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Research Paper

Disentangling the rhetoric of public goods from their externalities: The case of climate engineering

Robert Holahan [a, c, *], Prakash Kashwan [b, c]

[a] Environmental Studies and Political Science, Binghamton University, P.O. Box 6000, Binghamton, NY, 13902-6000, USA
[b] Political Science, University of Connecticut, 365 Fairfield Way, Storrs, CT, 06269, USA
[c] Ostrom Workshop in Political Theory and Policy Analysis, Bloomington, IN, USA

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ABSTRACT

Public goods are defined by the technical conditions of nonexclusion and nonrivalry. Nonetheless, public goods are frequently viewed in environmental policy and scholarly debates as providing strictly positive benefits (or, in the case of public 'bads', providing strictly negative costs). We provide a theoretical understanding of heterogeneous externalities produced by public goods to challenge this assumption, by highlighting the ways in which a single public good can simultaneously produce positive benefits for some and negative externalities for others. To demonstrate our argument, we apply the theoretical framework onto the contemporary debates over climate engineering projects proposed to mitigate climate change. Such projects inevitably harm some countries internationally and some groups intranationally such that aggregate predictions about the benefits of climate engineering are misleading without an accurate accounting for its negative externalities.

1. Introduction

Solving the impacts of large-scale climate change requires undertaking both *ex ante* mitigation measures and planning for *ex post* adaptation scenarios. As atmospheric carbon dioxide concentrations increased over the past decade, passing the 400 ppm threshold in September 2016, scholars have increasingly turned their attention on adaptation policies, reasoning that humanity is already past the point of effective mitigation. However, with the signing of the Paris Agreement, in which national governments agreed to "a long-term goal of keeping the increase in global average temperature to well below 2 °C above pre-industrial levels; [and] to aim to limit the increase to 1.5 °C,"[1] a revitalized focus has been placed on large-scale geoengineering projects that either remove carbon from the atmosphere, or that manipulate solar radiation absorption to offset increased temperatures. In particular, the Intergovernmental Panel on Climate Change (IPCC) Special Report on the impacts of a global warming of 1.5 °C above pre-industrial levels, summarizes the available scientific evidence showing a "high agreement that (solar radiation management) could limit warming to below 1.5 °C" [1].[2] Many CE experts that the target of keeping global warming below 1.5 °C is unlikely to be feasible unless active strategies for carbon dioxide removal (CDR) or solar radiation management (SRM) techniques are deployed [2]. In this manuscript, we add to the debate surrounding proposed CE projects by examining the distributional impacts of these projects through the use of a public goods framework. We argue that touting CE, in particular SRM, as a public good misrepresents the technical definition of a public good by confusing aggregate and distributional impacts of this class of economic goods.

While the proponents of climate CE recognize the risks linked to its deployment, proponents also argue for comparing those risks to the near certain and staggering costs that catastrophic climate

* Corresponding author. Environmental Studies and Political Science, Binghamton University, P.O. Box 6000, Binghamton, NY, 13902-6000, USA.
E-mail addresses: rholahan@binghamton.edu (R. Holahan), prakash.kashwan@uconn.edu (P. Kashwan).

[1] http://ec.europa.eu/clima/policies/international/negotiations/paris/index_en.htm.

[2] The text of the Paris Agreement, which argued for "rapid reductions … in accordance with the best available science," may be seen as the placeholder for a variety of carbon reduction and geoengineering options.

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change will impose. Because the need to avoid catastrophic climate change is regarded as a collective global responsibility, some scholars consider the deployment of CE to that end as an act of public interest. Others, such as the writers of the "Oxford Principles" for governance of climate CE, argue that CE be provided as a "public good" (Rayner et al., 2009; [3]. However, critics of this approach have argued that a public goods-framing of CE is misleading, because it marginalizes ethical and distributional concerns [4]. What this debate largely overlooks, however, is that 'public good' is a technical term that refers to a good's non-excludability and non-rivalry. By disentangling the technical details of what it means to be a public good and focusing on the production and provisioning processes associated with CE, we highlight the difficulties in implementing a governance system that both effectively regulates the public goods-aspects of CE and ensures an equitable distribution of its costs and benefits. We further argue that analyses of CE cannot be done in isolation of its interactions with other parts of climate system, such as potential impacts on seasonal monsoons or other regularized climate phenomena. Accordingly, we draw on research on climate modeling of CE and the proximate phenomenon of historical volcanic eruptions which CE seeks to mimic.

We begin by defining public goods. We then develop the theoretical framework of public goods with heterogeneous *ex post* externalities and then introduce the policy debate over a specific form of CE, solar radiation management, by highlighting two key points about this form of CE: that it is relatively inexpensive to provide, but that its externalities are uncertain and heterogenous. We then engage in an institutional analysis that provides a thorough understanding of solar radiation management within the public goods framework. We finish with discussion and conclusions regarding the importance of planning *ex ante* for the *ex post* governance challenges CE produces.

