisciplinary research program to assess climate engineering
- Research aims at critical assessment of climate engineering, not its deployment
- A general trend of results so far indicates that the potential of climate engineering becomes smaller the closer we look

Corresponding author:
A. Oschlies, aoschlies@geomar.de

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1. Introduction

The ongoing rapid increase in atmospheric CO_2 concentrations despite sound scientific evidence about its climatic impacts and despite all political efforts to reduce anthropogenic CO_2 emissions at national and international levels has brought climate engineering (CE) ideas more and more into the focus of the scientific and political search for possible options of action. In the years following *Paul Crutzen's* [2006] editorial, the debate intensified, and an increasing number of media reports, scientific reviews, and new scientific research appeared on the scene.

In Germany, early scientific research on CE included work on simulating solar radiation management, which later became part of the European Implications and risks of engineering solar radiation to limit climate change (IMPLICC) project [*Schmidt et al*., 2012] and the Geoengineering Model Intercomparison Project [GeoMIP, *Robock et al*., 2011]. At the Marsilius Kolleg at the University of Heidelberg, an interdisciplinary research project was established in 2009 with a cohort of PhD students from different disciplines investigating various aspects of CE. A group of oceanographers at the Alfred Wegener Institute in Bremerhaven engaged in small-scale field experiments in the Southern Ocean to study biogeochemical and ecological impacts of iron fertilization, the latest of which became known as the German-Indian LOHAFEX experiment carried out from the German research icebreaker RV Polarstern in early 2009. After protests from non-governmental organizations and concerned citizens, the relevant federal ministries called for a rapid independent scientific assessment regarding possible side effects and the legal situation before the experiment could be allowed to go ahead. This happened while the ship was already on its way from Cape Town into the Southern Ocean. The concentrated and intensive effort of writing these assessments within a few days brought together scientists from different disciplines to assess the justification and possible implications of the planned experiment and stimulated further work, leading to several interdisciplinary scientific publications regarding iron fertilization [*Güssow et al*., 2010; *Oschlies et al*., 2010; *Rickels et al*., 2010, 2012].

2. First Steps Towards a Coordinated Research Strategy

Apart from these early uncoordinated and often narrowly focused local research efforts, the German scientific community had been mostly reluctant, if not skeptical, to engage in research on geoengineering. Traditionally, the focus of research has been on mitigation, which has also been in the centre of the public debate and societal efforts, such as the "Energiewende," and many scientists did not even regard CE as a sensible option [*Schellnhuber*, 2011] worth studying. However, in response to the intensifying international debate, in summer 2008, the National Committee for Global Change Research, jointly funded by the German Research Foundation (DFG) and the Federal Ministry of Research (BMBF), initiated the first of a series of DFG-funded round table discussions that were open to all scientists eligible for DFG funding. This event, entitled "Geoengineering – the Role of the Sciences," brought together about 40 concerned scientists from a wide range of scientific disciplines, including natural sciences, social sciences, international law, and ethics. The aim of this bottom–up approach was to collaboratively develop a responsible framework to identify the relevant scientific issues regarding CE and to discuss whether, and if so, what kind of research might be required to better inform the scientific and political debate surrounding CE.

The series of interdisciplinary round table discussions gained momentum over subsequent meetings held in Eisenach, Kiel, and Hildesheim between 2010 and 2012. In parallel, the BMBF commissioned a scoping study to describe the state of the debate on CE, which was written by an interdisciplinary group of authors, many of them part of the round table discussions [*Rickels et al*., 2011]. Following the earlier Royal Society report [*Royal Society*, 2009], the more detailed BMBF study provided a comprehensive survey of scientific, economic, political, social, ethical, and legal aspects of the CE debate. The various CE methods were categorized into radiation management (RM, which largely overlaps with solar radiation management [SRM] but also includes ideas to modify the long-wave radiation impacts of cirrus clouds) and carbon dioxide removal (CDR).

