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Section C. Socioeconomic and Ecological Outcomes

Summary

The potential risks and benefits to human health and well-being associated with scenarios involving the use of SRM need to be considered relative to risks and benefits associated with plausible trajectories of ongoing climate change not involving SRM. This "risk vs. risk" framing, along with cultural, moral, and ethical considerations, would contribute to the necessary context in which policymakers can consider the potential suitability of SRM as a component of climate policy.

Decisions concerning whether and how to deploy SRM should be based upon an understanding of the risk and benefits to human health and well-being of its implementation relative to those anticipated under the current climate trajectory. Of particular importance is consideration of potential jeopardy to diverse communities and intergenerational equity.

Cultural, moral, and ethical considerations are often overlooked in model-based evaluations and may be equally, if not more, important to different communities. In addition to physical scientists and engineers, philosophers, ethicists, and other social scientists are needed to help answer questions related to the human dimensions of climate change and efforts to manage that change through SRM.

There is a potential for adverse outcomes to ecosystems and the services they provide with the implementation of SRM, but the nature and intensity of these outcomes—in comparison to those in scenarios without SRM—remain unclear, particularly over the long time periods anticipated in many scenarios. Further assessment of outcomes to ecosystems in SRM scenarios relative to those in scenarios without SRM is needed.

Climate change raises geopolitical risks. SRM deployment could also carry significant geopolitical risks. Research into the geopolitical ramifications of SRM would be aimed at reducing the likelihood and/or severity of these risks.

Context

The human consequences of an altered climate, today and in the future, are primary considerations for climate policies. Socioeconomic impacts are those human impacts that encompass both tangible economic and social factors, as well as factors that are difficult or, perhaps, impossible to quantify, such as intergenerational equity, identity, and values. Here the report discusses issues related to the human outcomes of potential deployment of SRM relative to the trajectory of climate change impacts and risks, and outlines research priorities related to the implications for human health and well-being, food and water scarcity, ecosystem services, geopolitical security, human social systems, and equity. Understanding these impacts is crucial to enable informed decisions around a possible role for SRM in addressing human hardships associated with climate change.

This section summarizes key knowledge gaps and research priorities related to potential socioeconomic and ecosystem risks and benefits of SRM, reviews what is known about public perceptions of SRM, and briefly discusses possible institutional approaches to performing research to close key gaps.

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State of Understanding

Research into SRM has been largely focused on natural science-based topics, examining the basic understanding of SRM approaches and their physical outcomes. The 2021 NASEM report, *Reflecting Sunlight*, reported that about 14% of studies on SRM published between 1983 and 2020 addressed the topics of economics, ecosystems and ecology, health, oceans, agricultural impacts, or Arctic impacts.[23] Research into the human dimensions of SRM impacts to date has been ad hoc and fragmented, rather than being the product of a comprehensive strategy; as a result, substantial knowledge gaps and uncertainties exist in many critical areas.[24] Research to understand the potential nature, magnitude, and distribution of SRM impacts on ecosystems, human health and well-being, political and economic systems, and other issues of social concern does not currently provide a sufficient basis for supporting informed decisions with regard to SRM implementation.

Examples of critical open questions regarding the potential of SRM to ameliorate adverse climate-driven human impacts may include to what extent could SRM:

- preserve human life;
- reduce climate-induced stress on ecosystems and biodiversity;
- preserve the reliability and nutritional value of agricultural regions;
- minimize water scarcity;
- reduce the risk of housing, insurance, and other market failures;
- bolster the weakest links in global and national supply chains;
- reduce climate-induced geopolitical stress in areas susceptible to political strife and potential conflict;
- preserve the integrity and function of physical infrastructure so it does not fail under climate stress;
- ensure continuation of ecosystem services and natural capital dividends; and
- improve sustainability by meeting current needs without compromising the ability of future generations to meet their own needs.

Depending on how it would be used, SRM holds the potential for a range of human impacts, from adverse to beneficial and real to perceived. Large historical volcanic eruptions can serve as natural analogs to understand the potential human impacts of SRM—in particular, stratospheric aerosol injection (SAI) scenarios—separately from the effects of increased atmospheric greenhouse gases. As would be the case for human deployments of SRM, the effects of volcanic eruptions and other proxies depend on the specifics of the event in question, and the outcomes of one event do not necessarily apply to others. As an example of one large event, the 1815 Tambora eruption cooled the Earth by 0.7°C and led to a "year without summer" (1816), altered

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[23] National Academies of Sciences, Engineering, and Medicine. (2021a). *Reflecting Sunlight: Recommendations for Solar Geoengineering Research and Research Governance.* Washington, DC: The National Academies Press. https://doi.org/10.17226/25762

[24] Ibid.

