 Article

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The social costs of solar radiation management

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In this essay, we argue that the all-things-considered "price" of Solar Radiation Management (SRM) is much higher than its modest technical costs would indicate. First, we estimate that Stratospheric Aerosol Injection (SAI) will generate between \$0 and \$809 billion annually in side-effect harms, while the number is likely to be considerably higher for Marine Cloud Brightening (MCB). Second, SRM would depend on unprecedented international cooperation and, therefore, risk global instability. Third, politicians may hesitate to support SRM since they may be held politically accountable for everyday "bad" weather as well as extreme weather events. Fourth, SRM poses "termination risks." Finally, we observe that when the holistic, "true" cost of SRM is fully accounted for, the comparison between SRM and what we term "large-scale" Carbon Dioxide Removal becomes complex.

Multilateral emissions treaties have proven to be an inadequate response to climate change, with growth in emissions from China, India, and other developing nations overwhelming the very modest emissions reductions in the United States and the European Union[1]. Indeed, every year since the first emissions treaty was adopted in Kyoto in 1997, global carbon emission and atmospheric carbon dioxide levels have increased steadily[2]. Even with significant advances in clean energy technologies and rising global concern over the warming planet, humans released 37.8 billion tons of carbon dioxide in 2024 due to energy combustion and industrial processes—the highest ever annual level[3].

Given the apparent limitations of emissions treaties, many climate scientists and activists now envision climate intervention as a supplemental solution to climate change[4,5]. While historically lumped together under the category of "geoengineering"[6,7], there are two distinct forms of climate intervention: (1) Solar Radiation Management (SRM), which seeks to reflect solar radiation back to space, most promisingly by injecting sulfur gasses into the stratosphere (SAI) and by seeding clouds over the ocean surface (MCB); and (2) Carbon Dioxide Removal (CDR), which seeks to absorb and store atmospheric carbon dioxide, for instance with "direct air capture" technology that collects carbon from the air anywhere on Earth (DAC) and with approaches that capture the carbon released when biomass is converted into a fuel source or burned directly to generate energy (BECCS). For simplicity, we do not focus on more localized forms of CDR in this paper, such as land- or nature-based methods like planting trees or improving soil carbon uptake[8]. Meanwhile, our SRM analysis is narrowly focused on SAI and MCB, disregarding other potentially important albedo modification methods that are applied at the regional scale[9].

In this essay, we argue that the all-things-considered "price" of Solar Radiation Management (SRM) is much higher than its merely technical costs would indicate. In recent years, SRM has drawn increasing support due to its "incredible" back-of-the-envelope economics[10], which promise to reduce global mean temperature by 1 °C for approximately \$18 billion a year in deployment and maintenance costs[11]—about the annual revenue of California's organic agriculture sector. By contrast, the economic damages from unmitigated climate change are projected to reach into the trillions annually, making SRM appear extraordinarily cost-effective. However, SRM comes with at least four political and social challenges that are not accounted for in such calculations. First, best estimates from Irvine et al. indicate that SAI will harm 0% to 7% of the world's population as a side-effect[12], such that those people would demand compensation from the technology's winners. Using existing (and conservative) metrics to calculate the amount of side-effect harm for SAI, we estimate that such harms would fall between \$0 and \$809 billion annually. The number would likely be considerably higher for MCB since it is deployed regionally and imposes stronger side effects than SAI in places beyond the target region[13]. Second, SRM would depend on unprecedented international cooperation and consensus and, as a result, risk global instability. Third, given that voters tend not to reward politicians for preventing would-be future harms but do tend to punish them for creating present harms, politicians may hesitate to support SRM given that they may be held politically accountable for everyday "bad" weather as well as extreme weather events. Fourth, SRM poses "termination risks," meaning that if deployment stopped suddenly, the global temperature could rise very rapidly until it matches the atmospheric carbon concentration.

Finally, we observe that when the holistic, "true" price of SRM is fully accounted for—that is, its all-things-considered set of costs and risks—the comparison between SRM and what we term "Large-Scale" CDR (LCDR) becomes complex. We envision an immense program of DAC and BECCS that is administered by a consortium of developed states and which is

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capable of capturing 10 to 20 gigatons of carbon each year[14,15]. Were the industry target of $100 per captured ton of CO2 achievable[5], the consortium could absorb roughly a quarter of the amount of humanity's 2024 emissions (9.5 gigatons) for $950 billion a year in public spending —about 1% of global GDP[16], or approximately the size of the US Defense Department's 2024 budget[17]. While accepting that the technical costs of SRM should be dramatically cheaper, we demonstrate that none of the four challenges that may beset SRM would apply to LCDR to nearly the same degree (Fig. 1).

