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Improving risk governance strategies via learning: a comparative analysis of solar radiation modification and gene drives

Khara Grieger[1,2,3] · Jonathan B. Wiener[4,5] · Jennifer Kuzma[3,6]

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Abstract
Stratospheric aerosol injection (SAI) and gene drive organisms (GDOs) have been proposed as technological responses to complex entrenched environmental challenges. They also share several characteristics of emerging risks, including extensive uncertainties, systemic interdependencies, and risk profiles intertwined with societal contexts. This Perspective conducts a comparative analysis of the two technologies, and identifies ways in which their research and policy communities may learn from each other to inform future risk governance strategies. We find that SAI and GDOs share common features of aiming to improve or restore a public good, are characterized by numerous potential ecological, societal, and ethical risks associated with deep uncertainty, and are challenged by how best to coordinate behavior of different actors. Meanwhile, SAI and GDOs differ in their temporal and spatial mode of deployment, spread, degree and type of reversibility, and potential for environmental monitoring. Based on this analysis, we find the field of SAI may learn from GDOs by enhancing its international collaborations for governance and oversight, while the field of GDOs may learn from SAI by investing in research focused on economics and decision-modeling. Additionally, given the relatively early development stages of SAI and GDOs, there may be ample opportunities to learn from risk governance efforts of other emerging technologies, including the need for improved monitoring and incorporating aspects of responsible innovation in research and any deployment.

Keywords Gene drives · Risk governance · Stratospheric aerosol injection

1 Introduction

Our society is confronting a multitude of serious, complex, and interrelated environmental and societal challenges that demand urgent solutions. If unaddressed, these challenges pose increasing damages and suffering, some steadily accumulating and some risking abrupt catastrophes. For instance, a recent study by Richardson et al. (2023) highlights the significant impact of anthropogenic activities on the Earth's climate and ecosystems, and estimates that six of the nine planetary boundaries it assessed have already been surpassed. These boundaries include those related to the genetic and functional integrity of the biosphere and the radiative forcing that contributes to climate change (Richardson, Steffen et al. 2023). Addressing these challenges is vital to maintaining biodiversity, preserving ecosystem health, securing natural resources, ensuring food security, and safeguarding human health, among other reasons.

In addition to public policies and management practices, emerging technologies may offer potential solutions (as well as risks) to address and mitigate these environmental and societal challenges (National Academies of Science 2019, Redford, Brooks et al. 2019, Hofmann et al. 2020). Emerging technologies refer to new or novel technological advancements that have the potential to significantly impact and transform society, often characterized by rapid development and deep and varied uncertainties (Rotolo

✉ Khara Grieger
kdgriege@ncsu.edu

[1] Department of Applied Ecology, North Carolina State University, Raleigh, NC, USA

[2] North Carolina Plant Science Initiative, North Carolina State University, Raleigh, NC, USA

[3] Genetic Engineering and Society Center, North Carolina State University, Raleigh, NC, USA

[4] Duke Law School, Nicholas School of the Environment, Sanford School of Public Policy, and Center On Risk, Duke University, Box 90360, Durham, NC 27708, USA

[5] Resources for the Future (RFF), Washington, DC, USA

[6] School of Public and International Affairs, North Carolina State University, Raleigh, NC, USA

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et al. 2015). Past experiences with other emerging technologies, particularly those that are disruptive in nature and have the potential to become widespread in society, have underscored the importance of considering and managing potential risks to human health, the environment, and society alongside research and development, while also ensuring transparency and inclusion (Grieger et al. 2019a, b; Kuzma and Grieger 2020; Florin 2022, 2023; Maynard and Dudley 2023). For example, there has been significant pushback to the acceptance and adoption of first generation agricultural biotechnologies, largely due to issues associated with lack of transparency, inadequate regulation and oversight, and lack of inclusion within research, innovation, and commercialization (Kuzma 2018, 2023). More recently, the development and deployment of AI (including large language models such as ChatGPT) has been met with various societal and ethical concerns, including job displacement in some sectors, biased and unfair decision-making, misinformation, and potential control over political and military systems, among others (McLean et al. 2023).

To help address complex and entrenched environmental problems, solar radiation modification (NASEM 2021) and gene drives (NASEM 2016) are both receiving attention as potential technological responses. A form of solar radiation modification, stratospheric aerosol injection (SAI), could be used to reflect a small portion (around 1%) of incoming sunlight through the injection of sulfate aerosols into the stratosphere, emulating a large volcano, and thereby help stave off some of the worst impacts of climate change by cooling the planet (NASEM 2021). Gene drive organisms (GDOs) are a type of genetic engineering technology that could be used to spread a genetic trait through a given population within ecosystems through Super-Mendelian inheritance. GDOs such as gene drive mice, mosquitos, and fruit flies have been proposed as a potential solution to manage invasive pests and eradicate diseases (Teem, Alphey et al. 2020, Bier 2022). Although they largely aim to address different societal and ecological problems (i.e., climate change vs. pest-control, human disease eradication, or ecological protection), both technologies implicate features of emerging risks that are characterized by high uncertainty and lack of knowledge about potential impacts, complexity, and systemic interdependencies that can lead to non-linear impacts and surprises, and risk profiles that are intertwined with variations in societal contexts (Aldy et al. 2021; Florin 2022). Given their potential to be highly disruptive and possibly lead to cascading or systemic risks, risk governance frameworks have been proposed to manage these emerging technologies (Horton and Reynolds 2016, Kofler et al. 2018, Kuzma et al. 2018, Grieger et al. 2019a, b, Long et al. 2020, Felgenhauer, Bala et al. 2022, Hourdequin 2022, Taitingfong et al. 2023).

