nature food

Article

https://doi.org/10.1038/s43016-023-00853-3

Optimal climate intervention scenarios for crop production vary by nation

Received: 1 October 2022

Accepted: 7 September 2023

Published online: 05 October 2023

Check for updates

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Stratospheric aerosol intervention (SAI) is a proposed strategy to reduce the effects of anthropogenic climate change. There are many temperature targets that could be chosen for a SAI implementation, which would regionally modify climatically relevant variables such as surface temperature, precipitation, humidity, total solar radiation and diffuse radiation. In this work, we analyse impacts on national maize, rice, soybean and wheat production by looking at output from 11 different SAI scenarios carried out with a fully coupled Earth system model coupled to a crop model. Higher-latitude nations tend to produce the most calories under unabated climate change, while midlatitude nations maximize calories under moderate SAI implementation and equatorial nations produce the most calories from crops under high levels of SAI. Our results highlight the challenges in defining 'globally optimal' SAI strategies, even if such definitions are based on just one metric.

Recent studies have shown that climate change is diminishing the rate of growth of global food production[1,2]. Regional production decreases and food shortages in lower-latitude developing nations could be a large negative consequence of climate change[3]. With diminishing food production and increasing global population, researching methods to limit warming is increasingly important. One of the most discussed and researched methods for intentionally manipulating the climate system to counteract anthropogenic warming is the use of stratospheric aerosols[4,5]. This climate intervention strategy aims to mimic volcanic eruptions by injecting sulfur dioxide into the stratosphere, where it oxidizes to form sulfuric acid, which then forms reflective aerosol particles[6]. Injections would need to occur continuously to maintain decreased solar radiation and surface temperatures[7,8]. These continued injections would have large impacts on the climate system, including temperature, precipitation, humidity and direct and diffuse radiation, which are controlling climate factors for crop production. These climate variables are all expected to change due to stratospheric aerosol intervention (SAI)[6].

Crops are grown to optimize their production in the current climate. Additional heat stress in the future is expected to reduce global yields of maize and push other crops such as wheat to higher latitudes[9]. Limiting that additional heat stress with SAI could improve yields in the future and possibly maintain the present-day distribution of crop growth. This also means that SAI could decrease yields in higher-latitude nations relative to warming. Global carbon dioxide concentrations are anticipated to continue to grow, increasing the CO_2 fertilization effect and thus benefiting crops. C_3 crops such as rice, soybean and wheat would benefit from increased CO_2 and reduced heat stress, since C_3 crops tend to prefer cooler environments and their photosynthesis is limited by CO_2 (ref. 10). C_4 plants such as maize are not as CO_2 limited, since they have an anatomical adaptation that allows them to increase the CO_2 concentration around the atmospherically isolated Rubisco enzyme, reducing photorespiration[11]. This means that increased CO_2 in the future would tend to benefit C_3 plants more than C_4 plants. SAI would change regional precipitation patterns and humidity, potentially impacting regional crop production[12]. It would also decrease total incoming solar radiation while increasing downward diffuse radiation due to scattering by the stratospheric aerosols, which would have opposing impacts on crop production[13]. The changes that SAI would bring to the global and regional climate would have implications for crop production and food security.

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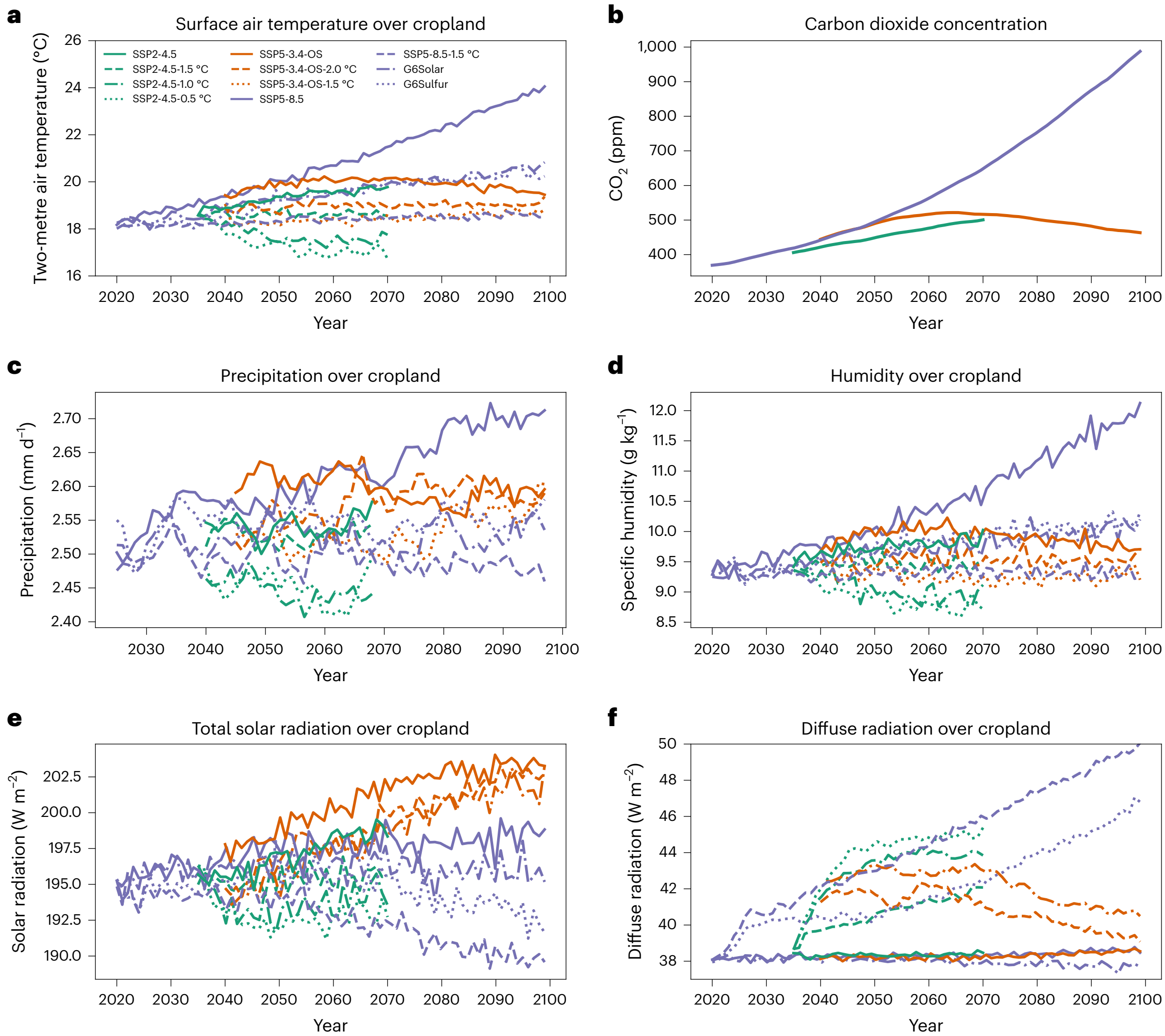