Results

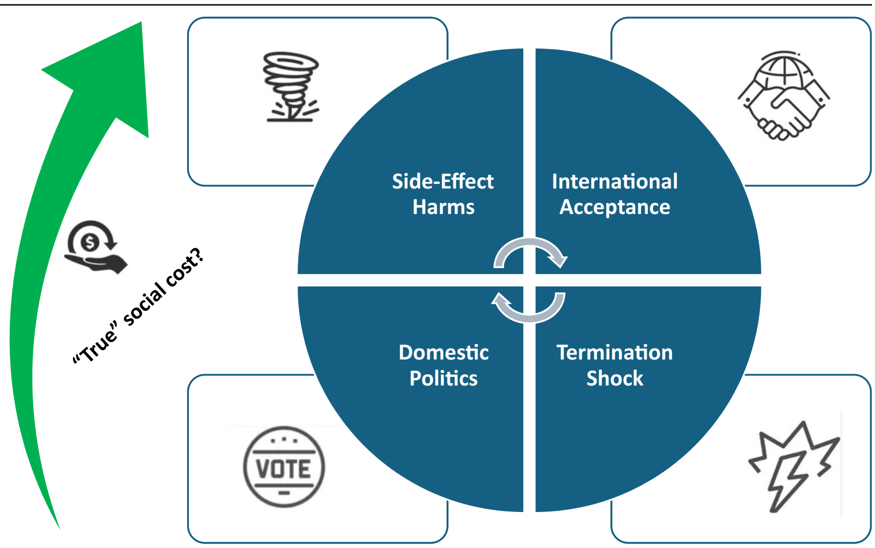
Side-effect harms

From the very beginning of SRM research in the 1970s, scholars have recognized that the technology would likely harm certain regions of the world as a side-effect, such that those regions would be better off bearing the effects of unmitigated climate change[18]. While the heating effect of greenhouse gasses on ground-level climate is largely uniform across the Earth, the cooling effect of SRM would be more pronounced in locations with naturally high levels of solar irradiation[19]. As a result, the temperature and precipitation effects of SRM will vary regionally[12,20], with some places experiencing novel risks of floods or droughts, for instance[21,22]. While there remains very significant uncertainty in terms of which regions will be harmed, in what manner, and to what degree[23,24], it is nearly guaranteed that some significant percentage of the world will be worse off as a result of SRM (again, relative to the baseline of taking no climate actions at all)[25–28]. Even if SAI were optimized to mimic the pole-to-equator temperature gradient, it would still likely introduce large side effects, especially in tropical regions in the global South[29,30]. The risk is especially pronounced with MCB[31–34]. MCB is deployed lower in the atmosphere than SAI to leverage the existing thick marine boundary-layer clouds. As a result, the radiative forcing it introduces will be relatively confined to the limited region of the lower troposphere, leading to uneven impacts in places outside the zone of deployment, as demonstrated by the recent Earth system model[35,36].

The costs of SRM's side effects. Tort law generally recognizes that parties whose activities impose non-reciprocal risks on others have a duty to compensate those people if harm results (e.g., if a defendant sprays pesticides on his pasture, he must pay for any resulting damage caused to his neighbor's cotton field)[37,38]. With an awareness of such moral and perhaps legal responsibilities, SRM's proponents have recognized that, as a consequence of SRM's side-effect harms, the net winners of SRM would have a duty to compensate the net losers[19,22,39–48]. However, they have either downplayed the worry given uncertainty over the precise nature of such harms[49] and the scale of the climate change problem that SRM seeks to solve, or they have undervalued the likely amount of compensation required. Through no fault of their own, Horton et al. fall into the latter camp[41]. They make the strong but helpful "working assumption" that the side-effect harms of SRM would be equivalent to the harms of climate change itself. But according to best estimates at the time of their writing in 2015—based on William Nordhaus's Dynamic Integrated Climate Economy (DICE) model—that would amount to about 1% of global GDP[16,50]. The numbers look different in 2024, though it depends on who you ask[51]. According to Barrage and Nordhaus, if we assume 3 °C of warming by 2100, then the DICE model now suggests a 3.1% loss when incorporating adjustments for possible tipping points and unmeasured non-market impacts (and 7% loss if we assume 4.5 °C of warming)[52]. However, the numbers are an order of magnitude higher in models that assume a permanent temperature change will impact growth rates over the long-term. In this vein, Burke, Hsiang and Miguel conclude that climate change will cost the world economy roughly 23% of GDP by 2100[53]. Meanwhile, a recent study by Bilal and Känzig follows the DICE model but incorporates not only the costs of increased temperature but also of the increased likelihood of "extreme climactic events"—extreme temperature, droughts, extreme wind, and extreme precipitation—and finds a 46% decline in global GDP in 2099 assuming 3 °C of warming[54]. Another recent study by Wadelich et al. also looks beyond temperature change to analyze the economic impact of precipitation, temperature variability and extreme weather events, and concludes that 3 °C of warming will lead to a 10% loss in global GDP[55]. Finally, Howard and Sterner's meta-analysis of studies reveals a mean loss estimate of 8% of GDP[56]. With this variation in mind, we will move forward with the rough assumption that unmitigated climate change will lead to a 10% loss in global GDP, but with an understanding that this number could be at least three times too high or low.