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precipitation patterns,[25] disrupted monsoons,[26] and led to flooding that provoked crop failure, famine,[27] and the outbreak of disease.[28] Understanding these and other potential negative impacts of SRM is as important as understanding potential benefits. While limited work has been done to examine how SRM may alter precipitation patterns, net primary production, and other aspects of the physical environment, very little has been done to connect these changes to ensuing human outcomes.

The adverse human impacts of continued global warming have been extensively studied,[29] though much remains to be learned. However, as noted in Sections A and B, SRM would not simply reverse the effects of human GHG emissions. Regional differences and spatial heterogeneity in impacts, in particular, between a climate with SRM and a climate without SRM at the same global temperature may be significant. The current understanding of relationships between projected global temperature increases and resulting human impacts cannot be assumed to apply directly to future climate conditions altered by SRM. Adding further uncertainty is the potential for climatic conditions at a new equilibrium to differ considerably from those experienced during transient warming. Land areas warm more quickly than oceans, leading to the potential for higher temperatures over land during transient warming prior to eventual redistribution of heat as equilibrium is approached.[30] It is unclear how SRM may affect this response and the associated impacts to socioeconomic and ecological end points.

Avoiding climate tipping points has provided a rationale for SRM research and potential deployment, and a recent synthesis suggests that important tipping point thresholds may be crossed at 1.5°C of global warming.[31] Even so, there are significant gaps in our ability to forecast the timing of such tipping points, some of which would unfold over timeframes as long as centuries. Challenges remain in our ability to understand the extent to which near-term SRM

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[25] Kandlbauer, J. et al. (2013) Climate and carbon cycle response to the 1815 Tambora volcanic eruption. *J. Geophys. Res. Atmos.*, *118*(12), 12,497– 12,507. http://doi.org/10.1002/2013JD019767

[26] Gao, C., Gao, Y., Zhang, Q. et al. (2017). Climatic aftermath of the 1815 Tambora eruption in China. *J. Meteorol. Res.*, *31*, 28–38. https://doi.org/10.1007/s13351-017-6091-9

[27] Oppenheimer, C. (2003). Climatic, environmental and human consequences of the largest known historic eruption: Tambora volcano (Indonesia) 1815. *Progress in Physical Geography: Earth and Environment*. *27*(2), 230-259. https://doi.org/10.1191/0309133303pp379ra

[28] Ibid.

[29] Masson-Delmotte, V. et al. (2018). *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty*. https://doi.org10.1017/9781009157940.001; Pörtner, H.-O. et al. (2022). *Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. https://www.ipcc.ch/report/ar6/wg2/

[30] King, A.D., et al. (2020). Global and regional impacts differ between transient and equilibrium warmer worlds. *Nature Climate Change*, *10*(1), 42-47. https://doi.org/10.1038/s41558-019-0658-7

[31] E.g., Armstrong McKay, D.I., Staal, A., Abrams, J., Winkelmann, R., Sakschewski, B., Loriani, S., Fetzer, I., Cornell, S., Rockström, J., and Lenton, T. (2022). Exceeding 1.5°C global warming could trigger multiple climate tipping points. *Science*, *377*(6611). https://doi.org/10.1126/science.abn7950

deployment or other responses to climate change can effectively address climate tipping points with such long-term socioeconomic and ecological outcomes.[32]

Major Gaps to Inform Research Topics

There is far more research concerning SAI compared to marine cloud brightening (MCB) and cirrus cloud thinning (CCT) in the climate intervention literature. Reflecting this, the discussion below focuses strongly on SAI. Technical challenges associated with projecting extreme events in future climates limit our ability to quantitatively assess the human risks associated with extreme events in future climate scenarios with and without SRM. Although changes in mean climatic conditions are important, the rate of adaptation (e.g., water storage, flood defense, water sanitation) to new extreme event frequencies is highly variable, and is typically implemented at local, not national levels, and is a key factor in determining human outcomes.

