Potential ecological impacts of climate intervention by reflecting sunlight to cool Earth

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As the effects of anthropogenic climate change become more severe, several approaches for deliberate climate intervention to reduce or stabilize Earth's surface temperature have been proposed. Solar radiation modification (SRM) is one potential approach to partially counteract anthropogenic warming by reflecting a small proportion of the incoming solar radiation to increase Earth's albedo. While climate science research has focused on the predicted climate effects of SRM, almost no studies have investigated the impacts that SRM would have on ecological systems. The impacts and risks posed by SRM would vary by implementation scenario, anthropogenic climate effects, geographic region, and by ecosystem, community, population, and organism. Complex interactions among Earth's climate system and living systems would further affect SRM impacts and risks. We focus here on stratospheric aerosol intervention (SAI), a well-studied and relatively feasible SRM scheme that is likely to have a large impact on Earth's surface temperature. We outline current gaps in knowledge about both helpful and harmful predicted effects of SAI on ecological systems. Desired ecological outcomes might also inform development of future SAI implementation scenarios. In addition to filling these knowledge gaps, increased collaboration between ecologists and climate scientists would identify a common set of SAI research goals and improve the communication about potential SAI impacts and risks with the public. Without this collaboration, forecasts of SAI impacts will overlook potential effects on biodiversity and ecosystem services for humanity.

anthropogenic climate change | solar radiation modification | stratospheric aerosol intervention | ecosystem | biodiversity

Anthropogenic climate change* has enormous consequences for humans and nature. In particular, it is increasingly clear that the consequences of anthropogenic climate change for ecological systems† and their ecosystem services result in system degradation and transformation. These impacts are no longer merely warnings about distant future changes. They are happening now (e.g., refs. 1–4). Although climate scientists have

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*Here we use the term "anthropogenic climate change" to mean global warming and its impacts on all climate variables and their regional and temporal patterns, but we do not mean the potential anthropogenic climate change that could be produced by climate intervention.

†We use "ecological systems" broadly to mean biotic systems at any spatial scale, including ecosystem processes, and physiological functions and interactions among organisms with their biotic and abiotic environments (e.g., plant interactions with soil microbiomes; predator–prey interactions in terrestrial and aquatic communities; changing function, composition, area and location of biomes with climate change).

long warned of the urgency of climate change due to greenhouse gas (GHG) emissions (5, 6), current action and pledges to limit inputs of GHG are inadequate to prevent large and dangerous changes in the climate system (7–9). Climate intervention or geoengineering[‡] has been proposed to reduce some of the negative effects of climate change while efforts continue to reduce GHG emissions. One approach to climate intervention, solar radiation modification (SRM), proposes to reflect some of the incoming solar radiation to cool Earth's surface.

Although climate science research has resulted in greater understanding of predicted climate effects should SRM be implemented, little is known about how those changes would affect ecological systems. Filling this critical knowledge gap is essential to understanding how potential implementation could alter the structure and functions of Earth's biosphere, affecting biodiversity, ecosystem processes, and people. Here, we: 1) raise awareness of this knowledge gap; 2) highlight initial work on ecological consequences of SRM; 3) identify potential ecological impacts and risks from implementation scenarios of a prominent SRM scheme, stratospheric aerosol intervention (SAI); and 4) urgently advocate more research at the intersection of climate intervention and ecology, including exploring ways that ecological outcomes could steer SAI implementation scenarios.

The US National Academy of Sciences recommends that research be conducted to explore the risks and possible benefits of climate intervention, so that informed decisions can be made in the future about potential implementation (10). Yet, the consequences for ecological systems have barely begun to be investigated (e.g., refs. 11 and 12). More fundamentally, ecologists have not addressed the real possibility that climate intervention could take place, and awareness of extensive SRM modeling is limited within that community. At the same time, climate scientists have largely not considered the potential impacts that anthropogenic climate change and climate intervention strategies may have on ecological systems. Moreover, ecological outcomes of climate intervention have not been a focus of either group as potential guiding factors in decision making or designing intervention strategies.

Thus, many questions remain unanswered: If we could avoid a "hothouse Earth" and instead achieve a "stabilized Earth" (7) by deliberately manipulating Earth's climate system while also working to minimize GHG emissions, do the risks of climate intervention for humans and ecological systems outweigh the possible benefits? Do the risks and uncertainties of climate intervention outweigh those of anthropogenic climate change? When compared with ongoing anthropogenic climate change, which ecological systems and regions would be most helped or most harmed by climate intervention? Rather than only temperature reduction targets, could approaches to planetary climate intervention incorporate biodiversity and ecosystem outcomes as the targets, such as preserving the ecological integrity of the Great Barrier Reef, the Amazon, and the Arctic, reducing the decline of North Atlantic fisheries (13, 14), or reducing forest fire risk in vulnerable systems in Australia and California (15, 16)? The answers to these critical questions are necessary to inform future decisions about potential implementation.

