Risks from Solar Geoengineering with Stratospheric Aerosol Injection on Land Vertebrates

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Minor Dissertation presented in partial fulfilment of the requirements for the degree of Master of Philosophy in Climate Change and Sustainable Development

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Declaration

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Abstract

Solar Radiation Modification (SRM), otherwise known as ‘solar geoengineering’, is a proposed set of methods to limit the amount of sunlight that is able to reach the surface of the Earth in order to mitigate the effects of global warming. However, its potential effects on biodiversity and ecosystems have received minimal attention in literature. In this study, I investigated the risks to terrestrial biodiversity from stratospheric aerosol injection (SAI), one of the most studied methods of SRM, whereby megatons of sulphate or other aerosol particles are injected into the stratosphere to reflect sunlight back into space. Specifically, I assessed the temporal dynamics of exposure to potentially dangerous temperatures for more than 26,000 species of terrestrial vertebrates using a **G6sulfur** scenario, which provides simulations of a high emissions pathway (SSP5-8.5) with SAI deployed using sulphate aerosols to keep global warming levels similar to that in an intermediate-emissions scenario achieved through conventional mitigation (SSP2-4.5). The results showed that the magnitude of species populations exposed to potentially dangerous temperature conditions under **G6sulfur** was 14% higher than under SSP2-4.5. Tropical forests of South America, Central Africa, Southeast Asia and Australia are projected to have the most increase in risk from **G6sulfur** when compared to SSP2-4.5. Moreover, these places appear to be impacted by earlier and more abrupt exposure under **G6sulfur** when compared to SSP2-4.5, which could affect the time species have to adapt to temperature changes and could potentially prompt ecological disruption. However, for the Sahel region and India, SAI deployment may reduce risk of species exposure. This reveals the complexities of governing proposed SAI deployment and necessitates informed decision making on whether and how to deploy these types of interventions. More research is needed on the effects of various deployment scenarios on biodiversity and the increased participation of developing countries in SRM research and decision-making processes is essential.

Keywords: Climate change, Solar Radiation Modification (SRM), Stratospheric Aerosol Injection (SAI), G6sulfur, Biodiversity, Terrestrial vertebrates, Tropical forests, Developing countries.

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List of Abbreviations and Acronyms

BAU	Business As Usual
BDC	Brewer-Dobson Circulation
CDR	Carbon Dioxide Removal
CMIP6	Coupled Model Intercomparison Project Phase 6
CO2	Carbon Dioxide
COP26	United Nations Climate Change 26th Conference of the Parties
ENSO	El Niño Southern Oscillation
GeoMIP	Geoengineering Model Intercomparison Project
GHGs	Greenhouse Gases
Gt	Gigatonnes
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
IPCC	Intergovernmental Panel on Climate Change
IUCN	International Union for Conservation of Nature
MEA	Millennium Ecosystem Assessment
NAO	North Atlantic Oscillation
QBO	Quasi-Biennial Oscillation
SAI	Stratospheric Aerosol Injection
SO2	Sulphur Dioxide
SRM	Solar Radiation Modification
UN	United Nations
UNEP	United Nations Environment Programme
USA	United States of America

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Chapter 1: Introduction

1.1. Rationale

Anthropogenic climate change (hereafter climate change) refers to the long-term and persistent changes to average temperature and precipitation patterns caused by human activities, such as the burning of fossil fuels, deforestation, and the use of chemicals, which release greenhouse gases (GHGs) into the atmosphere (IPCC, 2021; Lovejoy, 2006). GHG emissions have climbed by around 12% in the last decade, reaching 59±6.6 GtCO$_2$-eq[9]in 2019 (IPCC, 2023). The average global surface temperature has increased by approximately 1.1°C compared to preindustrial levels and has been projected to reach 1.5°C by 2040 (IPCC, 2023). The adverse impacts of climate change are widespread, and warmer temperatures are causing more frequent heat waves, drought and forest fires (IPCC, 2021). Moreover, the melting of glaciers and polar ice caps is leading to sea level rise and an increased frequency of coastal floods (IPCC, 2021; Irvine et al., 2009). These impacts are affecting both the natural environment and human populations, with associated losses and damages from climate change occurring in many regions (IPCC, 2022a; Lovejoy, 2006).

Climate change is impacting human and ecological systems across sectors, including agriculture, water, and the economy (Aydinalp & Cresser, 2008; Elliot et al., 2011; IPCC, 2022; Lemi & Hailu, 2019; Tol, 2014). These changes in climate are also being felt by the world's ecosystems, asspecies are experiencing rapid changes in temperatures and precipitation patterns (IPCC, 2022a; Pecl et al., 2017; Sutherland et al., 2014). The shifting weather patterns and rising temperatures are altering the migration patterns of many species and reducing or shifting their geographic ranges, increasing extinction risk and contributing to biodiversity loss (Pecl et al., 2017). These ecological changes are directly translating to negatively impact many human populations because of their heavy reliance on ecosystem services (Bell et al., 1997; IPCC, 2022). This is particularly concerning for the most vulnerable people that are already disproportionately affected by climate change impacts (IPCC, 2022a).

Despite the significant impacts of climate change, the global response to the issue has been limited (IPCC, 2022a; IPCC, 2022b). Many countries have made commitments to reduce their GHG emissions, such as the Paris Agreement's target of "holding the increase in the global average temperature to well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5°C," (United Nations [UN], 2015: 3). To address the complex issue of climate change, it is important to reduce emissions, promote sustainable development, and develop inclusive policies. This will require a global effort, including the cooperation of governments, businesses, and individuals, to ensure that the impacts of climate change are limited, and the world is able to transition to a low-carbon future. While some progress has been made in reducing emissions and adapting to climate change, there is still much to be done to rapidly reduce GHG emissions this decade in order to hold global warming to 1.5°C or well below 2°C (IPCC, 2022b).

Solar Radiation Modification (SRM), also called 'solar geoengineering', is a proposed set of methods to limit the quantity of sunlight that reaches the Earth's surface to mitigate the effects of global warming (Robock et al., 2009). This is proposed to be achieved by increasing the proportion of insolation that is reflected back into space before it can reach the Earth's surface (Robock et al., 2009). In the context of slow action on reducing GHG emissions, SRM is gaining increasing attention because of its potential to rapidly reduce the rising temperatures of the Earth and other associated impacts like sea level rise (Irvine et al., 2009). However, SRM also presents a number of challenges and potential consequences that must be carefully examined, such as the risk of precipitation reduction (Irvine et al., 2016; MacMartin, Ricke & Keith, 2018; Robock, Oman & Stenchikov, 2008), the risks to ecosystems and people (Trisos et al., 2018a; Carlson et al., 2022) and various ethical issues (Svoboda & Irvine, 2014). Stratospheric aerosol injection (SAI) is the most studied form of SRM and proposes injecting reflective sulphate aerosols into the stratosphere to reflect sunlight back into space (Robock et al., 2009). Although the relationship between SRM and climate variables, such as temperature and precipitation, has been relatively well explored in the SRM literature, there remains a large gap in the literature surrounding the potential effects of SRM on biodiversity (Trisos et al., 2018a). More research is required to inform decisions on SRM policy, considering whether SRM could reduce or increase risks to global biodiversity.

Here, I investigated where and when species would be exposed to potentially unsafe temperature conditions beyond their thermal niche limits under a SAI scenario and compared this to an intermediate-emissions scenario. To my knowledge, this is the first global analysis on the potential of SRM, more specifically SAI, to reduce species exposure to climate change on land. The main goal here is to inform policy and decision-making regarding SRM by providing an analysis of whether SRM approaches like SAI could reduce climate change risks to biodiversity and how this compares to mitigation efforts consistent with an intermediate emissions scenario.

1.2. Aim and Objectives

The aim of this study is to conduct the first global assessment of how SRM, specifically SAI, could reduce risks to terrestrial land vertebrates.

The objectives of this study are to:

1) Quantify how SAI deployment could influence the temporal dynamics of exposure to potentially unsafe temperatures for terrestrial vertebrates (26,572 species) up to the year 2100.
2) Compare the results against those obtained using an intermediate-emissions scenario to assess where and when risks to biodiversity would be higher or lower under SAI deployment compared to an intermediate level of mitigation effort.

1.3. Research questions

1) What are the potential risks to biodiversity from SAI?
2) Can **G6sulfur** reduce exposure to potentially unsafe temperatures for over 26,000 terrestrial vertebrates compared to an intermediate level of mitigation effort?

1.4. Limitations to the study

The results presented in this study consist of only one SRM scenario, **G6sulfur**. In addition, I only investigated the potential effects of SRM on temperature. Other environmental parameters like precipitation were not analysed due to time constraints. Moreover, my study focussed on terrestrial vertebrates and did not include marine species. I did not include high emissions scenario SSP5-8.5 in my analyses due to time constraints and because it was assumed that species exposure levels would be higher under SSP5-8.5. The main goal of this study was not to compare G6sulfur with SSP5-8.5, but rather how it compares to SSP2-4.5.

1.5. Dissertation structure

The minor dissertation begins with an overall introduction to the study, covering the rationale, aim and objectives, research questions and limitations of the research. Chapter two consists of an overview of the relevant literature that explores why interventions like SRM are gaining relevance, specific SRM methods like SAI, the potential benefits and risks of SRM, the effects of climate change on biodiversity and the limited knowledge surrounding the possible risks of SRM to biodiversity. Chapter three describes the methods used in this study and explains how

I obtained historical climate data and biodiversity data to estimate species' realised thermal niche limits and estimate exposure to potentially unsafe temperatures. Chapter four presents the results of the study. Chapter five discusses the possible implications of my findings within the context of relevant literature. The minor dissertation concludes with Chapter six, which provides an overall conclusion of the study and suggestions for future research.

Chapter 2: Literature Overview

2.1. Introduction

Internationally, there have been various commitments to reduce GHG emissions, as seen in the 2015 Paris Agreement (UN, 2015). However, for these targets to be met, or to achieve a 50% chance of preventing global warming of 2°C beyond pre-industrial levels, global carbon dioxide (CO_2) levels would need to decrease considerably by 2050 or go as far as to reach negative values by 2100 (Irvine et al., 2017). This level of reduction in emissions is regarded as unlikely by some, due to the current political turmoil surrounding climate negotiations. With current pledges from governments we are headed towards a 1.4°C (very low-emissions scenario SSP1-1.9), 2.7°C (intermediate-emissions scenario SSP2-4.5) or potentially 4.4°C (very high emissions scenario SSP5-8.5) warmer world by 2100 (IPCC, 2023).

Climate change is exacerbating the frequency and intensity of extreme events, such as drought and flooding, through changes to highly variable El Niño phenomena, sea level rise, precipitation patterns, and land and ocean surface temperatures that all will impact both human and natural systems (IPCC, 2021; IPCC, 2022a; Sintayehu, 2018). Warming temperatures have not only had widespread repercussions on the overall structure and functioning of ecosystems but also on their resilience and natural capacity to adapt. Species have been experiencing alterations to reproduction, migration patterns, ranges and population dynamics, especially in tropical and polar regions (IPCC, 2022a). Not only will these changes have profound effects on biodiversity, but losses and damages to ecosystems incurred from climate change will have a direct impact on human livelihoods by reducing food and water security and causing dire socioeconomic consequences (IPCC, 2022a).

The latest Intergovernmental Panel on Climate Change (IPCC) Synthesis Report states there is "a rapidly closing window of opportunity to secure a liveable and sustainable future for all" (IPCC, 2023: 25). This sense of urgency, combined with the lack of progress in current mitigation efforts, and the increasing possibility of severe impacts despite these efforts, has motivated debate on the potential for using SRM as a possible complement to existing measures to alleviate the impacts of climate change (Irvine et al., 2017; MacMartin, Ricke & Keith, 2018). However, the extent to which SRM could be helpful or harmful is still not clear. Therefore, more research is required to explore the different possibilities of SRM and the associated benefits and risks before any decisions can be made.

2.2. Solar Radiation Modification (SRM)

Geoengineering can be defined as the “deliberate large-scale manipulation of the planetary environment to counteract anthropogenic climate change” (Shepherd et al., 2009: 1). SRM is a type of climate geoengineering that is characterised by reflecting sunlight back into space in an effort to limit or reduce the effects of climate change (Robock et al., 2009). One of the most studied and economically viable methods to do so is SAI, whereby megatons of sulphate or other aerosol particles are injected into the stratosphere and reflect sunlight back into space (Irvine et al., 2017; MacMartin, Ricke & Keith, 2018; Robock et al., 2009). Climate model simulations have demonstrated that SRM approaches may be able to partially counterbalance the temperature and precipitation changes and therefore reduce climate hazards (Russell et al., 2012). However, deploying SRM before we thoroughly understand the most efficient way to do so could pose serious environmental risks that we are not yet fully aware of (Trisos et al., 2018a). This is making it increasingly important to explore how these types of climate interventions may affect biodiversity, specifically how different species vary in terms of when their local climate niche boundaries may be reached.