This Perspective highlights some of the similarities in technological risk features of SAI and GDOs, and then considers ways that the two emerging technologies may learn from each other and other fields to inform their risk governance strategies. We chose SAI and GDOs as they represent two novel and disruptive technologies that are being investigated to remedy complex environmental challenges across large macro scales (i.e., global, regional). The local, point source release of both technologies can lead to ecosystem impacts well beyond the area of deployment. In this comparative analysis, the technological features of GDOs and SAI are compared and contrasted. In addition, key features related to their risk governance and decision-making are reviewed by the authors and based on the current literature and plausible projections. Results include a comparative analysis for the two technologies, followed by a discussion on key areas for shared learning for improving risk governance decisions. Findings from this paper may be useful for researchers, scholars, and decision-makers involved in the risk governance of SAI, GDOs, and other emerging technologies that are being investigated or considered as technological responses to complex environmental challenges.

2 Overview of SAI and GDOs

Stratospheric aerosol injection (SAI) is a proposed solar geoengineering technique that would rely on the use of aerosol particles, such as sulfur dioxide (SO_2), injected in the stratosphere to reflect a small portion of incoming sunlight (Fig. 1A). In this way, SAI could mimic the global cooling effect observed after some volcanic eruptions, reduce global temperatures, and help to address some negative climate change impacts (Irvine et al. 2016; Keith and Irvine 2016, National Academies of Science 2021). While atmospheric greenhouse gas (GHG) (e.g., CO_2, CH4 (methane), N_2O (nitrous oxide)) concentrations would not be decreased by SAI, it could help decrease levels of warming by shading incoming radiation, and stave off some of the worst effects of climate change, especially in a climate emergency (Morgan and Ricke 2010). Other studies explore SAI scenarios based on goals of reducing the rate of warming by the next century, stopping the degree of warming, or even reversing the amount of warming experienced thus far (Smith 2020). SAI technologies are currently in a very early stage of research, and have not yet been deployed in large-scale field studies (OSTP 2023).

SAI may pose both benefits and risks. The main benefits identified by proponents of SAI include that it may be one of the most cost-effective solutions to address climate change, costing on the order of (only) billions of USD, and that it can act relatively quickly to ameliorate global warming, on the order of years rather than decades