The extent of possible compensation reveals itself when we incorporate the range of people who may be harmed by SRM. Depending on the metrics considered (e.g., temperature, extreme temperature, drought, precipitation, and extreme precipitation), leading studies have indicated that between 0% and 7% of humanity can expect to be harmed by SAI, the more evenly distributed form of SRM[12]. In reaching these numbers, Irvine et al. focus on temperature and precipitation changes at the regional level, the two most robust responses that have been quantified in previous studies, finding that 10% to 40% of regions will be "statistically significantly exacerbated" with effects most pronounced in South America and Sub-Sahel Africa. However, beyond the hydroclimate, Irvine et al. omit consideration of many other potential side effects due to SRM, such as ozone depletion[57]. Further, they considered the side effects of using SAI to halve the warming trend. Had they

Fig. 1 | A schematic of key concepts.



considered more ambitious SAI deployment, such as largely offsetting global warming or stabilizing the climate to 1.5 or 2 °C above preindustrial levels, the land fraction and population percentage that would experience exacerbated climate impact as a result of SAI could be higher.

With an awareness of these caveats, as well as the fact that the side effect harm will likely be much greater with MCB, we can nonetheless make some progress on estimating SRM's side effect costs by using Irvine et al.'s relatively conservative 0% to 7% estimate for SAI. Accepting (1) Horton et al.'s "working assumption" that the costs of SRM's side-effects will be equivalent to the harm of unmitigated climate change; (2) our rough estimate that unmitigated climate change will reduce global GDP by 10%; (3) that global GDP is \$115.5 trillion (consistent with 2024 data, and therefore not assuming any further growth) (https://www.imf.org/external/datamapper/NGDPD@WEO/OEMDC/ADVEC/WEOWORLD); (4) Irvine et al.'s estimate that 0% to 7% of people will be harmed by SAI; and (5) that the people harmed by SRM produce an average amount of GDP, then the range of side-effect harms for SAI, in economic terms, is between \$0 and \$809 billion (\$115.5 trillion x .1 x .07) per year. Thus, the "true" social cost of SRM will likely be much higher than its technological cost alone, and the back-of-the-envelope calculations are indeed "incredible"[10]. As Gardiner explains: "The claim that albedo modification is cheap appears to focus only on the costs of actually delivering sulphur into the stratosphere, using cannons mounted on ships, or specially modified airliners. But this seems curiously myopic. (One doesn't decide whether to embark on brain surgery by focusing on the price of the knife.)"[58 (p. 348)].

There are further complications with SRM's side-effect harms. Winning and losing states will likely dispute which side bears the burden of proof in establishing causation and damages. They will also likely disagree on the appropriate amount and possibly form of compensation[22,59–62]. In addition to pecuniary remedies, whether in the form of cash transfers or loans, another possibility might be relaxed immigration laws by which members of negatively impacted regions gain the right to immigrate to other regions. Given the stakes, states may be unwilling to delegate such questions to a neutral arbiter, as several SRM advocates have suggested[43]. Ultimately, the compensation provided may be lower than that demanded by a neutral arbiter and perhaps much lower than the amount by which SRM's losers would willingly accept the technology's costs.

Finally, and crucially, if SRM's losers are unsatisfied with the compensation provided, it could provoke significant hostility and instability in the global arena. The failed history of corrective justice in the climate context suggests that such an outcome is plausible[63,64]. For instance, after years of contentious debate, the 2022 UN Climate Change Conference established a historic "loss and damage" fund to compensate developing nations for the harms of climate change[65]. Yet the fund's structure remains unsettled, and its legacy may ultimately prove more symbolic than material[66]. Although the board has convened several times, it has not resolved the most pressing issues: determining who qualifies for compensation, securing adequate contributions from historically high-emitting states, and designing effective governance mechanisms. As of January 2025, less than \$750 million had been pledged—far short of expectations[67]. Moreover, the United States has since withdrawn from the fund's board[68]. If this level of dysfunction persists for conventional climate harms, it is likely to be even worse for SRM, where attribution of harm is even more contested due to the absence of agreed-upon baselines. Any promise of fair and effective compensation for SRM-related losses must therefore be regarded with skepticism. And if compensation mechanisms fail, the resulting conflict may not remain confined to diplomatic channels. Disadvantaged states may respond with countermeasures ranging from trade sanctions to outright military action, with the scope of disruption shaped by the power and interests of those states and their allies. While it is difficult to price such a political fallout in dollar terms, it would substantially raise the overall "cost" of SRM.