2. Public goods and externalities

2.1. Defining public goods

The development of a typology of economic goods has a long history, though modern scholarship generally begins with the debate between [5,6]. As [7] explains, Musgrave and Samuelson were both interested in exploring the differences between private goods that are efficiently provided by markets and public goods that are efficiently provided by governments. The key difference in approach was that Samuelson identified private goods as either rivalrous (i.e. consumable to only one individual) or non-rivalrous (i.e. simultaneously consumable to multiple individuals), while Musgrave identified private goods as those for which an individual can relatively easily exclude others from accessing and public goods as those for which excluding others is highly costly [8]. combined the two concepts and produced a 2x2 typology of goods that is rounded out with the addition of common-pool resources and club goods.

These two attributes of an economic good jointly determine the magnitude of externality costs and benefits that the good produces. The rivalry of a good defines the opportunity costs of consumption, such that a rivalrous good produces relatively high opportunity costs for individuals competing over its consumption or use, while non-rivalrous goods have low opportunity costs in consumption or use. Therefore, a 'pure' private good has extremely high opportunity costs in rivalry, while a 'pure' public good has zero opportunity costs in rivalry.[3] Similarly, the relative costs of excluding individuals from accessing or consuming a good determines the extent to which an individual can capture a rivalrous good for individual use, or to which an individual can free-ride on the production or provision of a non-rivalrous good. In the extreme, a pure private good has no externalities since all of the benefits (and costs) of the good are easily captured by the provider or consumer of the good [9]. In contrast, a pure public good in the extreme produces a constant stream of externalities since it is virtually impossible at any cost to prohibit an individual from accessing or consuming it.

This inability to exclude others from accessing or consuming a public good, regardless of their contributions to the good's production or provision defines the classic free-rider problem. Using simple backward induction, a producer or provider may be disincentivized to produce or provide a public good at all if free-riding becomes so overwhelming that one cannot capture any revenue from its production or provision [10].

Clearly a producer or provider of a public good has an incentive to lower the costs of excluding free-riders from accessing or consuming benefits (direct or externality) from the good's production or provision. Similarly, however, a producer or provider of a negative externality-producing public good (i.e. smog) has an incentive to *increase* the costs of excluding free-riders from accessing or consuming the good, since exclusion defines the number of individuals sharing in the total costs of production or provision Anyone producing a negative externality-producing good wants as many people to share in those costs as possible. Therefore, one cannot a priori determine from a welfare-maximizing perspective whether the production or provision of a public good should be encouraged or discouraged without first knowing the totality of its costs and benefits. Notice this says nothing about the distributional impacts of those positive or negative externalities.[4]

2.2. An externality-focused framework of public goods

One means through which to evaluate a goods typology is through the types of externalities (positive or negative) that the good produces [9]. Collective goods (public goods and common-pool resources) are defined by their lack-of exclusion, which also implies that collective goods produce externalities in proportion to the degree of their (non)exclusion. For example, factory emissions are neither excludable nor rivalrous, and therefore a public good, the externalities of which manifest as smog. Similarly, carbon sequestration produced by a reforestation project is a public good, the externalities of which manifest as a decrease in the rate of global warming. Examples like these of strictly negative (smog) or strictly positive (decrease in rate of global warming) externalities abound in the literature on public goods. In such settings, the phrase "public good" is frequently used to invoke positive, or 'good' externalities, while the term "public bad" is used to invoke negative, or 'bad' externalities [11].

However, many public goods—especially those that exist at a global scale and transcend political boundaries—produce complex streams of externalities that don't fit neatly into the standard positive vs. negative narrative. For example, while the canonical public good example of a lighthouse may provide a universal positive for ships passing by, the glaring reflection may also prevent a nearby resident from getting an adequate night's rest. The light

[3] Of course, 'pure' goods are rare in the real world. Rather, the goods typology should be thought of as a continuum in which relative costs of exclusion and rivalry can place a good anywhere from 'pure' private to 'pure' public.

[4] This also raises an issue beyond the scope of the current manuscript: What are the bargaining or electoral consequences of groups asymmetrically impacted by positive and negative externalities, respectively?

produced by the lighthouse is, strictly speaking, a public good, even though it differentially impacts individuals—some positively and some negatively. Similar stories could likely be told of almost any public good; however, this differential impact *ex post* to a public good's provisioning is a relatively unexplored source of heterogeneity in the public goods literature.[5]

Scholars have instead long sought to understand the conditions which promote (detract) the provision of public goods (bads) [10]. noted that heterogeneity of group preferences is one of the most important variables in predicting whether or not a group will successfully produce a public good. While heterogeneity increases the costs of collective action, especially in larger groups, a heterogeneity of preferences or endowments also increases the probability that the public good's production provides so much personal benefits for some resourceful individuals or groups that they will produce or provision a public good regardless of free riders.[6] As a result, one cannot assume that heterogeneity makes collective action more or less likely, respectively, without understanding the nature of the public good in question and the forms of heterogeneity being investigated. Scholars subsequently have identified and studied myriad types of heterogeneity that are important for understanding the likelihood of a public good being produced or provided.