Fig. 1 | Climate impacts of SAI and climate change scenarios. a–**f**, Global cropland average time series of ensemble average temperature (**a**), carbon dioxide concentration (**b**), precipitation (**c**), specific humidity (**d**), total incoming solar radiation (**e**) and diffuse radiation over cropland (**f**) for climate change and climate intervention scenarios. Precipitation is presented as a five-year rolling average.

Previous studies have aimed to address potential impacts on crops from SAI. One study used a statistical model including temperature, precipitation and CO_2 fertilization under a future SAI scenario to offset high-CO_2 warming[14]. That study found a benefit to global rice, maize and wheat yields and a decrease in high-latitude rice. Another statistical study represented SAI on the basis of volcanic eruptions to capture impacts on crops from changes to global sunlight[13]. They concluded that little of the global agricultural damage due to climate change would be offset by climate intervention, as the negative impacts from SAI on maize, rice, soybean and wheat due to changes in sunlight were balanced by benefits from global cooling. A few studies using dynamic crop models simulated regional agriculture responses to SAI, but the results vary depending on the SAI scenarios and the crop models used[15,16]. The most recent study used output from the Norwegian Earth System Model with prognostic biogeochemical cycling to run offline simulations of the Community Land Model version 5 (CLM5) to analyse impacts of SAI on maize, rice, soy, spring wheat, sugar cane and cotton[17]. They concluded that SAI used to reduce radiative forcing from RCP8.5 to RCP4.5 could benefit global yields by about 10%. Our study uses a fully coupled Earth system model with an interactive crop model to analyse the impacts on maize, rice, soybean and spring wheat production under multiple SAI scenarios that limit global average surface warming to targets set at the international negotiations at the 21st Conference of the Parties (COP21) in Paris of 1.5 and 2.0 °C above pre-industrial levels[18,19]. We also use additional scenarios that go even further, reducing the global mean surface temperature increase to 1.0 and 0.5 °C above pre-industrial levels[20]. These scenarios may be considered more policy-relevant than those previously studied, since they implement only moderate amounts of SAI to meet defined policy goals, rather than using large amounts of aerosols just to obtain a robust signal-to-noise ratio. This study also compares the impacts on crops of reducing incoming solar radiation through reducing the solar constant instead of SAI. Offline simulations were then conducted to understand which individual climatic changes caused by SAI influence impacts on crop production. Past studies have focused on global average crop impacts from a single SAI scenario or impacts on certain regions or individual nations. Since proposed SAI schemes so far have been based on controlling regional or global surface air temperatures, they would not also be able to control regional temperature, precipitation and other factors important to plants, so different nations would be impacted differently[21]. This is particularly relevant considering that there may be many possible temperature targets that could be chosen for a SAI implementation. This study aims to understand which of these policy-relevant scenarios will produce the most future calories from crop production for each nation. It is important to compare scenarios and different intervention temperature targets so individual nations

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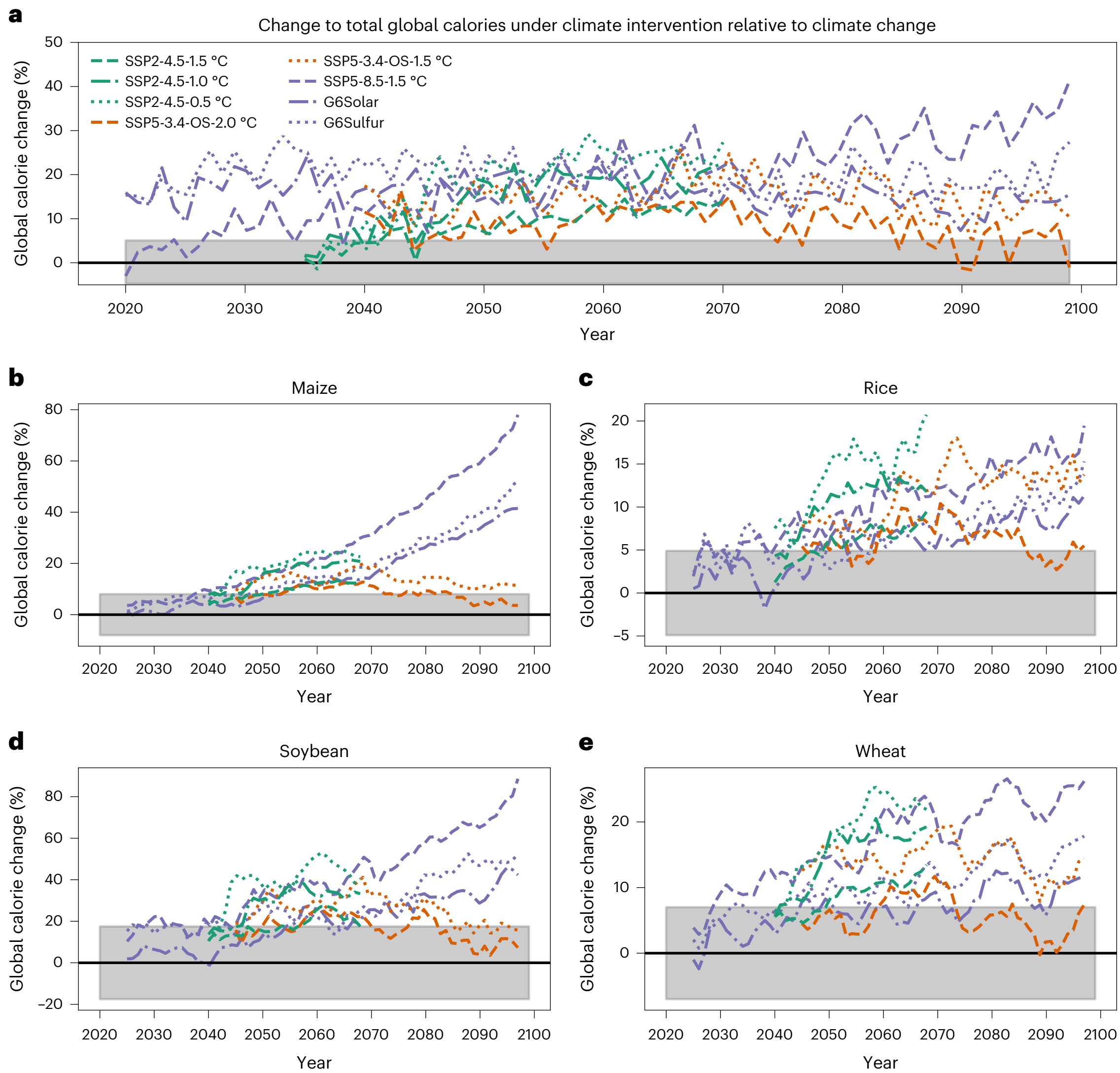