The moral stakes of SRM. Revealing these potential side effects clarifies the moral stakes of SRM. A choice to deploy SRM is almost certainly a choice to very seriously disrupt the climate, and, therefore the lives of millions of people[69]. Further, even if SRM's winning states willingly and generously compensated these individuals—which seems unlikely—the nature of such injuries means that they can never be made fully whole[70(p. 156)]. Thus, even the most well-meaning SRM system will have a non-compensable "moral remainder," with a large number of people essentially being discarded as the cost of saving the rest of us[71]. That SRM may be easily justified from an abstract consequentialist perspective does not change this conclusion.

Moreover, the side-effect harms would qualify as SRM's "byproducts," which means, according to Bronsther, that they are morally equivalent to intentional harms[72]. Bronsther explains that a "byproduct" is an undesired outcome that results directly from an agent's "intended causal combination," that is, from the "recipe" of causal ingredients that an agent is intentionally "mixing" together to achieve their desired result. Meanwhile, a traditional "side-effect" results from an intended causal combination mixing with additional, unwanted elements. For example, if one intends to blow up a munitions factory in war, such that their intended causal combination involves "mixing" the bomb and the factory, the fact that there are civilians nearby is an additional, unwanted element, and the ensuing harm to them would qualify as a traditional side-effect. If one could bring about their intended causal combination in a perfectly clean laboratory environment, where there are no extraneous environmental elements or impurities, then the byproduct will emerge but not the side-effect. For instance, alcoholic fermentation is the chemical process by which glucose, catalyzed by yeast, converts into ethanol and carbon dioxide (i.e., $C6H12O6 \rightarrow 2\ C2H5OH + 2\ CO2$). Bronsther explains that a beer brewer ferments primarily for ethanol, which is an intoxicant, while a baker ferments for carbon dioxide, which causes their bread to rise. So, for the brewer who does not want any natural carbonization in their beer, the desired "product" is ethanol and the "byproduct" is carbon dioxide, and vice versa for the baker who does not want any leftover ethanol in their bread.

However, were it harmful to create ethanol in any form, we would hold the brewer and baker equally and fully responsible, assuming they created the same amount of the compound. In this way, byproducts—at least when the agent is aware of them—are morally equivalent to intentional products. The baker is aiming at a reaction that, even in a clean laboratory environment, would naturally result in ethanol. While they might regret that outcome, they should still be held responsible for it to the same degree as the brewer who desired such a product. Both actors specifically intended to bring about the same precise causal mixture, knowing that it would necessarily lead to the production of ethanol.

Similarly, the "recipe" for SRM involves intentionally "mixing" particles and the Earth's atmosphere, with certain beneficial and negative climate outcomes resulting naturally from that reaction. Following Bronsther, then, we ought to understand those negative outcomes to be SRM's "byproducts." Now, Bronsther is clear that harmful byproducts are equivalent to intentional products only to the extent that the agent, like the baker, believes that the byproducts are guaranteed to emerge. Thus, an intended causal combination that (a) has an 80% perceived probability of generating 100 units of byproduct harm or (b) a 100% perceived probability of bringing about 60 to 100 units of byproduct harm is thus morally equivalent to (c) intentionally creating 80 units of harm. The uncertainty over the precise extent of SRM's side effects will play some mitigating role, though our awareness of SRM's consequences would likely sharpen rapidly with each deployment. In the end, deploying SRM would be morally equivalent to intending to save the climate of most of the world while at the same time intending to seriously harm the climate of some of the world. That does not mean that deploying SRM is impermissible, but rather that—by imposing such byproduct harms—SRM bears an especially high burden of justification. By comparison, climate change would be a traditional "side-effect" rather than a "byproduct" of using fossil fuels, given that using fossil fuels does not involve intentionally interacting with the atmosphere or climate. The impacts on the atmosphere, in that case, are akin to the impacts on civilians living near the munitions factory that one sets out to destroy––which is to say that they are morally hugely important but that such harms would be yet harder to justify were they brought about intentionally or as byproducts of one's intended causal combination.

International political challenges

Regardless of deployment location and scale, both leading forms of SRM—Stratospheric Aerosol Injection (SAI) and Marine Cloud Brightening (MCB)—will impact the atmosphere and climate of every state. The impact will be swift and very significant, and, as indicated above, the results will very likely be net negative for some people in certain regions, meaning that for them, the consequences of unmitigated climate change would be further exacerbated by SRM. Beyond its effect on the global climate, SRM would involve physical sovereignty intrusions. That is, SRM typically requires transboundary deployment, such as aircraft flying across time zones spreading particles in the upper atmosphere (in the case of SAI), or vessels crossing major ocean basins to seed marine cloud layers (in the case of MCB). Accordingly, every state will want—and be entitled to—a say in whether and how the technology should be deployed and maintained over time[58,73–81], just as they would want and be entitled to a say over any global program that would impact their sovereign land or waters. While it is technically and financially feasible for a single actor to install SRM[82], the notion that SRM might be deployed unilaterally by a swashbuckling billionaire, a single nation, or even a regional group of nations[83,84] is make-believe. There is general agreement in the research community that SRM demands the involvement of every nation on Earth and a globally coordinated system of governance[85,86]; however, that is foreboding for at least four reasons.