Carbon Dioxide Removal (CDR) is another climate intervention besides SRM that has been explored as a potential method of removing CO2 directly from the atmosphere to lessen the greenhouse effect (IPCC, 2022b; Kravitz et al., 2016; Russel et al., 2012; Shepherd et al., 2009). Not only would CDR directly address rising CO2 from GHG emissions, but it would also confront associated CO2-induced ecological effects, like ocean acidification, if used in conjunction with other mitigation strategies (Russel et al., 2012). The term refers to anthropogenic activities, like afforestation, reforestation and soil carbon sequestration that remove CO2 from the atmosphere and permanently store it in terrestrial, ocean, or geological reservoirs, or in products (IPCC, 2022b). If CDR could be implemented on a wide scale and be economically viable, it may be a good concept with lasting effects, however, it would not happen immediately (Zarnetske et al., 2019). Hence, SRM is a newer technique that is being proposed for its ability to rapidly cool Earth on a shorter time scale. However, it also carries a number of risks and concerns and would require continuous deployment. No current practical SRM technique can restore both temperature and precipitation to a pre-industrial condition due to the trade-offs in SRM effects on both variables (Kravitz et al., 2016).

A wide variety of SRM options are being investigated, such as enhancing land surface reflectibility by increasing the brightness of urban spaces by painting roofs white (Oleson et al.,

2010) and planting highly reflective crops (Akbari, Menon & Rosenfeld, 2009). Other approaches include marine cloud brightening that enhances reflectiveness over the marine boundary layer by increasing the quantity of evaporated salt particles over the ocean to prompt condensation (Latham, 1990; Latham et al., 2008) and reducing the amount of insolation by constructing mirrors in space (Angel, 2006). However, it is doubtful that these interventions would be as successful as SAI in reducing global temperatures (National Research Council, 2015). SAI involves injecting reflective sulphate aerosols into the stratosphere to mimic volcanic eruptions (Crutzen, 2006; Wigley, 2006), and remains the most widely researched SRM proposal (Robock et al., 2009).

2.2.1. Stratospheric Aerosol Injection (SAI)

The concept of SAI was first conceived by Budyko (1974) and has since gained global research attention. The potential effectiveness of SAI is illustrated by large tropical volcanic eruptions, which provide a natural but imperfect example of geoengineering the climate (Rasch et al., 2008; Robock et al., 2009; Robock, 2000). The eruption of Mt. Pinatubo in 1991 has been used as a baseline for many studies, whereby 1.5 to 20 million tonnes of sulphur dioxide (SO_2) gas particles were ejected into the stratosphere, condensing into a cloud that reflected sunlight back into space. This decreased the global mean surface temperature by approximately 0.3°C to 0.5°C globally over a period of two years (Soden et al., 2002). However, SAI involves the continuous injection of aerosol particles, usually SO_2, into the lower stratosphere to promote a decrease in global temperature, which differs from the natural process of aerosols departing the stratosphere in the years following a volcanic eruption (Kravitz et al., 2011; Rasch et al., 2008; Robock, 2000). Simulations have been carried out to investigate the efficiency of this method and the lifespan of the resulting aerosol particles would range from one to three years, depending on their size (Kravitz et al., 2011).

With SAI, there are many adjacent factors that could influence decision-making. Design decisions like the location, timing and quantity of aerosol injection will have a significant influence (Irvine et al., 2017; Robock, 2020). Aerosols in the stratosphere reflect and absorb sunlight, warming and modifying water vapour concentrations and stratospheric dynamics, which in turn affect surface temperature and interfere with stratospheric ozone chemistry (Tilmes, Muller & Salawitch, 2008). Aerosol dynamics under SAI are likely to lead to the increased depletion of the ozone layer, which will ultimately increase the amount of incoming solar radiation and have both human and ecological effects (Blaustein et al, 1994; Madronich &

de Gruijl, 1994). While sulphate is frequently proposed for use in SAI, other aerosols may be used that have less impact on stratospheric dynamics and heating or could change the dynamics of the effect on ozone (Irvine et al., 2017; Reynolds, 2014).

Irvine et al. (2017) found that the most efficient way to distribute the aerosol layer globally and obtain the most uniform distribution of radiative forcing would be to inject particles into the equatorial stratosphere at a height of approximately 20 km, which has since been updated to between 16 and 25 km (United Nations Environment Programme [UNEP], 2023). If it is assumed that pre-industrial CO_2 concentrations doubled, initial calculations suggest that injecting 3 to 5 million tonnes of SO_2 annually would be adequate to counteract warming. However, the growth of aerosol particles would necessitate 90 million tonnes of SO_2 annually to offset GHG emissions under an RCP4.5 scenario by 2100 (Niemeier & Timmreck, 2015). This would equate to 5 to 7 eruptions of Mt. Pinatubo each year (Niemeier & Timmreck, 2015; Robock, 2009). Currently, the most practical method that is being investigated for delivering aerosols is high-altitude aircraft (Robock, 2009; Robock, 2020). This type of deployment is considered reasonably affordable and is significantly less costly than the predicted cost of decarbonising the global economy through conventional mitigation methods (Robock, 2009; Trisos et al., 2018b).

In order for decision-makers to reach an informed consensus regarding the deployment of any type of SRM, a determination of the most accurate estimate of the climatic response and associated human and ecological implications of various deployment options would be advised (Irvine et al., 2017). In addition, socio-political repercussions, including expected governance, should be evaluated as this remains a significant challenge. The majority of research to date has been on the physical and climatic effects of SRM, such as changes in temperature, precipitation, and coverage of sea ice (Field et al., 2018; MacMartin, Ricke & Keith, 2018; Trenberth & Dai, 2007). However, any conclusion on the use of SRM would ultimately depend on how the technology would affect both natural and social systems (Irvine et al., 2017).

2.3. Potential benefits and risks from SRM

The potential for SRM to rapidly reduce global warming has been acknowledged (IPCC, 2022a; UNEP, 2023). This is crucial given the pressing need to address the effects of climate change. Reduced surface air temperatures from SRM may mitigate or even reverse some of the harmful effects of global warming, such as sea ice melting, sea level rise, extreme storm events, flooding, and drought (Trisos et al., 2018b; Robock et al., 2009). While it is fair to assume SRM as separate from geoengineering approaches that directly address carbon, such as CDR, more comprehensive research is needed to understand how SRM could potentially benefit the carbon cycle by lowering the carbon burden (Keith, Wagner & Zabel, 2017).

In addition, SRM methods may result in enhanced primary productivity in the oceans and on land and can provide a greater terrestrial sink for CO_2 (Robock et al., 2009). This could lead to enhanced plant productivity and hence favourable agricultural outputs, as crop yields are estimated to be higher compared to the effects of global warming (Pongratz et al., 2012). Coral reefs and other sensitive ecosystems could be subjected to less heat stress and there may be decreased overall heat-related deaths among human and ecological populations (Robock et al., 2009). As previously mentioned, SRM is comparatively less expensive than other strategies for lowering GHG emissions, and can therefore be a desirable choice for nations with few resources (Robock et al., 2009). However, its affordability, combined with the apparent lack of a coherent global climate regulatory framework, could also lead to unilateral SRM deployment from those countries that stand to benefit (Trisos et al., 2018a; UNEP, 2023). This may cause conflict between nations that could ultimately lead to the failure of SRM, and negative consequences that could culminate in its immediate termination (Trisos et al., 2018a).

Although UNEP (2023) supports that current climate models indicate that SRM ameliorates some of the effects of GHG emissions both regionally and globally, they also consider that significant residual warming, or overcompensated cooling, may occur at a regional scale. This is further highlighted by the Intergovernmental Panel on Climate Change (IPCC) who state that: "Solar radiation modification (SRM) approaches have the potential to offset warming and ameliorate other climate hazards, but their potential to reduce risk or introduce novel risks to people and ecosystems is not well understood," (IPCC, 2022c: 69).

Simply said, the global mean temperature serves as a baseline for many different climate impacts. It is conceivable that SRM may achieve a temperature target without successfully lowering many of the specific climate risks that constitute any such global temperature target's implicit objective (UNEP, 2023). Even if SRM was able to significantly alleviate numerous climatic risks, the existing understanding of the response and effects of climate change is insufficient to support a well informed decision. In addition, there are ethical concerns, which include questions around compensation and socio-political risks such as governance challenges, the likelihood of conflict, and the possibility that the deployment of SRM will affect the commitment to mitigation (Svoboda & Irvine, 2014, Robock et al., 2020). A "quick fix" option like SRM may deter people from developing and implementing long-term sustainable alternatives to minimise GHG emissions, which might encourage the continuous use of fossil fuels and other destructive activities (UNEP, 2023; Robock, 2020).

Another cause for concern is the potential for tropical aerosol injection to result in an overcooling of the tropics and an undercooling of the poles (MacMartin, Ricke & Keith, 2018). This would have adverse effects such as a shift in temperature gradients that would cause changes to the mid-latitude storm track (MacMartin, Ricke & Keith, 2018; UNEP, 2023). UNEP (2023) suggests that these risks could be minimised by using SAI methods that operate across multiple latitudes. Irvine et al. (2017) further highlight that it would be possible to reduce changes in the intertropical convergence zone and its effects on tropical precipitation by adjusting the injection quantity independently in each hemisphere. However, although this may reduce risks to the climate system, impacts on people and ecosystems attributable to residual warming and overcompensation of cooling from SAI are likely to remain (UNEP, 2023). Moreover, SAI could possibly interfere with parts of the climate system that govern climate variability, such as ENSO, the North Atlantic Oscillation (NAO), Quasi-biennial oscillation (QBO), polar vortex and Brewer-Dobson Circulation (BDC) (UNEP, 2023). For instance, the high reflectivity associated with SAI could contribute to increased precipitation and flooding in Northern Europe and drought over parts of the Mediterranean by enhancing the positive phase of the NAO (UNEP, 2023).

An aspect that has been considered is the potential impact of SRM on the hydrological cycle (Lunt et al., 2008; Niemeier et al., 2013). Trenberth and Dai (2007) suggest that when comparing SRM to volcanic eruptions, a slowing of the hydrological cycle, and consequently precipitation, can be observed. This is concerning against the current backdrop of increases in CO_2, that result in a decrease in transpiration and a consequent reduction in precipitation (MacMartin, Ricke & Keith, 2018). By reducing solar radiation and cooling the planet through SRM methods, global mean precipitation could be reduced for a given global mean temperature in comparison to achieving the same temperature through mitigation alone. Therefore, restoring temperatures to pre-industrial levels through SRM could possibly overcompensate for precipitation and not reflect the best risk-benefit analysis (MacMartin, Ricke & Keith, 2018). However, Irvine, Ridgwell and Lunt (2010) suggest that there would be significant regional variation in how temperature and precipitation would respond to SRM, highlighting the need for more in-depth regional studies.

SRM would need to work in conjunction with conventional mitigation, as it would not individually tackle atmospheric CO_2 concentrations and the associated impacts, such as ocean acidification or changes to plant productivity and drought tolerance (Irvine et al., 2017; Rasch et al., 2008; Robock et al., 2009). Ocean acidification has previously been identified as a risk from SRM (Keith, Wagner & Zabel, 2017) but it is nearly entirely dependent on cumulative CO_2 emissions and, given that SRM has no direct impact on cumulative emissions, the major potential impact of SRM on ocean acidification would be if SRM is intended to replace emissions reduction, whereby the risk would come from the rise in emissions rather than SRM itself (Keith & MacMartin, 2015).

SRM's inability to reverse the effects generated by rising GHG emissions can also be seen as a risk in its own right (Svoboda & Irvine, 2014). SRM is generally not seen as climate change adaptation because the suggested methods aim to reduce the effects of climate change on human and natural systems rather than mobilising them to adapt to rising temperatures (Trisos et al., 2018b). It has therefore been suggested that SRM be employed together with other mitigation, adaptation, and CDR initiatives or simply be utilised as a transition tool to acquire more time for these methods to function adequately (Trisos et al., 2018b).

There has been very little attention paid to the potential impacts of SRM on natural and human systems (Horton & Keith, 2016; Irvine et al., 2017). There is limited literature on the potential impacts of SRM on terrestrial ecosystems, flood risk, fisheries, storm damage, and vector borne diseases, among others (Irvine et al., 2017). This exposes a definite need for climate impact assessments that cover a variety of SRM deployment scenarios, which is especially relevant for developing countries that are disproportionately vulnerable to climate change impacts (Irvine et al., 2017; MacMartin, Ricke & Keith, 2018).

