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REVIEW

Stratospheric aerosol injection may impact global systems and human health outcomes

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Solar radiation management (SRM) is a climate engineering strategy to reduce temperature increases due to global climate change. The most well-researched SRM methodology is stratospheric aerosol injection (SAI), which involves increasing the concentration of aerosol particles in the stratosphere to reduce the amount of solar radiation reaching Earth's surface. The most considered and heavily researched aerosol for SAI is sulfate. SAI has been extensively modeled using various climate scenarios and investigated using data from previous volcanic eruptions, which provide an analog of the climate effects of SAI. Prior research has determined that SAI will not only decrease global temperatures but is likely to have direct impacts on ecosystem and public health. This review seeks to investigate the various ways by which SAI may impact global public health outcomes related to hydrologic cycling, atmospheric chemical cycling, frequency of natural disasters, food system disruptions, and ecological health through the pathways of water, air, soil, and biota. SAI has the potential to decrease negative health outcomes associated with rising temperatures but may have a myriad of impacts on global environmental systems. Anthropogenically altering the global climate, through both the release of greenhouse gases or through climatic engineering, has unknown consequences, many of which will likely impact global health and quality of life. A more holistic approach is necessary to understand the relative benefits and harms in using SAI as compared to the implication of global climate change.

Keywords: Solar geoengineering, Stratospheric aerosol injection, Public health, Climate change

1. Introduction

Solar radiation management (SRM) is a proposed method to reflect incoming solar radiation and aims to reduce some of the negative consequences resulting from greenhouse gas (GHG) emissions (MacMartin et al., 2014; Irvine et al., 2016). A frequently examined method of SRM involves deploying stratospheric aerosol injection (SAI), which increases the concentration of aerosol particles, usually sulfate, in the stratosphere (Keith and Irvine, 2016). Although there are some studies exploring the use of nonsulfate aerosols for SAI (Weisenstein et al., 2015; Keith et al., 2016), the most widely researched aerosol for SAI is sulfate and there is inadequate literature to review on the impacts of such nonsulfate SAI. This review therefore focuses only on SAI using sulfate aerosols. The additional aerosol particles in the stratosphere would reflect incoming sunlight, thereby reducing the downwelling radiation reaching Earth's surface (Irvine et al., 2016). These effects lead to a decrease in overall global average temperature and could therefore mitigate some of the worst effects associated with climate change (Irvine et al., 2019). While there is a high degree of confidence in the use of SAI to offset the worst climatic effects of rising GHG concentrations, there are also some concerns regarding potential unintended consequences including ramifications for both ecological and public health (Intergovernmental Panel on Climate Change [IPCC], 2021).

Multiple methods have been proposed for the injection of aerosols into the stratosphere. While aircraft-based delivery mechanisms still need to be developed for successful deployment, estimates suggest SAI direct implementation costs are likely very cheap compared to the direct implementation costs of mitigation or the costs of

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unmitigated climate change (Barrett, 2008; Smith and Wagner, 2018). For example, SAI direct implementation costs have been estimated to be on the order of several billion USD per year, while global mitigation costs consistent with a pathway limiting warming to less than 1.5°C are estimated to be on the order of several trillion USD per year for just the electricity sector (Smith and Wagner, 2018; Riahi et al., 2021). The process of aerosol injection has been modeled using various scenarios and different locations for injection points. The most extensive research and modeling scenarios have focused on injection in the tropics (between 30°N and 30°S). Injection scenarios focus on the location of the aerosol emissions and the influence across the globe. As temperature changes can depend on the injection mechanism, other ecological, atmospheric, and public health outcomes are also dependent on the location of injection (Kravitz et al., 2015; Ferraro and Griffiths, 2016).

Aerosol injection through anthropogenic intervention is a relatively new concept; however, natural variations of this same phenomenon have occurred throughout history in the form of volcanic eruptions. During volcanic eruptions, sulfur dioxide (SO_2) is released into the atmosphere, leading to increases in stratospheric sulfate aerosols and inducing a series of environmental changes. Volcanic eruptions have therefore often been used as an analog for the implications of SAI, providing insights on the possible temperature and precipitation changes that may be induced by such an injection (Trenberth and Dai, 2007; Robock et al., 2010; Robock et al., 2013; Laakso et al., 2016; Proctor et al., 2018; Lopes et al., 2019). Regional temperature and precipitation changes following a volcanic eruption are also highly dependent on sampling and magnitude of injected aerosol, and this is likely also true of SAI, where regional impacts will be reliant on the amount of aerosol and injection location (Polvani et al., 2019; Polvani and Camargo, 2020; Azoulay et al., 2021; Banerjee et al., 2021).

Human climate control through SAI will not only present questions of governance, ethics, and technology development but likely pose additional questions about the long-term potential benefits or harms to global natural systems. Increases in planetary albedo from SAI have been modeled to show impacts on the global hydrologic cycle, reducing overall global precipitation (Ferraro and Griffiths, 2016; Ji et al., 2018; Tilmes et al., 2020). Other effects include changes in particulate air pollution, tropospheric ozone formation, and other aspects of atmospheric chemistry (Xia et al., 2017; Eastham et al., 2018b). These consequences must be weighed against the risk of not implementing SAI and the resulting challenges from climate change. The current impacts of climate change bring the possibility of many global public health challenges, such as natural disasters and heat waves, shifting ranges for disease vectors and changes in global agricultural production (Lobell and Field, 2007; Lafferty, 2009; Mitchell et al., 2016). Without GHG mitigation, these public health issues will occur regardless of SAI implementation, but deploying SAI may prevent some of the worst impacts.

A large body of research has evaluated social and political risks associated with SAI without GHG mitigation. These include geopolitical risks like weaponization of the technology and use for terrorism, "moral hazard" of overreliance on SRM to mitigate harm resulting from climate change, inequitable distribution of climate risk, and risks due to faulty implementation including "termination shock" if the use of SAI ceases abruptly (McCusker et al., 2014; Faran and Olsson, 2018; Flegal and Gupta, 2018; Parker and Irvine, 2018; Grieger et al., 2019). A smaller body of literature focuses on possible implications for human health and related ecological impacts (Irvine et al., 2017; Zarnetske et al., 2021). Here, we review the literature on unintended atmospheric, hydrologic, ecological, and food system disturbances from SAI that have the potential to impact global public health outcomes and identify gaps in the literature.

2. Methods

To investigate potential unintended ecological and public health consequences associated with SAI deployment, we reviewed the existing literature to build a preliminary qualitative health impact assessment (HIA) through causal chain analysis (Qiu et al., 2018). The causal chain analysis combines previously held theories and ideas with cited literature sources to bridge pathways between SAI deployment, environmental impacts, and human health effects. To build this, we begin with the literature on SAI and the natural analogs to understand how this might perturb the atmosphere. From those perturbations, we then review the literature to understand linkages throughout the earth and atmospheric systems, ecosystems, and eventually to human health. While this is not a comprehensive evaluation of the possible consequences of SAI, we attempted to collect the existing evidence on major linkages to ecosystems and health and to identify research gaps. This article focuses exclusively on effects and public health implications linked to sulfate SAI unless otherwise explicitly stated.

This review explores the major pathways by which changes in environmental exposures driven by geoengineering impact global public health and ecosystem health. The major pathways include air, water, and soil transport. Some implications of SAI's direct effects on atmospheric chemistry, air pollution, and precipitation have been previously cataloged; however, the indirect effects have been studied only in a limited capacity. The literature review here focuses on SAI modeling studies and studies including volcanic eruptions which can act as a proxy for SAI and their implications on air pollutant concentrations and associated public health consequences. While volcanic eruptions can act as an analog for SAI, the effects observed from volcanic emissions are an imperfect analog for the modeled effects of SAI, as a volcanic eruption represents a pulse injection rather than a sustained injection and there are additional differences such as latitude of injection and spatial distribution (Duan et al., 2019).

The reviewed pathways also included feedback cycles, linking multiple variables together in a single outcome path. We do not examine governance, political, or technological complications associated with deployment and the potential consequences associated with termination shock as previous literature already focuses on this (Frumhoff and Stephens, 2018; MacMartin et al., 2019; Reynolds, 2019).