Initially, interdisciplinary discussions put a lot of weight on the intricacies of SRM, arguably the CE idea that had been discussed predominantly and most controversially in the international scientific community, including *Crutzen's* [2006] paper. While a number of international studies had investigated the potential and some environmental impacts of idealized deployments of SRM, less scientific information was available on most CDR methods (with the possible exception of marine iron fertilization). Questions surrounding legal, economic, societal, and ethical issues of SRM and CDR were just beginning to be addressed by the scientific community. In the round table discussions, the aim therefore emerged to develop a thorough, critical, and unbiased analysis and assessment of CE across a broad range of scientific, environmental, economic, social, legal, political, ethical, and communicative dimensions. To facilitate the provision and exchange of information among the scientists (most of those participating in the round table discussions had not previously been engaged in CE research) and the interested public, the website www.climate-engineering.eu was established at the Kiel Earth Institute in summer 2011, which since then collects and provides all available national and international information regarding CE on a daily basis.

3. The Emergence of the DFG-Priority-Program on CE

In light of the intensifying international scientific debate about CE and personal concerns regarding the need to critically assess CE in an unbiased and transparent framework, members of the round table discussions decided to apply for a Priority Program, a special funding instrument offered by the DFG that aims at regionally distributed, dedicated interdisciplinary research activities. In this funding scheme, a first review process evaluates a framework proposal and subsequently approves the installation and the funding volume of such a Priority Program. In the second round, an open call for individual proposals is issued, and all DFG-eligible scientists can bid into this funding envelope, again in a bottom–up fashion. A scientific review panel that is independent of the Priority Program's coordinator(s) then evaluates these proposals, ensures scientific quality, and eventually decides about the composition of the individual projects funded within the Priority Program. The open call and independent review process ensured a fair and unbiased science-driven bottom–up procedure and successfully brought in a number of scientists not previously involved in CE research.

A first attempt to install such a Priority Program in 2011 failed since the DFG Senate was not convinced that research on CE should be funded at all by the DFG. The Senate therefore asked the National Committee for

Global Change Research as well as the two DFG senate commissions for oceanography and for future tasks of the geosciences to prepare a statement specifying whether research on CE should be supported by the DFG and, if so, suggesting fundamental research needs regarding CE. This statement, available only in German (dfg.de/dfg_magazin/forschungspolitik_standpunkte_perspektiven/climate_engineering/index.html), acknowledges substantial research needs addressing scientific questions regarding CE and recommends multidisciplinary research for assessment and not deployment of CE, specifically with respect to evaluating effects and side effects considering the scientific, technical, political, legal, societal, and ethical dimensions. The Senate of the DFG endorsed the statement and opened the way for a reconsideration of the research proposal.

A revised proposal for setting up the Priority Program addressed these recommendations and was submitted by the consortium of concerned scientists in autumn 2011 and approved in spring 2012 under the name "SPP 1689: Climate Engineering – Risks, Challenges, Opportunities?" with a funding envelope of about 5 Mio Euros for each of the two 3-year funding periods. The main scientific aims put forward in this framework proposal were:

1. Assessing the potential effects, uncertainties, and challenges of CE
2. Evaluating the legal, moral, and public acceptability issues of potential CE measures

To organize the research, three classes of exemplary CE measures were chosen to address atmospheric, oceanic, and terrestrial measures: aerosol injection into the troposphere and stratosphere, ocean alkalinization, and terrestrial biomass CDR. These three classes were selected because they differed not only in approach and deployment but also in response timescale, climate-change potential, and likely extent of potential side effects. They were also considered to cover a large part of the spectrum of ethical, cultural, legal, political, and other societal issues.

Individual proposals had to address at least one of the scientific aims and one of the exemplary CE measures. They also had to be genuinely interdisciplinary or be closely linked to a partner proposal from a different discipline. After careful evaluation by an international review panel, the first phase of the Priority Program started in spring 2013 with nine scientific projects and one coordination project. Altogether, 19 PhD-students and 7 PostDocs were funded at 16 institutions distributed all over Germany with partners in Austria and France. In the spirit of the bottom–up initiative of concerned scientists that led to the Priority Program, all interested scientists who could not be funded within the limited funding envelope were invited to become associated members of the Program. They were asked to submit a brief statement of interest that had to be approved by the Priority Program's executive board consisting of one voting member per participating institute. All members and associated members have full access to unpublished data and model output generated within the Program; they are also invited to all project workshops. Workshops are held about twice a year to foster collaboration across disciplines and among the different participating institutions. Additional workshops have been set up among the PhD students to inform each other about their respective disciplinary research approaches. A complete list of projects, activities, and publications can be found at www.spp-climate-engineering.de/.