First, "votes" in favor of SRM will not be easy to secure, even if the technology is an all-things-considered sensible bet for humanity. Nations may play "hardball," seeking compensation, dispensation, or special treatment of some sort for allowing others to deliberately control, alter, and potentially damage their climate. While such demands will be most salient coming from states that expect to be harmed by SRM and by historically low-emission states, other more powerful states may attempt to play this form of politics too. SRM requires a global negotiation—and ultimately, rather intimate forms of cooperation—between highly self-interested and aggressive parties, the leaders of which are responsive not to humanity as such but to domestic constituencies that are very protective of their national sovereignty. Given that SRM needs to be regularly deployed, there is a further issue of whether international agreements must be secured at regular intervals, say, every ten years.

Second, even assuming there is a global consensus on deploying SRM in principle, what exactly constitutes the "optimum" global temperature and precipitation level will prove contentious, given that different national economies have different needs when it comes to temperature and precipitation, and SRM can be engineered only at the wholesale, global level rather than at the retail, national level[19]. This debate would apply even between states that expect to benefit from any form of SRM, given that what constitutes optimal SRM "setting" may differ from region to region[87]. To be sure, locally deployed MCB holds some promise of "fine-tuning" the local climate, as seen with Australia's field experiments in thickening tropical clouds as a means of saving their coral reefs[88]. However, such activity will almost certainly induce a negative transboundary net effect and would thereby require international involvement and coordination as well.

Third, although it is increasingly recognized that SRM requires global dialogue and governance, states that provide a disproportionate share of the funding and scientific expertise may feel entitled to a disproportionate share of decision-making power. They may resist delegating authority to a global SRM bureaucracy, whether run through the United Nations or a novel organization dedicated to SRM management. They may even attempt to engineer the climate in a "predatory" manner that favors their own economy[58] (p. 369).

Fourth, several of the most powerful states are explicit or implicit adversaries on the global stage, and SRM would require them to leave all other disagreements on the ground, as it were. For instance, Russia will not quietly cede control of its climate to the judgment of the United States and its allies.

Given these political challenges, it is no surprise that early attempts at reaching international agreement over geoengineering have failed, as seen with the unsuccessful and "surprisingly bitter" negotiations at the UN Environment Assembly (UNEA) over a draft resolution regarding a simple SRM study[89,90] (p. 21). Ultimately, the risk is not merely that SRM loses the global "vote" and is never deployed, having failed to secure global consensus. The risk is also that the technology is deployed *without* the world's consent or without the consent of particular regions or states, perhaps led by a coterie of powerful allies[89]. Such an outcome risks serious global instability—beyond the instability generated by a lack of compensation for side-effect harms—as states that have not given their approval or feel that they have not been adequately consulted react aggressively and punitively in response. In this vein, Stephen Gardiner explains that solar geoengineering is "the kind of issue on which international agreement will be absolutely necessary if serious social, economic, political and military conflict is to be avoided."[58] (p. 348).

In sum, when assessing the set of costs and benefits attached to SRM, the calculation becomes much less favorable when it incorporates international politics. The international dimension of SRM increases the chances that the technology will fail operationally—thereby wasting humanity's time, attention, and resources—or produce global instability, which generates its own set of costs beyond climate change. Furthermore, the technical costs of SRM would likely increase if deployed in a non-cooperative setting. Estimates in the literature generally assume that SRM would be implemented with ready access to the world's best located airports and every country's climate and atmospheric data. If such access were not forthcoming because of international disagreement, then the deployment and maintenance costs would accordingly rise.

Domestic political challenges

SRM comes with an unusual political risk profile at the domestic level. By either injecting gasses into the high stratosphere or releasing salt particles over cloudy ocean surfaces, the technology introduces *a new causal force* into the atmosphere that does not "naturally" exist. The natural/artificial divide is surely on a spectrum, expressing the degree to which something is the product of human craft, with perhaps untouched rainforest on one side and abstract art on the other. SRM pushes the climate toward the artificial side, turning it into something of an "artifact"[91]. The result will directly impact ground-level temperature as intended, but also the hydrological cycle and cloud coverage indirectly. Politicians who enable SRM could thus potentially be held accountable for any undesirably cold, hot, wet, snowy, stormy, or gray days. Given that the expected electoral reward of mitigating climate change is relatively (and surprisingly) modest, politicians may resist a solution that forces them to take on the burden of being blamed for everyday weather.