Key Solar Radiation Modification Knowledge Gaps Related to Health and Well-Being: An impetus for research into SRM is to understand its potential to alleviate adverse human impacts related to health and well-being. Increased morbidity and mortality due to extreme heat is the most direct impact of a warming climate,[33] and is perhaps the health impact most likely to be ameliorated by implementing an SRM strategy.[34] Health endpoints related to air quality are more complex than direct heat impacts and have been studied more for SAI scenarios than for MCB and CCT. SAI is expected to result in changes in temperature and sunlight that would affect atmospheric chemistry and thus ground-level formation of ozone and particulate matter (PM) compared to conditions without SAI. Substantial regional variation confounds succinct description of impacts. Increases in ozone formation caused by higher temperatures are expected to be reduced with SAI. However, some work suggests those potential health benefits may be offset by the impacts of increased exposure to particulate matter from injected aerosols and changes in radiative forcing.[35] Health impacts due to wildfire smoke exposure may also be reduced, although some areas may see increased wildfire and smoke exposure risk.[36] Limiting temperature increases by SRM may reduce health impacts related to waterborne disease driven

[32] Sillmann, J., et al., 2015. Climate emergencies do not justify engineering the climate. *Nature Climate Change, 5*(4): 290-292. https://doi.org/10.1038/nclimate2539

[33] Sarofim, M.C., S. Saha, M.D. Hawkins, D.M. Mills, J. Hess, R. Horton, P. Kinney, J. Schwartz, and A. St. Juliana, 2016: Ch. 2: Temperature-Related Death and Illness. *The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment*. U.S. Global Change Research Program, Washington, DC, 43–68. http://dx.doi.org/10.7930/J0MG7MDX

[34] Raymond, C., et al. (2020). The emergence of heat and humidity too severe for human tolerance. *Sci. Advances, 6*(19). https://doi.org/10.1126/sciadv.aaw1838

[35] Eastham, S.D., et al. (2018). Quantifying the impact of sulfate geoengineering on mortality from air quality and UV-B exposure. *Atmospheric Environment. 187*, 424-434. https://doi.org/10.1016/j.atmosenv.2018.05.047

[36] Burton, C., Betts, R. A., Jones, C. D., and Williams, K. (2018). Will fire danger be reduced by using Solar Radiation Management to limit global warming to 1.5 °C compared to 2.0 °C? *Geophys. Res. Letts., 45*, 3644-3652. https://doi.org/10.1002/2018GL077848

by extremes in temperature[37] and precipitation,[38] although simulations of SAI suggest the potential for increased risk in some regions.[39,40] Further research, particularly with models appropriate to the spatial scales necessary to accurately attribute health impacts, would be informative.

Well-being includes livelihood, mental health, and additional aspects that are affected by increasing temperatures and other climate impacts.[41] Implementation of SRM may reduce mental health impacts related to increasing temperatures, but it is unclear how an SRM scenario of any type may affect eco-anxiety given the potential for adverse outcomes of deployment and cessation of SRM. Well-being is linked to social trust,[42] and better understanding is needed regarding how trust may be affected by SRM implementation.[43] Concerns about livelihood—a measure of a community's quality of life—are paramount, as even temporary climatic disruptions can have long-lasting consequences: Dust Bowl towns in the United States that experienced outward climate-driven migration still have not fully recovered nearly 100 years later. These communities, on average, continue to suffer lower economic growth, per capita income, and education rates.[44]

Climate change is increasingly identified as a main driver for human migration, although confidence in these projections is low.[45] The many factors that drive migration and uncertainties in physical science and human behavior make it difficult to accurately project total numbers of climate migrants in a hypothetical climate with and without SRM. Wage effects and cost of living will influence the spatial distribution of climate-driven resettlement. Current statistical

[37] Beard, C.B., R.J. Eisen, C.M. Barker, J.F. Garofalo, M. Hahn, M. Hayden, A.J. Monaghan, N.H. Ogden, and P.J. Schramm, 2016: Ch. 5: Vector-Borne Diseases. *The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment.* U.S. Global Change Research Program, Washington, DC, 129–156. http://dx.doi.org/10.7930/J0765C7V

[38] Trtanj, J., L. Jantarasami, J. Brunkard, T. Collier, J. Jacobs, E. Lipp, S. McLellan, S. Moore, H. Paerl, J. Ravenscroft, M. Sengco, and J. Thurston, 2016: Ch. 6: Climate Impacts on Water-Related Illness. *The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment.* U.S. Global Change Research Program, Washington, DC, 157–188. http://dx.doi.org/10.7930/J03F4MH4

[39] Wei, L., et al. (2018). Global streamflow and flood response to stratospheric aerosol geoengineering. *Atmos. Chem. Phys., 18*(21), 16033-16050. https://doi.org/10.5194/acp-18-16033-2018