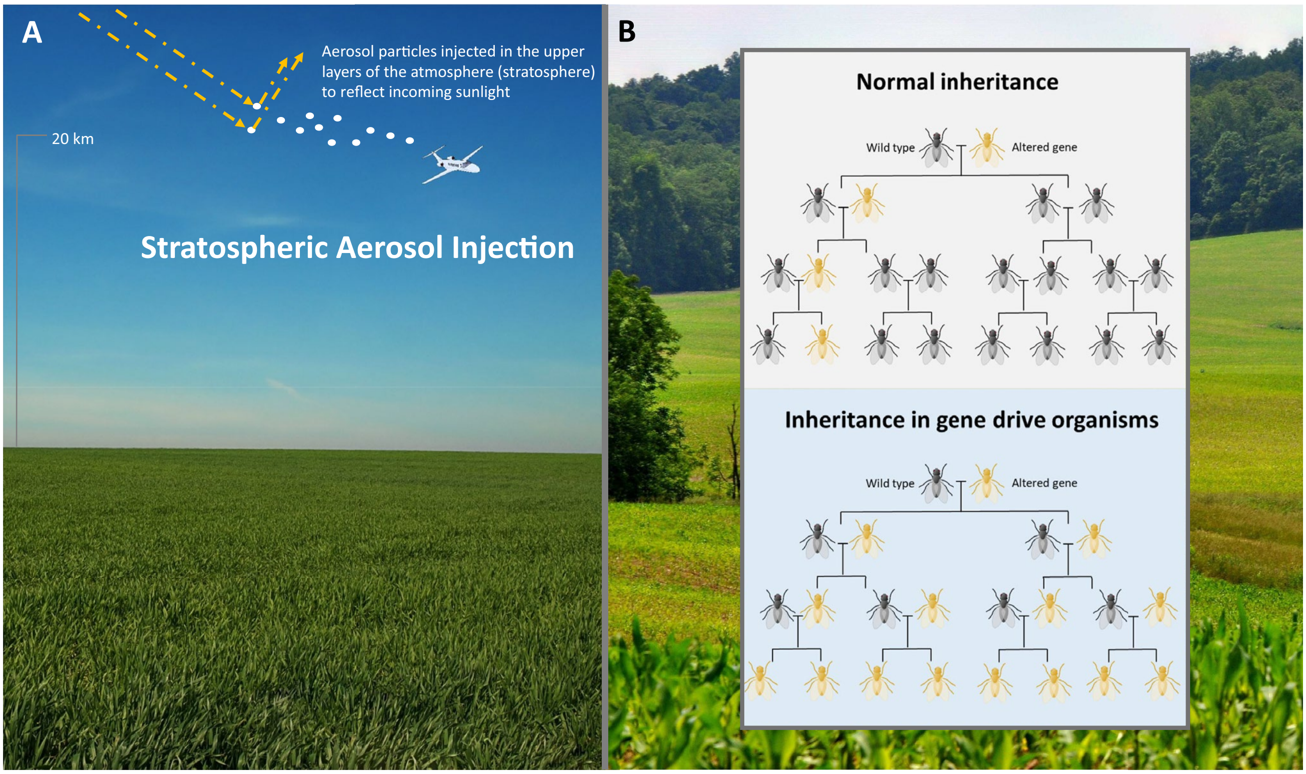

Fig. 1 Overview of **A** stratospheric aerosol injection and **B** Super-mendelian inheritance in gene drives (adapted from (Mariuswalter 2017))

(Smith and Wagner 2018; Smith 2020). Another proposed benefit—but also a risk—is that SAI can be developed and deployed without relying on collective action, which can often require substantial time and negotiating power (Horton and Reynolds 2016). Stakeholders who may benefit from SAI could include governments interested in relatively cost-effective and rapid solutions to global warming, industrial partners, or contractors interested in developing and/or deploying SAI technologies, and potentially larger society, especially those who are most vulnerable to peak climate damages (such as sea level rise, extreme weather, flooding, fires, and heat waves). At the same time, there are many potential environmental, technical, ethical, and socio-ethical risks potentially posed by development and deployment of SAI (Felgenhauer, Bala et al. 2022, Climate Overshoot Commission 2023). These include environmental risks, such as potential shifts in regional heat and precipitation patterns, excessive global cooling, acid deposition, and stratospheric ozone depletion (Xia et al. 2017; Krishnamohan and Bala 2022, Tracy, Moch et al. 2022). In addition, SAI may pose sociopolitical risks, such as possible disincentives to emissions mitigation, unwise unilateral or corrupt deployment, international conflict, and termination shock yielding rapid warming (Tang and Kemp 2021, Felgenhauer, Bala et al. 2022). There are substantial ethical and governance challenges regarding who decides if and/or when deployment could occur, especially given that benefits and risks are expected to be unequally distributed across different regions or countries (Svoboda et al. 2018). Risk perceptions are expected to be critical to the case of SAI, including perceptions of the technology itself and its acceptability, as well as its risks juxtaposed against the risks of climate change and the influence of these perceptions on GHG mitigation efforts (Merk et al. 2015; Merk and Pönitzsch 2017; Sugiyama et al. 2020). Stakeholders who may be adversely affected by SAI could include the diverse publics who are most vulnerable to its adverse side effects, both physical and geopolitical, as well as government agencies who need to manage the unintended consequences of deployment.

Gene drive organisms (GDOs) are a form of genetic engineering that relies on Super-Mendelian rules of inheritance to increase the prevalence of targeted genes through a given population (Grunwald et al. 2019) (Fig. 1B). The use of GDOs can result in a spread of genes through a population, essentially biasing the rate of inheritance of altered genes and introducing a trait much faster than through normal Mendelian inheritance. In sexually reproducing species, altered genes could result in a particular trait being exhibited in a population within a few generations (Kuzma 2020). Gene drives can be used to disrupt existing genes (e.g., drive deletions through the population) or introduce new genes. They can include genetic changes that serve to suppress the population over time (e.g., introduce population suppression genes to reduce the number of mosquitos in an ecosystem that carry diseases like malaria or Dengue) or to introduce a beneficial gene into a desirable species (e.g., introduce a resistance gene to protect a species from disease thereby immunizing it and protecting it) (Marshall, Buchman et al. 2017; Bier 2022). Most GDOs currently under development capitalize on CRISPR-Cas molecular tools that cleave DNA at "clustered regularly interspaced short palindromic repeats" (CRISPR) frequently present in genomes (McFarlane et al. 2018). CRISPR-Cas systems can be targeted toward any site in the DNA by "guide RNA" (gRNA) sequences. After the CRISPR-Cas system (with the gRNA) cuts the target DNA site, a double-strand break results which can either be repaired by the cell or result in a mutation. However, if engineers provide an additional DNA template sequence with homology to either side of the break at its ends, it can be used for repair instead and copied into the break site. If the repair template includes DNA sequences coding for the CRISPR-Cas system and the gRNA, the gene drive system copies itself into cleavage sites via homology directed repair (Bier 2022). When this gene drive system is introduced into germ-line cells, it biases inheritance away from 50% (predicted by Mendelian inheritance) toward 100% (depending on the efficiency) (Esvelt, Smidler et al. 2014, Bier 2022) (Fig. 1).