4. Key Findings of the First Phase of the Priority Program

Key findings of the first phase include a first comparison of different CE measures within a single, intermediate-complexity Earth system model [*Keller et al*., 2014], which revealed that even under optimistic assumptions about large-scale deployment, the CDR methods investigated are unlikely to have sufficient potential to turn the climate of a high-emission scenario (IPCC's Representative Concentration Pathway [RCP] 8.5 scenario) into one resembling a medium mitigation one (RCP 4.5). An unexpected side effect of simulated SRM was a substantial increase in terrestrial carbon storage, predominantly in soils, resulting from reduced respiration at lower temperatures. (We refer to side effects as any effect that is not the primary target of the respective CE method. There is no value judgment in this term. One person could view an effect positive that another one may perceive as negative.) For the simulated SRM intensity, the associated drawdown in atmospheric CO_2 was even larger than for any of the simulated massive CDR deployments [*Keller et al*., 2014]. After termination of SRM, most of the carbon stored was quickly released back to the atmosphere, resulting from enhanced respiration in response to the rapid warming after termination known from earlier studies [*Matthews and Caldeira*, 2007]. Large-scale afforestation generated a substantial

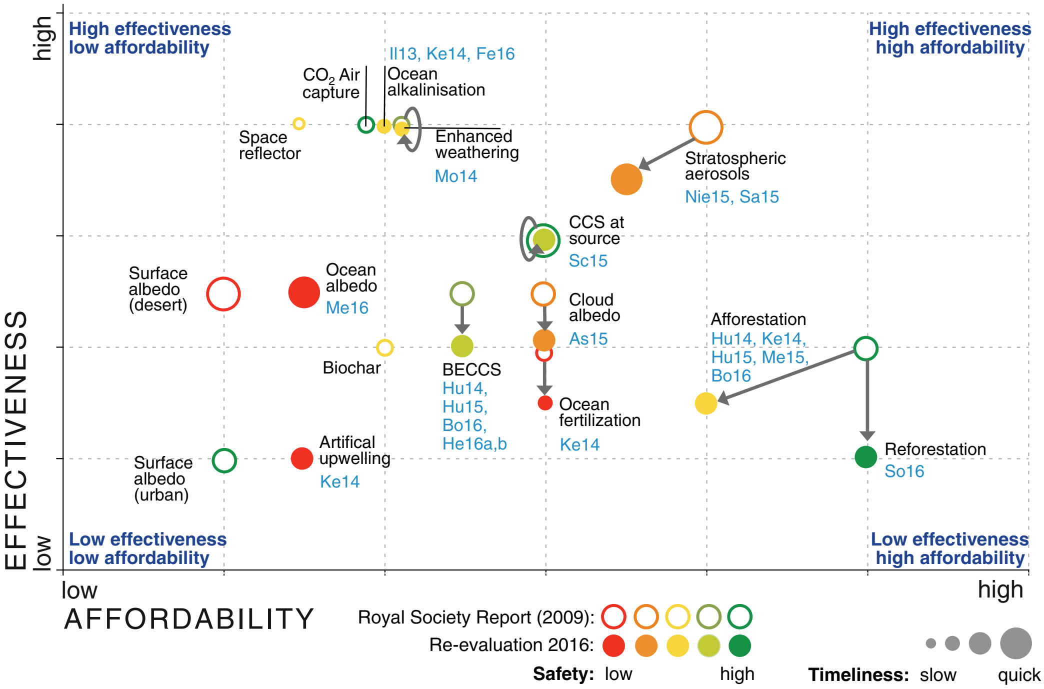

Figure 1. Update of the "blob" diagram of the *Royal Society* [2009] report that assessed individual CE ideas with respect to the dimension's effectiveness (vertical), affordability (horizontal), timeliness (blob size), and safety (color). Arrows indicate the direction of change in the assessment by new studies since the Royal Society report. Abbreviations in blue refer to the first letters of the first author's name and year of the respective publication of the Priority Program [Ilyina *et al.*, 2013; Humpenöder *et al.*, 2014, 2015; Moosdorf *et al.*, 2014; Aswathy *et al.*, 2015; Mengis *et al.*, 2015, 2016; Saxler *et al.*, 2015; Bonsch *et al.*, 2016; Sonntag *et al.*, 2016 in addition to references cited elsewhere in the paper], all provided in the reference list of this article.