Climate Intervention Approaches

There are two main proposed climate interventions to reduce global average temperature: carbon dioxide removal (CDR) to reduce atmospheric CO_2 concentrations, and SRM. Although CDR is considered to be lower-risk, it is currently prohibitively costly at scales large enough to reduce global average temperature. The costs and technology of implementing SRM are more attainable (17), but SRM also includes risks that are poorly understood, including uncertainties in international governance (10, 18, 19). The most researched SRM scheme, SAI, would reduce some of Earth's incoming solar radiation by enhancing the reflective aerosol layer in the stratosphere (Fig. 1). This scheme is inspired by the way that volcanic eruptions cool the global climate and involves injecting gaseous precursors of reflective sulfate aerosols into the stratosphere (20, 21). The models used for SAI are often the same Earth system models (ESM) used to study anthropogenic climate effects without SAI, or to study the effects of volcanic eruptions on climate. For studying the effects of SAI, however, models must additionally be able to represent complex stratospheric aerosol processes.

Various other SRM approaches have also been proposed, including marine cloud brightening, adding deflectors in space to reflect solar energy, or altering Earth's surface albedo (e.g., brightening urban roofs, crop, and other land-use changes) (19, 22), but these schemes alone are unlikely to be as effective as SAI in temperature reduction at global scales (10). We focus on SAI as the most feasible, most studied, and most likely SRM approach to be implemented.

Implementation of SAI

The impacts and degree of climate change reduction would vary by SAI scenario, including SAI phases of initiation, continuation, and termination of injecting sulfate aerosol precursors, as well as the location, timing, and amount of the injections. Different SAI

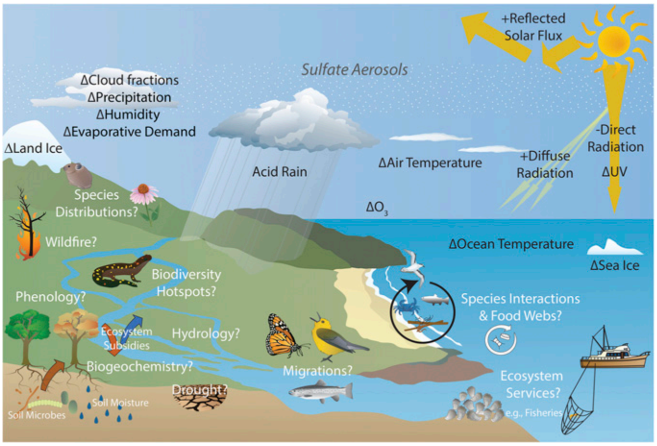

Fig. 1. Although some effects of SRM with SAI on the climate are known from certain SAI scenarios (indicated with + for likely increases, − for decreases, Δ to indicate change), the effects of SAI on ecological systems are largely unknown. Such biotic and abiotic changes would vary across Earth and depend on the SAI scenario. Stratospheric aerosols from SAI would reflect more sunlight—including UV radiation—to space, reducing surface UV. SAI could also destroy stratospheric ozone, increasing surface UV (Fig. 2*A*). The net effects of SAI on UV and ozone depend on the amount and distribution of aerosols in the stratosphere, the type of aerosols used, and how the aerosols interact with the chemistry and radiation of the atmosphere (e.g., refs. 23 and 141). Potential changes in ocean temperature and ocean pH in different regions are illustrated below (Fig. 3). Symbols courtesy of the Integration and Application Network, University of Maryland Center for Environmental Science (https://ian.umces.edu/symbols/).

[‡] The National Research Council (NRC, 2015) has recommended using "climate intervention" because "geoengineering" implies a more controlled process than is possible with the Earth–Atmosphere system.

scenarios can be initiated or terminated gradually or at once, further affecting the impacts. Scenarios can range from completely balancing the forcing from unchecked global warming, resulting from failure of emission reductions (23), to "peak shaving," in which limited aerosol injections balance strong decarbonization in the second half of the 21st century (24), with the goal of keeping global mean temperatures under 2 °C above preindustrial temperatures (Fig. 2).

Although temperature reduction is the main objective, SAI does not simply turn back the clock to the climate at some previous time. SAI could change many climate variables other than temperature that are important for ecological systems. Many direct impacts and unintended side-effects on Earth's climate have been explored across SAI scenarios (e.g., 28 potential risks are listed in table 2 of ref. 17), but others remain to be discovered. SAI could alter key ecological drivers, such as the ratio of diffuse to direct radiation (25), UV radiation (26), the connection between temperature and CO_2 (27), precipitation distribution, intensity and seasonality (e.g., ref. 28), acid precipitation (but see ref. 29), and air quality, including changes to surface ozone (30) (Fig. 1). In addition, while particular global cooling metrics can be attained in climate models, there would be regional perturbations to many aspects of the climate system, including seasonal and diurnal cycles of temperature, precipitation, humidity, and snow and ice cover, and temperature and precipitation extremes (23, 31–34). Studies of SAI scenarios using ESMs have investigated how the location, timing, and amount of the aerosol precursor injections affect numerous climate variables (e.g., refs. 23, 35, and 36), while consequences for ecological systems have been minimally investigated (Fig. 1).