There are also a number of different types of GDOs, including variations in their ability to (i) be restricted in time and space (i.e., restricted vs. unrestricted), (ii) suppress or replace populations (i.e., self-limiting gene drives), and (iii) have an effective "dose" needed to achieve full spread (i.e., ratio of GDOs compared to wild populations vs. few individuals to spread to population through random mating) (Friedman et al. 2020; Kuzma 2020). To help control or limit the spread of GDOs, researchers have focused on developing reversal drives (e.g., (Vella et al. 2017), using drives targeting the local variant of a biological population, and investigating other ways to limit the spread through formal research programs (DARPA 2017). Because of their ability to disperse a trait faster in a population, GDOs have been proposed in a range of fields to improve human health and/or the environment. For example, GDOs have been proposed to combat mosquito-borne malaria and improve public health, to eradicate invasive species and restore natural ecosystems for conservation purposes, and to control or eliminate agricultural insect pests (Godwin et al. 2019; Adolfi et al. 2020; Legros et al. 2021; Bier 2022). To date, GDO research has consisted of laboratory-based studies. No field trials have occurred to date; however, some field trials in the U.S. and other countries using other genetic engineering methods to suppress pest populations have occurred (Oxitec 2019; EPA 2022).

GDOs may pose both benefits and risks. Stakeholders who may benefit from GDOs include the diverse publics who may be saved from diseases suppressed by GDOs, government agencies, and non-governmental organizations tasked with protecting public health from vector-borne diseases, natural resource managers, and agricultural industries and farmers. At the same time, GDOs may pose various environmental, health, and socio-ethical concerns. Releasing GDOs into the environment may, for example, have unintended consequences for ecosystems, including the spread of engineered genes to non-target related populations, reductions in prey for other ecological species, or niche replacement by more harmful organisms (Brown 2017; Kuzma 2020). Releasing GDOs on human populations before long-term effects are better understood also raises a number of ethical concerns, further pointing toward the need for better oversight and public participation (Kofler et al. 2018; Kuzma et al. 2018; Long et al. 2020; Taitingfong et al. 2023). Risk perceptions are also expected to play a critical role in the case of GDOs, largely shaped by worldviews and key benefit-risk factors, including balancing the, e.g., management of invasive species or improvement of public health with the spread of gene drives and their impacts on native species (MacDonald et al. 2020, Jones et al. 2019, Evans et al. 2024). Factors such as dread, catastrophic risk, level of trust, and "tampering with nature" among others are also likely to play key roles in shaping perceptions (Slovic 1987; Sjöberg 2004, Klinke and Renn 2004). Stakeholders who may be adversely impacted by GDOs may include the diverse publics afflicted by the adverse unintended or unforeseen ecological and health impacts, government agencies and NGOs tasked with protecting public health and the environment, and agricultural industries and farmers.

3 Technology comparative analysis

SAI and GDOs share several common features as well as some important differences. First, they both share the feature of offering to *improve or restore a public good* in the form of an environmental, climate, or public health benefit across regional or global scales (Column A, Table 1). In the case of SAI, the technology could alleviate climate change impacts by reflecting incoming sunlight and providing temporary cooling of the Earth. Notably, SAI would not result in climate change in reverse; rather, it is an additional and novel climate intervention that would, in combination with rising greenhouse gas concentrations, create a new climate rather than restoring the climate to any historical state (Felgenhauer, Bala et al. 2022). In the case of GDOs, the technology could improve public health (e.g., against

Table 1 Comparative matrix across risk governance features of SAI and GDOs

	A. Purpose/ benefits	B. Deployment	C. Spread	D. Potential risks	E. Societal impacts	F. Reversibility	G. Stakeholders	H. Int'l governance	I. Monitoring
SAI	Alleviate climate change impacts by reflecting a fraction of incoming solar energy	Studies are primarily modeling and lab-based; Low technology readiness level. A hypothetical well-designed deployment would occur at multiple latitudes over both hemispheres, with potential for wide-ranging impacts; Deployment would require sustained and repeated implementation	Not self-propagating;	Numerous ecological risks, such as regional precipitation pattern changes, excessive cooling, acid deposition, ozone depletion, unintended ecosystem impacts; possible mitigation disincentive; international conflict; termination shock, technology dependency; Extensive uncertainties and recognized ignorance; Trade-offs between impacts of climate change and risks of SAI	Climate change as primary topic for debate thus far, with SAI as potential solution; ethical concerns to engineer climate; cross-boundary effects that may have heterogeneous impacts could lead to conflict	Reversibility of SAI is possible by discontinuing deployment; Premature termination could yield warming shock; Dependency may arise if need to continue deployment and GHG concentrations are not substantially decreased, or to avoid termination shock; Unclear if impacts on the environment are reversible	Some funding from NGOs, private actors, philanthropy, some gov't such as DOE, NOAA; Assessments by academic researchers; international input from e.g., Climate Overshoot Commission, UNESCO, Degrees Initiative, Alliance for Just Deliberation on SG, etc	No formal governance; some may apply, such as UN FCCC, ENMOD, Convention on Long Range Transboundary Air Pollution; Voluntary Codes of Conduct have been proposed;	Not currently monitored; growing interest; possible monitoring via national technical agencies such as NOAA, and/or international organizations