The literature on group heterogeneity and public goods is too large to adequately summarize here, so instead we note what is largely missing from this literature[7]—discussion of heterogeneous externalities *ex post* to a public good's production. Instead, existing studies have tended to focus on *ex ante* heterogeneity of endowments (e.g. Refs. [12,13], ethnicity [14–18], and asymmetries of power [19–21], among others. Understanding *ex ante* heterogeneity is important for untangling when a group will endogenously produce and provide a public good and when, for example, a government may have to step in to produce or provide a public good.

However, understanding *ex post* heterogeneity of externalities is similarly important for predicting distributional outcomes once a public good is produced. Heterogeneity of externalities implies that the production of a public good has winners and losers who should be identified to protect against, among other concerns, environmental or social injustice. When a powerful actor has the ability to produce a public good that negatively impacts disadvantaged groups (economically or politically), a full accounting of the costs and benefits of the public good are essential to ensure that the rhetoric of public goods isn't confused with something in the public's interest. From a positive perspective, understanding these externalities also helps to reduce rent dissipation and provides additional information to encourage welfare-enhancing policies.

2.3. The production and provisioning of public goods from an externality-perspective

When one identifies a public good and tries to match an effective policy intervention to manage its production or provision, one is essentially attempting to either minimize or maximize the externalities of the good, respectively, depending on which increases social welfare in the particular case. For example, a policy goal of discouraging free-riders from consuming a public good would entail minimizing the positive externalities of the good (by somehow overcoming the high costs of exclusion) to ensure only those who contributed towards its production receive benefits. However, it may also be a policy goal to maximize the total positive externalities of a good, such as in creating a new park in a blighted area intended to encourage developers to 'capture' these externalities as an incentive to build in that particular neighborhood. The same is of course true for negative externalities, the point simply being that managing negative or positive externalities are an inherent dilemma of the production or provision of any public good. In the examples noted earlier, the goal of policy is typically to minimize smog, while still permitting factories to operate, and to maximize the decline in the rate of global warming, by encouraging additional reforestation projects, respectively.

Table 1
Economic goods typology.

	Rivalrous	Non-Rivalrous
Low Exclusion Costs	Private Good	Club Good
High Exclusion Costs	Common-pool Resource	Public Good

Adapted from Ref. [8].

Traditional debates over public goods tend to view this good-type as 'naturally' produced and provided by governments (i.e. public provision), though there is no a priori reason that a public good is necessarily most efficiently provided or produced via public mechanisms [8]. Indeed, any of the four types of goods identified in Table 1 can be produced or provided by at least three mechanisms—though private action, by government action, or by voluntary collective action [7,22]. For example [23], detail the private provisioning of so-called lightships in lieu of fixed lighthouses during 18th century British commerce. The efficiency of a specific good's production or provision through one of these three mechanisms is specific to the good's costs and benefits, and to the context in which the good is produced or provided.

All goods require both a production mechanism that creates the good and provision mechanism that distributes the good, though these two mechanisms need not be the same for a given good because the externalities of the good may differ between its production and provision processes. For example, while the aerosol product used in stratospheric aerosol geoengineering (discussed in-depth below) might be efficiently produced by a private firm, the provision of the same product into the stratosphere might be efficiently handled by the voluntary collective action of multiple countries. This theory of polycentricity—that there are potentially different economies of scale in the production and provision of a given collective good was first noted by Ref. [24] in their seminal study of the diversity of metropolitan organization, which we now extend to the context of international environmental organization (see also [25–28].

The question of *who* (or *what* unit) should produce or provide a public good, especially in the context of an international transboundary public good, is core to understanding the implications of a public good's heterogeneous externalities. In general, public goods can be provided by private actors (individuals or firms), by voluntary associations, and by governments. Because there is no central coordinating government at the international level, however, public goods provided at this level must be the product of voluntary individual or voluntary collective action. At the international level, then, public goods are potentially provided by private actors or the voluntary association of governments, non-governmental actors, or a combination of governments and non-governmental actors, respectively. For some, the provision of a public good will produce positive direct benefits and for some, the provision of the same public good will produce negative externality costs (and for some, perhaps most, a combination of positive

[5] While far from a perfect measure, a Google Scholar search of the terms "public goods" & "heterogeneous externalities" together only returns 38 total citations.

[6] The literature on climate geoengineering refers to this as the "free-driver" problem [60].

[7] For heterogeneity in experiments see Refs. [12,13,61,62].

benefits and negative costs). Given the voluntary nature of international public goods provisioning, it is reasonable to postulate that the provision of an international public good will be undertaken by an actor or actors for whom its provision results in direct positive benefits in excess of the costs paid for its provisioning by those actors.