Possible ecological consequences of SAI implementation are wide ranging, from species' decline and relocation to population stabilizations and even increases, changes to ecosystem processes, and the emergence of novel ecological communities and ecosystems in response to novel climates (3, 37–39). These consequences must be evaluated in relation to those of anthropogenic climate change. Because SAI has physical effects (e.g., surface shortwave radiation reduction, cooling) that are unique and distinct from those caused by GHGs (e.g., warming, ocean acidification [OA], photosynthesis enhancement), the ecological impacts would also likely be distinctive (Fig. 1). SAI would affect some of the same ecological processes that are responding to anthropogenic climate change, but the nature of the responses is likely to differ. Organism physiology and morphology, genetic diversity, phenology, ecosystem processes and biogeochemistry (e.g., alterations to productivity, the water cycle, nutrient dynamics), ecosystem feedbacks to climate, population dynamics, biotic interactions, species' range shifts, and community (re)assembly are all likely to be impacted. SAI implementation, and geoengineering more broadly, involves many complex decisions; however, we lack sufficient information about potential ecological responses to SAI to inform these decisions.

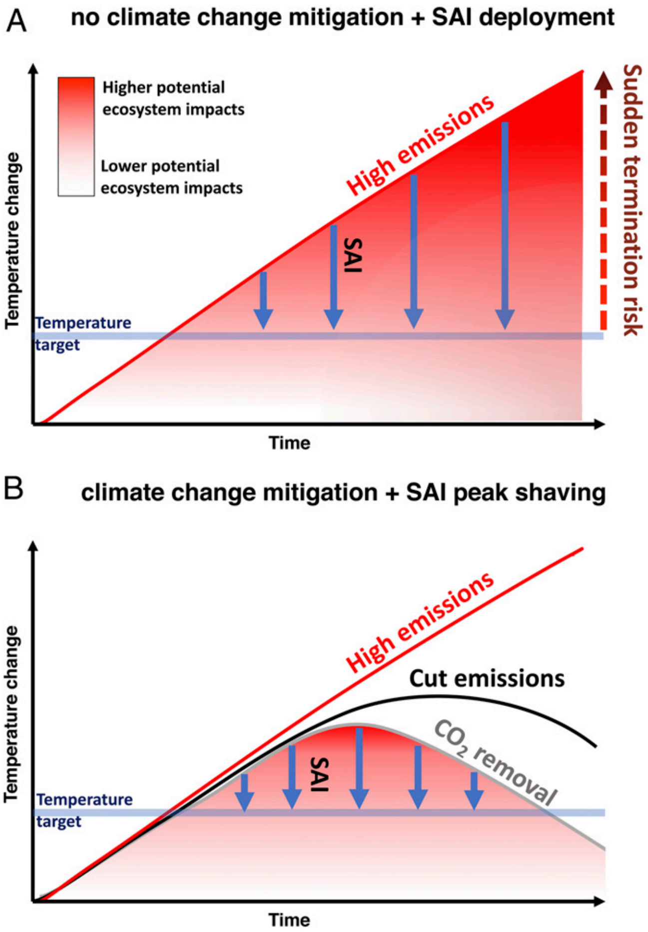

Fig. 2. **Potential temperature change over time for two different SAI scenarios. (*A*) In a future with no climate change mitigation and with SAI deployment, high emissions result in rising temperatures (red line). Increasing amounts of SAI would have to be deployed to reduce temperature (blue arrows) to a specific temperature target (blue line). The risk of sudden SAI termination also increases (red arrow). (*B*) In a future with climate change mitigation and SAI "peak shaving," temperature changes are first reduced by a combination of emission reduction (black line) and CDR (CO_2 removal, gray line), then further reduced by SAI (blue arrows). The red shaded areas below the two curves indicate the potential overall risk for ecological systems from increased temperature and SAI deployment; carbon emissions alone would not create the same degree of risk reduction as shown in *B*. We note that SAI is not akin to a global thermostat that would only control global temperatures to remediate GHG-induced warming. GHGs add energy to the system at the surface and throughout the atmosphere, whereas reducing sunlight with SAI only changes the energy balance at Earth's surface. Furthermore, GHGs operate 24 h a day and all year long, whereas reducing sunlight primarily has a direct impact during the daytime and more so in summer than winter. Data from refs. 142 and 143.**

Different SAI Scenarios Would Have Contrasting Effects on Ecological Systems. The impacts of SAI on particular ecological systems would depend on both the severity of anthropogenic climate change and which SAI scenario is applied (40). To illustrate, we consider a range of potential climate and ecological outcomes resulting from two contrasting SAI scenarios (Fig. 2). Continued high GHG emissions with consequent large temperature increases pose great risks for many ecological systems (6), including changes to global average and extreme temperatures and precipitation, seasonality, storm behavior, and regional variation in these responses. A large SAI deployment is expected to have larger side effects and risks than a smaller amount of SAI, especially for regional precipitation patterns and ozone loss (Fig. 2). In a high-emissions, high-input SAI scenario (Fig. 2*A*), SAI might be able to partially balance climate forcing by lowering average global temperatures (23), but it would come with large costs, including stratospheric polar ozone destruction and consequent increases in surface UV (26, 41), sulfate deposition (29, 42), and substantial changes to global and regional hydrological cycles (regional drought, flooding, and large changes to tropical monsoons) (33, 43). In this scenario, SAI would not be able to counter all consequences of the climate forcing from GHGs (32); in addition, the nonradiative but ecologically damaging intensification of OA would not be mitigated by SAI (Fig. 3).