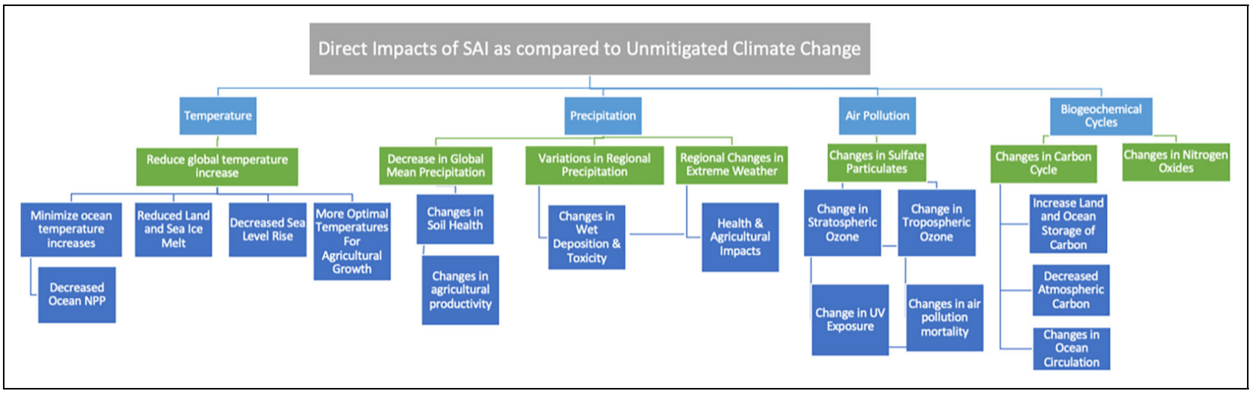

Figure 1. Diagram of select major of impacts and pathways of importance for stratospheric aerosol injection (SAI) as compared to unmitigated climate change. Light blue boxes indicate a primary pathway for SAI impacts. Green boxes indicate a primary impact of SAI, while dark blue boxes indicate a secondary impact.

A complication when reviewing the SAI literature is that the response for a given pathway can vary based on the way in which SAI is implemented and the underlying scenario in which the implementation occurs. The location, timing, and magnitude of the SAI can all alter the magnitude and sometimes even direction of the impact that SAI has on different global systems (Kravitz et al., 2015; Ferraro and Griffiths, 2016; Tilmes et al., 2017; Tilmes et al., 2018b; Irvine et al., 2019; Kravitz et al., 2019; Visioni et al., 2020; Krishnamohan and Bala, 2022). The counterfactual with which an SAI scenario is compared to, such as different trajectories for GHG emissions, can change the impact of a given SAI intervention (Jones et al., 2018). Although some impacts of SAI have been examined across multiple studies, for other impacts, the literature is more limited. For these less studied impacts, there remains the possibility that the impact of SAI could change under different scenario designs.

We classify the known direct impacts of SAI into seven direct effects, specifically changes in sea-level and sea-ice, hydrologic cycling, temperature, sunlight, particulate air pollution, tropospheric ozone, and stratospheric ozone. Effects were further categorized based on the environmental medium of interest (air, water, or soil) and potential pathway of influence (agriculture, contamination, direct exposure, pathogenic, food/water, or ecological). From the initial seven direct pathways, additional downstream effects were incorporated into the HIA. For example, potential air pathways include public health effects, such as asthma related to $PM_{2.5}$ and ozone and additional outcomes associated with fluctuations in ultraviolet (UV) light exposure.

3. Results and discussion

The resulting literature review consisted of an analysis of over 200 papers on the potential consequences of SAI. Of those papers, the majority specifically addressed downstream SAI effects using climate modeling, while some papers relied on information collected from previous volcanic eruptions and others relied on information from solar reduction models. The literature covered a wide range of effects including multifaceted climate change implications, such as temperature change; ice and permafrost changes; soil, sea-level, and ocean response; hydrological changes; agriculture and vegetation; air quality; chemical cycling; and ecosystem impacts. We also included numerous papers that do not deal directly with SAI but can be used to elucidate potential consequences of SAI deployment. The results and pathways of importance are summarized in **Figure 1**. A listing of the number of sources referenced for each paper subsection is shown in Supplementary Table S1.

3.1. Atmospheric disruption

3.1.1. Tropospheric air pollution

A direct public health consequence of SAI deployment is changes in air quality. The injection of sulfur into the stratosphere induces changes in atmospheric chemistry. SAI results in changes in atmospheric concentrations of tropospheric ozone and particulate matter (PM) through a variety of mechanisms including changes in photochemistry and changes in wet and dry deposition (Eastham et al., 2018b; Visioni et al., 2018). SAI deployment results in increased sulfur particulates in the Earth's stratosphere, altering a series of reactions that result in stratospheric ozone depletion (Pitari et al., 2014; Xia et al., 2017). Tropospheric ozone, or surface ozone, is an air pollutant with known human health consequences and is linked to a myriad of respiratory illnesses (Nuvolone et al., 2018; Lu et al., 2020). Changes in stratospheric ozone concentrations also impact the composition of the troposphere due to photochemical reactions resulting from changes in UV absorption (Jacob, 2000).

The potential public health implications of SAI need to be considered in the context of climate change. Changes in future air pollution concentrations will be driven by both changes in emissions levels and changes in climate (Jacob and Winner, 2009; West et al., 2013; Silva et al., 2016; Shen et al., 2017; Markandya et al., 2018). Therefore, several variables such as those related to potential policy changes, emission types, population levels and distribution, and warming scenarios can complicate attempts to quantify premature mortality changes due to changing air pollution and climate.

We are aware of only one published study so far that looks at the health impacts of SAI on health due to air quality changes (Eastham et al., 2018b). The scenario of Eastham et al. (2018b) uses SAI sufficient to offset 1°C of surface warming in 2040 to examine how air quality changes may influence public health. Understanding the changes in air pollutants due to SAI was done using v11-01 of the GEOS-Chem global chemistry-transport model. SAI health impacts from photochemical changes are dominated by the likely decrease in tropospheric ozone, which occurs due to decreased ozone mixing into the troposphere and from changes in tropospheric ozone photochemistry (Eastham et al., 2018b). One other study has examined the impact of SAI on tropospheric ozone, also finding a general decrease in surface ozone due to SAI, but with a slight increase in surface ozone in the tropics and without a calculation of resulting health impacts (Xia et al., 2017). Cooling due to SAI can impact air quality by decreasing surface ozone concentrations through slowing down the photochemical reactions that produce ozone. However, the lower temperatures due to SAI can also increase surface $PM_{2.5}$ concentrations by promoting increased particulate nitrate due to greater partitioning of gaseous nitrate into aerosol. Increased mortality due to $PM_{2.5}$ was also simulated due to decreases in rainfall and resulting wet deposition as well as an increase in particulate sulfate due to the settling of the injected stratospheric sulfate (Eastham et al., 2018b).

For Eastham et al. (2018b), the comparison of estimates between global SAI injection scenarios and unmitigated climate change scenarios suggests that air pollution and UV exposure-related premature mortality and additional deaths may be slightly higher in a scenario with SAI introduced. There is large uncertainty, even within this single study, with regard to both the sign and magnitude of the impact of SAI on air pollution-related mortality. In total, it was simulated that changes in UV, $PM_{2.5}$, and ozone exposure due to SAI could cause between a net decrease in mortality of 30,000 deaths per year to a net increase in mortality of 79,000 deaths per year. This net change is due to an increase in mortality related to $PM_{2.5}$ (+88,000 deaths per year; 95% CI: 53,000 to 120,000) and a small increase related to UV exposure (+4,500 deaths per year; 95% CI: 1,600 to 8,800), counterbalanced by a decline in mortality related to ozone exposure (−67,000 deaths per year; 95% CI: −110,000 to 28,000). Mechanistically, photochemical changes were simulated to decrease mortality, driven by declines in ozone, while changes in temperature and precipitation caused increases in mortality, driven by increases in $PM_{2.5}$. The impact of changes in photochemistry, rainfall, and temperature changes due to SAI were all simulated independently, leaving the interactions between these 3 mechanisms as an additional unexamined source of uncertainty. Another source of uncertainty is the changes in population-level pollutant exposure that would result from changes in atmospheric dynamics due to SAI, which have yet to be examined in any study.