This observation highlights two important asymmetries between providers of public goods and those bearing *ex post* externality costs that naturally result from the provisioning of a public good with heterogeneous externalities. First, those providing a public good have a natural asymmetrical information advantage relative to those facing the *ex post* externality costs of its provisioning. The providers of the public good do so precisely because of information that its provisioning will benefit them. On the other side, those who will bear externality costs *ex post* clearly have less *ex ante* incentive to gather information about the good, assuming the externalities are not known *ex ante* with certainty.

Second, those providing a public good have a natural advantage in asymmetrical bargaining power relative to those facing the *ex post* externality costs of its provisioning. Because providers know *ex ante* the benefits of the public good's provisioning, but externality cost bearers only learn about these costs *ex post* to its provisioning, there is a natural coalition to advocate for the public good, but no counter-balancing coalition to advocate against the public good. Together, these two asymmetries make it, all else equal, likely that an international public good with large direct benefits will be provided regardless of its externality costs—even if those externality costs are, in net, larger than the benefits—because the providers of the good benefit directly, while those negatively impacted only do so after the good has already been provided.

3. Tying the theory of public goods to stratospheric aerosol geoengineering (SAG)

The Royal Society Report [29] defines CE as "the deliberate large-scale manipulation of the planetary environment to counteract anthropogenic climate change." Similarly, Morrow and Svoboda (2016, 3) define CE as the "deliberate, large-scale intervention in one or more Earth systems for the purpose of counteracting the causes or symptoms of human-caused climate change". CE is really the umbrella term used for two basic types of proposed technologies: (i) Solar radiation management manifest as stratospheric aerosol geoengineering (SAG), in which large amounts of reflective aerosol compounds are released into the stratosphere to effectively reflect a small fraction of solar radiation back into space and thereby cool the earth, theoretically counteracting the effects of global warming; and, (ii) Carbon dioxide removal, manifest as removing carbon dioxide or other greenhouse gases from the atmosphere and sequestering the resulting carbon compounds in either liquid or solid forms for long periods of time in biological, geological, or oceanic reservoirs [30].

Both general forms of CE—sequestration and SAG—are distinct economic good-types and have a distinct bundle of externalities, the respective production and provisioning of which will take different forms as different actors compete (or cooperate) to produce and provide them. Therefore, while this paper's analysis is, for simplicity, restricted to SAG, an analysis of the biophysical aspects of *ex ante* carbon dioxide removal will necessarily be a next step in a larger project to isolate the nature of CE goods and its interaction with the international environmental or climate policy regimes. For simplicity, we focus only on SAG interventions in this analysis, though we believe the general analysis is applicable to multiple forms of CE interventions.

The benefits to SAG are naturally heterogeneous as, in the aggregate, countries with the most to lose from climate change gain the most from successful SAG interventions. These potentially large benefits do not negate the potential that countries most prone to climate change impacts also have the largest externality costs from SAG-induced weather changes—i.e. country X is prone to climate change and thus benefits from provisioning of SAG, but is also agriculturally-dependent such that incidental changes to monsoon schedules from SAG lead to increased costs as well [31]. While we can't possibly calculate the true benefits and costs of large-scale SAG, we can establish theoretical ranges and explore how different states-of-the-world will interact to produce distributional impacts.

Similarly, if SAG is a public good based on the technical definition, this says nothing about its distributional impacts; it may indeed have a net positive global benefit (though nothing in the definition of a public good requires this), but it could negatively impact some regions, nations, or subnational units. Furthermore, it is also possible that SAG could have a net negative impact if it so harms some countries or groups to such an extent that this outweighs positive social gains from climate change mitigation [32].; for theoretical considerations, see Ref. [33]. Indeed, considering the nature and scale of atmospheric interventions that any CE entails, its distributional consequences cut across national and subnational boundaries. In essence, any CE, including SAG, will likely produce negative transboundary externalities for some actors, even while producing positive transboundary externalities for others.

4. Climate engineering and its distributional consequences

4.1. Background on debate over CE

The debates over the use of one or more the CE technologies as a way of keeping the global average temperature well below 2 °C have intensified in recent times (Irvine et al., 2019; [34]. The National Academies of Sciences, Engineering, and Medicine has commissioned a study to develop a research agenda and recommend research governance approaches for climate intervention strategies that reflect sunlight to cool Earth.[8] Equally important, the government of Switzerland introduced a resolution at the UN Environment Assembly in Kenya in March 2019, calling for an assessment of the potential methods and governance frameworks for each one by August 2020.[9] While the scholars of CE recognize the risks linked to its deployment, they also argue for comparing those risks to the near certain and staggering costs that catastrophic climate change will impose (e.g. Ref. [35]; for an explanation of risk-risk tradeoff framework, see, [36]. Because the need to avoid catastrophic climate change is regarded as a collective global responsibility, some scholars consider the deployment of SAG, and CE more generally, to that end as an act of public interest [37].[10] Others, such as the writers of the "Oxford Principles" for governance of CE, argue that CE be provided as a public good [3,29]. However, critics of this approach have argued that a public goods-framing of CE is misleading, because it marginalizes ethical and distributional concerns [4,38].