Fig. 2 | Crop production impacts under SAI scenarios relative to climate change. a–e, Time series of global percentage change in total calories (maize, rice, soybean and wheat) (**a**), calories from maize (**b**), calories from rice (**c**), calories from soybean (**d**) and calories from wheat (**e**) under climate intervention relative to the corresponding climate change scenario. The grey shaded regions indicate the standard deviation of a 50-year (1950–2000) detrended historical period. The values in **b**–**e** are presented as five-year rolling averages.

can understand which may be best for them if an informed, global decision on SAI is ever needed to be made.

Results

Solar constant reduction to represent SAI

Previous studies of crop and vegetation impacts from SAI have used solar constant reduction to represent impacts from SAI[15,22]. The Geoengineering Model Intercomparison Project Phase 6 experiments use both solar constant reduction (G6Solar) and sulfate aerosol intervention (G6Sulfur) to limit radiative forcing from Shared Socioeconomic Pathway (SSP; see Methods for details) scenario SSP5-8.5 down to what it would be with SSP2-4.5 (ref. 23). These two scenarios result in similar temperature, precipitation, humidity and total solar radiation responses over all cropland area globally (Fig. 1). Although most yield responses to these climate forcings are not significantly different between the G6 experiments, there is a slight benefit to yields under G6Sulfur compared with G6Solar (Supplementary Fig. 1). We expect increased crop yields under G6Sulfur due to the increased scattering of solar radiation by the sulfate aerosols, enhancing downward diffuse solar radiation in the G6Sulfur experiment relative to G6Solar (Fig. 1f). This enhanced diffuse radiation increases yields for maize, rice, soybean and spring wheat in G6Sulfur compared with G6Solar. Previous studies that used solar constant reduction to simulate SAI, or that used a crop model that did not partition between direct and diffuse radiation, could thus have underestimated crop yield responses to SAI.

Crop production changes due to SAI

Limiting anthropogenic warming increases the global sum of calories from maize, rice, soybean and spring wheat under all SAI scenarios (Fig. 2). Under the scenario SSP5-8.5-1.5 °C, the number of global calories from the four crops simulated increases by 22 ± 1% relative to SSP5-8.5 during the years 2060–2069 (Fig. 2a). Total global calories during the years 2060–2069 increase by 24% under SSP2-4.5-0.5 °C, 20 ± 1% under SSP2-4.5-1.0 °C, 12 ± 3% under SSP2-4.5-1.5 °C, 18% under SSP5-3.4-1.5 °C, 12 ± 1% under SSP5-3.4-2.0 °C, 16 ± 1% under G6Solar and 19 ± 1% under G6Sulfur (Fig. 2a). These changes to caloric production under climate intervention are all beyond the standard deviation of the 50-year historical period of ±5% (Fig. 2a). How much total calories increase depends on the time period and therefore the CO_2 concentration and the amount of SAI (Fig. 2).

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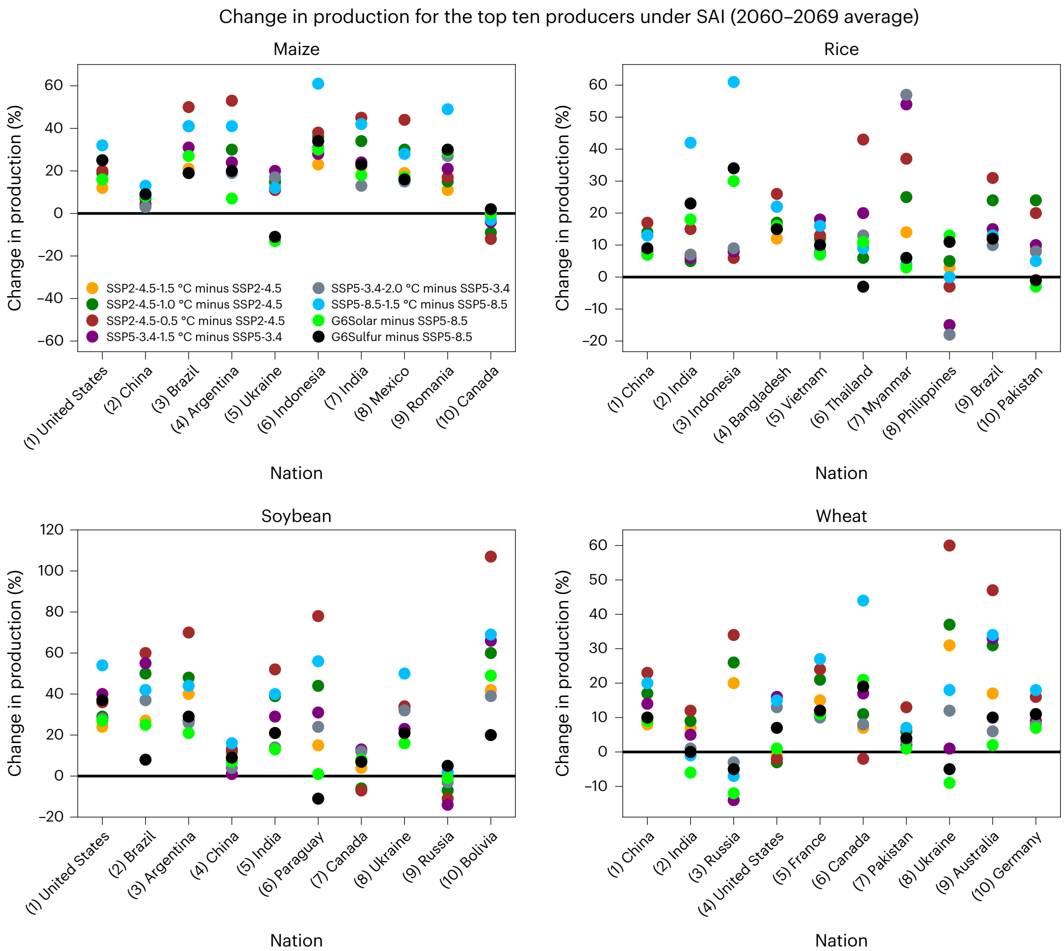