Limited other modeling work has specifically calculated the potential air quality-related public health impacts of SAI. One additional study has characterized potential occupational and exposure impacts from potential SAI materials, but these toxicity measures have largely been limited to direct sulfate inhalation within an occupational scenario (Effiong and Neitzel, 2016). As noted above, sulfur aerosols and related dry and wet deposition products of SO_2 and sulfate may impact human health as respiratory irritants and induce cell damage in respiratory tissue. Related compounds such as hydrogen sulfide and carbonyl sulfide also have known adverse health effects, including respiratory distress, neurological complications, and cardiac arrhythmia (Reiffenstein et al., 1992; Jäppinen et al., 1993; Effiong and Neitzel, 2016). However, additional modeling efforts are needed to investigate the potential atmospheric changes, regional differences, and temperature fluctuations and how these may influence human health.

Through changes in atmospheric dynamics and temperatures, SAI may also affect particulate air pollution by changing the sources and distribution of dust or wildfire smoke. Future desertification due to climate change can result in dustier environments, with negative downstream consequences for public health though both increases in airborne particles and dust-borne diseases such as Valley fever (Achakulwisut et al., 2018; Li et al., 2021). SAI could reduce the potential for dust increases under such scenarios. Wildfire smoke is also a cause of premature mortality that may increase along with global temperatures (Reid et al., 2016; Li et al., 2020b). If SAI can reduce the incidence of wildfires, which has not yet been investigated, it could also reduce mortality due to smoke exposure. Overall SAI changes to atmospheric chemistry will not only induce public health implications but may also have long-term effects for wildlife and global habitats.

3.1.2. Stratospheric ozone and UV radiation

SAI is known to have various interactions with stratospheric ozone levels, such as changes in heterogeneous chemistry, photolysis rates, and changes in stratospheric dynamics (Heckendorn et al., 2009; Tilmes et al., 2009; Pitari et al., 2014; Tilmes et al., 2022). Although the importance of different mechanisms varies among studies, examinations of the impact of SAI generally find that SAI decreases stratospheric ozone in high latitudes compared to a scenario without SAI, while the simulated effects in the midlatitudes and tropics can vary depending on how different stratospheric processes are included in the model (Heckendorn et al., 2009; Tilmes et al., 2009; Tilmes et al., 2012; Pitari et al., 2014; Xia et al., 2017; Robrecht et al., 2021; Tilmes et al., 2022).

A main negative repercussion of decreases in stratospheric ozone is increased UV radiation at the planet's surface (Pitari et al., 2014; Nowack et al., 2016; Eastham et al., 2018a). As mentioned above, decreased stratospheric ozone may also lead to decreased tropospheric ozone pollution, assuming ozone transport remains the same. Reduced tropospheric ozone exposure is a function of decreased transport of stratospheric ozone to the troposphere and of changes in photochemistry. As compared to global warming scenarios, SAI will reduce surface-level ozone exposure as ozone concentrations will decrease with temperature as photochemical production slows (Eastham et al., 2018b).

For SAI, the frequently simulated depletion of stratospheric ozone may alter the distribution of UV radiation reaching Earth's surface (Pitari et al., 2014; Eastham et al., 2018b; Madronich et al., 2018). While SAI has generally been modeled to increase UV-B irradiation, there is evidence that SAI may both increase or decrease UV-B transmission. UV-B is normally absorbed by stratospheric ozone, limiting transmission to the Earth's surface; however, when sulfate particles are introduced into the atmosphere, the particulates may alter the optical path of the UV-B transmission as well as induce changes in stratospheric ozone, enhancing or reducing UV-B transmission depending on the relative changes in particulates and stratospheric ozone (Xia et al., 2017; Madronich et al., 2018).

Modeling studies indicate that increases in UV wavelength exposure due to stratospheric ozone depletion may be more important than UV wavelength decrease due to increased reflection by higher levels of stratospheric aerosol, although there are latitudinal variations in the balance between these two effects (Pitari et al., 2014; Eastham et al., 2018b). UV radiation exposure has known human health consequences particularly related to increased rates of melanoma and potential long-term DNA damage. High levels of UV exposure have genotoxic impacts as DNA absorbs UV-B, converting it to photochemical enegry which may distort DNA strands (Roy, 2017). Increases in UV exposure are an important factor in causing skin cancer, but SAI modeling to date has been limited. Eastham et al.'s (2018b) results suggest global net mortality changes due to UV exposure-related skin cancers may be small, on the order of approximately 4,100 additional deaths per year. However, this does not take into account that UV exposure may be nonlinearly related to skin cancer and global skin cancer rates are underreported, particularly in the Global South.

Unmitigated climate change will also impact the interaction between stratospheric ozone and UV radiation. Under a global warming scenario, additional climate change-related factors may interact with UV radiation and lead to subsequent increases in exposure (Bornman et al., 2019). Changes in Earth's surface due to climate change, such as temperature increase, alterations in land cover, increases in carbon dioxide (CO_2) levels, and decreasing water availability, may alter UV exposure levels. Shifting weather patterns and related changes in cloud cover linked to increasing global temperature as also likely to impact UV exposures, potentially increasing in some regions and decreasing in others. Climate change-related changes in UV will also change biogeochemical cycles, impacting the carbon cycle and cycles of GHGs (Zepp et al., 2011). Climate change will also impact stratospheric ozone levels, and in some cases, stratospheric ozone depletion is directly contributing to increased climate change in the Southern Hemisphere (Barnes et al., 2019; Bornman et al., 2019). Changes in the climate modifying temperature, moisture, wind speed, and direction can deplete stratospheric ozone and therefore influence levels of UV radiation reaching Earth's surface. Various GHGs, including methane and nitrous oxide, also modify the atmospheric chemistry regulating ozone level (Barnes et al., 2019). Continued increases in GHG concentrations along with the potential impacts of climate change are likely to change both stratospheric ozone concentration and human exposure to UV radiation.

The likely impacts of SAI on stratospheric ozone and UV radiation are largely comparable to the impacts that are predicted to occur due to unmitigated climate change. Both SAI and global warming contribute to decreased levels of stratospheric ozone and likely increased levels of UV radiation, which has known adverse health impacts. The magnitude of risk of these impacts is currently uncertain as they depend on either the quantity and duration of SAI or the quantity of GHGs released into the atmosphere.

3.1.3. Biogeochemical cycling

SAI can have consequences on atmospheric chemistry and on the biogeochemical cycling and distribution of elements including nitrogen, sulfur, and carbon (Tjiputra et al., 2016; Lee et al., 2021a). Existing modeling evidence suggests that introduction of SAI may lead to a decrease in atmospheric CO_2 concentrations through an increased ocean CO_2 uptake (Tjiputra et al., 2016; Tilmes et al., 2020). There is also evidence to suggest that introduction of any SRM, including SAI, would impact vegetative carbon storage, most prominently carbon storage changes due to land cover changes, but this effect varies by regional biome (Cao and Jiang, 2017; Lee et al., 2021a). The cooling effects of SAI would also decrease ocean temperatures, increasing CO_2 solubility and ocean CO_2 uptake by as much as 10% (Tilmes et al., 2008; Tjiputra et al., 2016). The effects of SAI on terrestrial and ocean CO_2 uptake are still relatively unknown and could be greatly impacted by nitrogen cycling effects (Thornton et al., 2009; Glienke et al., 2015; Tjiputra et al., 2016). Research also suggests the impacts of SAI on the land-carbon cycle, where lower temperatures improve soil carbon retention, thereby decreasing atmospheric carbon concentration (Tjiputra et al., 2016). Other research suggests SAI could reduce net terrestrial ecosystem respiration and lead to fewer ecosystem disturbances, also leading to an increased land carbon sink (Yang et al., 2020). Lastly, SAI is likely to impact methane concentrations (Visioni et al., 2017), although the amount and magnitude of the change remain unclear.

Stratospheric aerosols can also play a direct role in the overall chemical balance of the atmosphere. Stratospheric sulfate aerosols are also particularly important in midlatitudes for the conversion of nitrogen oxide (NO_x) compounds to reservoir form HNO_3 (Fahey et al., 1993; Pope et al., 2012). Changes in NO_x alter the balance of photochemical reactions that produce and destroy ozone, which, as mentioned above, may have effects on UV light penetration and subsequent public health outcomes, such as increases in UV-related skin cancers (Fahey et al., 1993; van Dijk et al., 2013). Changes to atmospheric ozone are also largely dependent on the aerosol distribution, which is likely to vary depending on SAI altitude

(Tilmes et al., 2018b). For a tropical injection scenario, modeling suggests a small increase (less than 5%) in stratospheric ozone (Butler et al., 2016; Tilmes et al., 2018b).