What this debate largely overlooks, however, is the technical definition of public good that refers to the good's non-excludability and non-rivalry. By disentangling the technical details of what it means to be a public good and focusing on the production and

[8] https://www8.nationalacademies.org/pa/projectview.aspx?key=51415.

[9] https://www.climatechangenews.com/2019/02/26/swiss-push-talk-geoengineering-goes-sci-fi-reality/.

[10] One of the first outdoor experiment with plans for aerosol injections into the earth's upper atmosphere is being planned by Harvard University https://www.theguardian.com/environment/2017/mar/24/us-scientists-launch-worlds-biggest-solar-geoengineering-study.

provisioning processes associated with SAG (as a proxy for this and other CE interventions), we highlight the difficulties in implementing an international governance system that both effectively regulates the public goods-aspects of SAG and ensures an equitable distribution of its costs and benefits (see also [39]. We further argue that analyses of climate SAG cannot be done in isolation of its interactions with other parts of climate system, such as potential impacts on seasonal monsoons or other regularized climate phenomena.

4.2. Background on SAG

Before going further, however, it is important to emphasize that while robust modeling research programs for developing SAG technologies exist, to date, SAG exists only as a future theoretical possibility [40].[11] Nonetheless, the policy debates over SAG governance are ongoing and, for the most part, the discussion is driven by its purported positive attributes like its purpose-driven, intentional, and global-scale deployment. Scrutinizing the public good nature of SAG requires a careful analysis of the attributes of the good being produced or provided [7].

SAG entails injecting sulfate particles into the stratosphere, which is a layer of the atmosphere that begins between 10 and 18 km above the surface. The injected particles are expected to scatter and reflect solar radiation, which will increase the planetary reflectivity and lead to cooling of earth's atmospheric temperatures [41]. This technique is often likened to the natural processes of large volcanic explosions, which also produce similar effects of sulfate injections followed by the cooling effects. The injected aerosol particles are expected to have a lifetime of 1–3 years, which necessitates the re-injection of stratospheric aerosol over long periods of time to maximize the desired cooling effect. An early termination of stratospheric sulfate injections is likely to cause a rapid warming, which is often referred to as 'termination shock' [41].

Two features related to the input and output ends of SAG merit specific attention. First, in the context of the global interventions, SAG can be carried out at relatively low cost compared to other climate change adaptation or mitigation strategies. We focus on the cost aspect of SAG when developing the theoretical model of goods production and provisioning to note that, among other possibilities, its relative low-cost deployment makes it susceptible to provisioning by both state and non-state actors. Second, SAG is likely to lead to significant changes in global hydrological cycles, the effects of which will vary significantly between land and sea surfaces, as well as across different regions with distinct climactic conditions [31,42,43]. We therefore also focus on the effects of the hydrological cycle to emphasize the asymmetric distributional impacts of SAG, which will locally produce positive or negative impacts depending on the status quo climactic conditions in a region, as well as, ironically, that region's ability to adapt to changes caused by SAG.

To understand the distributional impacts of SAG as a public good, we first identify the mechanisms through which its production and provision take place. The purpose of our exercise is to establish bounds of externality costs (or benefits) and demonstrate the potential for either negative impacts to a wide range of actors, or in the extreme to demonstrate the possibility for net negative social welfare. The primary theoretical questions are two-parts. 1) Is SAG a positive-externality public good, a negative-externality public good, or a combination of positive- and negative-externality producing public good (or, indeed, a public good at all?). 2) What are the general externality costs relative to the direct benefits and costs from SAG[12]?

5. SAG and its provisioning: insights from public goods theory

5.1. Is SAG a public good?

To begin exploring question 1, SAG is generally viewed as meeting the technical definition of a public good, since its impacts are non-excludable and non-rivalrous at the stratospheric level [44]. We first turn to identifying the positive and negative externalities expected with likely SAG interventions by disentangling the production and provisioning processes associated with public goods.

According to V. [24]; it may be the case that the externalities of a good are different during its production than from its provision such that the nature of the good itself might be different. In the example of the aerosol spray, its production is likely best handled by a private firm precisely because it is a rivalrous good that is relatively excludable in production (i.e. it produces relatively few positive or negative externalities in its production)—a classic private good scenario in which markets are fully capable of ensuring efficient production. Indeed, the nature of SAG as a private good in production is one of the factors that makes it relatively low cost to produce since the transactions costs of preventing free riders in its production are virtually nonexistent [45]. For a free rider in production to exist, someone would have to be exposed to externalities from the good without participating in its production; however, exclusion costs are so low as to make this scenario trivial.

However, after being produced, the aerosol is then provided into the stratosphere, as part of a large-scale field experiment or deployment, at which point its externalities are highly non-excludable and non-rivalrous. What was a private good in production becomes a public good in provision; one that is as close to a theoretical 'pure' public good as any engineered good we can imagine. This provisioning process is what proponents of SAG generally focus on and label SAG as a public good. Nonetheless, the production and provision of collective goods like SAG are distinct processes that result in efficiencies at potentially different scales of organization, depending on the externalities. This is an important insight since many SAG proponents typically view the good as a unidimensional public good, which itself may not be the case.