Western politicians are rarely punished by their constituents for climate change because of its gradual effect, with future generations bearing the greatest costs[92]. Preventing future would-be harms—whether it's the harm of climate change itself or the harm of expensive mitigation efforts—tends not to be the meat-and-potatoes of winning campaign platforms[93,94] (p. 250–51). Rebecca Willis has demonstrated how little pressure British MPs receive from their constituents on climate change[92,95]. Meanwhile, in the American context, a recent Pew poll tested people's policy priorities, and "dealing with climate change" came in 18th out of 20 available policy concerns, below "reducing the availability of illegal drugs" and "improving transportation," to say nothing of issues related to the economy or national security[96]. The politics of climate change are even less demanding in the developing world[97]. Further, voters tend not to pin the blame for climate change on individual politicians because of its array of international, historical, public, and private causes, and because responding to it is a devilishly complex global project. Climate change is a failure with a thousand fathers.

By comparison, despite significant causal uncertainty, SRM means that any given weather event—not only "bad" everyday weather but also extreme events like tornados and hurricanes—may be attributed *politically* to those responsible for installing and maintaining the technology. That will be the case whether or not the average number of "bad weather" days would increase with SRM, though there is good reason to believe that it would in some places, as discussed above. We could expect a discussion of "the Biden climate" or "the Trump climate" in the same manner that people now discuss Biden or Trump's "economy." All else being equal, that's politically risky. People tend to complain about the day-to-day weather, and they often wax nostalgic about the perceived better weather of their youth.

Voters may also have concerns about their leaders "playing God" with the atmosphere[98,99], especially those environmentally sensitive voters that would otherwise form a base of support for climate policies[100]. All this may create an opening for opposition candidates who promise to end the SRM "experiment" and restore the "natural" (or at least "more natural") weather. Such concerns will be particularly salient for incumbent politicians who have built-in electoral advantages and who are thus risk-averse when it comes to championing new programs[101,102].

Climate change is a global problem, but politics are local. That SRM seems to have a perilous domestic (and international) political profile decreases its chances of long-term success as a climate intervention strategy. Indeed, the European Parliament[103], the German Federal Environment Agency[104], and a group of African nations[105] are now calling for a global SRM non-use agreement—and Mexico has outright banned SRM experiments[106]. It is ultimately a matter of opportunity cost, given that not every climate intervention strategy can be pursued in earnest. And political feasibility—no less than technical feasibility—ought to inform the decision of which strategy or strategies to prioritize.

Mitigation deterrence and termination risk

As many scholars have discussed, SRM (and even SRM research) may disincentivize the transition to a renewables-based economy[107]. There's less need to take the economically and politically expensive path of reducing emissions or adapting to the effect of a warming Earth, goes the argument, when SRM can simply be tweaked to block out more of the Sun's rays as needed. While more sulfates would need to be injected into the atmosphere as people emit more carbon, the technical costs of SRM are so modest that it would not be necessary to invest much political capital in emissions reductions. In this way, SRM is relatively decoupled from the general efforts of carbon mitigation. However, as CO2 continues to accumulate in the atmosphere, the risk is that if SRM deployment is suddenly terminated—whether as a result of war or ordinary politics—the global temperature will very rapidly increase until it matches the level fueled by the long-lived atmospheric carbon concentration[44]. And humanity will not be ready, goes the worry. Matthews and Caldeira estimate that once the negative forcing of SRM is removed, the rate of temperature change could be as much as 20 times faster than current rates of climate change, up to 4 °C/decade, causing significantly more harm than if such change occurred gradually[108]. To be sure, Parker and Irvine argue that the risk can be mitigated assuming SRM received the support of powerful nations committed to maintaining backup SRM hardware[109].

Discussion

A comprehensive evaluation of an option requires a comparison with alternatives. Of course, one alternative to SRM would be a world without climate intervention entirely. A growing body of literature adopts a "risk-risk" framing centered on this possibility, weighing the potential harms of SRM against the potential harms of not deploying it and thereby facing unmitigated climate change[110–112]. In this section, however, we consider a comparison within the category of climate intervention, contrasting SRM with an ambitious model of Carbon Dioxide Removal (CDR). While climate scientists and activists increasingly recognize CDR as a necessary—but modest—complement to emissions reductions schemes, we explore the implications of "Large-Scale" CDR (LCDR). Specifically, we envision an immense program of Direct Air Capture (DAC) and Bioenergy with Carbon Capture and Storage (BECCS) administered by a consortium of developed states and capable of capturing 10 to 20 gigatons of carbon annually[14,15]. We do not intend to present a binary choice between SRM and LCDR, nor to argue specifically for the latter. Rather, we aim to observe that when the holistic, true "price" of SRM is fully accounted for, the comparison between the two approaches becomes more complex than a merely technical assessment would suggest. What follows considers the comparative costs, politics, and deterrence risks of LCDR.