Table 1 (continued)

	A. Purpose/ benefits	B. Deployment	C. Spread	D. Potential risks	E. Societal impacts	F. Reversibility	G. Stakeholders	H. Int'l governance	I. Monitoring
GDOs	Improve public health; restore ecological land-scape; improve sustainable agriculture	Studies conducted thus far are laboratory and field-based; Medium technology readiness level; Designed for point source deployment with potential for wide-ranging impacts; Can be designed for one-time deployment (self-sustaining)	Self-propagating;	Numerous ecological risks, such as impacts on non-target organisms, modified genes that could spread and persist in the environment, effects on ecosystem services; Extensive uncertainties and recognized ignorance; Trade-offs between existing environmental, health, and agricultural issues and risks of GDOs	GDO technology as primary topic for debate; concerns re "acting as God" and modifying "nature"; cross-boundary effects could lead to conflicts; differing national policies	GDOs are self-propagating, although research is underway to create reversible GDOs or to limit spread; If self-sustaining GDO, may have irreversible ecological impacts	Foundations, academe, nonprofit orgs, gov't, emerging companies for agriculture	Some efforts underway for governance, including IUCN / UN CBD, AHTEG / LMO under Cartagena Protocol; Voluntary Codes of Ethics have been proposed	Not currently monitored; biotech regs do not traditionally include long-term monitoring

vector-borne diseases), restore ecological landscapes (e.g., eradicating invasive pests), and improve sustainable agriculture with societal benefits (e.g., reducing insect populations while reducing chemical insecticides).

Second, both SAI and GDOs have numerous *potential ecological risks, societal impacts, and ethical concerns related to deployment* and *are characterized by extensive uncertainties and recognized ignorance* (Table 1, Columns D, E). For SAI, these risks include the aforementioned impacts to the environment and ecosystem services (e.g., changes in precipitation patterns, excessive cooling, acid deposition, slowed stratospheric ozone recovery), as well as geopolitical effects and heterogeneous impacts across regions, potential unilateral deployment, international conflict, possibly discouraged mitigation, or sudden termination yielding rapid warming (Felgenhauer, Bala et al. 2022). For GDOs, there have been a number of ecological risks raised, such as impacts on non-target organisms, potential risks of modified genes that spread and persist in the environment (gene flow), reductions in prey for other ecological species, or niche replacement by more harmful organisms, as well as unintended risks to ecosystem services (National Academies of Sciences 2016). Both of these technologies have been characterized by extensive uncertainties and recognized ignorance about key impacts (e.g., (Grieger et al. 2019a, b, National Academies of Science 2019). Overall, it is important to note that the risks of each of these emerging technologies should be weighed against the risks of the existing problem which these technologies could reduce (e.g., climate change, invasive species, vector-borne diseases), using tools such as a risk–risk framework that compares diverse risks and also seeks even better "risk-superior" options to reduce multiple risks in concert (Graham and Wiener 1995).

Third, both technologies share the common governance challenge of how *best to coordinate behavior among multiple actors and stakeholders*, including those who could deploy the technology(ies) unilaterally without broader consent or agreement, or stakeholders with competing interests, or stakeholders from neighboring regions where impacts could spread beyond national and regional boundaries. Common stakeholder groups would include affected publics, government agencies, industry, NGOs, academic researchers, and private foundations (Table 1, Column G). Ideally, these stakeholders and other actors would be coordinated through collaborative governance frameworks, although formal, international governance mechanisms are lacking for both of these technologies. Some commenters have examined the use of existing governance mechanisms (e.g., for SAI, the UN Framework Convention on Climate Change (FCCC), the ENMOD Convention, the Convention on Long Range Transboundary Air Pollution, and other potentially applicable international regimes; and for GDOs, IUCN/UN Convention on Biological Diversity (CBD), the AHTEG / LMO provisions under the Cartagena Protocol, and other regimes) (Column H) (Oye et al. 2014; Talberg et al. 2018; Rabitz 2019; Reynolds 2020; Climate Overshoot Commission 2023). There have also been private or soft law Codes of Conduct (e.g., Hubert 2017, 2021)) and Codes of Ethics (e.g., (Annas et al. 2021)) proposed to guide research responsibly for both SAI and GDOs, perhaps because there are no formal, technology-specific governance frameworks in place.

SAI and GDOs also differ across several technological and governance features, which offer opportunities and challenges for learning across policy domains and over time. These include their *temporal and spatial mode of deployment*, *spread*, *degree and type of reversibility*, and *potential for environmental monitoring*. First, in terms of *their temporal and spatial model of deployment* and ability to *spread* in the environment, SAI would involve repeated and sustained deployments of aerosol particles that spread in the stratosphere and that continue reflecting incoming sunlight. Each aerosol injection might only stay in the stratosphere for a year or two, so that a successful SAI program would rely on re-deployments to inject additional particles, as the aerosol particles are not themselves self-propagating. At the same time, if deployment were to stop prematurely while GHG concentrations had continued to rise, a "termination shock" could occur, resulting in a rapid rise of global temperatures posing heightened or even catastrophic risk. By contrast, GDOs are currently designed or envisioned to involve just one or a few deployments, followed by self-propagating reproduction and spread of particular genes and associated trait(s) throughout a population (Table 1, Columns B, C).