5.2. The costs of SAG provision

Recall previously we noted that two issues regarding SAG are salient for our theoretical development—that it can be provided at relatively low cost and that its provision asymmetrically impacts hydrological cycles across geospatial regions [31,46,47]. The low cost of physically distributing the aerosol into the stratosphere (provision) is itself partly a function of the low cost of production—potentially low enough for an individual or an individual nation to take upon itself to provide, if that individual or individual nation believes its individual benefits from climate change mitigation outweigh its individual costs of SAG-provision. An IPCC report, for example, suggest that the injection of 10 million tons of sulfur annually into the stratosphere is likely to produce the effect of reversing fully the atmospheric warming caused by the doubling

[11] Calculating the true costs and benefits is beyond the scope of our theoretical argument here.

[12] The net effect of SAG would depend on the total amount of aerosol, the size of aerosol particles. While aerosol particles scatter radiation in the visible band, they also absorb some solar and thermal radiations, which results in atmospheric heating [27].

of the CO2 concentration as compared to the pre-industrial era.[13] Aerosol injections of this magnitude could be accomplished on the order of a cost of USD 1–10 billion that is estimated to be the cost of injecting one mega-ton of material per year [41]. These low costs are relatively easily born by individual nations or non-state actors, such that economic factors are unlikely to motivate actors to seek international cooperation, which triggers concerns about the risks of rogue non-state actors acting unilaterally to deploy SAG.

Such possibilities of rogue action are of great consequence, especially considering the risks of termination shocks[14] once a SAG intervention has been set in motion. Furthermore, such possibilities are not just theoretical, despite recent commentary to the contrary [48,49]—as recently as 2012 a businessman from California dumped in excess of 100 tons of iron dust into the Pacific Ocean in a self-described "state-of-the-art study" to experiment with the geo-engineering principle of iron fertilization in which, theoretically, plankton blooms living off the produced iron oxide can sequester large amounts of carbon [50]. This makes collaborative international governance and regulation of SAG necessary, but difficult to enforce [36,51,52].

When the benefits to an individual or a group of actors of providing a collective good outweigh the costs, they will provide the collective good regardless of the presence of free-riders [10]. Since the costs of SAG provisioning are low, the benefits to an individual (nation) need not be particularly high for an individual (nation) to privately provide SAG regardless of the externalities it produces. Thus, if the individual provider believes that SAG is a public 'good' in the sense that it produces only positive externalities, because the rhetoric of CE debates emphasizes this view, it is possible—or likely—that s/he will provide SAG without seeking international consensus precisely because s/he will view its provision as strictly Pareto-improving.

Herein lies the crux of our argument: If SAG produces differential externalities, including negative costs borne by some regions, nations, or individual actors, then such a rosy-view of SAG as *in the public interest* could obfuscate complex distributional issues associated with SAG's deployment. While inadvertent misunderstandings of the rhetoric of (in the) public good is relatively innocuous, some strategic actors who stand to benefit from the deployment of SAG could also use the rhetoric of *in the public interest* to mask other intentions. Whether or not SAG is a public good in the technical sense has no direct bearing on whether or not it is Pareto-improving at the least, or, in the extreme, results in net social welfare loss [33].

This becomes clear when incorporating the asymmetrical impacts on regional hydrological cycles that any large-scale SAG project would create [42,43,47].

5.3. Hydrological cycles and SAG

Climate patterns are notoriously difficult to predict given the complexity of global atmospheric and stratospheric dynamics. When discussing the need for mitigation strategies, IPCC reports frequently discuss how climate change itself will produce unpredictable regional impacts—while the average global temperature may increase, so too will extreme weather events, though it is unpredictable where these extreme weather events will occur (for an opposing view see Ref. [2]. Similarly, SAG will produce unpredictable shifts in regional hydrological cycles that are likely to change monsoonal conditions, and potential non-linear effects about which we know little at present [40]; Robock 2016; [53]. These shifts are most likely to disproportionately impact already marginalized communities.

Most climate models predict that a warmed climate is likely to make wet areas wetter and dry areas drier [31,41]. The SAG interventions, as can be expected, are likely to modulate the effects of atmospheric warming, which means that many regions in the world are likely to see reduced precipitation. One recent study predicts a "robust and significant decrease of monsoonal precipitation over land for East Asia (6%), North America (7%), South America (6%), and South Africa (5%), and a robust but not significant decrease of 2% over India" [31]; 11054). Based on an analysis of precipitation and streamflow records from 1950 to 2004, linked to the effects of volcanic eruptions from El Chicho'n in March 1982 and Pinatubo in June 1991, Trenberth and Dai suggest that "major adverse effects, including drought, could arise from geoengineering solutions" [54]; 1).