[40] Carlson, C.J., Colwell, R., Hossain, M.S., et al. (2022). Solar geoengineering could redistribute malaria risk in developing countries. *Nat Commun, 13*, 2150. https://doi.org/10.1038/s41467-022-29613-w

[41] Lawrance, E., et al. (2021). The impact of climate change on mental health and emotional wellbeing: current evidence and implications for policy and practice. Briefing Paper No 36, Grantham Institute, London. https://doi.org/10.25561/88568

[42] Helliwell, J.F., H. Huang, and S. Wang. (2016). New evidence on trust and well-being. National Bureau of Economic Research, Working Paper 22450. https://www.nber.org/papers/w22450

[43] Cairns, R. (2016). Climates of suspicion: 'chemtrail' conspiracy narratives and the international politics of geoengineering. *The Geographical Journal, 182*(1), 70-84. https://doi.org/10.1111/geoj.12116

[44] Lustgarten, A. (2020). Climate Change Will Force a New American Migration, Propublica, available: https://www.propublica.org/article/climate-change-will-force-a-new-american-migration; Arthi, V. (2018). "The Dust Was Long in Settling": Human Capital and the Lasting Impact of the American Dust Bowl. *The Journal of Economic History, 78*(1), 196-230. https://doi.org/10.1017/S0022050718000074

[45] Kaczan, D.J. and J. Orgill-Meyer. (2020). The impact of climate change on migration: a synthesis of recent empirical insights. *Climatic Change, 158*(3), 281-300. https://doi.org/10.1007/s10584-019-02560-0

relationships that link climate to productivity, wages, and cost-of-living are developed from historical data that may not apply to future climate conditions with or without SRM deployment.

Food and Water Systems: Food production is heavily concentrated geographically and is increasingly vulnerable to the impacts of climate change.[46] Extreme events including prolonged dry spells and excessive rain reduce crop yields. Excessive heat destroys crops and kills livestock. Warming and drought are projected to result in substantially increased likelihood of multi-breadbasket crop failures as soon as 2030.[47] Food insecurity in Central America's dry corridor is rising and export commodities are decreasing due to a lack of water that threatens continued livelihood in the region.[48]

It is unclear how the combination of limited temperature increases and increased CO2 concentrations expected with SAI implementation may affect crop yields and nutritional value. SAI approaches could worsen soil acidity, with impacts to food production, compared to warming at Representative Concentration Pathway 8.5 (RCP8.5) levels without SAI in some regions due to acidic deposition (e.g., the Pacific Northwest, southern Greenland, the Himalayas, and polar regions).[49] The impacts of sunlight scattering could have negative effects on crop growth that harm nutrition and negate the benefits of limiting temperature increases using SAI.[50] SRM would not address ocean acidification or its implications for ocean ecosystems.[51] These potential impacts emphasize the value of understanding the outcomes of SRM for ecosystems, including managed ecosystems (e.g., agriculture, aquaculture, forestry), more fully.

Evidence from volcanic eruptions is suggestive that asymmetric SAI deployment alters hydrological cycles,[52] can weaken Indian summer monsoons, and reduce Sahelian precipitation

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[46] Gowda, P., J.L. Steiner, C. Olson, M. Boggess, T. Farrigan, and M.A. Grusak, 2018: Agriculture and Rural Communities. In *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II* [Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart (Eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 391–437. https://doi.org/10.7930/NCA4.2018.CH10

[47] Caparas, M., et al. (2021). Increasing risks of crop failure and water scarcity in global breadbaskets by 2030 *Environ. Res. Lett. 16*, 104013. https://doi.org/10.1088/1748-9326/ac22c1

[48] M. Abi-Habib and B. Avelar. (2022). Mexico's Cruel Drought: 'Here You Have to Chase the Water', New York Times, accessed 3 Aug. 2022. https://www.nytimes.com/2022/08/03/world/americas/mexico-drought-monterrey-water.html

[49] Visioni, D., et al. (2020). What goes up must come down: impacts of deposition in a sulfate geoengineering scenario. *Environ. Res. Lett.*, *15*(9), 094063. https://doi.org/10.1088/1748-9326/ab94eb

[50] Proctor, J., et al. (2018). Estimating global agricultural effects of geoengineering using volcanic eruptions. *Nature, 560*(7719), 480-483. https://doi.org/10.1038/s41586-018-0417-3