The technical costs of LCDR would indeed be immense, especially by comparison to the above SRM estimate of $18 billion a year per degree of warming avoided. At the outset, we estimated that LCDR could cost $950 billion a year to capture an amount of carbon equivalent to 25% of the world's 2024 emissions (9.5 gigatons), assuming $100 per captured ton of carbon. However, the costs may be significantly higher (or lower), depending upon how much carbon in fact needs to be stored—as determined by the extent of emissions reductions and on the technology's real-world efficiency. For instance, Irvine et al. considered the side effect costs of using SRM to halve the warming trend[12]. Were LCDR used to achieve that result, its costs would be double the above estimate for a 25% reduction ($1.9 trillion). In any event, while there are eighteen DAC facilities currently in operation and at least nine more in development, DAC has never been attempted on the industrial level imagined here, and $100 per ton of captured carbon remains today in the realm of fantasy[5].

That said, the science is evolving rapidly in ways that promise greater efficiency[5]. That is the case even without robust public or private funding for CDR, given the lack of a natural market for captured carbon, unlike, say, the market for captured solar energy. While the American Physical Society estimated in 2011 that air capture would cost $600 per metric ton of captured carbon[113], the industry target is now indeed $100 per captured ton, which the International Energy Agency (IEA) estimates will be possible by 2030, assuming low heat and electricity prices, among other variables[5]. The US Department of Energy has created a historic but embryonic program, the "Carbon Negative Shot," to promote research into air capture and other carbon removal technologies, and it hopes to bring costs below $100 per ton within a decade[114]. Long-term, the IEA estimates that the Middle East offers the possibility of $50 per ton, given its potential for low capital expenditures due to cheaper materials and manufacturing, combined with low gas and electricity prices[5]. Meanwhile, Klaus Lackner believes that the limits of the technology hover around $30 per ton, assuming mass production efficiencies[115,116]. In this vein, progress is sometimes exponential—even outside the realm of software. For instance, solar panels are almost 100 times cheaper than they were in the 1950s[117]. And the gas turbine engine, which was "a scientific curiosity" in the 1930s[115], continues to get more efficient.

Further, the financial costs of large-scale CDR are not necessarily economically harmful. The money spent is not a mean of rectifying losses or damage, and it is not simply thrown away. Ultimately, it is a counterfactual question of whether the resources might have been more productively deployed elsewhere. Moreover, public expenditures can be conducive to full employment, and many people of varying degrees of education will need to be employed to run what may be a new $1 trillion per year sector[118]. Public expenditures can also support a strong economy more generally, especially when the sector receiving public funds is research- and innovation-driven, as would be the case with DAC and BECCS projects[119,120]. It remains an open macroeconomic question, then, of whether and to what degree large-scale CDR expenditures would help or hinder economic growth and full employment goals.

The cost comparison between SRM and LCDR should include both technical and compensation expenses. As discussed above, SRM should be cheap in the former category but expensive in the latter—with compensation costs roughly estimated to be between $0 and $809 billion. The ratio is flipped for LCDR, with the lion's share of the expense being a matter of technical engineering and production, not compensation. That is not to say, however, that LCDR would not cause any harmful side effects. There is wide recognition that CDR's resource demands may negatively affect sustainability goals[121,122], leading to biodiversity loss and food insecurity[123], especially as a result of land-based approaches like enhanced rock weathering and bioenergy crops. CDR also poses a risk to the energy-water-land system, and Furhman et al. have accordingly called for more diverse CDR approaches, including land, ocean, and technological methods[124]. Moreover, there are several "cold weather" states, such as Canada and Russia, that may benefit from climate change in certain ways, for instance by experiencing prolonged growing seasons, and CDR may to some degree "harm" them as a side effect by removing that benefit. Nonetheless, such states would doubtfully assert a moral or legal entitlement to such a benefit, given that it results from a phenomenon that causes so much undeserved harm.

Moving from finance to politics, SRM would require unprecedented worldwide cooperation, a fact that would both decrease its likelihood of long-term success and increase global instability. By comparison, LCDR—understood as a public project run by several powerful states—has a more stable international political foundation. It does not depend on global consensus, nor the direct involvement of the developing world. While SRM involves transboundary deployment, the operation of removing carbon from the atmosphere with DAC (or BECCS) does not represent an intrusion on any other state's sovereignty. As CO2 is distributed relatively evenly across the atmosphere, the world's carbon emissions can be absorbed by DAC from anywhere on Earth, say, from an American or Middle Eastern desert. Thus, for states that do not contribute to the DAC program—perhaps because of their limited responsibility for climate change given their limited historical emissions or because of their limited capacity given their status as a developing economy—the program promises an uncomplicated, cost-free benefit. Since nothing is asked of them, financially or otherwise, and since their sovereign territory is neither impacted nor intruded upon, their consent is not required (even though it would likely be easy to secure).