While the research on climate modeling of Monsoons, especially in the wake of climate change, is in its nascent stages [55], it is reasonable to argue that SAG is likely to have different inter-regional impacts (Ricke et al., 2013; [40]. More specifically, land-locked dryland regions in Asia and Africa, inhabited by large populations of socially and politically marginalized communities, are likely to be bear the brunt of adverse impacts of SAG. On the other hand, SAG is certainly likely to help control sea-level rise, thereby effectively avoiding the harm that climate change is likely to cause to coastal infrastructure concentrated in some of the wealthiest cities of the world. It is worth noting that even in poor countries, coastal cities are often the wealthiest regions within the country, while the poorest regions are often located inland. It is therefore possible, indeed likely, that SAG simply shifts the costs of climate adaptation from the wealthy to the poor intra-nationally and internationally; the distributional consequences of SAG are likely aligned with the skewed concentration of political and economic power in the status quo.

Our answer to the question 1 posed above (what type of externality-producing public good is SAG?) is that SAG is a non-rivalrous and non-excludable good at the point of provision and, therefore, is a public good; however, its provision results in neither strictly positive externalities nor strictly negative externalities. Instead, the provision of SAG is best thought of as resulting in asymmetrically distributed positive and negative externalities and cannot, therefore, be assumed to be strictly Pareto-improving, except for under some specific and restrictive modeling conditions that are unlikely to be replicated in the real world. As a result, SAG should not be referenced in relation to "the public good", even if it is *a* public good, without first clearly establishing the relative benefits and costs of those heterogeneous externalities and weighing the appropriateness of these and other equity concerns. This concern is further exacerbated because of its low costs of production and provision., The temptation for individual actors to unilaterally provide SAG without the consensus of an international agreement is real, the impacts of which could be devastating in some places. Proponents of SAG or other large-scale CE interventions, therefore, must change the rhetoric from one that equates a public good with the public interest, to one that carefully examines the range of regional and localized costs and benefits that will result from unilateral or collective action on its provision.

5.4. Externality costs of SAG

The presence of asymmetrical externality costs is not in-itself

[13] A termination shock occurs when SAG has been implemented and then suddenly is stopped. Previously trapped carbon is released as a shock, rather than a slow release [55].

[14] There is another theoretical possibility, which we ignore here, in which climate change would not happen in any situation, but SAG is still provided. In this case, the externality costs of SAG would be relative to a climate-changeless world. However, given the of debate over SAG presumes a world with climate change, we do not feel such an analysis is fruitful.

sufficient to argue for or against the provision of SAG. Instead, a full cost-benefit analysis would need to be conducted to account for the individual regional/sub-national costs and benefits in order to determine if the aggregate benefits of climate change-avoidance still outweigh its aggregate costs. If indeed SAG is net cost-beneficial, then it still may be normatively justifiable so long as reasonable compensation schema can be developed to ensure that those most vulnerable to its negative externalities are ultimately not made worse-off by its provisioning, a Kaldor-Hicks styled compensation [3]. Such a comprehensive cost-benefit analysis is beyond the scope of our current analysis; however, to get at our second question (what are the relative externality costs of SAG?) we can sketch out the basic outline of what an analysis would look like and still draw theoretical bounds for outcome scenarios.

The direct benefits and the externality costs from SAG can be aggregated at international, national, and sub-national levels. At each such level, the benefits from SAG are equal to the prevented economic costs of climate change attributable to the specific SAG intervention plus the additional economic benefits from the opportunities that climate change prevention creates within the specific jurisdictional level. Though it is likely that climate change will have positive economic benefits for *some* nations or sub-national units [56]; Bonch et al., 2016), it is reasonable for us to assume that the economic costs from climate change outweigh the costs from mitigation and adaptation policies at the international level (indeed, without that assumption there would be neither a normative nor a positive justification for a SAG intervention in the first place).

The externality costs from SAG are simply the additional costs from SAG to each jurisdictional level relative to a world with climate change[15]. Notice that a jurisdiction could have a net benefit from SAG, but still incur externality costs. If this occurs at any level, then policymakers might consider ways to offset those costs or compensate actors harmed by redirecting some of the benefits accrued to other actors. To further complicate matters is the observation that for some nations or sub-national units, climate change would be net costly relative to no climate change, but a SAG intervention that lessened monsoons may be either more or less costly than the impacts of climate change, depending on the specific ecological, institutional, and technological characteristics of that nation or sub-national unit.

Given the heterogeneity of costs and benefits to national and subnational (or non-state) actors, it is likely that SAG benefits some and harms others, both relative to a world with climate change and a world without climate change [57]. However, the actors who stand to benefit from SAG have an asymmetrical advantage to provide it, relative to actors who wish to prevent its provision. This is seen by examining the relative costs of provisioning against the costs of organizing to prevent provisioning. As noted previously, the relatively low cost of provisioning makes it an easy task for an individual or individual country to undertake. However, actors harmed by SAG cannot simply provide a substitute good at an equally low cost; instead, they must organize politically to argue against SAG in order to prevent its provision. These actors (countries, subnational units, or individuals) face large transactions costs in collectively acting to prevent its implementation, which puts them at an asymmetrical disadvantage to beneficiaries and also places the burden of proof on these disadvantaged actors. Given the large uncertainty that plagues many aspects of climate change debates, but particularly for the discussions of untried and theoretical interventions like SAG, these costs of collective action are even higher than they would be under perfect information. If monsoonal-dependent regions are indeed the most likely to be negatively impacted by SAG and these regions are already political disadvantaged intra- and inter-nationally, then an obvious environmental or climate injustice emerges.