Fig. 3 | Crop production changes for top producers under SAI relative to climate change. Percentage change in maize, rice, soybean and wheat production for the current FAOSTAT top ten producers of each crop (2060–2069 average) under different climate intervention scenarios relative to climate change[30].

While global caloric production shows benefits under SAI, there are also many regions and nations where production will be reduced from SAI relative to warming without SAI. Maize, rice, soybean and spring wheat yields are anticipated to increase in high latitudes from warming due to climate change[9]. Some of the world's largest crop producers are in high-latitude regions (Fig. 3). Reducing warming with stratospheric aerosols tends to decrease production in these high-latitude nations relative to a warming scenario (Figs. 3–6). Comparing the magnitude of calories produced under a given scenario must be done between scenarios that share the same SSP, since different SSPs have varying amounts of nitrogen fertilizer application, cropping area and CO_2 concentration (Fig. 1 and Supplementary Fig. 3). Canada produces the most calories under the climate change scenario SSP2-4.5 (Fig. 4). Russia produces the most calories under the high-emission scenario SSP5-8.5 (Fig. 5) and climate change scenario SSP5-3.4-OS (Fig. 6). Midlatitude nations tend to prefer more moderate amounts of SAI to maximize crop calories (Figs. 4–6). Other, lower-latitude nations benefit from larger amounts of SAI, showing the most calories from crop production when temperatures are limited the most, such as in SSP2-4.5-0.5 °C (Fig. 4). The majority of the world's top crop-producing nations show increases in their production under SAI, but each SAI scenario has multiple top producing nations with decreases in their production relative to climate change (Fig. 3). None of the 11 climate change or climate intervention scenarios analysed here benefit everyone. Although global production tends to increase with more SAI, the number of nations that show a decrease in their production does also (Supplementary Fig. 4). Under SSP2-4.5, total calories from maize, rice, soybean and spring wheat are the highest in 102, 31 and 21 nations when maintaining temperatures that are 0.5, 1.0 and 1.5 °C above pre-industrial levels with SAI during the years 2060–2069, respectively (Fig. 4). There are 12 nations that maximize calories from crops under the unabated climate change scenario SSP2-4.5 during the years 2060–2069 (Fig. 4). Even if 102 nations would produce the most calories from limiting temperatures to 0.5 °C above pre-industrial levels under SSP2-4.5 using SAI, there would still be 64 nations that would not, including the 12 that may not benefit at all from SAI. Under SSP5-8.5, 121 nations produce the most calories under SSP5-8.5-1.5 °C, 20 under G6Sulfur, 9 under G6Solar and 18 others produce the most calories from crops under the high-emission scenario SSP5-8.5 during the years 2060–2069 (Fig. 5). Under SSP5-3.4-OS, 89 nations produce the most calories from maize, rice, soybean and spring wheat under the scenario SSP5-3.4-1.5 °C, 56 nations under SSP5-3.4-2.0 °C and 22 nations under SSP5-3.4-OS (Fig. 6). The number of nations that maximize their calories under a specific temperature target varies by crop (Figs. 4–6). Calories from rice are greater in more nations under climate change relative to those from other crops (Figs. 4–6). Soybean calories tend to be largest in more nations when temperatures are limited the most with climate intervention compared with other crops (Figs. 4–6). This is due to the respective low and high temperature sensitivity of rice and soybean (Fig. 7). Most of the world's top crop-producing nations increase production under climate intervention (Fig. 3). Although most nations would produce the most total calories from crops under the more extreme SAI scenarios, there are still many countries that would not, potentially causing conflict (Supplementary Fig. 4).

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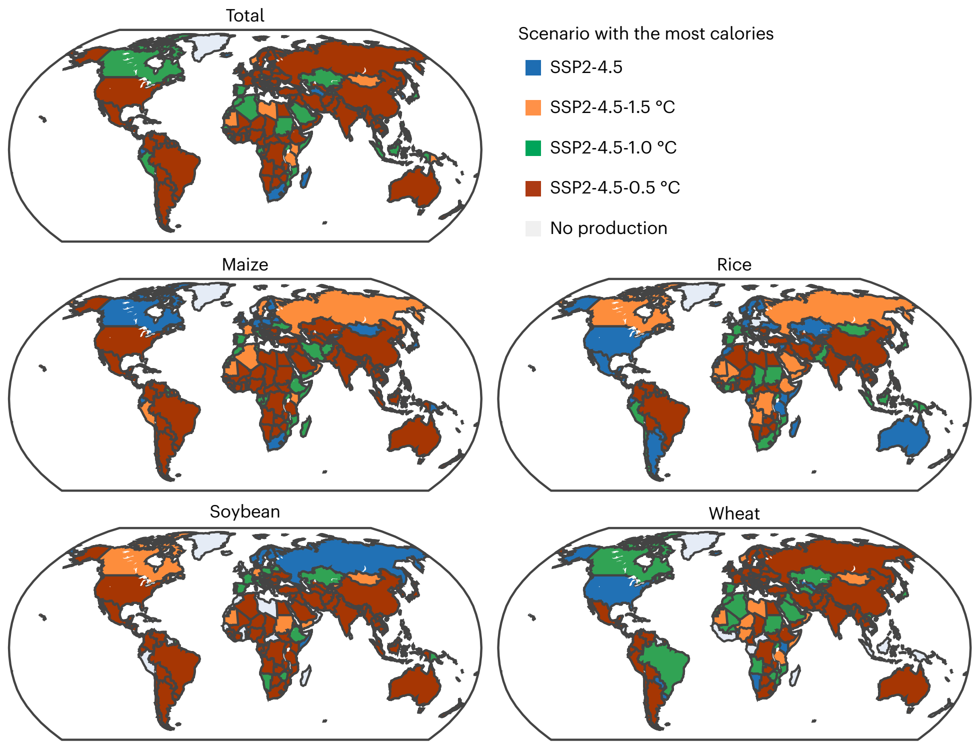

Fig. 4 | Climate change or SAI scenario that produces the most calories for each nation under SSP2-4.5. SSP2-4.5 scenarios that produce the most calories from total crop production (maize + rice + soybean + wheat) and from the individual crops maize, rice, soybean and wheat for each nation during the years 2060–2069.