Second, SAI and GDOs differ in their *degree and type of reversibility* (Table 1, Column F). In the case of SAI, because the aerosol particles have a short residence time in the stratosphere, the technology's impacts could potentially be stopped (or reversed) within a year or two by discontinuing the ongoing deployments of aerosol injections. This is in contrast to GDOs, where gene drives could self-propagate, and the degree of reversibility becomes more limited post-deployment. For SAI, there may also be political challenges to its reversibility, both because SAI programs would need to be managed to avoid premature abrupt reversal (yielding possible termination shock), and to avoid lock-in (political dependence on SAI as a salve for GHG accumulation). In other words, whereas GDOs could exhibit self-propagation through biological reproduction, SAI could be interrupted (or perpetuated) through sociopolitical systems that disrupt (or encourage) continued use. If SAI were deployed (i.e., particles injected in the stratosphere), it is unclear if the climate impacts of SAI could then be reversible, but discontinuing SAI deployments would soon end further climate impacts as the particles precipitate out of the stratosphere. This is in contrast to GDOs, where self-propagating gene drives could intentionally lead to irreversible impacts on ecological systems in terms of the distribution of modified genes (Column F). There has been some research to develop reversal gene drives that could undo or overwrite genetic changes that were introduced with the initial drive, possibly restoring the original genetic sequence, although any ecological effects experienced by the GDOs also may not necessarily be reversible (Brown 2017).

Third, in terms of their *potential for environmental monitoring*, neither technology has established monitoring programs and both technologies would benefit from developing adequate monitoring programs to better understand the technologies as well as their effects on the environment and society. Indeed, environmental monitoring is one of the key features to risk governance frameworks of emerging risks including novel technologies more broadly (IRGC 2015). A monitoring system for SAI could be developed before any deployment of SAI might occur and could offer several benefits, including providing advance warning of (and thus helping to deter) potential unilateral deployment, observing any collective deployment, reducing international conflict, assessing the intended and unintended impacts of SAI to inform adaptive decision-making, and attributing any adverse effects to assist or compensate those affected (Wiener and Felgenhauer 2024). There may be options to monitor SAI activity through national programs (e.g., the US SABRE program (NOAA 2024)), or joint ventures akin to the US-India NISAR earth observing satellite, but several of the benefits of SAI monitoring just noted could be enhanced by adding a transparent multilateral monitoring system (Wiener and Felgenhauer 2024). For GDOs, there has been some interest in monitoring, but no formal monitoring programs have been proposed for GDOs and none implemented for biotechnology more broadly (Table 1, Column I). A global registry for GDOs has been proposed; however, there is no formal implementation yet (Taitingfong et al. 2023).

4 Opportunities for learning and governance

Building on the comparative analysis of SAI and GDOs, we identify opportunities for mutual learning related to their risk governance. First, we find that the field of SAI may learn from the field of GDOs by *enhancing participation in international collaborations related to governance and oversight*. In the case of GDOs, there have been a number of international collaborations and initiatives focused on governance and oversight of synthetic biology and gene drives, including efforts under the International Union for the Conservation of Nature (IUCN), United Nations Convention on Biodiversity (UN CBD) with its Ad Hoc Technical Expert Group (AHTEG), and the Cartagena Protocol on Biosafety for Living Modified Organisms (LMOs) (Redford, Brooks et al. 2019, UNEP 2020; Hartley et al. 2022; UNEP/CBD Secretariat of the Convention on Biological Diversity 2022). The Conventional on Biological Diversity (CBD) and its Cartagena Protocol on Biosafety l (BSP) for Living Modified Organisms may be the most significant venue for future international governance for GDOs. Under the CBD-BSP, GDOs would be considered "living modified organisms" and the regime would obligate all countries that are parties (the U.S however is not a signatory) to ensure the safe handling, transport, and use of LMOs resulting from modern biotechnology. The BSP establishes "advance informed agreements" whereby countries are notified with sufficient information founded in science-based risk assessment in order to make decisions about whether to accept the transboundary movement of LMOs into their country. If GDOs are found to adversely impact biodiversity conservation or health, then CBD-BSP parties may regulate, manage, or control their movement under the BSP (Reynolds 2020). The CBD-BSP would apply to GDOs governance, although whether it needs additional provisions or how it would specifically apply is still under discussion. While some countries, stakeholders, and experts have criticized the BSP for embracing a form of the precautionary principles at its core, it provides an example of a venue for international collaboration focused on governance and oversight of living modified organisms produced by modern biotechnology, such as GDOs. In addition, the Nagoya – Kuala Lumpur Supplementary Protocol on Liability and Redress to the Cartagena Protocol on Biosafety establishes international rules and procedures for liability and redress if damage to biodiversity or health should result from the transboundary movement of LMOs. The transboundary movement of GDOs is of particular concern given that GDOs are meant to spread in unmanaged ecosystems in order to bias inheritance in the natural population. As of early 2024, there are 173 nation states that are party to the CBD-BSP and 54 that are parties to the Nagoya Protocol, suggesting a significant international policy venue for governance which would apply to GDOs.