[51] Russell, L. M., Rasch, P. J., Mace, G.M., Jackson, R. B., Shepherd, J., Liss, P., Leinen, M., Schimel, D., Vaughan, N. E., Janetos, A. C., Boyd, P. W., Norby, R. J., Caldeira, K., Merikanto, J., Artaxo, P., Melillo, J., and Morgan, M. G. Ecosystem impacts of geoengineering: a review for developing a science plan. *AMBIO, 41*, 350-69. http://doi.org/10.1007/s13280-012-0258-5

[52] Cheng, et al. (2022). Changes in Hadley circulation and intertropical convergence zone under strategic stratospheric aerosol geoengineering. *npj Clim Atmos Sci, 5*, Article 32. https://doi.org/10.1038/s41612-022-00254-6

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to contribute to drought and subsequent humanitarian disaster.[53,54] Overall, relative to the RCP8.5 scenario, CCT and SAI scenarios alleviate dryland expansion, while specific implementations of MCB are expected to expand the spatial extent and severity of drylands.[55] Changes in amount and/or timing of precipitation can have substantial impacts on the ability of existing water infrastructure to manage water resources, with adverse outcomes for cities, agriculture, and other water consumers. Most importantly, tested scenarios in all simulations highlight the regional nature of impacts from SRM deployment.

Ecosystem Services: Beyond the fundamental needs of food and water, healthy ecosystems provide substantial and often unrecognized services to people and societies. Changes in the environment due to climate change and other human-driven stressors result in changes in the ability of ecosystems to provide those services. The ongoing Holocene extinction event is likely driven largely by human-driven stressors, resulting in loss of biodiversity in terrestrial and marine environments throughout the Earth at a rate unprecedented in human history.[56] Biodiversity and ecosystem health are fundamental to the Earth's natural cycles (e.g., water, carbon, nitrogen, phosphorus) that are the foundation of core societal systems.[57] Implementing SRM is expected to limit the risks to biodiversity associated with higher temperatures but is also expected to affect the characteristics of solar radiation and potentially cloud cover (associated with changing precipitation patterns) without impacting higher CO2 levels. These changes could have significant effects on vegetation and ecosystem health broadly, leading to unknown impacts to biodiversity, particularly when combined with other anthropogenic stressors (deforestation, urbanization, chemical use, etc.).[58]

Threats to ecosystem services abound. Ecosystem services such as pollination[59] and nutrition[60] are in rapid decline. Drier and warmer climates will increase the risk that Pacific Northwest forests will fail to regenerate following fires, resulting in reduced ability of the forests to provide

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[53] Haywood, J., Jones, A., Bellouin, N. et al. (2013). Asymmetric forcing from stratospheric aerosols impacts Sahelian rainfall. *Nature Clim Change, 3*, 660–665. https://doi.org/10.1038/nclimate1857

[54] Ramanathan et al. (2005). Atmospheric brown clouds: impacts on South Asian climate and hydrological cycles. *Proc. Natl. Acad. Sci., 102*(15), 5326-5333. https://doi.org/10.1073/pnas.0500656102

[55] Park, C.E. et al. (2019). Inequal Responses of Drylands to Radiative Forcing Geoengineering Methods. *Geophys. Res. Letts. 46*(23), 14011-14020. https://doi.org/10.1029/2019GL084210

[56] UN Sustainable Development Goals. (2019). Nature's Dangerous Decline 'Unprecedented'; Species Extinction Rates 'Accelerating,' accessed 3 Aug. 2022. https://www.un.org/sustainabledevelopment/blog/2019/05/nature-decline-unprecedented-report/

[57] Marselle, M.R. et al. (2019). Review of the Mental Health and Well-being Benefits of Biodiversity. In Marselle, M., Stadler, J., Korn, H., Irvine, K., Bonn, A. (Eds), *Biodiversity and Health in the Face of Climate Change*. Springer, Cham. p. 175-211. https://doi.org/10.1007/978-3-030-02318-8

[58] Williamson, P., and Bodle, R. (2016). *Update on Climate Geoengineering in Relation to the Convention on Biological Diversity: Potential Impacts and Regulatory Framework*. Technical Series No.84. Secretariat of the Convention on Biological Diversity, Montreal, 158 pp. https://www.cbd.int/doc/publications/cbd-ts-84-en.pdf

[59] Osterman, J. et al. (2021). Global trends in the number and diversity of managed pollinator species. *Agriculture, Ecosystems & Environment. 322*, 107653. https://doi.org/10.1016/j.agee.2021.107653