It is not surprising that the purposeful injection of aerosols into the stratosphere, through geoengineering, may alter global biogeochemistry and atmospheric cycling; however, humans have been injecting particulates into the atmosphere in mass quantities since the start of the industrial revolution. Under a scenario of unmitigated climate change, global biogeochemical cycles will be altered due to increased air pollution, increased temperature, and changes in precipitation patterns (Piao et al., 2019; Piao et al., 2020). Increased global temperatures are linked directly to a higher concentration of CO_2 in the atmosphere through a positive feedback cycle where increased CO_2 emissions generate increased temperature, in turn leading to an increase in atmospheric CO_2 concentrations (Harde, 2019). Climate change reduces both land and ocean uptake of CO_2, leading to even higher concentrations in the atmosphere (Friedlingstein et al., 2001; Mitchard, 2018). The impacts of major weather events and extreme changes in regional climates (increased high temperatures and decreased low temperatures) will also induce regional implications for the global carbon cycle in relation to terrestrial carbon storage (Piao et al., 2019). As discussed in the previous section, unmitigated climate change will also have direct implications on stratospheric ozone concentrations. Several other global chemical cycles, notably nitrogen, methane, and mercury, will also be disrupted in various directions and magnitudes with increasing global temperatures (Schaefer, 2019; Yang et al., 2019; Li et al., 2020a).

The implications of SAI are likely to change global biogeochemical cycling in ways that both mirror and oppose the global responses initiated by unmitigated climate change. However, SAI is modeled to decrease atmospheric CO_2 concentrations due to decreases in global temperature, resulting in increased ocean and land carbon storage. Additional biogeochemical implications of both SAI and climate change are still being investigated, as many variables and nuanced mechanisms can have a drastic impact on changes in global cycling and downstream impacts on ecological systems.

3.2. Hydrologic system disruption

The global hydrological system is vital for human life with direct impacts on global drinking water supply, crop production, and ocean productivity. The global hydrologic cycle is likely to be altered by SAI and climate change. One of the most well-known and strongly studied implications of SAI is the overall decrease in global mean precipitation (MacMartin et al., 2018). While the decrease in global mean precipitation is modeled to be small in magnitude, larger magnitudes of fluctuation (both increases and decreases) will be experienced regionally (Ferraro et al., 2011; 2014; MacMartin et al., 2018). SAI can affect precipitation through changes in atmospheric circulation. Hydrologic systems are sensitive to SAI-induced changes in downwelling solar radiation, which can impact the frequency and amount of precipitation events. The magnitude of precipitation changes is highly dependent on the magnitude of temperature change due to SAI (Keith and MacMartin, 2015).

The current literature suggests that global mean precipitation will decrease as temperature increases are prevented, but this will likely result in an unequal decrease and in some cases a precipitation increase across global regions (MacMartin et al., 2018). Precipitation will generally increase as global temperatures increase through unmitigated climate change, so SAI can play a role in counteracting this increase (Keith and MacMartin, 2015).

3.2.1. Monsoons and tropical storms

Along with alterations in precipitation, SAI may impact the frequency and intensity of extreme precipitation events. Currently, there is conflicting evidence within modeled systems regarding the direction and magnitude of potential effects, as effects are dependent on the amount of aerosol and location of injection (Kravitz et al., 2019). Some studies have found that tropical SAI may suppress monsoon precipitation, such as over the Asian and African monsoon regions (Robock et al., 2008; Ferraro et al., 2014; Sun et al., 2020). A modeling study specifically focusing on monsoon effects in West Africa showed that a level of SAI effective enough to mitigate all future warming would offset precipitation changes in the Northern and Southern Sahel Regions but overcompensate and lead to decreased precipitation in Western Africa (Da-Allada et al., 2020). However, additional modeling evidence suggests that effects on regional monsoon variation are highly dependent on the latitude of injection. While injection at any latitude is likely to alter global mean temperature and global mean precipitation, greater variation is seen in regional temperature changes and regional precipitation changes. A scenario where 12 Tg of SO_2 are injected at various latitudes (30°S, 15°S, equator, 15°N, and 30°N) demonstrated that relative to an RCP8.5 scenario, mean summer monsoon precipitation decreased in the hemisphere, where aerosols were injected and increased in the opposite hemisphere (Krishnamohan and Bala, 2022). A similar result was found for a study of the effect of SAI via Arctic injection, where monsoon precipitation decreased in the northern hemisphere but increased in the southern hemisphere (Nalam et al., 2018).

Variability in monsoonal precipitation has a direct effect on agricultural production and associated economic productivity. For example, in Indian agricultural production, deficit rainfall is more damaging than increased monsoon precipitation (Gadgil and Gadgil, 2006). Rainfall dependability is a major factor in crop determination and yield; regions experiencing decreased rainfall due to climate change have already started changing their normal crop production to accommodate new rainfall patterns (Surianarayanan et al., 2018). As compared with an unmitigated climate change scenario where wet regions will likely get wetter and dry regions will have an increased risk of drought, model simulations find SAI may overmitigate current climate change trends for some regions, such as the tropics (Abiodun et al., 2021). On the other hand, different simulations find a more complicated picture, such as simulating a net increase in tropical preciptaiton outside of cyclone season (Ji et al., 2018). It is thus currently unclear whether SAI would over or undercompensate for precipitation changes relative to global temperature changes as this would be dependent on injection strategy.

In addition to impacts on monsoonal precipitation, a major implication of unmitigated climate change is the increased intensity of natural disasters, including higher precipitation associated with cyclones (IPCC, 2018). Natural disasters, including cyclones and monsoons, lead to human mortality and infrastructure destruction, as well as contamination of local water systems, increased risk of communicable disease, and forced human migration (Diaz, 2007). SAI could reduce climate change implications associated with natural disasters by preventing increasing global temperature, but the impact would vary based on injection methodology. Models suggest global application of SAI would decrease tropical cyclone formation relative to unmitigated climate change, although this is heavily dependent on the latitude and location of injection (Moore et al., 2015; Jones et al., 2017). Additional evidence using data following volcanic eruptions suggests that low-latitude eruptions also decrease tropical cyclone frequency in the Atlantic (Guevara-Murua et al., 2015). Some modeling studies also suggest SAI could reduce tropical cyclone intensity (Moore et al., 2015; Ji et al., 2018; Irvine et al., 2019).

Changes in precipitation frequency or variations in precipitation volume can have wide implications for potential droughts and flooding. Observational and modeling evidence from the eruption of Mt. Pinatubo in 1991, used as a proxy of pulse injection SAI and not as a direct analog, show drought effects in water scarce regions of the world or areas that rely on isolated precipitation events to supply the majority of annual water supply (Trenberth and Dai, 2007). SAI modeled using Stratospheric Aerosol Geoengineering Large Ensemble (GLENS) models at a level to compensate for changes in temperature was shown to overcompensate for precipitation, changing drought risk over major river basins in Africa (Abiodun et al., 2021). Other work has found SAI can change the drought pattern over East Asia (Liu et al., 2021). Work examining SRM with a uniform solar reduction has found that, with globally varying effectiveness, SAI may reduce the likelihood of drought by reducing the frequency of heatwaves and consecutive dry days (Dagon and Schrag, 2017). Drought conditions can have major public health impacts as well as ecological implications, including famine, water scarcity, and decreased quality of available water (Alpino et al., 2016; Liu et al., 2020b). For example, recent work has suggested a drought may increase arsenic levels in private well water sources suggesting an SAI pathway to affect water quality via impacts on drought (Effiong and Neitzel, 2016; Lombard et al., 2021).

There are also major consequences of SAI associated with flooding. In normally arid areas of the world, increases in precipitation could pose a serious threat to flood plain regions by causing massive runoff as the soil is not equipped to handle large precipitation volumes (Bae et al., 2015). Flooding can also lead to increased toxic runoff from agricultural systems or industrial areas, leading to freshwater contamination and associated public health and ecological toxicity repercussions (Euripidou and Murray, 2004; Alderman et al., 2012). SAI has the potential to reduce flooding risk, particularly in the flood prone regions of Southeast Asia; however, flood risk may be increased in drought prone regions, such as Mexico, Australia, and the Southwestern United States (Wei et al., 2018). If by changing regional precipitation levels SAI can reduce flooding, it could therefore have important public health benefits.