2.4. SRM and developing countries

Despite their historically lower contributions to GHG emissions, developing countries have been the most disproportionately affected by climate change impacts (IPCC, 2022a; Rahman et al., 2018). This is even more concerning within the context of forthcoming global CO_2 emissions, which will be primarily determined by the developing world as they have experienced rapid growth in emissions over recent decades and now account for 63.4% of total global emissions (Jiang, Ye & Liu, 2019). The IPCC is anticipating impacts on small island states from sea-level rise (Nurse et al., 2014), great losses to biodiversity in South America (Magrin et al., 2014), and intense water stress across the African continent (Niang et al., 2014).

Not only will climate change and its compounding impacts disproportionately affect developing countries, but low-income and marginalised groups in every nation will be the most vulnerable to these effects (IPCC, 2022a). This is in part due to more limited access to resources and basic services when compared to wealthier groups, with the largest adaptation gaps among low income groups (Horton & Keith, 2016; IPCC, 2022a; Mertz et al., 2009). With an increase in the frequency and intensity of climate change-induced heat waves, low-income and marginalised groups are likely to be more vulnerable to the effects of drought. Many staple crop yields are likely to decrease under a drier climate, which will likely exacerbate food insecurity and have disastrous impacts on the economies of many developing countries that rely on agricultural contributions (Horton & Keith, 2016; Mertz et al., 2009). Moreover, since they have the least ability to migrate from the coast, low-income and marginalised groups in these areas are likely to be disproportionately affected by rising sea levels (Horton & Keith, 2016).

In the literature, SRM has received both positive and negative responses concerning how it will affect developing countries (Rahman et al., 2018). It has been suggested that the local impacts resulting from SRM will not only benefit these countries but will have a positive ripple effect on a global scale (Horton & Keith, 2016). Moreover, modelling studies suggest that SRM, if used in moderation, might mitigate many of the worst climate change hazards for developing nations and vulnerable groups (Reynolds, 2014). Yet, there are probably limits to how much cooling may be accomplished, particularly in scenarios with significant GHG emissions (Rahman et al., 2018).

There are also arguments against SRM, whereby similar to how climate change impacts will disproportionately affect developing countries and low-income and marginalised groups, SRM risks would also manifest in the same way (Horton & Keith, 2016). Essentially, SRM has the potential to increase the benefits for some, for example, by reducing sea level rise and extreme heat waves (IPCC, 2022a; Robock et al., 2009) while simultaneously increasing the risk for others through decreases in precipitation that leads to drought and directly affects agricultural production (Pongratz et al., 2012).

More research on SRM is needed to understand the benefits or risks as a potential tool of climate policy to complement mitigation and adaptation in the interest of developing countries (Horton & Keith, 2016; Rahman et al., 2018; Svoboda & Irvine, 2014). An essential part of continued SRM research needs to include developing countries and the most vulnerable at the centre of the conversation, which is not the current reality (Rahman et al., 2018; UNEP, 2023).

2.5. Climate change and biodiversity

Biodiversity is collectively known as "all of the plants, animals, fungi, and microorganisms on Earth; their genetic and phenotypic variation; and the communities and ecosystems of which they are a part," (Dirzo & Raven, 2003: 138). The importance of biodiversity is demonstrated in the ecological services it provides to both human and natural populations, including nutrient cycling, the regulation of climate and water cycles, and food production (Millennium Ecosystem Assessment [MEA], 2005; Newbold et al., 2019; Ohashi et al., 2019; Pereira, Navarro & Martins, 2012). However, the efficiency with which ecosystems acquire vital biological resources, generate biomass, decompose, and recycle biologically important nutrients is being threatened by biodiversity loss that is occurring at an unprecedented rate (Cardinale et al., 2012; IPCC, 2022a; MEA, 2005; Mooney et al., 2009). This is concerning because the stress of climate change on biodiversity is anticipated to intensify quickly in the coming years (IPCC, 2022a).

As the global temperature increases, which it has by 1.1°C since 1880, biodiversity loss is occurring on all levels, from the individual organism to entire ecosystems (Bellard et al., 2012). Species are faced with the choice to either migrate, adapt or face possible extinction (Pecl et al., 2017). The current trajectory of extinction is higher than the background natural rate of extinction, making it vital to understand the drivers of climate change-induced extinction and species' responses to this threat (Urban, 2015). This will help to inform international policy and the implementation of various conservation strategies (Urban, 2015). Although there is a current lack of consistent global estimates, studies have shown that 7.9% (Urban, 2015) or between 16-30% (Roman-Palacios & Wiens, 2020) of species may face extinction from climate change. Roman-Palacios and Wiens (2020) found that extinctions transpire at locations where the hottest annual temperatures increased more rapidly than the mean annual temperature. Although precipitation did not have as much of an influence as temperature, local extinctions were more likely in regions with a decreasing precipitation trend (Roman-Palacios & Wiens, 2020).

Historically, a species’ predominant response to a changing climate has been a change in range in order to escape an increasingly warming environment and return to favourable conditions (Bell et al., 1997; Pecl et al., 2017). Indeed, further adaptations including genetic adaptation, phenotypic plasticity, adjustments to microhabitat and altered phenology will likely take place (Scheffers et al., 2016). Several organisms have exhibited temperature-driven plasticity attributes, which allow them to acclimate to higher temperatures and therefore, maximise fitness. However, other responses have indicated an incapacity to cope with temperature changes and other climate-induced impacts (Scheffers et al., 2016). Although it has been suggested that populations may be granted more time to adapt via plasticity, it remains unclear if this will be sufficient given how quickly the environment is changing (Fox et al., 2019). We cannot presume that plasticity would be a more efficient adaptation approach than evolution merely because it operates at the individual level (Fox et al., 2019). Either evolution, plasticity, or a combination of both, may result in population recovery and persistence, depending on the kind and rate of environmental change (Fox et al., 2019).

However, there are limits to each species' capacity to adapt, and for those already encountering increasing temperatures that are close to their threshold capacity, these limits are not very likely to increase (Newbold et al., 2019; Pecl et al., 2017; Reside, Butt & Adams, 2017). Because each species’ is different and additionally differ in their responses to change, there is often a disturbance of crucial interactions between them, thus causing entirely new interactions to transpire as a result (Reside, Butt & Adams, 2017; Scheffers et al., 2016).

Regions characteristic of having the strongest climate drivers, the most vulnerable species, and human populations with the lowest responsive capacity will be the most disadvantaged by species range shifts (Pecl et al., 2017). This is significant because the most susceptible species to extinction are often located in regions with constrained climatic ranges, specific habitat needs, and/or small populations, such as endemic mountain species and biota confined to islands (IPCC, 2022a). Developing nations nearing the equator will be severely affected and range shifts are likely to prompt local extinctions (Pecl et al., 2017). Consequently, these factors are also more likely to bring about dire economic constraints and conflict and cause a variety of challenges to development and sustainability (Pecl et al., 2017).

Throughout history, humans have altered ecosystems to increase food production and reduce ecological competition (Pereira et al., 2012). However, the manner in which climate change is indirectly affecting food webs is expected to translate directly onto crop production (Trisos et al., 2018b; Pecl et al., 2017). The decline in the abundance and distribution of species that would originally aid in the removal of pests has had severe consequences for the economy of some European states, especially those that rely heavily on agricultural contributions (Pecl et al., 2017). Many of the negative effects that arise from a shift in natural resources tend to disproportionately affect developing countries. These changes can have profound effects on culture and society with indirect costs to food security, systems of traditional knowledge and indigenous societies (Pecl et al., 2017).

For a significant majority of the species reviewed for the International Union for Conservation of Nature (IUCN) Red List, degradation and loss of habitat have been recognised as noteworthy risks (IUCN, 2023). Anthropogenic activity has continuously contributed towards biodiversity loss through alterations to land use/land cover, the deterioration and pollution of soil, water, and air, the fragmentation of habitat, species loss, the introduction of alien species, and stratospheric ozone depletion (IPCC, 2022a; Newbold et al., 2019; Wilson, 1989). At present, the primary cause of biodiversity loss is the extinction of species resulting from direct disturbances, such as the widespread clearing of tropical forests for agriculture (Brook, Sodhi & Bradshaw, 2008). Although these threats may not culminate in extinction right away, the resultant secondary processes and feedbacks could lead to eventual extinction (Brook, Sodhi & Bradshaw, 2008). Extinctions that occur at the local level do not always result in global extinctions. This is significant because local extinctions are surprisingly higher than global extinctions (Bellard et al., 2012). These global estimates do, nonetheless, indicate significant losses to future biodiversity that are driven by climate change and are generally greater than current rates of loss (IPCC, 2022a).

Studies indicate that over the next few decades, climate change may surpass habitat degradation as the greatest threat to biodiversity worldwide, despite the minimal evidence that supports current extinctions being initiated by climate change (Bellard et al., 2012; World Wildlife Fund [WWF], 2022). According to global forecasts, the aggregated effects of both climate change and land use may cause the average biological community to lose up to 38% of its species, which will likely be exacerbated by the rapidly expanding human population, which is anticipated to total 9 billion by 2050 (Newbold et al., 2019; Robock et al., 2009). Projections estimate that the typical community will lose 17% of its species as a result of future land use development, while the Amazon and Afrotropical regions would experience a 30% reduction in species abundance (Newbold et al., 2019). Therefore, it has been vital to assess our knowledge of how climate change affects biodiversity and possible future repercussions using models (Bellard et al., 2012). However, these effects can only be partially quantified because the data and models required to estimate the magnitude and complexity of upcoming ecological changes, and changes in species' geographic distribution, are insufficient (Bellard et al., 2012; Sequeira et al., 2018).

2.6. Biodiversity and SRM

Although SRM has received greater research attention on its potential climatic impacts, there are very few assessments covering the potential ecological impacts of SRM, particularly on biodiversity and ecosystems (Trisos et al., 2018a). To comprehend how prospective deployment can change the composition and functioning of the biosphere on Earth, influencing biodiversity, ecosystem processes, and humanity, it is crucial to close this gap (Zarnetske et al., 2019). However, the lack of historical precedents makes it difficult to extrapolate ecological effects, and new issues regarding possible responses from species and ecosystems are raised. The effects and consequences of SRM would largely depend on the deployment scenario, the effects of climate change, the geographical region, and the individual ecosystem, community, population, and organism. Responses to SRM would be further influenced by existing complex relations between Earth's climate and biotic systems (Zarnetske et al., 2019).

Climate change is already having a significant influence over various ecological drivers, such as temperature and precipitation, which is likely to exacerbate if we fail to mitigate the current rise in temperatures. However, although its numerous direct outcomes and unforeseen repercussions on Earth's climate have been explored (Robock et al., 2009; Robock, 2020), SRM schemes like SAI could also alter important climate variables that ecosystems depend on. Potential effects to UV radiation (Ballaré et al., 2011; Madronich et al., 2018), the relationship between temperature and CO_2 (Keenan et al., 2013) and precipitation (Robock, Oman & Stenchikov, 2008) need more research. Using the Mt Pinatubo eruption as an illustration, Gu et al. (2003) indicated that photosynthesis and CO_2 uptake could be enhanced by the increase in diffuse radiation caused by volcanic aerosols. However, it still remains highly ambiguous about whether ecosystems would suffer from increases in diffuse energy or UV radiation, highlighting that more research on the dynamics between SAI deployment and ecosystems is necessary (Rasch et al., 2008). Moreover, although climate models can reveal particular global metrics, there are also predicted regional effects that need more attention (Zarnetske et al., 2019).

The deployment of SAI could result in various ecological implications, including changes to species numbers and locations, population dynamics and ecosystem functioning (Zarnetske et al., 2019). This could also lead to the introduction of entirely new ecosystems and communities in response to novel climates (Scheffers et al., 2016; Williams & Jackson, 2007). These factors need to be compared against those generated by climate change-induced GHG emissions. The specific ecological impacts of SAI would probably differ from those of GHGs since SAI has distinct physical effects (reductions in incoming shortwave radiation and cooling) opposed to those produced by GHGs (warming, ocean acidification, and photosynthesis intensification) (Zarnetske et al., 2019). Although responses are likely to vary, SAI would still have an impact on similar ecological processes that are currently responsive to climate change (Zarnetske et al., 2019).