[60] Springmann, M. et al. (2016). Global and regional health effects of future food production under climate change: a modelling study. *The Lancet, 387*(10031), 1937-1946. https://doi.org/10.1016/S0140-6736(15)01156-3

clean water, habitat, timber, and carbon sequestration.[61] Wetlands provide water purification and storage, carbon sequestration, flood mitigation, nutrient cycling, and habitats that support biodiversity, all of which are threatened by a warming climate.[62,63]

The extent to which SRM can mitigate these risks and the impacts of SRM on ecosystem services is unclear. SRM is expected to reduce the GHG-driven increase in global temperature and alter precipitation patterns compared to scenarios without deployment of SRM but would not directly affect increases in atmospheric CO2 concentrations.[64] Species and ecosystems (including microbes, insects, and larger flora and fauna and their interactions) have evolved in response to stable ranges of temperature and precipitation patterns, solar input, and CO2 levels. Both a changing climate and SRM will alter temperature and precipitation ranges and patterns, with results for ecosystems and their provision of goods and services that require further investigation.

Changes in ecosystems may also affect decarbonization strategies. The reduced temperature increase due to SRM deployment might indirectly reduce future atmospheric GHG concentrations compared to a non-SRM scenario by lessening temperature-driven carbon cycle feedbacks that would otherwise be expected to result in higher GHG emissions from natural sources.[65] It is important to recognize that aggressive decarbonization strategies may also affect ecosystems and ecosystem services through changes in land use for low-carbon energy and increased extraction of materials used in low-carbon energy systems.

Ecosystem services also encompass cultural, recreational, and other non-extractive services that can be more difficult to quantify. SRM may provide some benefits to these services, for instance by reducing the magnitude of sea level rise and risks to low-lying cultural heritage sites.[66,67]

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[61] Halofsky, J.E., D.L. Peterson, and B.J. Harvey. (2020). Changing wildfire, changing forests: the effects of climate change on fire regimes and vegetation in the Pacific Northwest, USA. *Fire Ecology. 16*(1), 4. https://doi.org/10.1186/s42408-019-0062-8

[62] Kingsford, R.T., A. Basset, and L. Jackson. (2016). Wetlands: conservation's poor cousins. *Aquatic Conserv: Mar. Freshw. Ecosyst.*, *26*(5), 892-916. https://doi.org/10.1002/aqc.2709

[63] Barbier, E.B. (2017). Marine ecosystem services. *Current Biology. 27*(11), R507-R510. https://doi.org/10.1016/j.cub.2017.03.020

[64] Park et al. (2019). Inequal Responses of Drylands to Radiative Forcing Geoengineering Methods. *Geophys. Res. Letts. 46*(23), 14011-14020. https://doi.org/10.1029/2019GL084210

[65] Canadell, J. G. et al. (2021). Global Carbon and other Biogeochemical Cycles and Feedbacks. In *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V. et al. (Eds)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 673–816, doi:10.1017/9781009157896.007

[66] Ferguson-Bohnee, P. (2015). The Impacts of Coastal Erosion on Tribal Cultural Heritage. *Forum Journal, 29*(4), 58-66. https://ssrn.com/abstract=2742326

[67] Reimann, L. et al. (2018). Mediterranean UNESCO World Heritage at risk from coastal flooding and erosion due to sea-level rise. *Nature Communications, 9*(1), 4161. https://doi.org/10.1038/s41467-018-06645-9

Previous research has raised concerns about possible shifts in sky coloration from SAI, and resulting psychological impacts, which would merit study.[68,69]

Key questions regarding ecosystems and biodiversity include improving understanding of how the unprecedented environments of both a warming climate and a climate with increased CO2 and moderated temperatures (as would occur with SRM implementation compared to climate scenarios without SRM) affect net primary production of natural and managed ecosystems. Nearly all research to date has evaluated the responses of ecosystems and ecosystem services based on projected temperature–CO2 combinations in the absence of SRM. Understanding how these different conditions can affect the biodiversity and functionality of ecosystems is foundational to understanding how SRM and alternative strategies may affect ecosystem services relative to other climate response strategies.

Research could improve understanding of ecosystem sensitivities and responses to expected climate and atmospheric conditions under a range of SRM scenarios. Social science research could also help us understand the cultural, psychological, and other non-extractive services provided by ecosystems under conditions associated with continued warming, aggressive decarbonization, and SRM.