Extreme precipitation events including changes in monsoon patterns, droughts, and flooding are all also likely outcomes of unmitigated climate change (Bell and Masys, 2020). An increase in extreme weather (hurricanes, floods, and droughts) has been linked with increases in global temperatures and changes to atmospheric circulation due to climate change (Mann et al., 2018). As with SAI, these effects will be seen largely at a regional level with small island nations, coastal communities, and the Global South seeing the strongest magnitude of impact (Le, 2020; Thomas et al., 2020). In contrast to predictions from SAI models, unmitigated climate change has been modeled to increase the magnitude and duration of monsoon season in Asia and Africa, likely increasing the humidity over desert biomes in these regions (Seth et al., 2019; Jackson et al., 2022). Extreme weather events from climate change pose many of the same public health implications as potential weather modifications due to SAI, including increased risk of disease, displacement, and threats to global food and water supply (Tong and Ebi, 2019).

3.2.2. Ice melt, runoff, and sea-level rise

One of the most widely publicized and well-known implications of unmitigated global climate change is the melting of polar ice caps. Ice caps and glaciers are one of the largest reservoirs of freshwater; however, this water is mostly inactive in the global hydrologic cycle as its natural residence time in ice caps is long enough to be considered irrelevant for human time scales (United States Geological Survey, 2020). In addition, melting ice generates a positive climate feedback loop, with declines in ice surface area decreasing surface albedo leading to further warming (Curry et al., 1995). Under a tropical injection SAI scenario equivalent to ¼ of the Pinatubo Volcano eruption (G4 scenario), SAIs have been modeled to slow mass loss from the melting of the Greenland ice sheet by 15%–20% as compared with RCP4.5, stabilizing radiative forcing at 4.5 watts per meter squared in the year 2100 (Moore et al., 2019). Modeled effects on ice melt are directly dependent on the injection scenario and injection amount, with different injection latitudes contributing to different effects on ice melt, temperature change, and overall climatic effects. Additional studies have also noted a likely decline in surface ice melt of the Greenland ice sheet through the use of SAI as compared to historical data (Tilmes et al., 2020). Preservation of ice, particularly in the Arctic, is also sensitive to location and timing of injection, with some models indicating greater ice preservation with injection in the spring months to alleviate increased summer heat (Lee et al., 2021b).

Prevention of ice melt and decreased risk of sea-level rise directly protects coastal dwellings from flooding damage and prevents saltwater intrusion of city water supplies (Werner and Simmons, 2009). SAI could also improve climate resilience in small island states, which have a disproportionately higher risk of damage due to unmitigated climate change (Pernetta, 1992).

In addition to sea-level rise from ice cap melting, thermal expansion of sea water can contribute to sea-level change. Recent modeling suggests SAI will actively prevent sea-level rise related to thermal expansion of sea water; however, there is uncertainty surrounding the response of ice sheets and precipitation reductions (Irvine et al., 2016). One study estimates that SAI of a constant 4 W m^{-2} reduction in radiative forcing could delay sea-level rise by 40–80 years under the RCP3PD scenario (Moore et al., 2010). Previous models and estimates derived from historical sea level data after volcanic eruptions show a global mean sea-level decline of up to 5 mm 1 year after the eruption, due to both reduced thermal expansion and decreased precipitation; however, any changes in sea level linked to volcanic eruptions are directly dependent on the magnitude of the eruption (Church et al., 2005).

Along with terrestrial ice melt, another impact of climate change is the disappearance of sea ice (Johannessen et al., 2004). As atmospheric temperatures rise, so does global ocean temperature leading to increased melting of sea ice (Serreze et al., 2019). Due to the concept of displacement, the melt of sea ice does not directly impact sea-level rise; however, it will have ecosystem impacts (i.e., habitat loss, ocean freshening) and could lead to shifts in weather patterns (Wadhams and Munk, 2004). Sea ice loss can also reduce surface albedo and lead to further warming as positive feedback (Dai et al., 2019). A simulation of arctic injection of SO_2 at an altitude of 14.5 km in a 1-km deep layer showed remediation of losses of Arctic sea ice by the year 2043 (Jackson et al., 2015). Models using the GLENS simulation under RCP8.5, with injection occurring at multiple latitudes and altitudes (15°N and 15°S at 25 km, 30°N and 30°S at 22.8 km) (Tilmes et al., 2018a) found that SAI will have influence over high-altitude seasonal cycles resulting in warmer winters and cooler summers, leading to an overcompensation of 52% in summer arctic sea ice recovery and an under compensation of 8% in the winter as compared to the present-day climate (Jiang et al., 2019). While additional climatic variables are difficult to predict, a decrease in global temperature by SAI is likely to decrease the loss of sea ice and possibly reverse sea ice loss that has already commenced.

3.2.3. Ocean circulation and biogeochemistry

The oceans are also a key stabilizer of the global climate with direct connections to atmospheric circulation and global food supply. They also act as the one of the most important global carbon sinks alongside the biosphere. Public health is directly connected to the ocean, particularly in communities deriving most of their food from the oceans. There are several mechanisms through which SAI could change the circulation of the ocean, such as the effect of SAI on ocean temperatures or surface winds. Changes in the circulation within the ocean, along with global temperature reductions caused by SAI, could have effects on the ocean temperature distribution (Cao et al., 2016). For large-scale ocean circulation, multiple studies have found that SAI can lead to an acceleration in the Atlantic meridional overturning circulation compared to a scenario without geoengineering (Muthers et al., 2016; Fasullo et al., 2018; Xie et al., 2022).

Oceanic phytoplankton, such as diatoms, are a crucial component of ocean ecosystems and the functioning of the planet as a whole, acting as both a food source for ocean ecosystems and as a major carbon sink (Benoiston et al., 2017). As diatom growth depends on the radiative spectra of light, if SAI changes the profile of light reaching diatoms, it could affect their growth and the functioning of this keystone component of the ocean ecosystem and climate system (Lavaud et al., 2007). SAI only indirectly affects ocean acidification through biogeochemical processes, but since ocean acidification is primarily driven by GHG emissions, SAI does little to address the root cause of ocean acidification. However, as ocean acidification is accelerated by rising ocean temperatures, SAI may deter further ocean acidification by reducing global mean temperature. Temperature is also directly related to additional ocean health phenomenon including events like coral bleaching (Cornwall et al., 2021). SAI would most likely impact ocean health indirectly by controlling global temperature. Due to this temperature effect, one study found SAI could reduce coral bleaching in the Caribbean (Zhang et al., 2018).

Ocean biogeochemistry also has impacts on oceanic net primary production (NPP) (Rubin et al., 1998). Tropical injection SAI with an injection strength of 40 Tg of SO_2 per year was modeled to induce a decrease in ocean NPP relative to an RCP4.5 Scenario by the year 2100 (Lauvset et al., 2017). This decrease was due mostly to circulation changes but also influenced by changes in incoming solar radiation, decreased temperature, nutrient availability, and subsequent impacts on phytoplankton biomass, which persist up the food chain (Lauvset et al., 2017). Additional models have demonstrated opposite effects, showing that SAI of a magnitude to keep temperature at 1.5°C above preindustrial levels, will mitigate the impacts of climate change on ocean NPP, particularly in North Atlantic regions (Tilmes et al., 2020).

Unmitigated climate change will also have direct implications for ocean circulation, chemical cycling, and net primary productivity (Bijma et al., 2013). Global ocean temperatures are expected to rise in accordance with global increases in atmospheric temperature, contributing to large-scale ocean warming. Along with temperature increase, high concentrations of GHGs are a known contributor to ocean acidification, which can have detrimental impacts on ocean organisms, particularly those with calcium carbonate shells (Rastrick et al., 2018). Widespread ecological impacts, like coral bleaching, also result from the combined effects of ocean acidification, changes in chemical cycling, and rising ocean temperatures

(Diraviya Raj et al., 2018). While contradictory evidence exists on the implications for net primary productivity in the oceans, recent reports estimate that total marine animal biomass will decrease significantly under an RCP8.5 scenario (Bijma et al., 2013; Bryndum-Buchholz et al., 2019). Ocean warming is also predicted to change global ocean currents including alterations to the intensity and frequency of seasonal events, such as El Niño and La Niña (Allison and Bassett, 2015). The magnitude of these impacts is difficult to determine as it depends heavily on atmospheric CO_2 concentrations and efforts to reduce GHG emissions. As compared with SAI, unmitigated climate change presents many of the same if not more risks to oceanic system disruption that will directly stem from increases in atmospheric global temperature and increased GHG concentrations.