In the case of SAI, there are also a number of existing international frameworks, such as UN FCCC, ENMOD, Convention on Long Range Transboundary Air Pollution, Montreal Protocol and Vienna Convention for the Protection of the Ozone Layer, proposed as potentially applicable, although their exact relevance remains uncertain (Felgenhauer, Bala et al. 2022). While there have been a number of attempts to put SAI and other solar geoengineering technologies on formal agendas at international climate conferences (e.g., COP meetings) (IPCC 2024; Watts 2024), these attempts have largely been met with important challenges (Harvard's Solar

Geoengineering Research Program 2019). While there are some international groups and consortia focused on governance of SAI (e.g., Carnegie Climate Geoengineering Governance Initiative 2018; Alliance for Just Deliberation on Solar Geoengineering 2024)), SAI governance has not yet gained significant traction within international regulatory fora to effectively move forward at intergovernmental policy levels. Given that SAI has been proposed as one of the most cost-effective solutions to mitigate the worst effects of climate change and the growing recognition of the need to prevent climate tipping points (Wunderling et al. 2023), and the potential for unilateral deployment, establishing better international governance in the near future could be crucial for proactive and cooperative decision-making before urgent or emergency actions become necessary. Further, international consortia and partnerships can also be effective to share data and information from environmental monitoring programs, as discussed in subsequent sections.

Second, the field of GDOs may also learn from SAI by *investing in research focused on economics and decision modeling*. Over the past decade, significant research efforts have been made in the fields of economics and decision-modeling to assess SAI (Moreno-Cruz and Keith 2013; Harding and Moreno-Cruz 2019; Cherry et al. 2023a, b; Cherry et al. 2023a, b). These studies have provided meaningful insights on the behavior of different actors working in competitive and collaborative relationships and how decisions related to SAI deployment may influence broader climate policies. For example, in a recently conducted study focused on decision-modeling using controlled experiments, researchers found that offering the option of SAI led participants to increase their investments in climate mitigation efforts (Cherry et al. 2023a, b)—contrary to predictions that offering the option of SAI may discourage mitigation efforts (the "moral hazard" risk). In a related study, these authors found that the option of SAI, to the extent that it poses its own risks which participants find concerning, may thereby promote increased cooperative mitigation behavior among actors (Cherry et al. 2023a, b). Similar levels of research focused on economics, decision-modeling, and decision-making have not yet been undertaken in the case of GDOs. As for SAI, the strategic behavior of actors involved in GDO decisions may affect the benefits and risks of GDO policies and projects. For this reason, the GDO community may benefit from enhancing their investments in research focused on economics and decision-modeling as a way to better understand the behavior of different decision-makers and actors in governance regimes, as well as the cost-effectiveness and risks of deploying GDOs compared to other management solutions.

In addition to the aforementioned areas of mutual learning across SAI and GDOs, there may also be ample opportunities to incorporate "lessons learned" from other emerging technologies (Florin 2022), especially given that SAI and GDOs are in relatively early development stages. One central theme from these past cases is the often observed lag time between a technology's emergence and development, data, and information on the technology's impact on health, environment, and society, and subsequent decision-making, known as the "pacing problem" (Linkov, Satterstrom et al. 2009, Marchant, Allenby et al. 2011). In the cases of SAI and GDOs, the "pacing problem" is also prevalent if the rate of technological development outpaces our ability to understand the full range of ecological, societal, and ethical risks of their impacts. To help address this issue that is often characteristic of emerging technologies, one approach that may be helpful is to incorporate aspects of responsible research and innovation (RRI). RRI emerged in the past decade to attempt to reduce the lag time between technological emergence and decision-making, develop safe(r) technologies or products in early innovation stages, and broadly align science and technology with societal needs and wants (Stilgoe et al. 2013; Grieger et al. 2022). RRI is related to other practices that address safety hazards (e.g., Safe-by-Design, Green chemistry) (van de Poel and Robaey 2017; Zimmerman et al. 2020), by incorporating health and environmental considerations in research and innovation with broader societal and ethical aspects. Overall, the ultimate goal of RRI is to align research and innovation with societal needs and wants with an underpinning of principles of anticipation, reflexivity, responsivity, and inclusion (Stilgoe et al. 2013, 2017; Grieger et al. 2022). For these reasons, research communities may benefit from framing their research and innovation within broader RRI contexts, through for instance anticipating potential impacts of the research or innovation, including considering diverse stakeholders in innovation cycles, being reflexive about the assumptions and values underpinning research and innovation design, and being responsive to new information and stakeholder perspectives. In addition to RRI, others have proposed another approach to the "pacing problem"—incorporating learning into the regulatory process, via planned adaptive regulation that employs policy design, monitoring, and iterative review to enable updating in response to changing knowledge and conditions (McCray et al. 2010; Bennear and Wiener 2019). Planned adaptive regulation could be a particularly useful approach if planned deployment of either technology could occur, and could ideally be coupled with established monitoring programs to evaluate the technology(ies) as well as potential impacts.