In another SAI scenario (Fig. 2*B*), emissions reduction resulting in climate change mitigation with a more moderate "peak shaving scenario" (e.g., scenario SSP5-34-OS) (24), strong decarbonization would be combined with SAI to bring global temperature down to some target (e.g., 1.5 or 2 °C above preindustrial temperatures) (3). The combination of climate change mitigation and SAI in a peak shaving scenario might reduce risks and potential for harm to organisms and ecosystem processes (44) (Fig. 2*B*). On the other hand, this scenario might be insufficient in some regions to reduce serious ecological losses. For example, this scenario may not reduce Arctic permafrost thaw, resulting in vegetation change and biodiversity loss, as well as feedbacks to the climate system through methane release.

There is particular concern about extremely rapid climate change when initiating SAI or after sudden termination of SAI

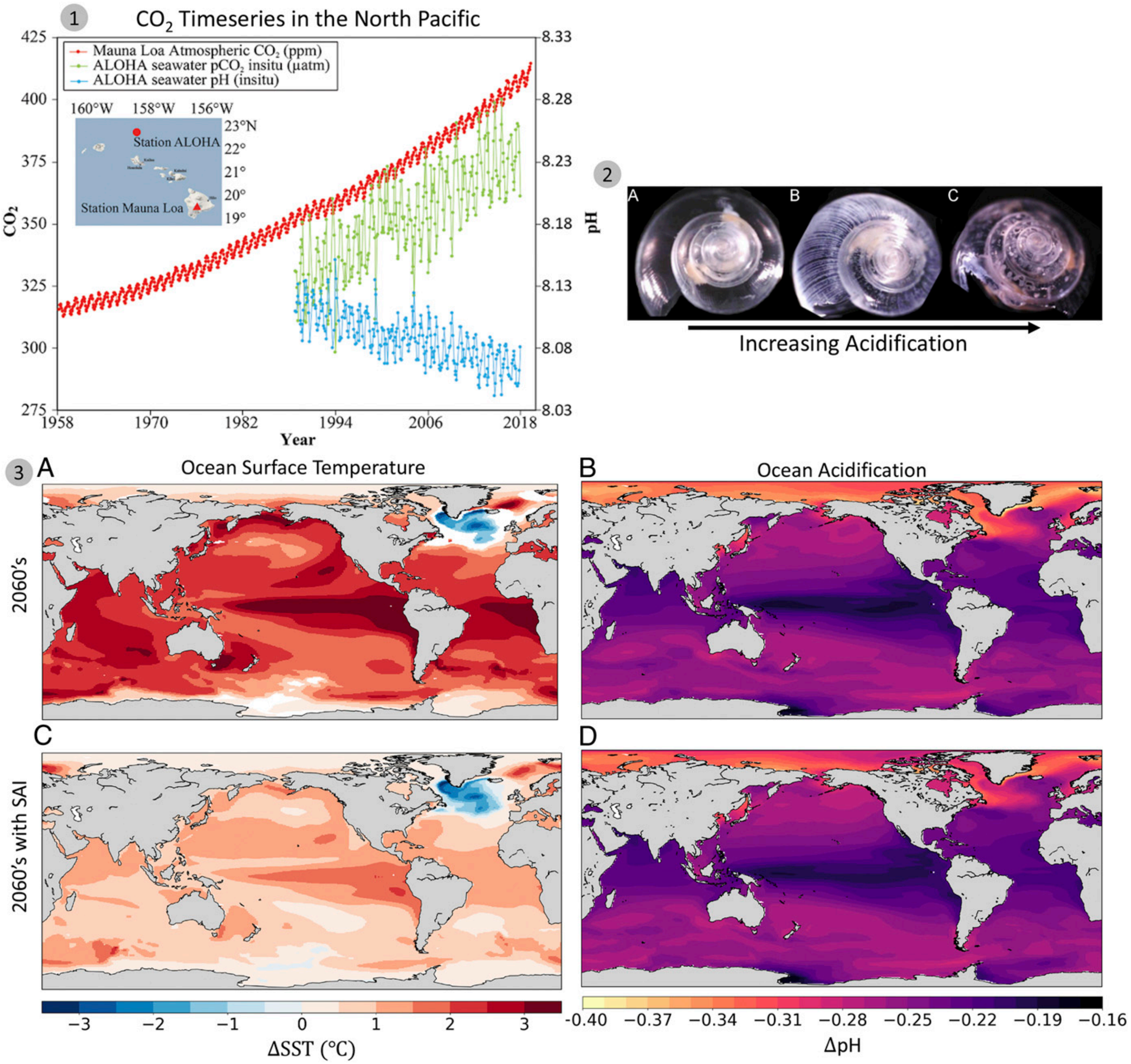

Fig. 3. **SAI alone would not reduce OA, which strongly impacts marine ecosystems. 1) Historical time series of CO_2 and OA at station ALOHA (figure from https://www.pmel.noaa.gov/co2/file/Hawaii+Carbon+Dioxide+Time-Series). Anthropogenic carbon emissions (red line) have been absorbed by the ocean (green line), reducing pH and creating more acidic conditions that harm calcifying marine organisms at the base of the marine food web (blue line). 2) Shells of calcifying marine plankton (pteropods) are negatively affected by OA (figure from ref. 144). 3) Stratospheric aerosol intervention applied to a "peak shaving" future climate scenario as in Fig. 2*B* reduces sea surface temperature anomalies (ΔSST) (*A* and *C*) but would not ameliorate OA (ΔpH) (*B* and *D*). Scenario shown is SSP5-3.4-OS (see ref. 24 for simulation details) 2060s mean relative to preindustrial.**