3.2.4. Wet deposition and toxicity

Significant evidence has been collected regarding the association between atmospheric particle number concentration, particle type, and acidic wet deposition (Stumm et al., 1987; Pye et al., 2020). The impacts of acid rain on ecosystem health were critical for the development of regulatory limitations on emissions of SO_2 and NO_x (Menz and Seip, 2004). Acid rain is formed by atmospheric processes, which convert SO_2 and NO_x compounds to sulfuric and nitric acid, leading to decreased precipitation pH (U.S. Environmental Protection Agency, 2016). Acid rain causes pH changes to lakes, rivers, and streams, disrupting water quality used for ecosystem and human consumption and resulting in harm to the health of humans and ecosystems (Likens and Bormann, 1974; Singh and Agrawal, 2008).

As of 2015, approximately 125 Tg of SO_2 are released to the atmosphere annually from anthropogenic sources, though emissions are trending downward globally due to technological advancement (Aas et al., 2019). Sulfur emissions are also naturally released by various environmental processes every year, including volcanic eruptions, fires, and biogeochemical cycles, but anthropogenic emissions are the main source of atmospheric sulfur (Fioletov et al., 2016). Almost all of the sulfur currently emitted into the atmosphere is wet deposited to the Earth's surface (Aas et al., 2019). For reference, the amount of SO_2 for SAI to maintain temperatures at 1.5°C above preindustrial levels is approximately 48 Tg per year; however, this amount is dependent on the climate scenario at the time of deployment and injection strategy (Tilmes et al., 2020).

While SAI injection would take place at a much higher altitude than the bulk of SO_2 and NO_x emissions that affect the troposphere, interactions between the stratosphere and troposphere do take place, and over time particles will eventually settle down to Earth's surface (Visioni et al., 2020). Modeling studies have not shown a significant increase in surface sulfur deposition from the direct settling of injected sulfur in SAI (Kravitz et al., 2009; Visioni et al., 2020). Prior estimates suggest that the largest additional deposition resulting from SAI use, approximately 0.05 mEq $m^{-2}a^{-1}$, is not enough deposition to negatively impact ecosystems; although the magnitude of the effect does depend on both injection mechanism of SAI and geographic variation (Kravitz et al., 2009). Other work suggests that the deposition of injected sulfur particles may increase acid deposition in pristine areas and in the ocean (Visioni et al., 2020). The deployment of global aerosols over a century for SAI would also be counterbalanced by the subsequent decreases in anthropogenic SO_2 emissions as humans shift from the use of fossil fuel sources (Visioni et al., 2020). However, work to date on the effects of SAI on deposition to the surface may underestimate the impact of SAI on sulfur deposition as prior work has not included variations deposition due to interaction with the nitrogen cycle (Gao et al., 2018; Visioni et al., 2020).

In contrast to the impact of settling stratospheric aerosol particles, decreases in precipitation due to SAI can lead to decreased rainout of particulates, slowing wet deposition, and increasing the lifetime of surface air pollution. This effect has only been calculated in a single study, but the calculated impact of decreased rainout on mortality due to air pollution was about twice as important, with an additional 14,000 (7,100–21,000) premature mortalities per year, as the mortality impact of increased settling of stratospheric aerosol particles (Eastham et al., 2018b).

SAI may also affect cycling of nitrogen or other nutrients important for aquatic and marine ecosystems, possibly changing the magnitude, intensity, extent, and spatial distribution of algae blooms and hypoxic "dead zones." Nutrient cycling and associated water quality has direct links to public health in terms of aquatic-based food supply, drinking water quality, and access to recreational water bodies. Currently, there is little clarity on the exact implication of SAI and water contamination and this area of research requires further exploration.

Unmitigated climate change, or unregulated emission increases, will also have direct impacts on wet deposition, with associated public health implications linked to toxicity of water and soil (Grennfelt et al., 2020). This is primarily through acid rain and linked to increased GHGs in the atmosphere that interact with the hydrological cycle resulting in rainwater that infiltrates surface water systems and soils. While continuing the current global path of continued warming does not directly introduce new compounds into the atmosphere, like with SAI, it results in a further accumulation of GHGs and particulates and could easily reach levels higher than those proposed in SAI models.

3.3. Surface disturbances

3.3.1. Soil

Healthy soils are important for agriculture, water quality, biodiversity, and promoting uptake of large quantities of GHGs including CO_2 (Lal, 2004). Anthropogenic activities (e.g., farming, construction, urban development) have introduced toxins, pesticides, and fertilizers that increase the release of GHGs and disrupt the sequestration of soil carbon (Snyder et al., 2009). Understanding the impacts of SAI intervention on soil moisture and soil health is critically important for understanding potential long-term impacts of SAI on weather, biodiversity, and ecosystems, as well as direct relationships to human health, such as through connections to agriculture, drought, and forest fire risk.

Modeling of geoengineering scenarios with SAI shows likely changes in precipitation frequency and amount with high levels of regional variation, as compared to climate mitigation without the introduction of SAI (MacMartin et al., 2018). Precipitation patterns are directly associated with soil moisture, a critical variable for soil health and agricultural productivity (Kibblewhite et al., 2008). The effect of SAI on soil moisture remains uncertain and can depend on the specifics of the geoengineering scenario. Scenarios modeling multiple different aerosol injection sites predict that if SAI is implemented under high CO_2 conditions, global mean soil moisture will be retained compared to unmitigated climate change where global mean soil moisture is simulated to decline; however, there is a high potential for regional variability associated with changes in precipitation patterns (Cheng et al., 2019). Comparing the GLENS 20-member ensemble of simulations with a high emissions global warming scenario, simulated soil moisture is most heavily impacted by SAI in equatorial regions, which see the largest decreases in precipitation, with simulated SAI reducing summer soil moisture in India and the Amazon by 42 ± 11 kg/m^2 (3.5%) and 27 ± 16 kg/m^2 (2.1%) compared to near present-day conditions (Cheng et al., 2019). Along with changes in soil moisture, changes in precipitation also perpetuate changes in soil carbon storage. Lower global temperatures, as compared to the current state, will decrease the respiration rate of vegetation, leading to increased soil carbon storage (Tjiputra et al., 2016). Other models using GeoMIP G4 scenarios have shown increases in soil moisture in southern Africa, southwestern North America, and South America, with decreases in soil moisture occurring in tropical Africa, South Asia, and most of middle North America (Wei et al., 2018).

SAI also has the potential to impact soil pH and influence soil toxicity. As discussed previously, SAI would lead to changes in both wet and dry deposition of air pollutants. Wet deposition of $PM_{2.5}$ can directly impact soil pH, leading to decreased soil quality (Nam et al., 2008). For example, decreased soil pH allows for greater mobilization of aluminum due to increased aluminum solubility, leading to increases in soil toxicity (Visioni et al., 2020). Aluminum is a metal naturally occurring in many soils; however, it can lead to toxic effects if mobilization occurs, impacting the health of plants, wildlife, and aquatic systems where aluminum runoff might occur (De Vries et al., 1989). More investigation into the route of SAI consequences on agricultural lands and associated soil systems will be necessary to understand how SAI may impact global food supply. However, existing modeling results suggest SAI may increase the potential for aluminum mobilization and thus soil toxicity in some areas of North America, Northern Europe, and Oceania (Visioni et al., 2020). Regardless of SAI introduction, global climate change will also drive large-scale ecosystem changes, leading to decreased soil quality, pH changes, and metal mobility (Rengel, 2011). While geographical deposition will vary and it is challenging to predict deposition patterns and exact effects, SAI appears likely to result in less disruption in soil quality and toxicity as compared to unmitigated climate change.

The role of vegetation and agriculture in regulating soil moisture is also highly variable as plant water use depends on a combination of atmospheric CO_2 concentrations, temperature, and precipitation. Soil moisture variations due to SAI could disturb the pattern of evapotranspiration, photosynthetic rates, and subsequently soil moisture and quality (Dagon and Schrag, 2016). Since precipitation rates will vary by region, soil moisture will also vary. These changes will depend both on precipitation variation and on baseline soil types. An area with low soil moisture, and high heat such as the desert, may see improved crop production due to improved soil health. However, an area with already high soil moisture, such as the rainforest, may have decreased crop or ecological activity if precipitation rates increase, as this may oversaturate soils and disrupt evapotranspiration rates. Changes in soil moisture are also likely to vary by region and by variations in precipitation.