In the case of GDOs, various organizations, regulatory agencies, and research institutions have incorporated concepts of RRI into gene drive research and governance frameworks to help navigate associated societal, ethical, and ecological challenges (e.g., DARPA 2017; GBird 2017; Thizy et al. 2020). For example, there has been significant public and stakeholder engagement and inclusion efforts for GDOs (Roberts and Thizy 2022; Hartley et al. 2023; Malaria 2024). These efforts could be coupled with more research and investments on designing GDOs with SbD principles in mind, such as efforts to help avoid unintended impacts on non-target organisms and improving reversal drive capabilities. In the case of SAI, there have been some cases of trying to engage some stakeholders in research and deployment stages (e.g., Parkhill and Pidgeon 2011; Alliance for Just Deliberation on Solar Geoengineering 2024)). Following principles of RRI, a diverse range of stakeholders should also be included in early research and innovation stages and particularly in cases where deployment is considered, including members of civil society, regulatory bodies, environmental and public health NGOs, advocacy groups, external research scientists, and other affected stakeholders (Carr et al. 2013; Renn 2015; Kuzma 2019). At the same time, it is also recognized that learning from other emerging technologies and incorporating aspects of RRI largely rely on "bottom up" efforts by individual researchers and innovators, and alone are likely not enough to drive responsible technological innovation and adoption at large scales (Grieger et al. 2019a, b; Grieger and Kuzma 2023). Effective governance mechanisms imposing remedies for adverse impacts will likely need to accompany efforts at RRI made by individual researchers, businesses, or governments.

More broadly, the fields of GDO and SAI would also benefit from developing and operating effective, long-term large-scale and transparent monitoring programs (Wiener and Felgenhauer 2024). Drawing from the broader risk governance literature, monitoring can be an effective mechanism to detect adverse impacts or consequences of emerging technologies in relatively early stages of their development. In the case of SAI, there has been growing interest and recognition of the importance of monitoring activities, although no formal programs have yet been established. As discussed above, a transparent multilateral monitoring system for SAI, which should be developed before any deployment of SAI might occur, could offer several benefits. These include providing advance warning of (and thus helping to deter) potential unilateral deployment, observing any collective deployment and reducing international conflict, assessing the intended and unintended impacts of any SAI deployments to inform adaptive decision-making, and attributing any adverse effects to assist or compensate those affected (Wiener and Felgenhauer 2024). A White House report recently highlighted the need for effective monitoring of SAI to support decision-making in federal programs (OSTP 2023). The 2021 NASEM report also addressed the need for post-deployment monitoring of SAI, suggesting that several U.S. government agencies have capacity and experience in climate monitoring but have not yet dedicated resources and personnel to monitor solar geoengineering nor do they have a mandate to do so (National Academies of Science 2021). As suggested above, a transparent multilateral monitoring system could offer greater benefits than national monitoring alone, such as avoiding international conflicts. In the case of GDOs, there has been little attention given thus far toward the needs of formal organizations including third party monitoring programs for effective risk governance and decision-making. The GDO community would also benefit from establishing organizations that would oversee environmental monitoring programs to ensure that control mechanisms work during early stages of GDO decision-making and deployment (e.g., restricted vs. unrestricted gene drives, GDOs that aim to suppress a population vs replace it; threshold vs. non-threshold drives) (Kuzma 2019). The NASEM 2016 report on gene drives does include post-release monitoring as part of a staged release framework, and calls for funders of gene drive research to establish monitoring standards throughout the world (National Academies of Sciences 2016). To the degree that biotechnology regulations for genetically engineered organisms in the environment (e.g., genetically modified plants) have not traditionally included post-market release monitoring, new programs and designated organizations responsible for their oversight of effective monitoring may be needed (Kuzma 2019). Policies and regulations for SAI and GDOs may also benefit from incorporating more adaptive approaches that allow for learning and updates over time—features that are important for overseeing emerging technologies deployed in the environment or within broader society (McCray et al. 2010; Bennear and Wiener 2019; Wiener 2020).

By comparing and contrasting the technical and risk governance features of SAI and GDOs, this Perspective identifies ways in which research and policy communities may learn from each other to inform future risk governance strategies. Key findings include similarities and differences between the two emerging technologies, as well as opportunities for learning across these two domains and from other emerging technologies. We further suggest challenges and opportunities for SAI and GDOs on issues including international cooperative governance, economics and decision research, reversibility, adaptive learning, and monitoring. Overall, these suggestions may be useful for researchers, scholars, and decision-makers involved in the risk governance of SAI, GDOs, and other emerging technologies that are being investigated or considered as technological responses to complex environmental challenges.

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Declarations

Conflict of interest All authors of this manuscript declare there are no conflicts of interest.

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