Individual climate impacts on crop production under SAI

To understand why crop production is changing under SAI, we ran offline simulations of CLM5crop that only allowed single climate variables to change due to climate intervention. We tested the individual contributions to crop production impacts from changing temperature, precipitation, specific humidity, total solar radiation and diffuse radiation separately under SAI used to maintain warming of 1.5 °C above pre-industrial levels under SSP2-4.5. The period 2060–2069 under these scenarios also represents 1 °C of global temperature reduction using SAI. Increased CO_2 fertilization has a large benefit to crop production under SSP2-4.5 and SSP5-8.5 during the years 2060–2069 (Supplementary Fig. 2). CO_2 concentrations in SSP5-3.4-OS increase slightly and then begin to decrease over the years 2060–2069, with a small overall benefit to crop production (Fig. 1 and Supplementary Fig. 2). CO_2 concentrations are prescribed and do not change under climate intervention, relative to climate change, in the model used in this study, so these changes are not due to SAI. This high sensitivity to CO_2 means that changes to maize, rice, soybean and spring wheat production under SAI in the future would still be an increase relative to present-day conditions for most nations (Supplementary Fig. 5). Changes to precipitation, humidity, total radiation and diffuse radiation had minimal impacts on global maize, rice, soybean and spring wheat production relative to temperature (Fig. 7). However, there are regional changes to these variables that may become important. Precipitation changes had a significant negative impact on midlatitude maize and spring wheat (Supplementary Fig. 7). Under SSP2-4.5-1.5 °C, aerosols are injected primarily in the Southern Hemisphere, meaning that impacts on Northern Hemisphere crops from increased diffuse radiation or decreased total radiation may be subdued[19]. Limiting warming under climate intervention had the most areas with a significant impact on yield for all crops compared with changes to other climate variables (Supplementary Figs. 6–10). Total solar radiation reduction under SSP2-4.5-1.5 °C had the least significant impact on crop production, showing almost no areas of statistically significant yield reductions relative to SSP2-4.5 (Supplementary Fig. 10) compared with regional yield responses to other climate variables (Supplementary Figs. 6–10). These results will depend on the amount of SAI implemented, the scenario and time period analysed, and the crop model being used.

Discussion

Using a state-of-the-art climate model coupled to a crop model, we analysed impacts on crop production under 11 future climate change and climate intervention scenarios (Table 1). We then ran offline crop model simulations to better understand what changes to the climate are contributing to the impacts of SAI on maize, rice, soybean and spring wheat production.

The Community Earth System Model version 2 (CESM2) with the Whole Atmosphere Community Climate Model (WACCM6) showed a satisfactory ability to model crops and their interaction with the Earth system and was included in Coupled Model Intercomparison Project Phase 6 (CMIP6)[24]. CLM5crop has also been tested substantially[17,25–27]. CLM5crop did a reasonable job capturing interannual variability in global and national yields from a historic period (Supplementary Fig. 11). The CLM5crop historical simulation portrayed in Supplementary Fig. 11 was run at 2° resolution using the GSWP3 atmospheric forcing data with transient climate, CO_2, nitrogen deposition, land-cover change, irrigation and fertilization[28]. We have detrended the yield time series in Supplementary Fig. 11 since differences in the magnitude and trend of yield are primarily due to cultivars, technology, planting and harvest dates, irrigation and fertilization practices in the real world that are not relevant to this study. We have also included a non-detrended version of Supplementary Fig. 11 to better compare to other studies (Supplementary Fig. 12). The interannual variability of national yield reported by the Food and Agriculture Organization Corporate Statistical Database (FAOSTAT) is the combined result of changing agriculture management and interannual climate variation. In the model simulation, the interannual variability of yield is mainly due to climate variability. CLM5crop shows larger rice yield variation than FAOSTAT for some

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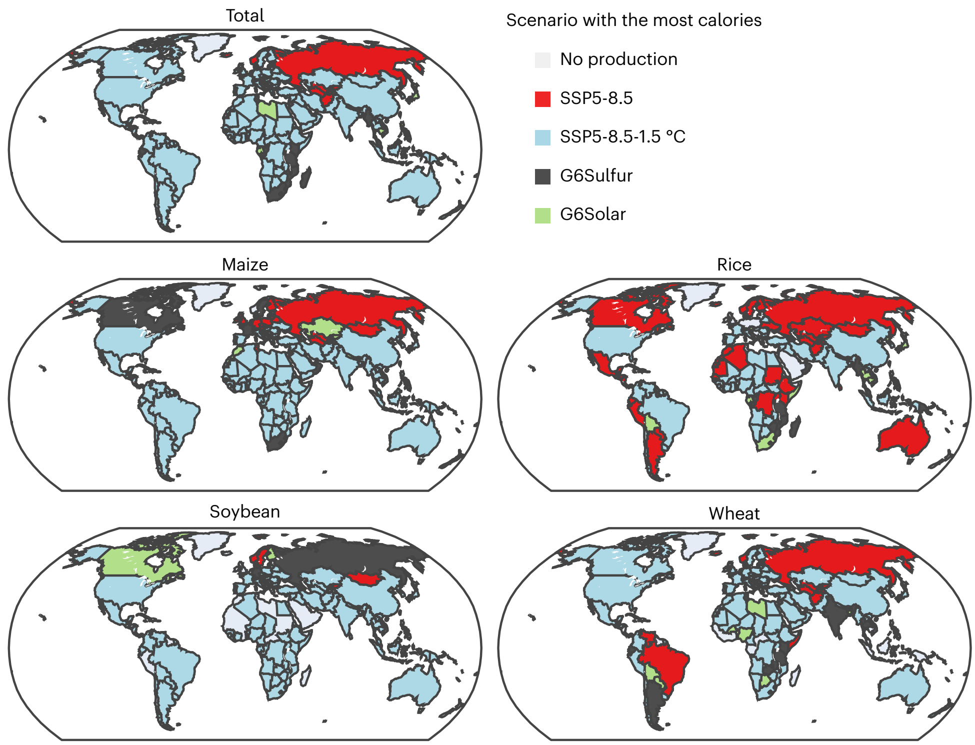