To be sure, large-scale CDR would still require cooperation between the contributing states. For instance, with BECCS, the carbon-rich biomass may be gathered in one country, burned and captured in a second country, and ultimately stored in a third. The precise nature of the cooperation may depend on which locations are optimal for CDR. For instance, as indicated above, the IEA estimates that the Middle East is the most promising region for DAC[5]. One possibility in this vein would involve a small group of countries maintaining and financing the program in an otherwise non-contributing country, whether in the Middle East or elsewhere. Meanwhile, the possibility that would require the least amount of international coordination would be for a single country—likely the United States—to handle all the technical aspects of CDR and to run the program on its own soil while other nations make financial contributions to the project. Whatever the exact details, by comparison to the unprecedented global agreement and coordination required by SRM, the prospect of building effective global governance for large-scale CDR is promising. NATO presents a relatively similar and hopeful example of cooperation between developed countries, as does the long history of treaties between the US and EU.

Meanwhile, at the domestic level, LCDR would likely have a different political profile than SRM, given that it involves *removing* a causal force from the atmosphere—carbon emissions—rather than adding a new force. Compare, for instance, the politics of using expansive netting to remove plastic garbage from the ocean with that of releasing a chemical into the sea that will dissolve the garbage (and perhaps other matter as a side effect). The resulting narrative stands to be less threatening and uncertain to politicians at the domestic level. Like SRM, constituents will hold politicians who support LCDR responsible for the technical costs of the program. But there may be less of an opportunity to hold them accountable for the resulting climate writ large, or to blame them for "playing God" with the weather. Furthermore, the financial costs of the large-scale program are not necessarily a political or economic negative, as suggested above.

The point is comparative. LCDR would itself be politically controversial, as evidenced by opposition to the use of eminent domain for carbon dioxide pipelines in Louisiana and South Dakota (https://lailluminator.com/2025/02/26/carbon-capture/, https://www.reuters.com/world/us/south-dakota-bans-use-eminent-domain-carbon-dioxide-pipelines-2025-03-06); public concern in Texas over CDR's environmental risks including the increased likelihood of earthquakes (https://www.reuters.com/world/us/earthquakes-blowouts-undermine-case-carbon-storage-texas-2024-12-13, https://www.kwbu.org/2024-12-20/west-texas-carbon-capture-project-could-help-the-climate-but-some-worry-about-potential-local-environmental-risks); and focus group research by Celina Scott-Buechler et al., which demonstrates the importance of community involvement in CDR projects (https://www.nature.com/articles/s43247-024-01334-6). However, there has not been an equivalent push to entirely prohibit the adoption or even the research of the technology, as has been the case with SRM in several jurisdictions worldwide, as discussed above.

Finally, LCDR would disincentivize emissions reductions[122]. But the problem is not as serious as it is with SRM. The reason is that the relationship between CDR and carbon emissions is dynamic, in the sense that the more carbon that people emit, the more carbon that needs to be removed. As such, were a group of nations to fully commit to capturing a significant percentage of the world's emissions as a means of reaching net zero (emission minus removal) goals, they would rationally be interested in limiting their own and other nations' emissions to ensure that their carbon removal efforts were as meaningful and cost-effective as possible. That is, by expending so many resources to keep net global emissions low, they would have good reason to aggressively enforce existing climate treaties, lest others' emissions render their expensive carbon capture efforts moot.

In any event, CDR does not pose the same termination risks as SRM since it removes CO2 from the atmosphere as opposed to "masking" its effect. In effect, DAC and BECCS technologies are similar to the decarbonization of oil and gas operations. Thus, were the CDR program abruptly shuttered, the climate would respond with only marginally higher warming rates, fueled by gradually increasing net carbon emission and atmospheric carbon concentration.

In light of its low deployment and maintenance costs, SRM has received a great deal of attention in recent years as a tantalizing hedge against global emissions treaties[44,125–128]. In this essay, however, we have clarified that the all-things-considered price of SRM is likely considerably higher than its technical costs alone would suggest. The broader set of costs and risks include expansive liabilities for side effect harms, international and domestic political challenges, and termination risks. Finally, we proposed state-led LCDR as a credible climate intervention alternative and argued that the holistic comparison between SRM and LCDR is complex.

Methodology

We do not analyze or generate any datasets. Our analysis is based on a literature review of the politics, ethics, and economics of Solar Radiation Management, Carbon Dioxide Removal, and climate change.

Data availability

No datasets were generated or analysed during the current study.

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J.B. and Y.X. jointly conceived the project, conducted the underlying research, and outlined the manuscript. J.B. was the primary author, with Y.X. contributing to the manuscript's review and revision.

Competing interests

The authors declare no competing interests.

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