If SAG is highly likely to occur, then it is still the case that its differential externalities (i.e. increased costs from diminished monsoons in some cases) could be effectively compensated for in myriad ways, including through a wealth transfer from those who stand to benefit from SAG (wealthy nations internationally or wealthy cities intra-nationally) to those who will bear the costs (poorer nations internationally or poorer regions intra-nationally). Such compensation schema are unlikely to be developed *ex post* to a SAG intervention as an individual actor need only care about the net benefits to itself (either national or individual). Hence, there is a danger in a well-intentioned, but lone state- or non-state 'entrepreneur' who provides SAG based on the individual net benefits it receives. Given the uncertainty over the impacts of hydrological changes in regional or local weather patterns, it is imperative that the provision of SAG take place via international consensus where compensation arrangements can be *ex ante* negotiated; otherwise, SAG is likely to exacerbate the same environmental injustices of climate change that geoengineering is purportedly designed to solve.

6. Discussion and conclusions

Nothing in our argument should be taken to mean that CE interventions like SAG will not ultimately be in the public interest. However, whether that is the case requires a careful calculation of the attendant aggregate benefits of climate mitigation relative to the various individual costs such an intervention places on a diverse set of global actors. Given the incentives of individuals to act outside of the international environmental consensus, it is crucial that these real costs and benefits are fully understood. We believe that the theories of political-economy have much to offer in this endeavor and future work will continue to push practitioners, scholars, and proponents towards a nuanced explication of the full range of benefits and costs such interventions entail.

The situation of uncertain and new climate interventions is even further exacerbated by arguments that focus solely on the aggregate benefits or costs from these interventions. If a subnational or national jurisdiction will be negatively impacted by such an intervention—relative to a world with or without climate change—then, currently, the onus of proof falls on these actors to demonstrate why, given the aggregate benefits, the intervention should not take place. However, these actors are naturally disadvantaged by their bargaining position—costs are uncertain and transactions costs of collectively acting are high. This is a normative dilemma in these interventions in that the actors most negatively impacted by CE are precisely the actors already most disadvantaged in national and international negotiations to begin with. Rich countries can mitigate the impacts of CE in the same way rich countries (or regions) can mitigate the impacts of climate change. Poor countries (or regions) are reliant on the decisions made by autonomous actors and international organizations and must bear the costs of those decisions without input. In essence, the same environmental and climate justice problem that CE could help solve, as some have argued [58], can actually be exacerbated by CE interventions. Any international governance system must take this asymmetrical situation into account.

Our recommendation for CE is simple: Take the considerations of marginalized or economically disadvantaged nations and regions seriously. Our purpose in this paper was not to provide specific recommendations for how best to implement CE, but rather to simply lay out the theoretical foundations for why the status quo debate over CE is falling short of its promise to bring true environmental justice to international climate debates. International actors must recognize the complexities of asymmetrical impacts from CE interventions when negotiating solutions for climate change and must be proactive in agreeing to institutions regulating the use of SAG before individual nations or subnational actors take it upon themselves. In this context, we support the various ongoing efforts and recommendations to deliberate over and develop CE governance arrangements, including anticipatory governance mechanisms [27,36,59]. Furthermore, scholars must use phraseology like 'public goods' with caution and not without specifying that even public goods are frequently bad, especially for subgroups of individuals.

Given the complex and multifaceted externalities and impacts of SAG, it is increasingly important that advocates and opponents alike understand the language used to debate the usefulness of SAG in mitigating climate change (see also [51]. While proponents frequently invoke SAG or CE more generally as a public good or in the public interest (for a counter-point see Ref. [52], both of these claims—which are themselves quite different statements—deserve serious scrutiny by scholars. We used CE as a motivating example precisely because it is an important contemporary debate; however, we believe the underlying arguments put forth regarding heterogeneous externalities and public goods are relevant for refining theoretical expectations and empirical studies on a wide-range of topics involving public goods.

As a general point, we believe political scientists and policy scholars too often confound *public goods* with *public projects*. However, we focused here on bringing in an understanding of heterogeneous externalities, rather than on critiquing this confounding. This was intentional in order to highlight how the widespread assumption that public goods are strictly beneficial skews important political debates and limits scholarly ability to fully assess the costs and benefits of engaging in public goods provisioning. The assumption that public goods make everyone better-off is too simplistic for salient models of policymaking and hinders further theoretical development. We hope that in highlighting the heterogeneity of externalities that public goods produce, scholars will pay more attention to both the positive and negative aspects of any goods production or provision.

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