(*SI Appendix*, Fig. S1). While it is highly unlikely that scientists would advocate suddenly terminating SAI (particularly if GHG emissions continue to increase), national or international political and economic instability could conceivably result in sudden termination. The implications of such a risk must be understood as part of evaluating implementation of SAI. The potential risks of sudden termination include large changes in temperature and precipitation velocities (increase or decrease, rate, and geographic direction of change) (45, 46), with severe consequences for ecological systems (47, 48).

We need substantially more research to learn where climate intervention would ameliorate ongoing climate change impacts on biodiversity and ecosystem services in terrestrial, freshwater, and marine systems, and where it could cause greater risks. This research is critical to determine how SAI impacts would differ from the impacts of anthropogenic climate change, and to address ecological and ecosystem service targets that could inform SAI scenarios. How do the impacts of different SAI scenarios compare from local to global ecological systems? Should we be designing SAI for a different target rather than average global temperature: for example, reducing wildfire by reducing hot and dry conditions in targeted vulnerable regions, preserving biome and ecoregion extents, preserving cold winter temperatures in temperate and polar regions, or maximizing ecosystem carbon sequestration? How would the targets be determined? Some of these can be addressed now with interdisciplinary research, whereas others require method development and new data. To help prioritize research needs, we focus next on the mechanisms by which ecological systems might be impacted by SAI scenarios, and then on examples of possible effects on ecological systems.

The Climate Effects of GHG Emissions and SAI Differ

A fundamental challenge when anticipating SAI impacts on ecological systems is that SAI creates a pathway for cooling the climate that is mechanistically distinct from the warming pathway created by GHGs (*SI Appendix*, Fig. S1). While GHGs cause global warming by absorbing and retaining energy that has already entered the Earth system, SAI would reduce the amount of solar energy that enters Earth's system in the first place. The consequences of these differences for natural systems are poorly understood. For example, some SAI deployment scenarios may not completely reverse some of the most ecologically consequential effects of GHGs, such as winter and nighttime warming, which accelerate soil respiration and carbon transfer from soil to the atmosphere without a balancing increase in photosynthesis (49), and the loss of extreme cold temperatures (32) that limit the range of organisms (including pests, such as the hemlock wooly adelgid and the tiger mosquito). Species' responses are likely to vary based on differences in thermal physiology, body size, and life history, and on their interactions with other species (50–54). Future research should evaluate how ecological systems will be affected by the imperfect correction of global warming and subsequent novel patterns of temperature, precipitation, and other climate variables.

Another difference in the way GHG and SAI alter climate is that SAI decouples increases in GHG concentrations in the atmosphere from increases in temperature. About half of the extra CO_2 humans have added to the atmosphere has been absorbed by the land and ocean, primarily through uptake by ecological systems (55). Globally, land and ocean sinks have thus far grown with emissions due to increased plant and plankton growth, stimulated by rising atmospheric CO_2 and temperatures, but constrained by light, water, and nutrient availability, increased respiration, and other factors (56). Cooler temperatures could reduce photosynthetic carbon uptake if warming leads to higher productivity; or cooler temperatures could increase uptake if heat stress on forests is reduced. While elevated CO_2 can increase photosynthesis and productivity (57, 58), other factors can dampen or eliminate this effect, including nutrient limitation (59) and drought (60). Even if CO_2 fertilization increases carbon uptake without increasing mineral nutrient demand, it could cause changes in the tissue stoichiometry of primary producers (61) that could be detrimental to herbivores (62, 63). Moreover, rising partial pressure of CO_2 (pCO_2) can also acidify freshwater systems, affecting aquatic species and food webs (64). Interactions between temperature, precipitation, and CO_2 levels in the atmosphere also affect the ability of ecosystems to absorb other GHGs (methane, nitrous oxide) in complex ways that are difficult to predict under SAI (65, 66).

The disconnect between temperature and CO_2 that could be induced by SAI would also have substantial effects on the hydrologic cycle. While the global average reduction in precipitation would very likely be small even for a large deployment of SAI [less than 2% compared to present conditions (43)], changes could be up to 10% in particular regions and seasons (33). A combination of elevated atmospheric CO_2 and SAI-induced cooling might synergistically reduce biological water use. Elevated CO_2 increases plant water use efficiency, mainly due to reduced stomatal conductance (2; but see ref. 67), while cooling reduces the vapor pressure deficit (VPD) that drives water out of stomata. Together, these factors could reduce transpiration, leaving more water in the soil and in streams draining terrestrial ecosystems (68). Consequent changes to runoff and streamflow could affect aquatic habitats, interactions between terrestrial and aquatic ecosystems, and biogeochemical processes that regulate nutrient export from watersheds (69).