albedo modification in the model that even led to a net warming of the planet. The simulated massive deployment of different CE measures in a single model showed that at scales large enough to have a significant climate impact in a high-emission world, CDR and SRM methods may be accompanied by side effects and raise governance issues, which are more similar than assumed previously (as, e.g., reflected in the separation of the National Academy of Sciences' report on Climate Intervention into CDR and SRM parts).

Other studies performed in the framework of the Priority Program found that the costs of CE often tended to be larger [*Klepper and Rickels*, 2014] and efficiencies lower [*Niemeier and Timmreck*, 2015] than previous studies had estimated. Overall, results of the Priority Program obtained so far tend to indicate that the closer one looks, the less efficient CE becomes. This is illustrated by an update of the earlier schematic "blob diagram" of the *Royal Society* [2009] report (Figure 1), which had been developed to provide a visual image of four dimensions of various CE measures.

The figure shows, on the vertical and horizontal axes, effectiveness and affordability of the different CE options using a qualitative scale. The size and the color of the dots represent their timeliness and safety. Note that there is no well-defined scale for any of the dimensions nor are these the only issues relevant for CE. They also include ethical, social, and political aspects; governance issues; and public perception and acceptance (see, e.g., *Kruger* [2015] for a critique of this diagram). Here, we show relative changes in the assessment of different CE ideas inferred from studies published as part of the Priority Program, acknowledging that other dimensions were also investigated. Studies on ethical aspects [*Sillmann et al*., 2015; *Baatz et al*., 2016] proposed that far-reaching mitigation is morally obligatory prior to any engagement into SRM [*Baatz*, 2016], and the examination of public perception and acceptance of CE revealed that knowledge about the possibility to lower global temperature through aerosol injection does not reduce individual mitigation efforts [*Merk et al*., 2016].

Overall, "blobs" have moved predominantly downward toward lower effectiveness but also to the left, i.e., indicating also higher cost of deployment. Many colors have moved into the direction of red, indicating lowered estimates of safety. The size, i.e., timeliness of one "blob," "CCS at source," has decreased because of new concerns about the speed of developing access to large-enough CO_2 storage sites in time [*Scott et al*., 2015]. None of the changes in assessment were toward higher effectiveness, high affordability, higher safety, or greater timeliness. The fact that the majority of changes with respect to the original Royal Society diagram have occurred along the vertical "effectiveness" axis is likely due to the timing of the studies. Many initial studies of the Priority Program had a predominantly natural sciences focus since they provided scenario results for other disciplines in their assessment of CE. Research on other dimensions such as the cost of CE measures (the axis affordability) have often started later and are still in progress, and some are not yet published.

5. Current Trends in CE Research

The intensive research activities and their results obtained during the last few years have begun to change the view of scientists on CE. The results of careful and critical scientific assessments of the sometimes visionary technological possibilities for a targeted manipulation of the earth system have reduced the enthusiasm about CE as a potential tool to combat undesirable climate effects of the fossil fuel-based world economy. At the same time, the Fifth Assessment Report (AR5) of the IPCC concluded that the objective of keeping global warming below 2°C within this century would most likely require substantial negative emissions in the second half or toward the end of this century. Creating negative emissions is more or less equivalent to using CDR technologies. Since all states at the 21st Conference of the Parties (COP21) of the United Nations Framework Convention on Climate Change in Paris at the end of 2015 have agreed to try to keep global warming well below 2°, CDR has essentially been added to the policy agenda for introducing measures that aim at reducing CO_2 emissions as far as possible and even move toward negative emissions. Current scenarios that meet these ambitious climate goals require negative emissions particularly in the electricity sector and in different land use practices, such as in forestry. Interestingly, the Paris agreement has been carefully crafted without CDR being mentioned. On the other hand, SRM has not entered the debate in similar proportions as the focus in policy is still predominantly on controlling carbon emissions and maintaining or enhancing the "natural" carbon sinks instead of controlling temperature directly.