Other major research topics include understanding the impacts of SRM on ocean ecosystems and the potential for impacts to algae and subsequent outcomes for marine food chains, aquatic ecosystems, and their ability to support multiple environmental goods and services (water quality, extreme weather protection, biodiversity, cultural resources, and commercial and recreational fishing). Underlying the marine ecosystem response to any SRM scenario are the effects on ocean acidification, which will not be directly affected by SRM, and marine net primary production (NPP), a research area where initial studies suggest relatively little to moderate effects.[70,71] In this arena, models could consider SRM with and without atmospheric CO2 reductions from GHG mitigation or CO2 removal efforts.

A major gap in current understanding is the ecological consequences of a rapid return to temperature levels corresponding to cumulative carbon emissions relative to termination shock, should efforts to maintain artificial radiation management techniques cease.

Environmental Justice: The communities most vulnerable to the climate crisis are often those who contribute least to the climate crisis.[72] In these communities, health, income, and other factors frequently limit access to resources. They disproportionately suffer from the adverse impacts of climate change. Environmental justice extends beyond disproportionate vulnerability and impact and includes the fair treatment and meaningful involvement of all people regardless

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[68] Robock, A. (2008). 20 Reasons Why Geoengineering May Be a Bad Idea. *Bulletin of the Atomic Scientists*, *64*(2), 14-59. https://doi.org/10.2968/064002006

[69] Kravitz, B., D.G. MacMartin, and K. Caldeira. (2012). Geoengineering: Whiter skies? *Geophys. Res. Lett.*, *39*, L11801. https://doi.org/10.1029/2012GL051652

[70] Tilmes, S. et al. (2020). Reaching 1.5 and 2.0°C global surface temperature targets using stratospheric aerosol geoengineering. *Earth Syst. Dynam.*, *11*(3), 579-601. https://doi.org/10.5194/esd-11-579-2020

[71] Dagon, K., and D.P. Schrag. (2019). Quantifying the effects of solar geoengineering on vegetation. *Climatic Change*, *153*(1), 235-251. https://doi.org/10.1007/s10584-019-02387-9

[72] Althor, G., Watson, J. and Fuller, R. (2016). Global mismatch between greenhouse gas emissions and the burden of climate change. *Sci Rep*, *6*, 20281. https://doi.org/10.1038/srep20281

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of race, color, national origin, or income, with respect to the development, implementation, and enforcement of environmental laws, regulations, and policies. Achieving environmental justice means that all persons and communities enjoy the same degree of protection from environmental and health hazards, and equal access to the decision-making processes to have a healthy environment in which to live, learn, and work.[73]

In the United States, frontline communities—those that experience the "first and worst" consequences of climate change—are largely low-income communities of color, immigrants, migrants, and people who speak languages other than English. These communities often have less access to health care, air conditioning, and greater exposure to the cumulative impacts of pollution and other stressors. They often live and work in locations that are more susceptible to climate-related harms, and generally have less adaptive and resilience capacity. SRM could potentially reduce these disparities by limiting the severity of temperature-driven impacts to the most vulnerable,[74] but there are important caveats to consider in the context of environmental justice. Differential risk and physical impacts are only one aspect. Cultural, moral, and ethical considerations are often overlooked and may be equally, if not more, important to different communities. These overlooked considerations are often missing from model-based evaluations.[75] Finally, if the potential requirement for SRM were that it would be maintained on timescales of decades, if not centuries, intergenerational equity is another dimension to be understood and considered, in the context of both SRM and alternative strategies without SRM.[76]

The potential for SRM to limit warming may reduce the inequities associated with a warming climate. The potential for SRM to exacerbate social inequities also needs to be analyzed, particularly as such inequities relate to fairness and involvement in decision-making.[77] These include the potential for climate impacts that could result from premature SRM cessation,[78] which would most likely be experienced more severely by frontline communities. The potential benefits to frontline communities of SRM could be reduced if it is used as a substitute for, or reduces, mitigation through emission reductions, although the environmental justice outcomes may depend to some extent upon where emissions are reduced. For example, enabling increased use of fossil energy in developing countries could enhance energy justice, although this could further the air quality impacts in those countries, which are likely to be worse for frontline communities.