How SAI Might Affect Ecological Systems

Ecosystem Productivity and Feedbacks to Climate. Cooling due to SAI could reduce nutrient cycling and ecosystem primary production, accelerating the accumulation of CO_2 in the atmosphere and the oceans (Fig. 3; see also further discussion below). Warming accelerates rates of nutrient (e.g., nitrogen, phosphorus) cycling that facilitate terrestrial carbon uptake. However, cooling from SAI could also reduce water stress and atmospheric VPD, leading to increased primary production. This effect would reverse the recent trend for global net primary productivity to plateau or even decline due to increased average VPD (70). Thus, it is uncertain whether SAI itself would accelerate or decelerate the CO_2 increase in the atmosphere as a feedback mechanism, or increase or decrease primary productivity. If SAI increased surface UV, this would further affect nutrient cycling and primary production. UV is more effective than visible light in causing photoinhibition, defined as light stress-induced damage or downregulation of the photosynthetic apparatus (71, 72). Even though SAI would reduce the total and visible radiation reaching the Earth's surface, possible SAI-caused increases in surface UV might worsen damage to primary producers, causing a decline in plant productivity. This could counteract other light-mediated effects of SAI on productivity, including the diffuse fertilization effect. In addition to influencing bottom-up effects in food webs, increased surface UV could reduce survival and growth of many marine and freshwater organisms across trophic levels (71). On the timescales of seasons and beyond, SAI could cause plant communities to shift in phenology (e.g., ref. 73), structure, functional traits, and geographic range, resulting in further indirect effects on terrestrial carbon uptake (74).

Potential Responses to Different SAI Scenarios Across Biomes. Ecological responses to SAI implementation will differ within and among species, populations, ecological communities, dimensions of diversity, ecosystems, and geographic regions, both because these regions differ ecologically and because different SAI scenarios generate heterogeneous regional effects. As entire food webs are already reshuffling in response to climate change (75), it seems likely that if SAI were implemented, these ecological systems would reshuffle into other novel states at varying rates (38, 39). Regions and taxa that may be especially sensitive to SAI implementation could become foci for research. For example, many top consumers, keystone species, and producers are sensitive to climate change, and are likely to create outsized impacts on ecological communities through their trophic position (76, 77). Focal regions could include those already experiencing rapid warming, like the polar regions, and regions that would experience especially strong impacts from the disconnect between temperature and CO_2, like forests and the oceans. Below we discuss potential ecological impacts of SAI scenarios within different biomes.

Terrestrial Biomes. The connection between terrestrial organisms and climate ranges from instantaneous plant physiological processes that regulate the exchange of mass and energy between land surface and atmosphere, to decadal community assembly and reassembly that structure broad-scale biogeography, and to longer-term evolutionary changes. With climate change mitigation and a moderate SAI deployment in a peak shaving scenario (Fig. 2*B*), SAI-induced change in light level (i.e., total radiation and diffuse/direct light ratio), UV, temperature, and VPD (*SI Appendix*, Fig. S1) could all exert direct impacts on plant physiology (e.g., photosynthesis and respiration) through either direct abiotic controls (78) or through indirect effects on the function of photosynthetic machinery through damage, repair, or acclimation (72, 79, 80). In contrast, without climate change mitigation and with a large SAI deployment (Fig. 2*A*), there is a risk for large and rapid climate changes with potentially disastrous and irreversible impacts on terrestrial ecological systems. The relevant question is whether SAI would reduce the impacts caused by anthropogenic climate change or send ecological systems in new and uncharted territory.

One telling example of potential SAI impacts comes from the comparable vegetative response to volcanic aerosols from the 1991 Mount Pinatubo eruption. Harvard Forest, a deciduous forest in the northeastern United States, showed noontime photosynthetic rates enhanced by 23% in 1992 primarily because volcanic aerosols increased diffuse light relative to direct light and reduced air temperature and VPD (81). This enhancement of photosynthesis is known as the diffuse light fertilization effect and is found in many biomes across the world (82, 83). Nevertheless, light scattering also causes slightly less light to reach the Earth's surface, which can partly or fully offset the benefits of light diffusion depending on its severity. For example, it is expected that SAI would neither increase nor reduce crop yields relative to the moderate climate forcing projected by RCP 4.5 (84). Besides diffuse light, terrestrial biomes also respond to many other climate variables (e.g., temperature, VPD, and UV). The dominant climatic controls differ across global biomes (85), including biomes that vary in their tolerance to future warming (86). Such biome-specific responses need to be carefully considered when designing and evaluating SAI scenarios if they are to benefit rather than harm (most) terrestrial biomes.