3.3.2. Permafrost

Anthropogenic climate change has led to an increase in high-latitude temperatures, causing increases in melting of what was once permafrost. Permafrost is not only necessary for maintaining ecological biomes but also prevents the release of sequestered soil carbon (Schuur et al., 2008). Frozen soils have limited activity within the global carbon cycle, not emitting or absorbing CO_2 or other GHGs. Concerns therefore exist about a positive feedback between permafrost thaw and climate change by which melting permafrost releases GHGs into the atmosphere and further adds to climate warming (Schuur et al., 2015), which would exacerbate all the public health issues connected to a warming climate. Permafrost is known to be sensitive to surface temperature and also dependent on yearly rainfall and snowfall, providing 2 major pathways by which SAI can impact permafrost thaw (Lee et al., 2019). Current modeling to predict the effects of SAI on permafrost shows that compared to the unmitigated climate trajectory, SAI with the previously mentioned GeoMIP G4 scenario, by decreasing global temperatures, could prevent the melting of permafrost layers (Chen et al., 2020). This could also prevent substantial carbon emissions; the same modeling study found that each 1°C warming in the Arctic permafrost resulting in a loss 13.7 Pg of carbon (Chen et al., 2020). A study using GLENS found an Arctic permafrost area decrease of only 5% by the end of the century as compared to models under the RCP8.5 scenarios, where annual permafrost area may decrease as much as 83% (Jiang et al., 2019). Another study found that under SAI sufficient to decrease global mean warming under the RCP8.5 scenarios to the RCP4.5 level, permafrost area decreases from approximately 11×10^6 km^2 to 4.5×10^6 km^2 by the year 2100, as opposed to decreases under the RCP8.5 scenarios where area is expected to diminish to approximately 2.5×10^6 km^2 (Lee et al., 2019).

3.4. Ecosystem disruption

3.4.1. Vegetation

Global vegetation plays a critical role in maintaining biodiversity, preserving habitats, and serving as a food source for both human and animal populations. Vegetation is also critical to the global hydrological cycle as evapotranspiration rates directly influence atmospheric water content (Wang et al., 2018). Adequate sunlight and water are the major requirements for maintaining rich global vegetation and a diversity of species (Zhu et al., 2008). One of the most well-known consequences of SRM implementation is the decrease in downwelling solar radiation and the blockage of sunlight dispersed by aerosol particles. Modeling has shown decreases in vegetative productivity with SRM implementation (Dagon and Schrag, 2019). The interaction between vegetation presence and the hydrological cycle may also potentially generate a positive feedback loop, where precipitation decreases lead to decreases in vegetation and subsequent decreases in evapotranspiration (Dagon and Schrag, 2019). However, SAI can also increase diffuse solar radiation even while net radiation reaching the surface declines (Xia et al., 2016). An increase in diffuse radiation can promote plant productivity due to more light reaching vegetated areas normally covered in shadows, such as those cast by other vegetation (Roderick et al., 2001). Work examining the effect of SAI on vegetation has found that this increase in diffuse radiation, together with decreases in temperature, can be more important than an overall decrease in solar radiation and thereby increase terrestrial gross primary productivity (Xia et al., 2016). Other work has found that, while the increase in diffuse light does impact photosynthesis, changes in temperature and precipitation changes from SAI may be larger drivers in changes in net primary productivity, which can be either positive or negative depending on the regional changes in precipitation and temperature (Lee et al., 2021a).

Vegetative systems are also impacted by the dry deposition of ozone. Ozone deposition into the plant's stomata can damage plant tissues and prevent continued growth (Clifton et al., 2020). Decreases in tropospheric ozone levels allow for healthier plant growth and subsequently greater uptake of CO_2 and increased leaf area index of vegetation (Zhou et al., 2018). SAI has been simulated to reduce tropospheric ozone levels (Xia et al., 2017; Eastham et al., 2018b), but the impacts of SAI on vegetation through changes in surface ozone have yet to be examined.

3.4.2. Biodiversity

Limited studies have explored the relationship between SAI implementation and ecological biodiversity (Zarnetske et al., 2021). The pathways connecting SAI and biodiversity are highly dependent on impacts to global temperature, precipitation, air quality, vegetative prevalence, and soil productivity. Current literature suggests that many risks to biodiversity are linked to termination shock—a fast, drastic rise in global temperature resulting from the sudden stoppage of SAI that occurs as global temperatures quickly rebound to what would have occurred in the absence of SAI (Parker and Irvine, 2018; Trisos et al., 2018a). Termination shock is not a feature of SAI deployment but rather a potential risk that may occur if once deployed SAI is suddenly stopped. However, the longer term impacts of SAI on biodiversity in the absence of termination shock have yet to be fully investigated. Biological hot spots, situated mostly over equatorial and tropical regions, are at the greatest risk of extinction due to unmitigated climate change (Trew and Maclean, 2021) but also may see the greatest changes in precipitation and soil moisture with SRM implementation counteracting the largest magnitude in changes from unmitigated climate change (Ji et al., 2018; Cheng et al., 2019).

The effects of SAI may lead to ecosystems disruption potentially causing additional stress among species sensitive to temperature and precipitation fluctuations; however, unmitigated climate change will also induce major changes in global temperature and precipitation patterns that will also incur additional stress. In both scenarios, specialized species that may vacate ecosystem niches leave opportunity for more generalist species, those with a wider range of suitable conditions, to fill in and out compete more specialized species. Ecosystem disruptions, from either SAI or continued climate change without intervention, could be propagated across various ecological niches and lead to major fluctuations in species interconnectedness through changes in food webs, species locations, and alterations in predator–prey relationships (Ainsworth and Drake, 2020; Henderson et al., 2020).

3.4.3. Zoonotic infection

Infectious disease and the transfer of potentially serious viral or bacterial infections from the animal kingdom to human populations has been a long-standing concern of global public health officials. The most notorious vectors (mosquitoes, mice, bats, and microorganisms) often live in prescribed optimized ranges, where they are adapted to thrive (Lafferty, 2009). The increasing global temperatures from climate change have extended the ranges of zoonotic infectors northward, while simultaneously allowing for the reemergence of endemic disease pathogens (Ogden and Gachon, 2019). The extended range of pathogens is a primary concern for human health specialists focused on mitigating climate change. There is also evidence to suggest an interactive effect between rising temperatures from climate change and animal infection rates, making some species increasingly sensitive to temperature fluctuations (Greenspan et al., 2017) and therefore sensitive to changes from SAI.

SAI deployment will uniquely modify global temperature gradients to control habitat range changes. Modeling scenarios conducted by MacMartin et al. (2017) suggest that atmospheric and climatic temperature response to SAI can be partially controlled with innovative deployment techniques, which could limit the potential for drastic temperature fluctuations and prevent increased ranges for zoonotic vectors. While there may be a certain degree of control possible over temperature gradients with SAI, other preliminary modeling work suggests that SAI could substantially increase malaria risk in low-lying West

African and Southern Asian countries while decreasing risk in high elevation areas of East Africa by roughly the same amount due to elevation-dependent temperature variations induced by SAI deployment (Carlson et al., 2022). However, this increase may also occur if carbon emissions were to decrease, as it is temperature dependent; any increase in global temperature would decrease malaria ranges and transmissibility across a wide portion of the globe (Mordecai et al., 2020; Diouf et al., 2022).

3.5. Global food system disturbances

3.5.1. Agriculture

Commercial and subsistence-based agriculture dominate the food supply, nutrition, and the livelihoods of millions of people. Agricultural success is heavily based on weather patterns and long-term predictable climate conditions (Musshoff et al., 2011). Global food systems and productive agriculture are also necessary to achieve adequate global nutrition and maintain regional populations through the prevention of malnourishment. The greatest benefits to agriculture from SAI are due to stabilization of global temperatures, creating more ideal growing conditions (Proctor et al., 2018; Xia et al., 2018). A simulation (GeoMIP) using G4 SAI, to offset RCP4.5, found that temperature is the dominant driver in predicting rice yield in China, with SAI resulting in yield increases throughout most areas of China (Zhan et al., 2019). Additional simulations focused on Chinese rice and maize production found that there was limited change in rice production, but an increase in maize production when using SAI (Xia et al., 2014). Models conducted on U.S. corn production show similar results when comparing G4 SAI (5 Tg SO_2/year) with carbon concentrations consistent with RCP4.5; where projected yields are higher under the SAI scenario, particularly in southeastern states which will experience greater extreme heat events in an unmitigated scenario (Crane-Droesch et al., 2018). As SAI effects differ regionally, agricultural impacts around the world are not likely to be equal. Models investigating the effects of GeoMIP G3 SAI on the Indian groundnut found that yields may decrease as much as 20% for the first 50 years of SAI until eventually stabilizing to current yield values (Yang et al., 2016). Empirical estimates using Mount Pinatubo and El Chichón eruptions also suggest a possible decline in sunlight, which may induce a negative impact on crops; however, volcanic eruptions exhibit pulse injection with a stronger concentration of sulfate particles in a single area (Proctor et al., 2018). Regional precipitation reductions due to SAI may also impact crop growth, particularly for water intensive crops like rice (Trisos et al., 2018b).