When assessing the climatic implications of SRM, it is important to note that climate change hazards are likely to change. However, they still need to be considered despite not immediately influencing the vulnerability of both human and ecological populations. Biodiverse-rich tropical coral reefs are extremely vulnerable to climate change, which has caused a significant increase in coral bleaching and subsequent mortality from rising ocean temperatures (Kwiatkowski et al., 2015; Pereira, Navarro & Martins, 2012). Kwiatkowski et al. (2015) found that although SRM could potentially reduce the risk to coral bleaching on a global scale when stabilising radiative forcing at 2020 levels relative to RCP2.6, the resulting tropical cooling would lead to increases in other risks to coral, such as ocean acidification. Intensive mitigation under RCP2.6 would be more beneficial because, unlike SRM, it would be able to address ocean acidification impacts. This highlights that there is certainly a need for more large-scale research on how SRM could potentially affect the biodiversity of other marine and terrestrial ecosystems.

While there is some research on the possible impacts of SRM on vegetation (Dagon & Schrag, 2019) and photosynthesis (Xia et al., 2016), minimal research has explored the potential impacts of SRM on biodiversity (Robock et al., 2009). The question of whether SRM could reduce impacts relative to current climate change or push ecological systems into novel territories therefore remains (Zarnetske et al., 2019). Trisos et al. (2018a) is one of the only existing studies to assess the potential effects of SRM to biodiversity through its sudden implementation or abrupt termination. After obtaining climate velocities, or the speeds and directions that species would need to migrate in order to remain within their climate niche, it was found that in the event of abrupt termination, species would lack the dispersal speeds necessary to avoid climate change risk. In comparison to a world without SRM, this would result in increased local extinction risk to marine and terrestrial biodiversity hotspots (Trisos et al., 2018a).

If SRM techniques like SAI were to be executed, ecological systems would likely reorganise into diverse forms at varying rates, given that entire food webs are currently transforming due to climate change (Urban, Zarnetske & Skelly, 2017). Research could concentrate on areas and taxa that may be particularly vulnerable to SAI. For instance, because of their trophic positions, many top consumers, keystone species, and producers are anticipated to have disproportionate effects on ecosystems attributable to climate change (Urban, Zarnetske & Skelly, 2017). The polar regions, which are already warming rapidly, might serve as focal locations in addition to forests and oceans, which would be particularly affected by increases in temperature and CO_2 (Zarnetske et al., 2019). Shifts in water supply, through the amount and seasonal distribution of rainfall, and demand, through changes to transpiration and evaporation, from SAI are expected to transform the biogeography of the tropics, specifically tropical forests (Zarnetske et al., 2019). Because tropical forests cycle the most carbon and water compared to any other biome (Beer et al., 2010), a change in vegetative biogeography prompted by SAI could have a significant impact on large-scale nutrient cycles. Moreover, this could have direct feedbacks on climate variability and change at both the regional and global scale, depending on the deployment scenario (Zarnetske et al., 2019).

2.7. Conclusion

Current mitigation policy remains insufficient to keep global warming below the 2°C long term temperature limit presented in the Paris Agreement. Furthermore, due to past global warming, biodiversity loss and degradation, as well as ecosystem alteration and harm are already occurring in every region, and the risks will only worsen as the temperature continues to increase (IPCC, 2022a).

Proposals to limit global warming like SRM are therefore gaining increasing attention. However, the potential of SRM approaches to reduce exposure of biodiversity to potentially dangerous temperatures induced by climate change remains largely unknown. Moreover, SRM will not be capable of reversing existing climate change or avoiding all future climate damage, highlighting that it should, at best, be a complement to mitigation strategies. Crutzen (2006), Wigley (2006), UNEP (2023), and others have stressed that mitigation and adaptation are the preferred ways to reduce risks from climate change and that SRM should only be considered if the earth faces a climate change emergency. Unfortunately, there are no existing global governance frameworks or norms that would make it possible to identify such an emergency (Robock et al., 2009). In order for decision-makers to reach an informed consensus regarding the deployment of any type of SRM, a determination of the most accurate estimate of the climatic response and associated human and ecological implications of various deployment scenarios would be advised (Irvine et al., 2017).

Chapter 3: Methods

3.1. Climate model data

To assess the potential of SRM in reducing species exposure I used temperature data from two scenarios: **G6sulfur** and SSP2-4.5. While SSP2-4.5 projects a world with intermediate levels of GHG emissions, **G6sulfur** simulations project a world which follows a very high emissions pathway (SSP5-8.5) where global warming levels are then reduced using SAI. The SAI deployment in **G6sulfur** is done in a way that the global warming levels under **G6sulfur** are intended to be similar to those in SSP2-4.5. Although **G6sulfur** is an idealised scenario, it offers a unique opportunity to compare the risks for biodiversity from the same or very similar global warming levels obtained through SAI or conventional mitigation. I obtained monthly mean temperature data for SSP2-4.5 from the Coupled Model Intercomparison Project Phase 6 (CMIP6) and monthly mean temperature data for **G6sulfur** from the Geoengineering Model Intercomparison Project (GeoMIP). Climate data was downloaded from https://esgf node.llnl.gov/search/cmip6/. I used a total of six climate models (CESM2, CNRM, IPSL, MPI ESM-1-2-HR, MPI-ESM-1-2-LR and UKESM1). For all models, I also obtained data from the historical run (1850-2014). I then extracted the historical and future climate data to an equal area 100 km x 100 km grid and calculated the mean annual temperature for each grid cell using the function *exact_extract* from the R package exactextractr 0.9.1 (Baston, 2022). This function extracts values accounting for the fraction of the cell covered by the data, providing a more accurate representation of the average value within each cell.

3.2. Biodiversity data

Range data for 26,572 terrestrial vertebrate species (amphibians, birds, mammals, and reptiles) was sourced from expert-verified geographic range maps from the IUCN (IUCN, 2017). I only used data from regions where the occurrence of the species was flagged as native or reintroduced. This range data was then transformed according to the 100 km x 100 km grid used to extract the climate data. This resolution is the most globally acceptable for these data without introducing false presences in species occurrence (Trisos, Merow & Pigot, 2020).

3.3. Species realised niche limits

I estimated the realised thermal niche limits of each species using geographical distributions and historical climate data. Specifically, I extracted the maximum of the mean annual temperatures that each species experienced across its range between 1850 to 2014. To avoid biases from climatic outliers or errors in distribution data, for each grid cell I calculated the mean and the standard deviation and then removed any values outside ±3 standard deviations (Meyer et al., 2022; Trisos, Merow & Pigot, 2020). After these outliers were excluded, I repeated the process using the resulting maximum mean annual temperature for all the cells across the species distribution range. Any values outside ±3 standard deviations were also excluded. The resulting maximum value was considered the species' realised niche limit (Trisos, Merow & Pigot, 2020).

3.4. Estimating species exposure

I estimated the exposure of species' to temperature conditions outside their realised niche limits by using the biodiversity climate horizons framework (Trisos, Merow & Pigot, 2020). This framework uses yearly climate projections and realised niche limits to estimate where, when, and how fast species will be exposed to potentially unsafe temperatures. By focusing on the temporal dynamics of exposure, the biodiversity climate horizons framework provides valuable near- and long-term information for comparing climate change risks to biodiversity across different scenarios. I classified a species as exposed when the future temperature in a grid cell exceeded the realised niche limit of the species for at least five consecutive years. I defined the time of exposure as the first year of the period where temperatures were projected to exceed the niche of the species. After species exposure was calculated, I constructed exposure profiles for species assemblages globally, considering each grid cell as an assemblage. The exposure profiles describe the cumulative number of species exposed to temperatures outside their niche limits over time.

From the exposure profiles, I extracted three metrics: magnitude, the percentage of species exposed from 2020 to 2100; timing, the median year of species' exposure; and abruptness, the percentage of species exposed in the decade of maximum exposure, which was identified using a moving ten-year window. To eliminate biases from species-poor assemblages, abruptness was only determined for assemblages in which five or more species were exposed. I also only mapped results from assemblages with five or more species exposed. Each species present in an assemblage was considered a population. The results reported are the median values across all six climate models.

To compare exposure levels between **G6sulfur** and intermediate-emissions pathway SSP2-4.5, I subtracted the magnitude, abruptness and timing estimates of SSP2-4.5 from **G6sulfur**. In addition, I calculated the number of species exposed per grid cell (i.e. the number of populations) in each country under SSP2–4.5 and **G6sulfur** in order to quantify country-level changes in risk from SRM deployment. Although I am not reporting data from assemblages with less than five species exposed, I included those assemblages when I calculated the exposure per country.

Analyses were carried out using the packages ncdf4 1.19 (Pierce 2021), raster 3-5.21 (Hijmans 2022), sf 1.0-12 (Pebesma 2018), and dplyr 1.1.0 (Wickham et al., 2023) in R version 4.2.2 (R Core Team, 2022).

Chapter 4: Results

4.1. Magnitude

In both SSP2-4.5 and **G6sulfur** the magnitude of exposure of species' to temperature conditions above their realised niche limits was greatest for tropical regions, specifically the tropical forests in South America, Central Africa, and Southeast Asia (Fig. 1a,b). A large portion of northern Brazil was projected to experience over 20% exposure, which was slightly higher under **G6sulfur** than SSP2-4.5 (Fig. 1a,b). Similarly, parts of the Democratic Republic of the Congo (DRC) were projected to experience over 20% exposure under both **G6sulfur** and SSP2- 4.5 but this rose to over 40% under **G6sulfur** (Fig. 1a). Some regions of South America had over 80% exposure, namely central Venezuela and parts of Brazil under both SSP2-4.5 and **G6sulfur** (Fig. 1a,b). Regions in Central America (Costa Rica, Panama, Cuba and Haiti), the Sahel region (Mali, Mauritania, Chad and Sudan) and northern Australia were projected to experience over 80% exposure under both scenarios (Fig. 1a,b). Exposure under SSP2-4.5 was slightly higher for the Sahel region, specifically Chad (Fig.1b). The majority of Southeast Asia, including Indonesia, Malaysia, Singapore and some smaller island regions were projected to experience over 80% exposure under **G6sulfur** and SSP2-4.5 (Fig. 1a,b).

Subtracting the magnitude of exposure for SSP2-4.5 from the magnitude for **G6sulfur** revealed where exposure was higher under **G6sulfur** or higher under SSP2-4.5 (Fig. 1c). In most tropical regions, exposure was higher under **G6sulfur** than SSP2–4.5. The northern parts of South America had a particularly high magnitude of exposure under **G6sulfur**. Specifically, assemblages in Peru and Brazil were projected to experience over 150 more species exposed locally, and in Ecuador, Columbia and Venezuela over 50 more species exposed. Central Africa, specifically the DRC, was also projected to experience high exposure under **G6sulfur**. Although the majority of the region had over 50 more species exposed under **G6sulfur**, for some areas this reached over 150. Southeast Asia and northern Australia were also projected to have higher exposure under **G6sulfur**. However, exposure was higher under SSP2-4.5 compared to **G6sulfur** over India, adjacent regions in northern Australia and the Sahel region (Fig.1c). Chad was projected to have 150 more species exposed under SSP2-4.5 than under **G6sulfur**.