At longer timescales, SAI-induced climate change could also restructure the vegetation distribution and associated fauna over large areas. For example, in the tropics, the distribution and biogeography of the three dominant vegetation types—tropical evergreen forests, deciduous/semideciduous forests, and savanna—is generally explained by water supply and demand theory (87). Tropical evergreen forests dominate hydroclimate zones of high water supply and low water demand, while tropical deciduous/semideciduous forests and savanna, by contrast, dominate the hydroclimate zones of low water supply and high water demand. This theory applies to both anthropogenic climate change (88, 89) and to SAI-induced climate effects. Specifically, the future SAI-induced changes in rainfall amount and seasonal distribution are expected to alter the water supply of these tropical forests, while the changes in other meteorological variables (e.g., wind speed, temperature, VPD, diffuse and direct light ratio, CO_2) are expected to alter the water demand component through changes in either evaporation in the land surface or plant transpiration. The changes in both water supply and demand will ultimately alter the biogeography of the tropics. Since tropical forests cycle more carbon and water than any other biome (90), SAI-induced change in vegetative biogeography, depending on the implementation scenario, could generate significant impacts on large-scale biogeochemical cycles, with direct feedbacks to regional- and global-scale climate variability and change (91).

Recent anthropogenic climate change has caused complex shifts in phenology, reduced sea ice extent, and led to cascading effects across food webs in the Arctic (92, 93). In a warming world, continued rise of atmospheric CO_2 may alter the relative abundances of different plant functional groups (e.g., favoring woody vs. nonwoody plants) (94; but see ref. 95), affecting ecosystem function even further as CO_2 emissions increase. Warming experiments in the Arctic show that higher temperatures can change the tundra vegetation composition to shrub-dominant (96–98); by 2100, shrubs are expected to expand by 20% (99) to 52% (100). These changes in composition could cause regional temperature increases via decreased albedo and increased evapotranspiration (99, 100), essentially causing a positive feedback between shrub expansion and warming. If a scenario including climate change mitigation and SAI peak shaving were to occur to reduce temperature, SAI may ameliorate the risk that tundra will transition to a shrub-dominated state. Alternatively, SAI may not reduce temperature enough to prevent the transition to a shrub-dominated state, but enough to reduce the productivity and CO_2 absorption of this new state. But this effect could itself be partly offset by an increase in diffuse light, which could improve the photosynthetic efficiency of shrubs and other plants with complex canopies (101). An unchecked rise in CO_2 could also continue to favor shrubs, and so climate change mitigation combined with SAI would be necessary.

SAI may diminish the extremes of seasonality, especially at high latitudes (32), leading to warming winters and cooler summers. Overall cooling due to SAI may slow phenological shifts and shrub expansion, but legacy effects from current changes are likely to influence any future costs or benefits to Arctic ecological communities. For example, in parts of the Arctic, large herbivores (caribou or muskox) may moderate the effects of warming temperatures on plant functional groups by consuming shrubs and favoring forb production (102). However, in Greenland, the earlier onset of spring associated with climate change has led to a mismatch between peak vegetation forage and caribou migration times to calving grounds, resulting in a decline in caribou fitness and an increase in calf mortality (103). Even if SAI delayed spring onset and shortened the thaw season, these species interactions are unlikely to fully return to previous states because rising CO_2 will continue to alter primary production.

In one extreme SAI scenario, extreme climate events decrease, reversing the trend under anthropogenic climate change (104). Precipitation extremes and storm events are currently increasing erosion both inland and on coastlines, and temperature extremes, heatwaves, and droughts have led to increased mortality, and shifts in species distributions and phenology (105). Would some SAI scenarios mitigate any of these effects?

Marine Biomes. If SAI were to be implemented, even with reductions of emissions, ocean temperatures would cool much less rapidly than air temperatures in terrestrial systems, due to lags caused by the high specific heat of water. Sea level rise would continue to threaten mangrove and other coastal ecological systems. SAI implementation would also fail to ameliorate the effects of anthropogenically increased atmospheric CO_2 on OA (Fig. 3) (106, 107). Yet, the relative benefits and risks of SAI on marine biomes are largely unknown because the combined impacts of warming, acidification, and deoxygenation on phytoplankton—the base of the marine food web—are poorly constrained (e.g., ref. 108). Critically, ESMs do not simulate the impacts of acidification or UV changes on primary production (but see ref. 109). Most SAI modeling studies have not simulated ocean biogeochemistry [e.g., GeoMIP (110), but see refs. 24, 111, 112)]; none have assessed the benefits and risks of SAI to higher trophic levels, which are expected to decline under anthropogenic climate change (14). Furthermore, the relative impacts of OA, changes in storm intensity, and extreme temperatures need to be better understood, especially for coral communities that are expected to be particularly vulnerable to these climate changes (107, 113–115). Coral reefs are marine biodiversity hotspots and supply ecosystem services estimated to be worth US$36 billion per year globally (116). Thus, a priority for SAI scenario evaluation is ESM development relevant to marine ecosystem services, along with studies of future scenarios with and without SAI for marine biomes.