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[73] Environmental Protection Agency. (6 March 2023). *Environmental Justice.* https://www.epa.gov/environmentaljustice

[74] Horton, J., and Keith, D. (2016). Solar geoengineering and obligations to the global poor. In C.J. Preston (Ed.), *Climate Justice and Geoengineering: Ethics and Policy in the Atmospheric Anthropocene*. Rowman and Littlefield, London, UK, pp. 79–92. https://keith.seas.harvard.edu/files/tkg/files/horton_and_keith_2016.pdf

[75] McLaren, D. P. (2018). Whose climate and whose ethics? Conceptions of justice in solar geoengineering modelling. *Energy Research & Social Science. 44*, 209-221. https://doi.org/10.1016/j.erss.2018.05.021

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[78] Baatz, C. (2016). Can We Have It Both Ways? On Potential Trade-Offs Between Mitigation and Solar Radiation Management. *Environmental Values, 25*(1), 29-49. https://doi.org/10.3197/096327115X14497392134847

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In model simulations of projected climate with stylized SRM emission scenarios from the Geoengineering Model Intercomparison Project (GeoMIP), the harms of warming and the benefits of cooling both accrue disproportionately in warmer and poor, more populous countries. While local-scale spatial distributions are model-dependent, the potential of SRM to reduce inter-country inequality, as measured by per-capita GDP, is consistent.[79,80] Even given a reduction in inequality of physical and health impacts, it remains unclear how to determine a fair distribution of benefits and burdens for SRM deployment, particularly given the potential significant non-physical outcomes. While there are indications that SRM could advance environmental justice efforts, there remain significant gaps in our understanding of how its research and potential deployment would affect environmental justice across and within countries and communities.

Specific research needs related to environmental justice include improving understanding of regional and community differences in

- food and water scarcity, disease, and air quality and their potential to affect human health;
- inequities and how they may vary across generations; and
- projected economic growth and productivity.

Infrastructure Services: Nearly all physical infrastructure in use today was designed based on the assumption of an unchanging, recent climate. Human-caused climate change means that existing infrastructure may be ill-suited to today's climate and future climates, and therefore be unreliable. The Fourth National Climate Assessment outlines climate change effects on infrastructure services, water, energy, buildings, transportation, etc.[81] Since infrastructure design and reliability are sensitive to climate extremes and seasonal patterns, a research topic is how SRM might affect infrastructure reliability, the need to replace infrastructure, and infrastructure design. The resultant insights, if discernable, could in turn inform the need for and design of climate adaptation measures, inclusive more resilient housing, and insurance markets.

Geopolitical Considerations: The cooling effects of SRM could lessen the tendency of climate change impacts like food scarcity, water scarcity, and migration to exacerbate geopolitical stresses, but could introduce other changes to weather patterns that cause problems and create separate geopolitical tensions. A research program would investigate the geopolitical risks associated with SRM in comparison to the geopolitical risks associated with current climate change trajectories.

An unexpected SRM deployment might incur significant geopolitical outcomes. A research program could assess the factors that might lead to an unexpected deployment; evaluate the

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[79] Kravitz et al. (2021). Comparing different generations of idealized solar geoengineering simulations in the Geoengineering Model Intercomparison Project (GeoMIP). *Atmos. Chem. Phys., 21*(6), 4231-4247. https://doi.org/10.5194/acp-21-4231-2021

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[81] USGCRP, 2018*: Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II* [Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart (Eds.)]. U.S. Global Change Research Program, Washington, DC, USA, 1515 pp. https://doi.org/10.7930/NCA4.2018

international community's capabilities in managing such an event; and might yield suggestions on how to deter, prevent, identify, and respond to such an event. A lack of country-level dialogue, governance bodies, and research norms might increase the possibility that state or non-state actors could move independently to develop and deploy SRM technologies.[82] This elevates urgency around assessing the geopolitical outcomes of unilateral or multilateral SRM deployment and identifying optimal international frameworks for cooperation, monitoring, deterrence, and response.

Research would investigate the challenges with multilateral SRM deployment, such as building consensus and creating a measurement, monitoring, and verification system designed to measure SRM deployments and their impacts to human and natural systems.

Multilateral SRM deployment scenarios, such as peak-shaving, would likely require decades of SAI, and a host of natural, economic, and political events could interfere—maybe in risky ways—with a long-term SRM deployment. A research program would identify and analyze the most impactful deployment scenarios, then evaluate potential international processes and structures to prevent the realization of natural, economic, and political interferences.

[82] National Intelligence Council. (2021). *Climate Change and International Responses Increasing Challenges to US National Security Through 2040*. NIC-NIE-2021-10030-A. https://www.dni.gov/files/ODNI/documents/assessments/NIE_Climate_Change_and_National_Security.pdf