Fig. 5 | Climate change or SAI scenario that produces the most calories for each nation under SSP5-8.5. SSP5-8.5 scenarios that produce the most calories from total crop production (maize + rice + soybean + wheat) and from the individual crops maize, rice, soybean and wheat for each nation during the years 2060–2069.

countries, which is a known issue of seasonality within CLM5crop for Southeast Asia that is currently being updated[29]. Also, FAOSTAT reports yields for a certain year according to when most of the growing season for a nation occurs, so we have shifted the time series of simulated historical yields in Supplementary Fig. 11 if the correlation coefficient with the FAOSTAT time series was increased by at least 0.3 to better compare similarities in interannual variability[30,31]. CLM5crop's ability to simulate national time series of crop yield and production is comparable to that of other state-of-the-art process-based crop models[31]. While no crop model is perfect, CLM5crop's interannual response to changing climate makes it a valuable tool to understand how national yield and production will change under future climate scenarios. CLM5crop still needs to be improved with a better representation of impacts from extreme weather events, the inclusion of ultraviolet radiation impacts on crops and surface ozone impacts on crops, and updated assumptions about changing future agricultural planting and harvesting dates. Uncertainties in future changes to nitrogen fertilization and how CLM5crop handles CO_2 fertilization and responses to climate (such as temperature change) are areas of ongoing work. CLM5crop currently plants spring wheat everywhere wheat is grown. Including winter wheat in the future could impact the results. Moreover, to ensure a robust understanding of crop responses to different climate scenarios, a multi-crop model assessment is needed, since the findings of this study are derived from only a single model, and the inclusion of other models could lead to variations in the results. Further work is needed to update the model to include these parameters to paint a more complete picture of potential impacts on crops due to SAI, and analysis using multiple climate and crop models is needed to help reduce uncertainties.

Limiting global warming from anthropogenic greenhouse gas forcing using SAI benefits global production of maize, rice, soybean and wheat relative to climate change without SAI under all the scenarios we analysed. Climate intervention to limit anthropogenic warming while maintaining elevated CO_2 increases global calories from maize, rice, soybean and wheat by 12–24% during the decade 2060–2069, depending on the scenario, which is consistent with the most recent SAI crop modelling study that also used CLM5crop but a different climate model[17]. Benefits to crop production from SAI relative to climate change without SAI are dominated by heat-stress reduction. Solar dimming to represent SAI impacts on crops underestimates yields due to lacking a representation of diffuse radiation fertilization. Diffuse fertilization may dominate the yield response to radiative changes under small amounts of SAI, but larger amounts of aerosols may decrease yields due to a reduction in total solar radiation[32]. Although global production increases under SAI, there are production decreases for top producers of each crop under all climate intervention scenarios. It cannot be easily argued that trade can offset regional losses under SAI, as the world currently produces enough food to feed everyone on the planet, yet many still face food insecurity and starvation due to crop production being unevenly distributed around the world[29]. These patterns of regional food insecurity could be shifted or exacerbated by SAI implementation, making regional crop impacts from SAI an important consideration. High-latitude regions such as Russia and Canada show the largest decreases in crop production under climate intervention relative to climate change. The number of countries that produce fewer calories under SAI relative to climate change increases with more temperature limitation. No SAI temperature target benefits everyone. Different parts of the world maximize calories from crops under different temperature targets, with higher-latitude nations producing the most calories under unabated global warming, midlatitude nations under moderate temperature limitation and equatorial nations maximizing calories under high levels of climate intervention.

These results introduce important governance concerns related to SAI deployment. Although crop production in most nations increases under SAI relative to climate change, there would probably be decreases relative to warming in several top producing nations. Nations that do increase crop production under SAI would prefer different temperature targets to maximize the calories produced from crops. How would SAI deployment be governed? Many have argued that since SAI would

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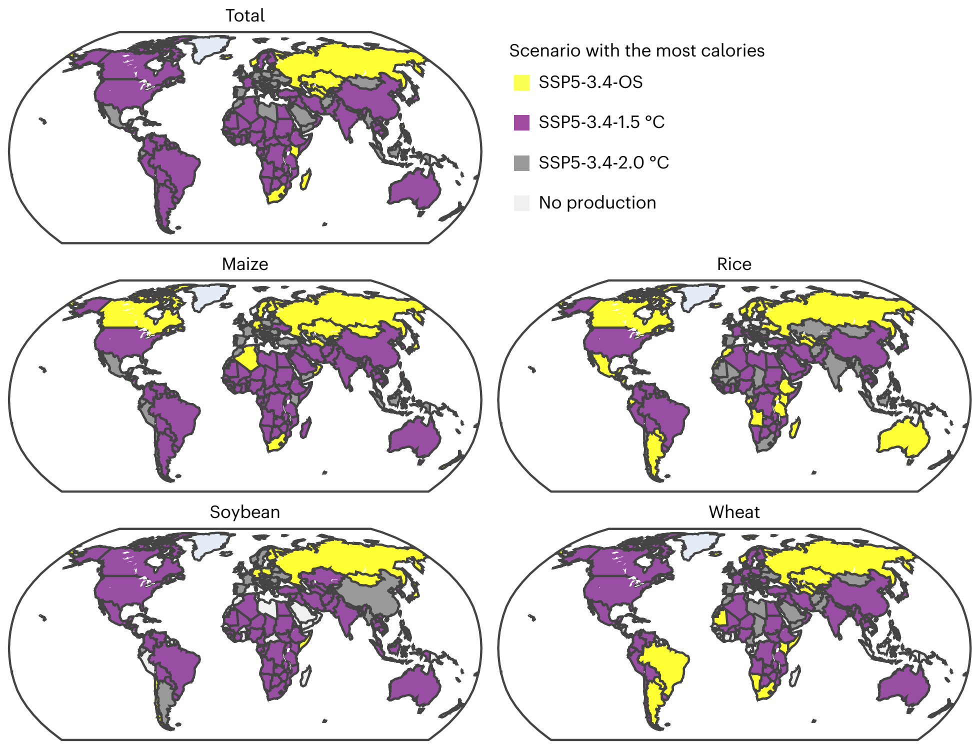

Fig. 6 | Climate change or SAI scenario that produces the most calories for each nation under SSP5-3.4-OS. SSP5-3.4-OS scenarios that produce the most calories from total crop production (maize + rice + soybean + wheat) and from the individual crops maize, rice, soybean and wheat for each nation during the years 2060–2069.