In addition to impacts on agriculture through changes on light and climate, SAI may lead to increases in crop growth through a reduction in tropospheric ozone levels (Xia et al., 2018). Ozone can damage crops by entering crop leaves through the stomata and causing internal damage to plant tissues, thereby significantly diminishing crop yields (Tai et al., 2014; Tai and Val Martin, 2017).

Agricultural pest populations are also impacted by global weather patterns and climate systems and could be affected by SAI. Warming temperatures extend the range of many species and the absence of cold weather spikes leads to larger ranges and increased populations numbers for multiple pest species (Estay et al., 2009; Langille et al., 2017). Climate change also may potentially wipe out natural pest predators leading to exponential pest population increases (Thomson et al., 2010). SAI has the potential to mitigate temperature changes due to global climate change and potentially control the exponential increase in agricultural pest populations that accompany unmitigated temperature changes. However, agricultural pests are also subject to the complexities of ecological system disturbances with dramatic climate events having major repercussions on their populations. SAI deployment and potential unknown consequences may lead to major fluctuations in species interactions and the natural predator–prey relationships that exist (Zarnetske et al., 2021). Disturbances in predator–prey relationships may also cause famers to alter pesticides application practices, which could further disrupt ecosystems. Additional investigation into the relationship between SAI deployment and predator–prey relations is necessary to fully investigate potential public health effects associated with disruptions in agricultural production.

3.5.2. Ocean food systems

Ocean food systems are a primary food source for over 1 billion people (Dewailly and Knap, 2006). Ocean health is of particular importance for individuals from small island states and those dependent on the oceans as a source of food. Conservation of food systems and protections from overfishing are vital to the continuation of adequate nutrition for communities relying on ocean food systems. Ocean NPP measures the amount of organic material in the ocean and provides an estimate of the material available to fuel the food webs (Finkel, 2014) and has been studied in the context of SAI. As previously noted, SAI would generate a global decrease in ocean net primary productivity (NPP) relative to the RCP4.5 scenario, having potential implications for the entire ocean food system (Lauvset et al., 2017). Also as previously noted, SAI will indirectly impact ocean chemistry including pH. SAI may lead to a small increase in pH; however, simulations suggest SRM at a level to return temperatures to preindustrial levels would not affect levels of aragonite saturation due to opposing responses to temperature changes for aragonite saturation and pH (Matthews et al., 2009). Aragonite saturation levels are key to the shell forming ability of calcifying oceanic organisms (Orr et al., 2005), suggesting that SAI may not significantly diminish this threat to oceanic ecosystems.

Coral reef fisheries, an important part of the global food supply, may also be impacted by SAI. Climate change and additional anthropogenic disturbances have led to coral reef decline and coral bleaching events as a result of temperature changes and ocean acidification (Hughes et al., 2012). Coral reefs are extremely sensitive environments, dependent on specific conditions, such as temperature, sunlight, and water quality. While SAI does not substantially change global CO_2 concentrations, a major driver of coral reef bleaching, solar radiation is also an important component of overall coral reef health (Crabbe, 2009). Ocean NPP, which may slightly decrease due to SAI (Lauvset et al., 2017), may also be an important driver of coral reef health. Coral reefs are also a primary driver of ocean primary production due to the recycling of organic material and the NPP from reefs is then distributed to the larger ocean environment (Crossland et al., 1991).

3.6. Pathways of major importance

All the exposure pathways for the effects of SAI on global public health discussed in this review are important to consider when determining the implications of SAI deployment. While all pathways are relevant for determining the total effects of SAI deployment on public health outcomes, there are some pathways that are more crucial than others for public health. Pathways with the greatest potential to influence public health are those pathways affecting water quality, water security, and global food systems, since these may influence the largest number of people. The dynamic connections between ecosystem and public health impacts also demonstrate a high degree of overlap between water, food, soil, and human health. Water quality, affected by rainfall and potential wet deposition from changes in particulate air pollution, has direct impacts on drinking water and ecological systems. Unintended consequences impacting water systems bridge into impacts on soil moisture, which has direct effects on agricultural food production. Soil moisture is also directly related to metal mobility in soils, potentially leading to toxic effects.

The other more obvious major pathway of influence is the downstream public health consequences from changes in atmospheric chemistry. Changes in particulate air pollution, in tropospheric ozone, and in sunlight exposures are all factors of concerns. Simulations suggest SAI deployment will not significantly change the total amount of particulate air pollution in the atmosphere, so particulate pollution effects appear likely to be small in magnitude.

Overall, all aspects of the ecosystems and implications for public health are either directly or indirectly connected. Any change in atmospheric dynamics will likely initiate change in other environmental domains including water, soil, food production, the animal kingdom, and human health. Since all ecological systems are connected and dependent upon one another, all pathways influenced by SAI are likely to have implication for other pathways, potentially resulting in unintended positive or negative consequences for global health.

3.7. Further research exploration

Additional investigation into SAI outcome pathways that may have a direct or indirect effect on public health requires continued extensive analysis and is necessary to better understand, and possibly quantify, the potential unintended consequences of SAI. Specifically, further analysis on the impacts to air and soil pathways that may impact agricultural systems and subsequently global food supply is critical as these will likely have large-scale global implications. While current climate models can make it challenging to look at downstream interactions and the many confounding variables present in a living system may make results uncertain, continued investigations taking into account potential public health implications of climate engineering should help reduce the uncertainty surrounding potential effects of SAI deployment or at least begin to illuminate a range of potential impacts.

Our review can help guide future research by highlighting the important pathways through which SAI can affect public health and inform additional pathways that future modeling research on SAI could include. This can help build a more holistic understanding of potential public health consequences, both helpful and harmful, of SAI, as compared to appropriate counterfactual scenarios of climate change. The response of vegetation and animal life to SAI deployment will also be increasingly important as we consider the interactions between human life, planetary health, and ecological systems. The relationship between anthropogenic action, the ecological world, and human health has become increasingly visible in light of the COVID-19 pandemic, with additional emphasis focusing on the need for climate action and preservation of biodiversity (Dobson et al., 2020). Our analysis shows that a joint ecosystem and human HIA and risk assessment framework is helpful, and possibly necessary, to capture the system interlinkages between ecosystem health and public health. More holistic modeling may be needed to understand these more distal linkages and interactions between the atmosphere, ecosystems, global carbon cycling, and health. A fuller HIA, directly assessing the various public health pathways, may become possible as the modeling of SAI progresses, and representation of these earth system linkages improves.

4. Conclusion

SAI has the potential to both help and harm public health and global ecosystems, and these consequences are still being evaluated. While mitigating the most severe consequences of global climate change, such as increased surface temperatures, SAI may introduce potential unknown consequences for public health outcomes that will need continued investigation. SAI has the potential to reduce the public health and ecosystem effects associated with temperature rise but may disrupt global environmental systems, potentially impacting water quality, agriculture, and zoonotic infection; however, continued unmitigated climate change will also bring about a variety of disruptions. There are many unknown or unintended consequences that may develop from fundamentally altering the global climate through SAI. While current models have predicted minimal negative impacts and highlight multiple positive impacts to improve public health and global ecology, there are many uncertainties surrounding SAI that remain. Geoengineering research has now reached a point at which some countries are beginning to develop national research programs (Temple, 2022). As research continues in this new era, it will be important to carry out more holistic modeling, including a focus on impacts, to continue to reduce the uncertainty surrounding the potential positive and negative consequences of SRM, especially those surrounding potential public health concerns.

Supplemental files

The supplemental files for this article can be found as follows:

Table S1. Summary of sources referenced for the direct implications of SAI. (Docx)

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Author contributions

- Substantial contributions to conception and design: SMT, JMM, JJB.
- Analysis and interpretation of complied articles: SMT, JMM, JJB.
- Drafted and revised article: SMT, JMM, SDE, JJB.
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