In that sense, 10 years after *Crutzen*'s [2006] paper that concentrated on SRM as the only CE option to complement mitigation in case of a "climate emergency," CDR is now getting increasing attention as a means for complementing insufficient mitigation efforts. This is especially the case since the AR5 contains many scenarios with negative emissions. Despite this, AR5 has not explained in detail how the negative emissions could be achieved in practice. The feasibility and the economic cost of different CDR measures are still poorly known. Most importantly, even for those CDR technologies for which the practical functioning is better known, it is not clear how such technologies can be scaled up to levels necessary to reach the desired quantities of CO_2 to be removed from the atmosphere. These uncertainties refer to the quantities of material inputs or natural resources such as land or water that need to be devoted to CDR activities. Even methods perceived as "green," such as afforestation or bioenergy, may not appear green once scaled up to have a substantial climate impact [e.g., *Heck et al*., 2016a, 2016b]. Uncertainties also exist with respect to potential unintended ecological side effects of globally unprecedented CDR activities. The combination of economic and ecological challenges for large-scale CDR activities is still not sufficiently investigated. Finally, the societal and political support is currently not obvious. Using the oceans as carbon sinks is legally not allowed, underground storage of CO_2 onshore or in submarine reservoirs is not supported politically, and it is economically not viable at current explicit or implicit carbon prices. A consensus about the necessity or desirability of a large-scale, possibly global, manipulation of terrestrial or marine ecosystems is not in sight. The planned IPCC's special report on 1.5°C warming will likely discuss negative emission strategies in greater detail, and ongoing research on CDR, such as that performed as part of the Priority Program, is expected to be highly relevant also in this perspective.

The second 3-year phase of the Priority Program that starts right now will pay specific attention to the new developments in the direction of CE research. Although all the proposals of the approved 10 projects (six of which are extensions of first-phase projects) had to be submitted just before the Paris COP21 meeting, there was a larger emphasis on negative emission technologies compared to SRM than in the first phase. While the call for proposals for the first and second phases of the Priority Program was virtually identical and equally open to proposals addressing CDR and SRM, the somewhat larger emphasis on CDR in the second phase reflects the scientific interest in the bottom–up process of individual scientists submitting proposals addressing research questions they find interesting and challenging. These individual decisions may also be influenced by the current policy dynamic with its focus on negative emissions and CDR, but they are not imposed by the Priority Program itself. The emphasis on CDR is, however, not exclusive. One new project on RM will, for example, investigate a relatively new proposal of altering polar-winter cirrus clouds to affect long-wave radiation, which could turn out as a RM option that may yield climatic effects more similar to those of CO_2 reduction than previously investigated SRM approaches. No field experiments will be performed within the Priority Program, although we envisage that small-scale feasibility studies and full life-cycle assessments may be addressed by possible follow-on projects funded by different schemes.

The coordination project of the Priority Program has successfully applied for flexible funds to carry out a few thematic workshops, which can be used to react to new developments, help bring together different participating projects and the international scientific community, and also bring together scientists and stakeholders. The first such workshop, entitled "On the 1.5°C target and climate engineering," has just taken place in Kiel with some 80 scientists and stakeholders (http://www.spp-climate-engineering.de/SPP1689WorkshopKielNov16.html). Through such activities, the Priority Program aims to move from scientifically driven fundamental research toward answering policy-relevant research questions. Special research foci currently discussed by several projects of the Program are the investigation of trade offs between different CE schemes and mitigation and the necessary development of appropriate indicators and metrics as well as decision analysis frameworks (see article by *Oschlies et al*., 2016, in this special issue). Thanks to its interdisciplinary culture and its ambition for transparent research, the Priority Program is viewed as a promising tool to engage the scientific disciplines relevant for a comprehensive assessment of CE and to constructively engage in the discussion with stakeholders and policymakers.

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