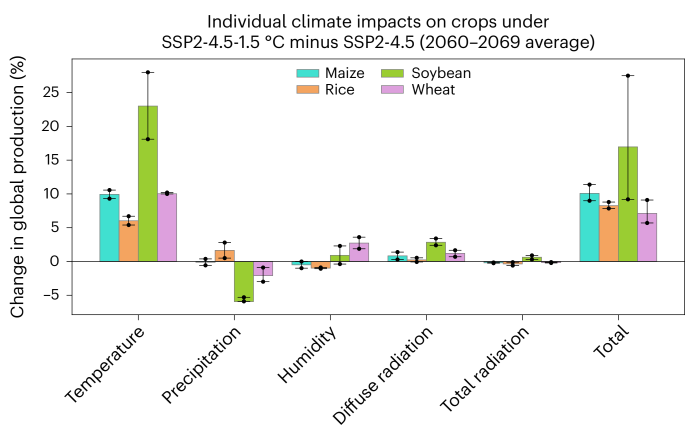

Fig. 7 | Individual climate impacts on crop production under SAI relative to climate change. Individual contributions to global crop production changes under SAI used to reduce global cropland temperatures by 1 °C under SSP2-4.5-1.5 °C relative to SSP2-4.5 during the years 2060–2069. The data are presented as ensemble mean values ± ensemble range of two ensemble members represented as points (n = 2).

impact all nations, universal agreement on deployment would be needed[33]. If an international group was charged with making a decision that accounted for the will of all or most nations in the world, coming to a decisive agreement would be challenging. It has also been argued that nations that would be harmed by SAI could be compensated in some way[33]. This method is unproven and would be challenging for many reasons. Associating climate or extreme weather impacts with SAI rather than with natural variability would be difficult[33,34]. Would harmful impacts be compared with some historical climate, or with the future climate without SAI[33,35]? Crop production is only a single metric, and incorporating the responses of other impact metrics to varying levels of climate intervention would only complicate the issue. Further work to better quantify the impacts of SAI and how SAI could be effectively governed is still needed to aid policymakers in decision making.

Methods

Model description

The climate change and climate intervention scenarios were simulated using CESM2(WACCM6) with troposphere, stratosphere, mesosphere and lower thermosphere chemistry, and CLM5 with coupled CLM5crop[24,25]. CESM2 is currently the only Earth system model with a built-in coupled crop model, making it ideal for analysing impacts on crops under future climates. WACCM6 has a resolution of 0.95° × 1.25° latitude–longitude with 70 vertical layers, reaching 150 km above sea level[18,36]. WACCM6 uses the updated four-mode version of the Modal Aerosol Module version 4 to represent tropospheric and stratospheric aerosol dynamics[37].

WACCM6 and other model components were coupled to CLM5 and CLM5crop. CLM5crop currently simulates only maize, rice, soybean, spring wheat, sugar cane and cotton. We chose to focus on maize, rice, soybean and spring wheat as those four crops comprise the majority of global food production as well as caloric consumption[30]. Land unit grid cells within CLM5 can be partitioned to include prescribed transient crop area when CLM5crop is active. Crops are planted and then transition through leaf emergence, grain fill and harvest phases[25]. To calculate yield, grain carbon is assumed to be 45% of the total dry weight, and a harvest efficiency of 85% is assumed for all crops[25]. The coupling between crops, the land surface and the atmosphere allows for the direct analysis of potential impacts on crops from changes in temperature, precipitation, CO_2, humidity and diffuse and direct radiation. Crop production was calculated using fully coupled CESM2–CLM5crop yield output and time-varying cropping area from the accompanying SSP scenarios. To determine how SAI would impact food production, yield output was converted to calories. Food caloric production is defined here as follows: Production (kilocalories per year) = Yield (tonnes per

Table 1 | Scenario names for climate change and climate intervention simulations with the years of the simulations and the number of ensemble members

Scenario	Years of analyses	Ensemble members	Mean temperature over cropland (°C) (2060–2069)
SSP2-4.5	2015–2070	10	19.6
SSP2-4.5-1.5 °C	2035–2070	10	18.6
SSP2-4.5-1.0 °C	2035–2070	2	17.6
SSP2-4.5-0.5 °C	2035–2070	2	17.0
SSP5-3.4-OS	2040–2100	3	20.1
SSP5-3.4-2.0 °C	2040–2100	3	19.0
SSP5-3.4-1.5 °C	2040–2100	3	18.3
SSP5-8.5	2020–2100	3	21.0
SSP5-8.5-1.5 °C	2020–2100	3	18.4
G6Solar (SSP5-8.5)	2020–2100	2	19.7
G6Sulfur (SSP5-8.5)	2020–2100	2	19.7

hectare per year) × Cropping Area (hectares) × Crop Nutritional Value (kilocalories per tonne)[30].

Description of simulations

Reference CMIP6 climate change scenarios SSP2-4.5, SSP5-3.4-OS and SPP5-8.5 (ref. 38) were simulated with accompanying climate intervention scenarios to limit anthropogenic warming to 0.5, 1.0, 1.5 or 2.0 °C above pre-industrial levels (Table 1). Different SSPs have varying amounts of nitrogen fertilizer application and land-use change. SSP2-4.5 is a medium-emission scenario, with the CO_2 concentration starting at 415 ppm in 2020 and increasing to 600 ppm by 2100 (ref. 38). SSP5-8.5 is an unmitigated high-emission scenario, with the CO_2 concentration growing rapidly throughout the twenty-first century from 415 ppm in 2020 to 1,100 ppm in 2100 (ref. 36). SSP5-3.4-OS starts in 2015 and goes to 2100; it follows SSP5-8.5 until 2040, and thereafter strong mitigation efforts (such as carbon dioxide removal) are implemented[38]. Even with strong mitigation and negative emissions starting in 2040, the CO_2 concentration still grows until 2065, when it reaches its peak of about 525 ppm (Fig. 1). All three climate change scenarios see an overshooting of both global average temperature targets set at COP21 of 1.5 and 2.0 °C above pre-industrial levels[39]. Temperatures above these targets have been deemed to have significant negative impacts on societies and ecosystems[40].