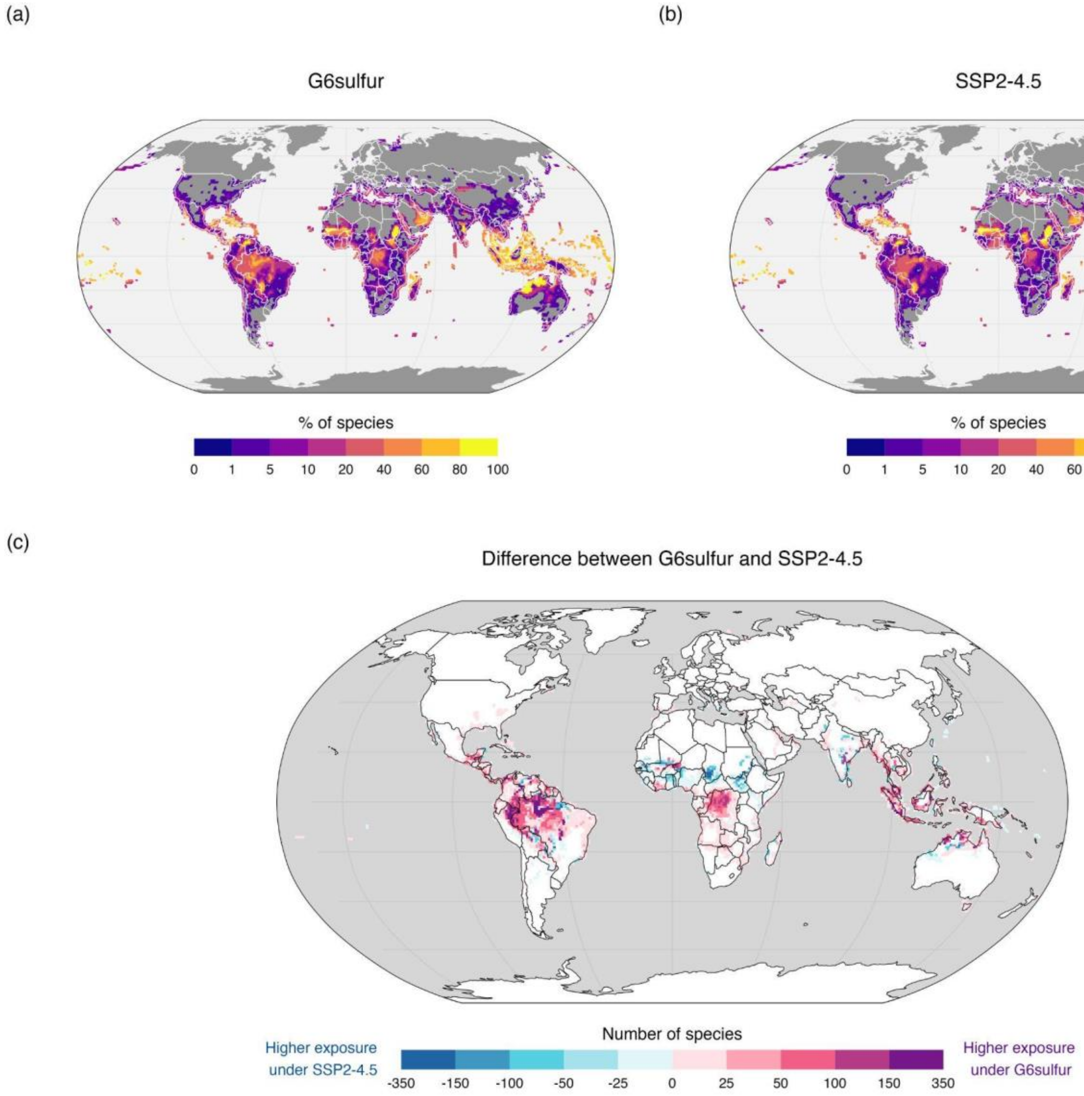


Figure 1: Magnitude of exposure to potentially unsafe temperatures for 26,572 terrestrial vertebrate species from 2020 to 2100. (**a**) Magnitude of exposure under intermediate-emissions scenario SSP2-4.5, (**b**) Magnitude of exposure under G6sulfur and (**c**) Magnitude of exposure calculated by subtracting SSP2-4.5 from G6sulfur to reveal where exposure was higher under G6sulfur or higher under SSP2-4.5. (**a**) and (**b**) represent percentages of species exposure and (**c**) is the number of species exposed in each grid cell. Positive values, or pink regions, show where exposure was higher for G6sulfur and negative values, or blue regions, show where exposure was higher under SSP2-4.5. Each species present in an assemblage was considered a population. Maps show data for grid cells with at least 5 species exposed. The results reported are the median values across all six climate models.

4.2. Cumulative exposure

The cumulative number of local populations was higher for **G6sulfur** with a total of 587,366 species populations exposed, while SSP2-4.5 experienced a total of 514,882 species populations exposed by the end of the century (Fig. 2).

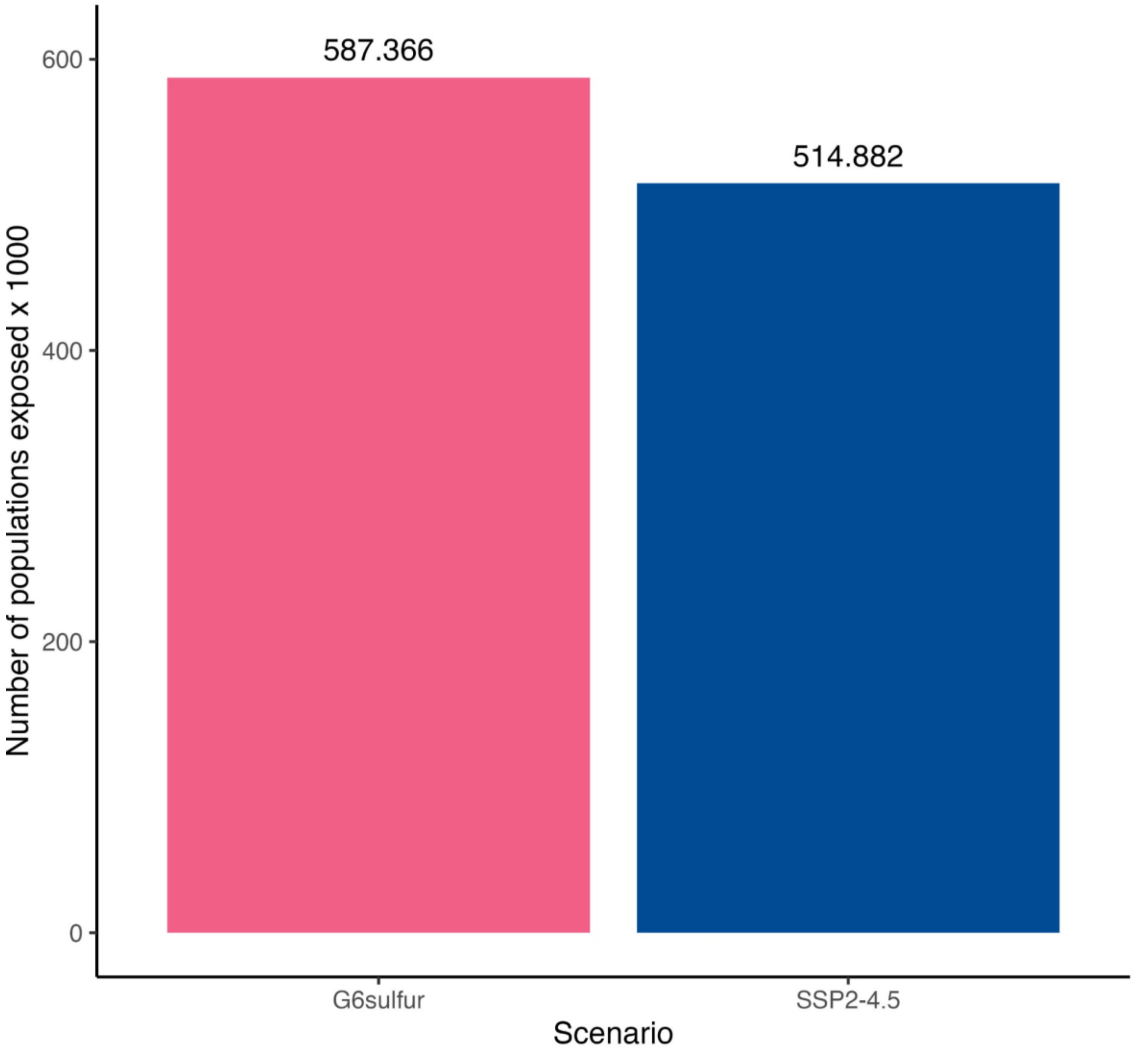
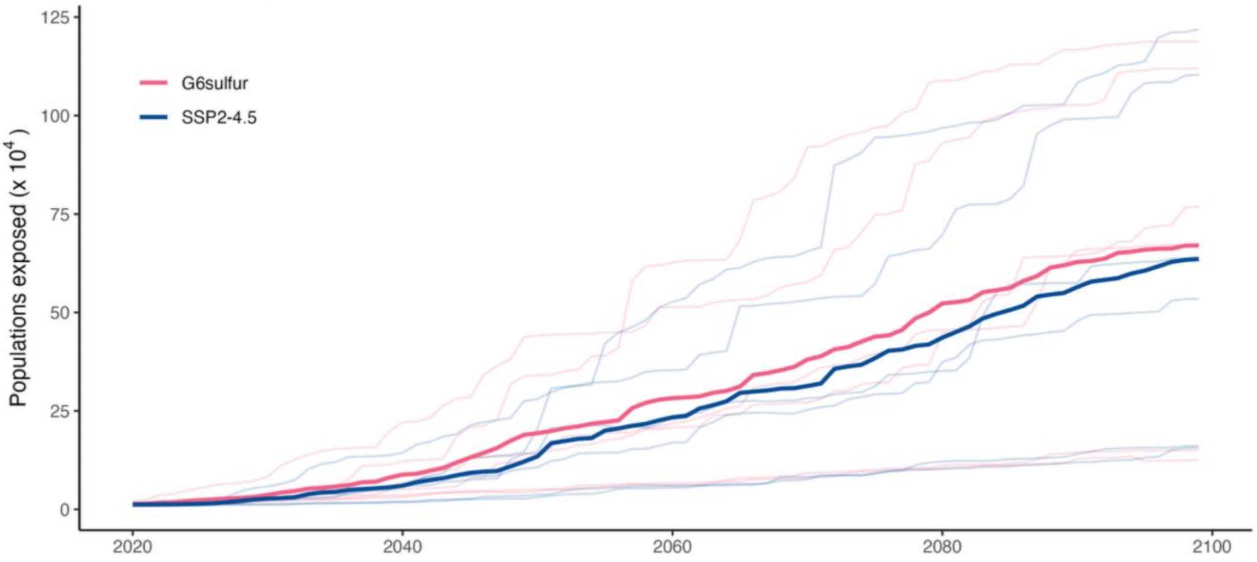


Figure 2: Total number of populations exposed from 2020 to 2100 for G6sulfur and SSP2-4.5.

Exposure under **G6sulfur** was higher than SSP2-4.5 over time (Fig. 3a). Although both scenarios experienced minimal exposure up until around 2040, exposure increased slightly earlier for **G6sulfur** and remained elevated from SSP2-4.5 until the end of the century. The global mean temperature was slightly higher under **G6sulfur** for the majority of the time period, reaching a median difference of 0.18 °C by the end of the century (Fig. 3b).

(a) Cummulative exposure



(b) Global mean temperature

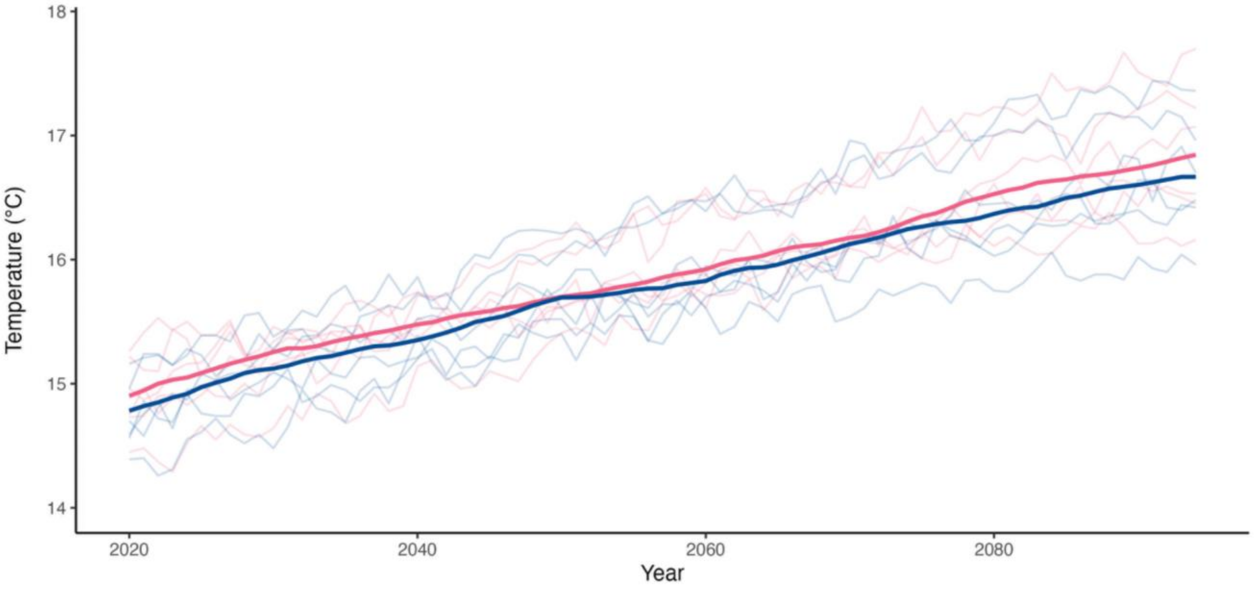


Figure 3: (**a**) Cumulative exposure of species populations from 2020 to 2100 for G6sulfur and SSP2-4.5 (top) and (**b**) global mean temperature (bottom). Thinner lines show individual simulation from the six climate models used in the study. Thicker lines show the median across all models. Global mean temperature was calculated using a ten-year moving window.