There is a growing understanding of how the changes in temperature, precipitation, sea ice, land ice, and sea level resulting from ongoing and predicted climate changes are affecting marine and coastal organisms and ecosystems. The potential for SAI to mitigate these impacts is unclear and will depend on the scenario and the ecological system. For example, with continued lengthening thaw season and diminishing sea ice in the Arctic, polar bear distributions may shift away from prey dependent on sea ice such as ringed seal pups, and toward prey on solid ground, such as snow geese eggs (117), a shift that could reduce polar bear body condition and survival and increase competition with land-based brown bears (118). In Antarctica, receding glaciers have enabled more breeding habitat and increased abundances of Adélie penguins in some areas (119), whereas continued sea ice decline is detrimental to emperor penguin breeding habitat and populations (120). Multiple SAI scenarios predict diminished seasonality in high latitudes, with warmer winters and cooler summers, resulting in sea ice decreasing during winter and increasing during summer (32). SAI scenarios that include sudden termination would cause rapid sea ice decline (121). It is possible that some SAI scenarios could preserve land ice and lower surface temperatures, eventually mitigating future sea level rise (24, 122, 123).

Advancing Research on Ecological Consequences of SAI

Despite the development of SRM schemes and SAI scenarios for modifying Earth's climate, little is known about how these scenarios would impact the health, composition, function, and critical services of ecological systems. Whereas there is abundant literature on the current and predicted ecological impacts of climate change (e.g., reviewed in ref. 3), only a handful of papers have addressed the ecological impacts and risks of SRM. Russell et al. (11) introduced questions about the effects of climate interventions more broadly on ecological systems, noting the potential benefits of cooling, the failure of SAI to limit OA from CO_2 absorption, the potential for effects of increased diffuse relative to direct light on productivity, and emphasizing how little is known and the need for additional research. McCormack et al. (12) reviewed many of the predicted climate changes and associated ecological consequences across a broad range of climate intervention schemes, and summarized key knowledge gaps regarding their potential ecological impacts. Trisos et al. (45) modeled climate velocities that would impact ecological systems for a single SAI scenario and its termination. Dagon and Schrag (46) contrasted SAI and anthropogenic climate change effects on global vegetation productivity, changes in seasonality, and climate change velocity using a single scenario, and noted that other scenarios might produce different results.

Although these studies have advanced understanding, they have not directly addressed the fundamentally different ways in which SAI versus GHGs alter the climate and therefore in how they alter ecological systems. Climate scientists working on SRM must begin to recognize the complexity of ecological effects and responses. Save for a few studies, ecologists have largely been unaware of the extensive climate science of SRM and SAI. We urgently advocate that ecologists join with their climate science colleagues to evaluate the ecological consequences of climate intervention. An interdisciplinary approach is essential for understanding the benefits and risks of SAI to ecological systems, so that any decisions about whether and how to initiate, continue, or terminate SAI are informed by their potential ecological consequences, but also by the consequences of not implementing SAI as GHGs continue to rise.

There are many opportunities for ecology to inform SAI scenarios. Impact assessment research could include experiments that evaluate how cooling and increased CO_2 affect ecological systems, and evaluations of the types of data and models required to assess ecological impacts of climate intervention scenarios versus no climate intervention (11). In addition, long-term and spatially distributed observations of species and ecosystem processes (e.g., the US Long Term Ecological Research and National Ecological Observatory Network programs), and insights from the geologic record (e.g., *Neotoma* paleoecology database), could be synthesized to understand how current and past climate change and extinction events alter biodiversity and ecosystem functions, as has been a focus of climate change ecology research. The extensive literature on climate change effects on ecology from model projections (e.g., refs. 14, 48, and 124–131), experiments (e.g., refs. 132–134), theory (e.g., refs. 135 and 136), and synthesis (e.g., refs. 2, 3, and 137) can help guide this research and expectations for SAI impacts on ecological systems.

Currently, SAI scenarios focus only on energy balance targets (36, 138), yet biodiversity and ecosystem function targets, including United Nations Sustainable Development Goal targets (139) could additionally inform SAI scenarios. For example, essential biodiversity variables—globally standardized state variables that capture critical scales and dimensions of biodiversity and which are sensitive to change (140)—could be used to establish biodiversity targets and influence SAI scenario development. Biodiversity hotspots—areas with the highest risk of losses where endemic diversity is also greatest—are already essential areas for conservation and could become focal areas to assess targets. Thus, the connection between SAI and ecology is more than just impact assessment but an essential part of a social deliberation about what SAI implementation aims, or should aim, to achieve. An essential component of this deliberation will be analysis of uncertainty. An assessment of just how well we can predict both SAI effects on climate and the complex ecological responses that flow from these effects will be required as society makes decisions about using climate intervention to mitigate the effects of GHG-induced climate change (18).

It is essential that the knowledge gaps posed above be addressed now, because policy changes are unpredictable, and it is critical to have robust predictions available to inform decisions. Coordination with existing efforts, including climate modeling efforts and ecological synthesis centers, observation networks, and atmospheric research centers would leverage existing investments in large-scale natural science and foster interdisciplinary work and more rapid advances. International research synergies and collaborations among ecologists and climate scientists will be especially important, because the entire Earth is at stake in this enterprise.

Data Availability. Data used to generate Fig. 3 are freely available from the links provided from The Community Earth System Model (CESM) (http://www.cesm.ucar.edu/) under https://doi.org/10.5065/D67H1H0V and https://doi.org/10.26024/t49k-1016.

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