To simulate SAI, a feedback controller algorithm is used to calculate the amount of SO_2 injected into the stratosphere each year at 15° N, 15° S, 30° N and 30° S. This calculation is made every year depending on the previous year's global mean temperature, interhemispheric temperature gradient and equator-to-pole temperature gradient[41]. A more in-depth exploration of the SAI strategies considered is available in accompanying papers[18–20].

Scenarios following SSP5-3.4-OS use SAI to limit global mean warming to both COP21 targets of 1.5 and 2.0 °C above pre-industrial levels[18]. The scenario SSP2-4.5-1.5 °C limits warming to 1.5 °C under SSP2-4.5 and is named Assessing Responses and Impacts of Solar Climate Intervention on the Earth System with Stratospheric Aerosol Injection (ARISE-SAI-1.5)[19]. SSP2-4.5-1.0 °C and SSP2-4.5-0.5 °C reduce the global mean temperature increase to 0.5 and 1.0 °C above pre-industrial levels, below the warming targets set at COP21 (ref. 20). SSP2-4.5-1.0 °C and SSP2-4.5-0.5 °C were carried out with a simpler version of CESM2(WACCM6): one containing interactive chemistry only in the middle atmosphere and not in the troposphere. This is not expected to impact crop results, as the two versions show almost identical responses to large stratospheric aerosol loads[42]. These simulations start SAI in the year 2035. There is also a scenario that follows SSP5-8.5 and uses SAI to maintain temperatures of 1.5 °C above pre-industrial levels[18]. In this scenario, climate intervention begins in the year 2020. Additional simulations used in this study were run as part of the Geoengineering Model Intercomparison Project Phase 6 (ref. 23). These include G6Sulfur and G6Solar. G6Sulfur uses SO_2 injections to bring global mean temperatures from the high-emission climate change scenario SSP5-8.5 down to the medium-emission scenario SSP2-4.5, and G6Solar uses solar dimming to achieve the same temperature reduction[43]. Table 1 summarizes the key features of the simulations described above.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

Output from the CESM2(WACCM6) SSP2-4.5 and SSP2-4.5-1.5 °C is freely available at https://doi.org/10.26024/0cs0-ev98. CESM2(WACCM6) output from SSP5-8.5, SSP5-3.4-OS, Geoengineering Model Intercomparison Project G6Solar and G6Sulfur is freely available on Earth System Grid at https://esgf-node.llnl.gov/search/cmip6/. CESM2(WACCM6) output from SSP5-3.4-OS-2.0 °C, SSP5-3.4-OS-1.5 °C and SSP5-8.5-1.5 °C is available at https://doi.org/10.26024/t49k-1016. Coupled and offline CLM5crop postprocessed yield data are available at https://doi.org/10.6084/m9.figshare.24085797.v1. Historical yield observation data were obtained from FAOSTAT at https://www.fao.org/faostat/en/#data.

Code availability

The source code for the CESM(WACCM) model used in this study is freely available at https://www.cesm.ucar.edu/working_groups/Whole-Atmosphere/code-release.html, and the code for CLM5 is available at https://www.cesm.ucar.edu/models/cesm2/land/. Postprocessing and figure generation scripts can be found at https://github.com/bjc204/Clark_etal_NatureFood_2023.

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Acknowledgements

This work was supported by NSF grant nos. AGS-2017113 and ENG-2028541 awarded to A.R. and L.X. and by a gift from SilverLining's Safe Climate Research Initiative. This material is based on work supported by the National Center for Atmospheric Research, which is a major facility sponsored by the NSF under cooperative agreement no. 1852977. Computing and data storage resources, including the Cheyenne supercomputer (https://doi.org/10.5065/D6RX99HX), were provided by the Computational and Information Systems Laboratory at the National Center for Atmospheric Research. We thank H. Stephens for developing the yield conversion script.

Author contributions

B.C., L.X. and A.R. designed the study. S.T., J.H.R. and D.V. conducted the climate model simulations. B.C., S.S.R. and L.X. conducted the offline crop model simulations. B.C. analysed the data with contributions from all the authors. B.C., L.X. and A.R. wrote the first draft, and all authors contributed to editing and revising the paper.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s43016-023-00853-3.

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Peer review information *Nature Food* thanks the anonymous reviewers for their contribution to the peer review of this work.

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Data collection	Data is computer output. No software was used for data collection.
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SSP5-8.5, SSP5-3.4-OS, GeoMIP G6Solar and G6Sulfur are freely available on Earth System Grid at https://esgf-node.llnl.gov/search/cmip6/. CESM2(WACCM6) output from SSP5-3.4-OS-2.0°C, SSP5-3.4-OS-1.5°C, and SSP5-8.5-1.5°C are available at https://doi.org/10.26024/t49k-1016. Coupled and offline CLM5crop postprocessed yield data is available at https://doi.org/10.6084/m9.figshare.24085797.v1. Historical yield observation data was obtained from Food and Agriculture Organization Corporate Statistical Database (FAOSTAT) at https://www.fao.org/faostat/en/#data.

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Study description	We used a climate and crop model to simulate the impact of stratospheric aerosol climate intervention on national crop production when used to limit global temperature to different targets.
Research sample	We used one climate model and one crop model forced by 11 different climate change and stratospheric aerosol climate intervention scenarios.
Sampling strategy	We used a total of 43 ensemble members across the 11 different scenarios output by the climate model.
Data collection	Data was used from coupled climate-crop model output. Climate model output was then used to force the crop model to test individual climate impacts under stratospheric aerosol climate intervention.
Timing and spatial scale	The climate and crop model output data at 0.95° × 1.25° latitude-longitude resolution and the crop model outputs yield data at monthly time intervals.
Data exclusions	No data exclusion.
Reproducibility	All data can be reproduced from utilizing the same climate and crop model output. Offline crop model runs can be reproduced from using the same climate model forcing. All data is available under data availability.
Randomization	The use of multiple ensemble members for each scenario acts to reduce noise due to internal variability, and additional randomization is not applicable to this study.
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