4.2. Timing

For both G6$_{\text{sulhpur}}$ and SSP2-4.5, the median timing of exposure for most locations was in the 2070s or later (Fig 4a,b). Exposure started slightly earlier for G6$_{\text{sulhpur}}$ than for SSP2-4.5, whereby the median year of exposure was 2076 for the former and 2079 for the latter (Appendix A). For both **G6sulfur** and SSP2-4.5, sections of South America and Central Africa had slightly earlier exposure from 2060 (Fig. 4a,b). The western margin of South America was projected to experience a much earlier exposure under both scenarios, from as early as the 2020s (Fig. 4a,b). Similarly, Sudan, Ethiopia and Saudi Arabia were projected to experience exposure from the 2020s under both G6$_{\text{sulhpur}}$ and SSP2-4.5, along with the United States of America (USA), Mexico and Southeast Asia (Fig. 4a,b).

When SSP2-4.5 was subtracted from **G6sulfur** it was possible to see where species exposure occurred earlier under **G6sulfur** or earlier under SSP2-4.5 (Fig. 4c). South America, Central Africa and the Sahel region, Southeast Asia and northern Australia were all projected to experience earlier exposure under **G6sulfur**. However, parts of these regions are also projected to experience earlier exposure under SSP2-4.5 (Fig. 4c).

A large proportion of Brazil, Venezuela, Paraguay, Bolivia and Argentina had earlier exposure under **G6sulfur** (Fig. 4c). Central Africa also had a relatively widespread risk of early exposure, with the DRC projected to experience exposure between 10 to 20 years earlier under **G6sulfur** (Fig. 4c). Parts of Europe, specifically Italy and Greece, as well as Turkmenistan had earlier exposure under **G6sulfur**. However, exposure was also earlier under SSP2-4.5 in some regions, including parts of South America, Central America, northern Australia, sub-Saharan Africa and Southeast Asia (Fig. 4c). Moreover, the USA, Mexico, Saudi Arabia, India and China were projected to experience both earlier exposure under **G6sulfur** and earlier exposure under SSP2-4.5 (Fig. 4c).

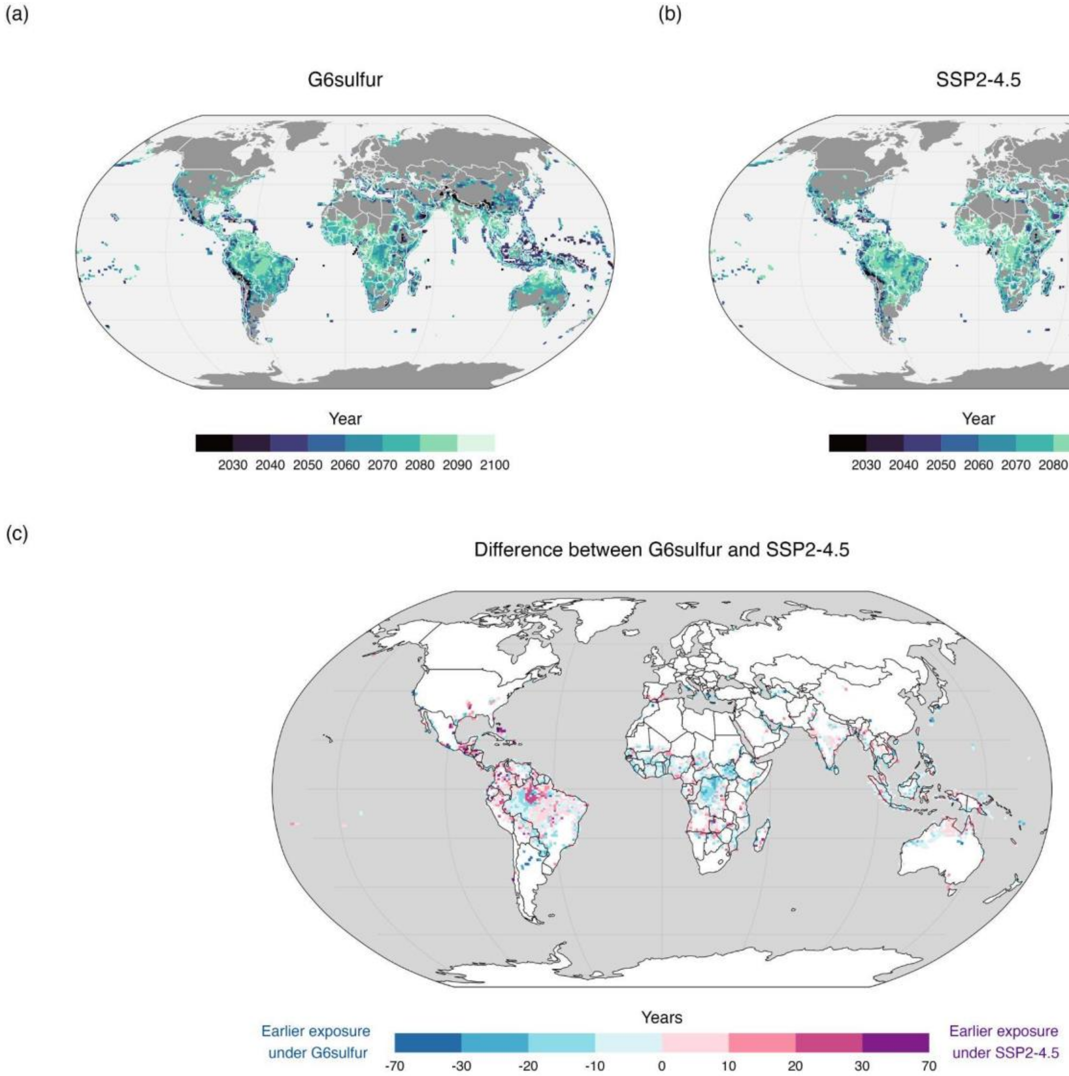


Figure 4: Timing of exposure to potentially unsafe temperatures for 26,572 terrestrial vertebrate species from 2020 to 2100. (**a**) Timing of exposure under intermediate-emissions scenario SSP2-4.5, (**b**) Timing of exposure under G6sulfur and (**c**) Timing of exposure calculated by subtracting SSP2-4.5 from G6sulfur to reveal where exposure was earlier under G6sulfur or earlier under SSP2-4.5. (**a**) and (**b**) represent the median years of species exposure and (**c**) represents the difference between the years in (**a**) and (**b**). Negative values, or blue regions, show where exposure occurs earlier for G6sulfur and positive values, or pink regions, show where exposure was earlier under SSP2-4.5. Maps show data for grid cells with at least 5 species exposed. The results reported are the median values across all six climate models.

4.3. Abruptness

The abruptness of exposure—defined as the percentage of species exposed in the decade of maximum exposure—was high for both SSP2-4.5 and **G6sulfur**, with high abruptness especially concentrated in the tropics (Fig. 5a,b). Parts of the Brazilian Amazon and Southeast Asia were projected to experience 40-50% abruptness under both $G6_{sulpur}$ and SSP2.4-5 (Fig. 5a,b). Countries in the Sahel region, specifically Mauritania and Mali, were projected to experience over 40-50% abruptness under both scenarios (Fig. 5a,b). Northern Australia had over 70-80% abruptness under **G6sulfur** and SSP2-4.5 (Fig. 5a,b). Parts of North and South Sudan were projected to have over 90% abruptness under both **G6sulfur** and SSP2-4.5 (Fig. 5a,b).

Figure 5c shows where abruptness was higher under **G6sulfur** or higher under SSP2-4.5. Overall, abruptness was higher under **G6sulfur** (also see Appendix B). For example, parts of the USA, Mexico, the Bahamas, Central America and South America were projected to experience up to 10% more abruptness under **G6sulfur**. Sub-Saharan and Central Africa had up to 10% more abruptness under **G6sulfur**, with over 10% more abruptness in parts of the DRC and Congo. Saudi Arabia, Italy, Greece, Turkmenistan, China and Southeast Asia had up to 10% more abruptness under **G6sulfur**. Northern regions of Australia experienced over 10% more abruptness under **G6sulfur**, with some sections rising to over 40%. Some parts of Niger and Mali were projected to experience over 20% more abruptness under **G6sulfur**.

However, abruptness was also higher under SSP2.4-5 in some regions (Fig. 5c). Adjacent regions of northern Australia were projected to experience over 10% more abruptness under SSP2-4.5, which rose to over 40% in some parts. India was projected to experience both higher abruptness under **G6sulfur** and higher abruptness SSP2-4.5 (Fig. 5c). Abruptness was higher under SSP2-4.5 over some parts of Brazil and the Sahel region, specifically Mauritania, Mali, Chad and North and South Sudan (Fig. 5c).

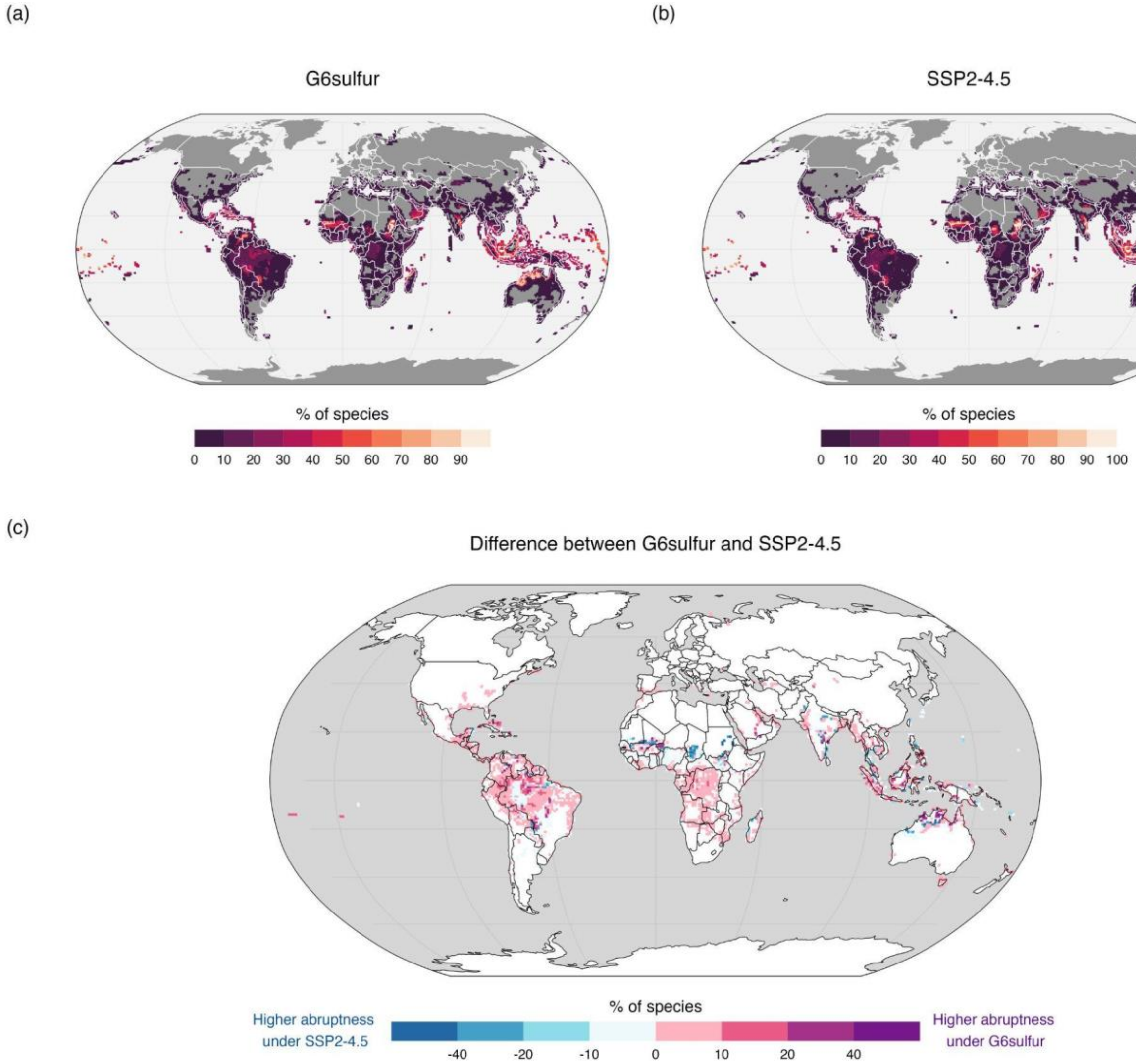


Figure 5: Abruptness of exposure to potentially unsafe temperatures for 26,572 terrestrial vertebrate species from 2020 to 2100 (**a**) Abruptness of exposure under intermediate-emissions scenario SSP2-4.5, (**b**) Abruptness of exposure under G6sulfur and (**c**) Abruptness of exposure calculated by subtracting SSP2-4.5 from G6sulfur to reveal where exposure was more abrupt under G6sulfur or more abrupt under SSP2-4.5. (**a**), (**b**) and (**c**) represent percentages of species abruptness. Positive values, or pink regions, show where abruptness is higher under G6sulfur and negative values, or blue regions, show where abruptness was higher under SSP2-4.5. Maps show data for grid cells with at least 5 species exposed. The results reported are the median values across all six climate models.

4.5. Exposure by country

South America, Central Africa, Southeast Asia and Australia were projected to experience the highest increase in exposure under **G6sulfur**, particularly Brazil which encountered close to 5,000 populations exposed (Fig. 6). In addition, Russia, the USA and Saudi Arabia were projected to have higher exposure under **G6sulfur**, with Russia experiencing just under 1,000 populations exposed. However, **G6sulfur** reduced exposure for countries in the Sahel region and in India (Fig. 6). Specifically, **G6sulfur** reduced exposure for close to 2,000 populations in Chad and over 500 species populations in Sudan.

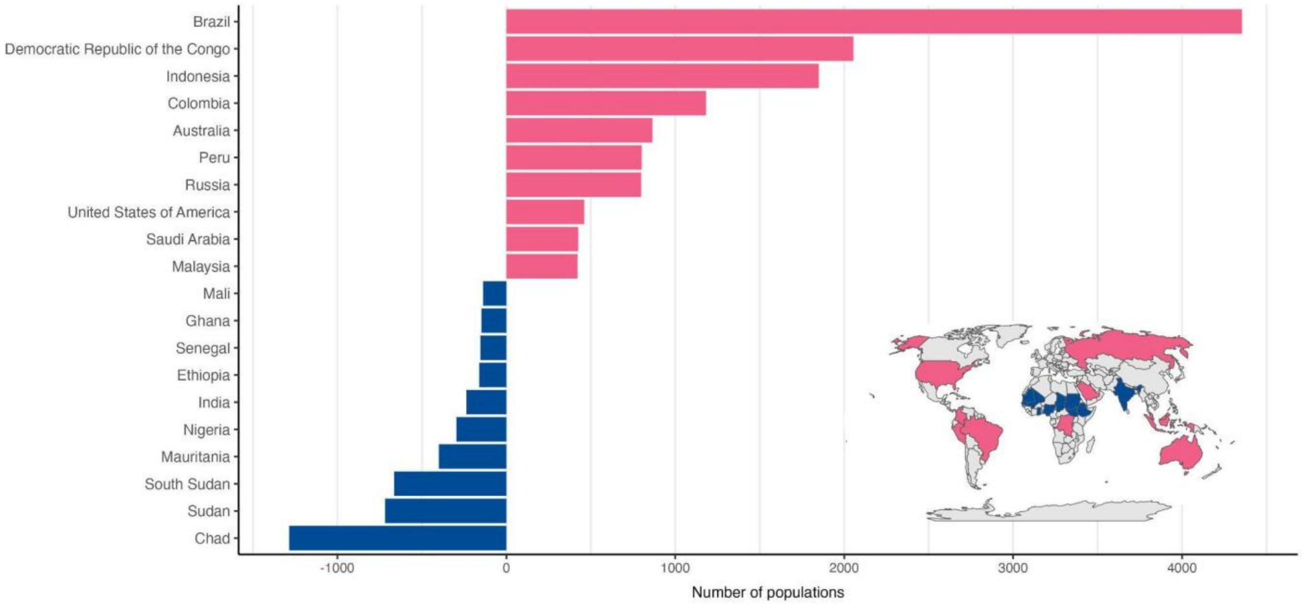


Figure 6: Differences in exposure of species populations to potentially unsafe temperatures under G6sulfur by country. Positive values show higher exposure under G6sulfur and negative values show higher exposure under SSP2–4.5. The ten countries with the largest difference in exposure are shown for both positive and negative values.

Chapter 5: Discussion

Solar Radiation Modification (SRM) is at the forefront of a complex research dilemma and more thorough analyses of the potential effects of various types of SRM on biodiversity are needed to better understand its potential advantages and risks, and support informed decisions (McCormack et al., 2016; Robock et al., 2009; Trisos et al., 2018a; Trisos et al., 2018b; Zarnetske et al., 2019). To my knowledge, this study is the first global assessment to compare where,when, and how fast terrestrial biodiversity could be exposed to temperatures that exceed their niche limits under a SRM scenario (specifically **G6sulfur**) and under an intermediate emissions scenario (SSP2-4.5). This allows a comparison to be made between risks to biodiversity in a world in which similar levels of global warming were achieved with and without SRM, and provides an important baseline to consider in further conversations regarding SRM.

The timing of exposure is projected to be earlier under **G6sulfur** when compared to SSP2-4.5, meaning that species could have less time to adapt to temperature changes. Time is an important aspect of adaptation, not only for species but also for people. A later exposure could buy valuable time for the development and implementation of conservation and ecosystem management policies. Many assemblages in tropical forests are predicted to have not only more populations exposed to unprecedented temperatures under **G6sulfur**, but exposure will occur earlier and will be more abrupt (Fig. 4c and Fig. 5c). This is concerning because earlier exposure under **G6sulfur** compared to SSP2-4.5 could cause species to experience a sudden rise in temperatures that they may lack the capacity to adapt to, leading to responses such as range shifts or local extirpations. Moreover, if species fail to either adapt or migrate rapidly enough, earlier exposure could lead to an increased risk of extinction.

A rapid reduction in emissions through mitigation efforts could help to delay the onset of species exposure to potentially unsafe temperatures and buy ecological assemblages crucial time that could ultimately reduce the severity of ecological disruption (Trisos, Merow & Pigot, 2020). For instance, Trisos et al. (2020) found that intensive mitigation under RCP2.6 delayed species exposure by approximately 58 years on land. The risk of early exposure under **G6sulfur** would not only impact species, but human populations may not be able to cope with rapid temperature changes and would have to come up with urgent solutions on a shorter time scale. Moreover, rapid species migrations and adaptations that arise from sudden changes in temperature could have serious consequences for livelihoods, economies, food security and human health (Pecl et al., 2017). The delayed exposure under SSP2-4.5 would allow time to implement longer-term intensive mitigation and adaptation strategies to reduce emissions and contribute towards lessening biodiversity loss.

The results show that exposure is projected to be more abrupt under **G6sulfur**, highlighting that SSP2-4.5 could reduce abruptness and the risk of ecological disruption (Fig. 5c). For species assemblages, the majority of the species are likely to experience a simultaneous exposure to potentially unsafe temperatures outside of their niche limits, which could have catastrophic impacts on local biodiversity and ecosystem services. Moreover, it was found that there is a positive correlation between abrupt exposure events and species richness, increasing the likelihood of immediate ecological disruption in some of the most biodiverse regions across the globe (Trisos, Merow & Pigot, 2020). The results show that these regions are the ones predicted to experience more abrupt exposure under **G6sulfur**, which highlights the higher risk of ecological disruption if we fail to mitigate climate change and have to rely on proposed approaches such as SRM.

In addition to earlier and more abrupt exposure, higher magnitude of exposure under **G6sulfur** is mostly concentrated over the tropical forests (Fig. 4c). This is concerning for several reasons. For instance, forests could generally reduce climate change-induced vulnerability for people, especially those who are disproportionately affected by climate change (UNEP, 2022b). The ecological services that forests provide are known for their great adaptation potential, which could help us make progress towards achieving at least 11 of the 17 United Nations Sustainable Development Goals (Seymour & Busch, 2016). Furthermore, not only are tropical forests biodiversity hotspots, supporting over half of all flora and fauna species worldwide, but they also contribute towards controlling global and local climatic conditions through biogeochemical cooling processes (Lawrence et al., 2022). They also play a huge role in monitoring the global carbon budget (Cook & Vizy, 2008; Hérault & Gourlet-Fleury, 2016; Huntingford et al., 2013). While occupying only around 10% of the planet's land area, tropical forests account for over 50% of global forest cover and house more than half of the world's forest carbon stock (Hérault & Gourlet-Fleury, 2016; Tang, 2019).

According to UNEP (2022a), by 2030, it is necessary to prevent the release of 15 gigatonnes of GHG emissions annually, in excess of the pledges already made by countries in their Nationally

Determined Contributions (NDCs) under the Paris Agreement, in order to have a 66% chance of keeping global warming to no more than 2°C. Forests generally have the ability to provide nearly 4 gigatonnes (Gt) of mitigation potential on a year-round basis by 2030, of which tropical forests account for 2.2-2.7 Gt (Goodman & Herold, 2014; IPCC, 2019; Roe et al., 2019; UNEP & IUCN, 2021). Hence, efforts to preserve, sustainably manage, and rehabilitate forests can make up about 27%, or 0.5°C of cooling globally, of the mitigation potential we urgently need for avoiding predicted catastrophic rises in temperature (UNEP, 2022b; WWF, 2022). The high exposure over tropical forests under **G6sulfur** is concerning because it could reduce the capacity for these forests to provide crucial contributions to reductions in GHG emissions and temperature (Betts et al., 2008; Brodie et al., 2011; Hérault & Gourlet-Fleury, 2016; Tang, 2019). Overall, these findings highlight the importance of evaluating the regional impacts of other SRM scenarios in future studies.

Although under **G6sulfur** exposure in tropical forests is projected to be higher globally, the results suggest that it is particularly elevated in the Amazon region (Fig. 4c). The Amazon is the largest tropical rainforest in the world and is home to some of the most biodiverse and species-rich landscapes on the planet, however, recent studies have suggested that if we surpass the ecological tipping point we are rapidly approaching, it will cease to exist (WWF, 2022). Deforestation and other impacts from climate change have already contributed towards the Amazon's decline, whereby 17% of its original extent has been lost, over and above the 17% that has been degraded (Tang, 2019; WWF, 2022). The higher exposure under **G6sulfur** across the Amazon is concerning against the backdrop of future estimates, whereby anthropogenic activity, fire, and drought are still predicted to be major challenges in the region (Marengo et al., 2018; Nepstad et al., 2008; Tang, 2019). This necessitates future studies on the potential impacts of SRM on iconic biodiversity hotspots.

The Amazon governs the local climate through evapotranspiration processes; however, deforestation and climate change are modifying the distribution and patterns of rainfall, making the Amazon drier and less resilient (Boulton et al., 2022). The water regime and biodiversity of the Amazon rainforest will suffer when these factors are combined with the dry conditions brought on by more frequent El Niño Southern Oscillation (ENSO) (Tang, 2019). Moreover, temperatures in the Amazon have been rising by approximately 0.25°C each decade and are expected to increase by 3-8°C over the course of the twenty-first century, which is likely to exacerbate drought (Betts et al., 2008; Hérault & Gourlet-Fleury, 2016). The occurrence of drought can serve as a major driver of variability and change in the Amazon environmental systems that are usually acclimated to high annual rainfall exceeding 1,680 mm and an intermittent fire regime (Betts et al., 2008; Brodie et al., 2011; Tang, 2019). This is also concerning for tropical forests in Southeast Asia, Central Africa, and Australia that are already experiencing drying trends and are projected to experience higher exposure under **G6sulfur** (Tang, 2019).

In addition, the findings show that exposure over the small islands of the Sundaland region and Southeast Asia is projected to be higher under **G6sulfur** when compared to SSP2-4.5. This is concerning because small islands fall under the umbrella of tropical forests and are already being disproportionately affected by climate change (IPCC, 2022a). Islands only make up around 5% of the earth's surface yet are home to numerous critically endangered species, many of which have distinctive traits that make them especially vulnerable to this threat, such as small distribution ranges and small population sizes (Leclerc, Courchamp & Bellard, 2020). Moreover, due to their isolated evolution and the restricted nature of their ecosystems, species are frequently not well suited to fluctuating environmental conditions (Leclerc, Courchamp & Bellard, 2020). The confined ranges of islands severely constrain species' ability to respond to climatic changes by shifting their latitudes or elevations or migrating to other landmasses (Leclerc, Courchamp & Bellard, 2020). As a result, many small island species rely on microclimates to adapt to macroclimatic changes (Leclerc, Courchamp & Bellard, 2020). However, small islands are presently experiencing habitat loss, meaning less microclimatic availability for adaptation and the increased risk of extinction. The higher exposure under **G6sulfur** could therefore put more strain on the already limited capacity for these species to adapt. This could potentially increase the risk of extinction for many endemic island species.

However, the results of this study additionally show that exposure, timing and abruptness are projected to be higher under SSP2-4.5 when compared to G6sulhpur in some places, mostly over the Sahel region and India. These regions would therefore experience less exposure risk to biodiversity under G6sulfur, resulting in fewer impacts from rising temperatures to both ecosystems and people. Biotic interactions among species, including predation, parasitism and competition would have delayed and less abrupt exposure under G6sulfur. This could increase the capacity for species to adapt to changing temperatures over time, therefore increasing resilience (MEA, 2005). Ecosystems would have an increased capacity to provide essential ecosystem services such as biomass production, nutrient cycling and acquiring essential biological resources (Mooney et al., 2009; Pecl et al., 2017). The provision of ecosystem services would have positive effects on human livelihoods, economies and cultures and reduce risk to the most vulnerable populations (MEA, 2005). In addition, delayed exposure under **G6sulfur** could allow time for us to implement other long-term mitigation strategies that are beneficial to biodiversity and local livelihoods, including CDR approaches like reforestation and soil carbon sequestration (IPCC, 2022b). However, the potential impacts of SRM on other important climatic variables other than temperature, such as precipitation, are likely to be more varied and could potentially counteract some of these benefits (Boucher et al., 2013; Niemeier et al., 2023; Ricke et al., 2023).

The findings presented here show that the impacts of SRM are mostly concentrated to developing nations, where most of the countries with the largest difference in exposure between **G6sulfur** and SSP2.4-5 are found. It is commonly perceived in the literature that developing countries have the most to gain or lose from SRM deployment (Rahman et al., 2018; Svoboda & Irvine, 2014). Here, I show that developing countries could be both the winners and losers from SRM. This could make governing the proposed deployment of SRM a significant challenge and underscores the importance for developing countries to further investigate the risks and benefits from SRM (Robock et al., 2009; Shepherd, J.G., 2009). However, developing countries are still largely excluded from SRM discussions (Rahman et al., 2018).

In this study, I focused only on risks from exposure. Yet, another source of risk from SRM to biodiversity is the possibility of rapid implementation or termination. If SRM is either implemented or terminated rapidly, global temperatures can change at unprecedented rates. This could cause a simultaneous exposure to unsafe temperatures for a large number of species (Trisos et al., 2018a), increasing the risk of sudden ecological disruption and biodiversity loss. Impacts are expected to be more pronounced in tropical oceans, the Amazon Basin, Africa, Eurasia, and polar regions (Trisos et al., 2018a). To adapt to rapid climate changes resulting from sudden termination or implementation, species would need to migrate at unprecedented speeds. However, it is currently unknown to what extent this would be feasible (Trisos et al., 2018a).

Although this study only assessed exposure from annual mean temperature changes, the impacts of SRM on other variables such as precipitation are also key. Studies have shown that SRM has the potential to offset the increases to precipitation from a rise in GHG emissions (Russell et al., 2012). However, research suggests that SRM could overcompensate GHG forcing, and hence cause a reduction in precipitation (Boucher et al., 2013; Niemeier et al., 2023; Ricke et al., 2023; Robock, Oman & Stenchikov, 2008). This is a concern, specifically for tropical regions and tropical forests that are already experiencing a drying trend (Betts et al., 2008; Malhi et al., 2008). Therefore, further research is needed to investigate whether changes in precipitation caused by SRM could increase or decrease risks to biodiversity.

Species exposure to unprecedented temperatures varies according to the intensity of climate change, with high-emissions pathways resulting in significantly more exposure. For instance, Trisos et al. (2020) estimated that under RCP8.5 geographic range contractions of land vertebrates are predicted to be around 20% higher when compared to RCP4.5. Moreover, the percentage of local populations exposed under RCP8.5 was also three to four times higher than under RCP4.5 (Trisos et al., 2020). Since the results presented here show that exposure profiles of **G6sulfur** and SSP2-4.5 are similar, one can assume that **G6sulfur**manages to reduce species exposure when compared to a high-emissions scenario such as RCP8.5. However, despite the potential of **G6sulfur** to reduce exposure, SSP2-4.5 would be not only more successful in reducing exposure, but it could also regulate other environmental parameters that SRM lacks the ability to control, such as ocean acidification, which will continue to increase both in the absence of appropriate mitigation intervention and under SRM as it is not designed to mitigate these effects. This highlights the potential of mitigation efforts consistent with intermediate emissions scenarios in reducing risks more effectively.

Overall, my findings indicate that species exposure to potentially unsafe temperatures could be higher, earlier and more abrupt under **G6sulfur**. This is concerning because the results also indicate that exposure is likely to be concentrated to tropical forests, which are highly biodiverse regions that are already vulnerable to the impacts of climate change (Tang, 2019). Betts (2008) suggests that the Andes, the Brazilian and Guyanan shields, and other extremely biodiverse highland areas deserve special consideration for future research because they could serve as refugia for species from lowland habitats that are unable to adapt to climate change. This is especially significant because earlier and more abrupt exposure will increase the likelihood of species migration or adaptation to temperature changes.

Although **G6sulfur** is projected to reduce exposure to potentially unsafe temperatures in many places, decision-makers should proceed with caution because any trade-offs to biodiversity from

SRM need to be considered. This is even more significant when evaluating the risks from rapid implementation and sudden termination. The findings of this study highlight that more research is needed that incorporates other SRM scenarios and additional environmental parameters such as precipitation and exposure to extreme events. Although the latest IPCC report highlights that temperatures are rising faster over land than in oceans (IPCC, 2023), it would be useful to explore the potential risks of SRM to oceans and to incorporate both terrestrial and marine vertebrate species to reveal the combined effects of SRM at a larger scale.

Chapter 6: Conclusion

6.1. Conclusion

SRM is receiving global attention as a proposal to reduce Earth's steadily increasing temperature and ameliorate risks from climate change. Although current emissions pathways are headed in the wrong direction and these types of interventions are gaining relevance, more research is needed to investigate the potential benefits and risks of SRM. These findings indicate that exposure to potentially unsafe temperatures for 26,572 terrestrial vertebrate species across the globe was higher under **G6sulfur** when compared to intermediate-emissions scenario SSP2-4.5. Although **G6sulfur** could potentially reduce biodiversity risk in some countries, it could also cause great losses to biodiversity in others. This could make governing SRM a significant challenge, especially in countries that are disproportionately affected by climate change and could potentially have the most to gain or lose.

Notably, tropical forests had the greatest increase in risk from SRM, which is concerning given their high biodiversity value. In addition, exposure would occur earlier under **G6sulfur**, which could hinder the ability of species to adapt to changes in temperature. This would be exacerbated by more abrupt exposure under G6sulfur and could potentially prompt ecological disruption. Although exposure was higher under SSP2-4.5 when compared to G6sulfur in some regions, the most effective way of mitigating the effects of climate change on biodiversity remains a drastic reduction in GHG emissions. Ultimately, the findings reported in this study urge further investigation into the effects of SRM on biodiversity and extreme caution in the creation of policy and governance structures that mitigate the possible ecological dangers as society considers using SRM to lessen climate change impacts (Trisos et al., 2018a).

6.2. Suggestions and future research

This study highlights that the potential risks of SRM deployment to biodiversity urgently needs more research. Despite the increasing attention in literature, studies have failed to address the fundamentally distinct ways that SRM, specifically SAI, and GHGs affect the climate and, consequently, how they affect natural systems (Zarnetske et al., 2019). There is room for biodiversity and ecosystem functioning targets, such as the various targets mentioned in the United Nations Sustainable Development Goals, to inform SAI scenarios (Diaz et al., 2020; Zarnetske et al., 2019). Moreover, the inclusion of additional environmental parameters that SRM is not able to address, such as ocean acidification, would be beneficial to decision-making processes about the risks and benefits from SRM.

This study only presents one SRM scenario, **G6sulfur**, and it would be crucial to broaden this research to include other scenarios like the Stratospheric Aerosol Geoengineering Large Ensemble (GLENS) and Assessing Responses and Impacts of Solar climate intervention on the Earth system with Stratospheric Aerosol Injection (ARISE-SAI). Although research using idealised SRM scenarios is still useful to make a comparison of the potential risks and benefits of SRM, Niemeier and Timmreck (2015) stipulate that some SRM scenarios are extreme and not recommended as practical, such as GeoMIP G1 that attempts to balance four times present CO2 levels, or continuing with BAU-GHG emissions until the end of the twenty-first century. Hence, further research that includes realistic deployment scenarios is recommended, such as avoiding a 1.5°C to 2°C temperature increase by balancing overshoot scenarios (Tilmes et al., 2016).

Moreover, this study assumed that species exposure levels would be higher under high emissions scenario SSP5-8.5 and omitted SSP5-8.5 from its analyses due to time constraints. It would be useful to include both SSP2-4.5 and SSP5-8.5 in future analyses as it would provide further insight into the potential of **G6sulfur** to offset or exacerbate the negative impacts projected under SSP5-8.5, considering that **G6sulfur** is SSP5-8.5 with SAI to keep warming at a level similar to that in SSP2-4.5.

UNEP (2023) stresses the need for broader international SRM research to explore different scenarios, potential benefits and risks, uncertainties and knowledge gaps. This includes the establishment of appropriate governance structures to make decisions surrounding the continuation of indoor research, which mainly incorporates theoretical analyses and climate modelling, small-scale outdoor experiments and actual SRM deployment. However, proposals to incorporate small-scale outdoor experiments into research are concerning because it would increase the likelihood of actual SRM deployment whilst still lacking inclusivity and representation from all stakeholders in decision-making processes (UNEP, 2023). This necessitates the formulation of new frameworks that complement other SRM-specific governance. One suggestion made by UNEP (2023) is to consider SAI within the context of a broad stratospheric governance system, so that perceived risk, experiments and potential deployment can be addressed more efficiently.

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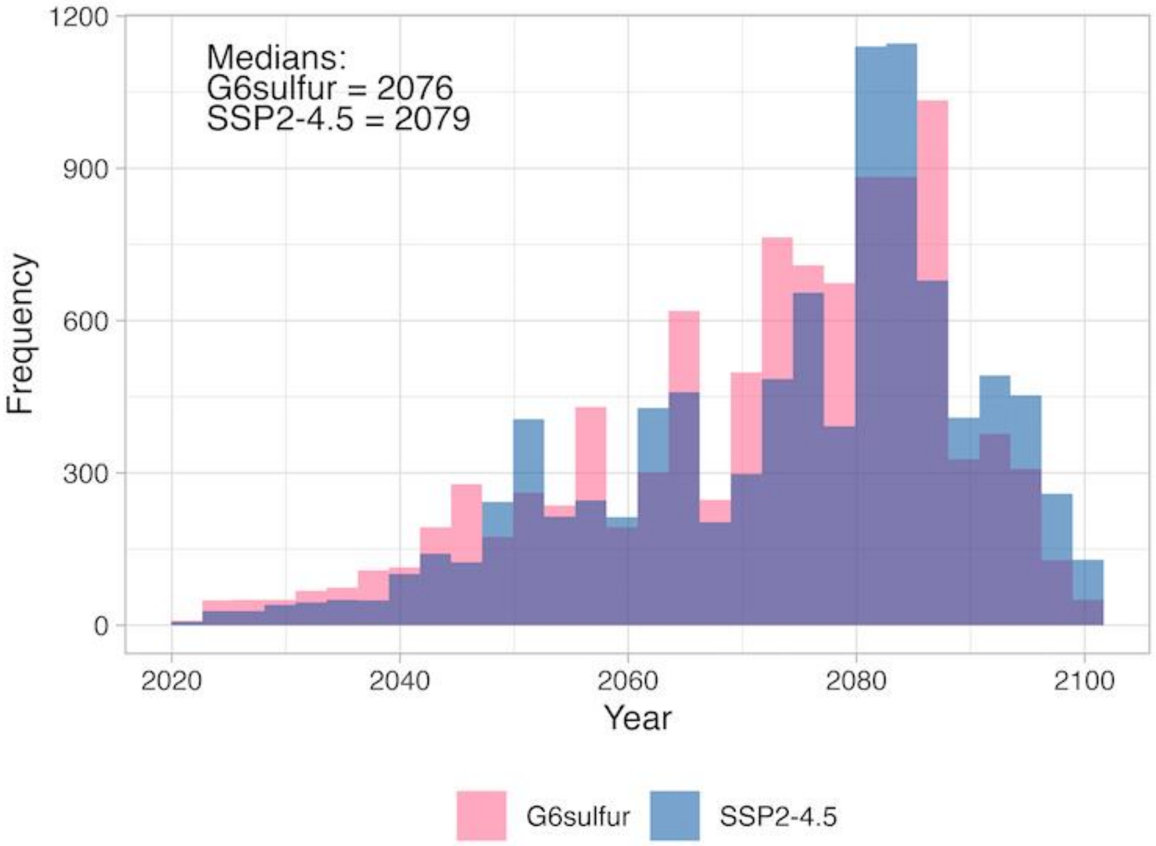
Appendices

Appendix A

Timing of exposure under G6sulfur and SSP2-4.5 represented as the median year of exposure



Appendix B

Abruptness of exposure under G6sulfur and SSP2-4.5