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Impacts on Indian Agriculture Due To Stratospheric Aerosol Intervention Using Agroclimatic Indices

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Key Points:

- Climate intervention could benefit rainfed wheat more than irrigated crops in India, with regional differences for rainfed rice
- Climate intervention could maintain temperatures in all growth stages and monsoon rainfall but would not stop winter precipitation changes
- From a climatic standpoint, shifting planting dates may offer relief under global warming but might not be feasible in all cases

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract

Climate change poses significant threats to global agriculture, impacting food quantity, quality, and safety. The world is far from meeting crucial climate targets, prompting the exploration of alternative strategies such as stratospheric aerosol intervention (SAI) to reduce the impacts. This study investigates the potential impacts of SAI on rice and wheat production in India, a nation highly vulnerable to climate change given its substantial dependence on agriculture. We compare the results from the Assessing Responses and Impacts of Solar climate intervention on the Earth system with Stratospheric Aerosol Injection-1.5°C (ARISE-SAI-1.5) experiment, which aims to keep global average surface air temperatures at 1.5°C above preindustrial in the Shared Socioeconomic Pathway 2-4.5 (SSP2-4.5) global warming scenario. Yield results show ARISE-SAI-1.5 leads to higher production for rainfed rice and wheat. We use 10 agroclimatic indices during the vegetative, reproductive, and ripening stages to evaluate these yield changes. ARISE-SAI-1.5 benefits rainfed wheat yields the most, compared to rice, due to its ability to prevent rising winter and spring temperatures while increasing wheat season precipitation. For rice, SSP2-4.5 leads to many more warm extremes than the control period during all three growth stages and may cause a delay in the monsoon. ARISE-SAI-1.5 largely preserves monsoon rainfall, improving yields for rainfed rice in most regions. Even without the use of SAI, adaptation strategies such as adjusting planting dates could offer partial relief under SSP2-4.5 if it is feasible to adjust established rice-wheat cropping systems.

Plain Language Summary

Climate change is causing significant problems for farming worldwide, affecting food quantity, quality, and safety. To tackle this, some are exploring new strategies like stratospheric aerosol intervention (SAI). This study focuses on how SAI could impact rice and wheat farming in India, a country highly dependent on agriculture and vulnerable to climate change. Yield results from a crop model suggest that SAI could increase rice and wheat yields relative to climate change, particularly rainfed rice and wheat in particular locations, but the differences are not significant over most of India for irrigated crops. Using an experiment called ARISE-SAI-1.5, we evaluate 10 agroclimatic factors that can influence rice and wheat at different growth stages to determine the reasons for these yield changes. We find that SAI could potentially reduce some of the negative effects of global warming with a medium emission path, including reducing extreme heat days and retaining the summer monsoon. SAI benefits rainfed rice and wheat especially during their sensitive growth stages, which could be important in a future where maintaining irrigation systems may not be sustainable. Without SAI, while adaptation strategies like adjusting planting dates could help with mitigating the effects, uncertainties remain.

1. Introduction

1.1. Climate Change and Agriculture

Climate change has already begun to negatively affect food systems around the world, impacting the quantity, quality, and safety (favorable conditions for pathogens and pests) of food produced (Bezner Kerr et al., 2023). The productivity growth rate of agricultural systems in tropical and mid-latitudes has also begun to decline despite advancements in management, such as fertilizers and pesticides (Bezner Kerr et al., 2023), and agricultural models suggest climate impacts on major crop yields could emerge even before 2040 (Jägermeyr et al., 2021). Under a high emissions scenario like Shared Socioeconomic Pathway 5–8.5 (SSP5-8.5), 10% of current land used for food production could become unsuitable for crops and livestock by 2050 (reaching 30% by 2100) (Bezner Kerr et al., 2023). Under SSP2-4.5, a medium emissions scenario, 14.3% of global rice cropland and 20.6% of spring wheat cropland may require new crop varieties by 2100 in order to avoid yield losses (Zabel et al., 2021). Yet, according to the Food and Agriculture Organization (FAO), to meet the needs of a growing population, the

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world will need to increase food production by 70% of 2009 levels by 2050 (FAO, 2020b). The estimated impacts on agriculture would thereby threaten the food security of an additional eight million (SSP1-6.0) to 80 million (SSP3-6.0) people around the world depending on the ultimate emission path (Bezner Kerr et al., 2023). Aside from food security, increased crop failures will also alter crop prices, which will have ripple effects in other sectors such as meat production from livestock, clothing, and energy.

1.2. Current Trajectory and Solar Radiation Modification

Current emissions and climate policies indicate that the world is significantly off course from achieving the Paris Climate goal of capping global warming at 1.5°C above preindustrial temperatures, which roughly corresponds to the scenarios SSP1-1.9 or SSP1-2.6 (Lee et al., 2021; United Nations Environment Programme, 2023). Emissions projections are not even on track to achieve the less ambitious but still critical goal of 2°C. With the current climate policies in place, average global temperature increases would reach 2.9°C by 2100 (United Nations Environment Programme, 2023). Even considering the current conditional national contribution pledges, this still would only bring the peak warming down to 2.5°C (United Nations Environment Programme, 2023). According to multi-model averages from the Coupled Model Intercomparison Project Phase 6, these global mean temperatures roughly align with middle emission scenario SSP2-4.5 (mean: 2.9%; 5%–95% range: 2.1–4.0) (Lee et al., 2021).

These estimates and the already growing impacts of climate change have inspired increased interest in investigating alternative methods for curbing the warming, like climate intervention. Climate intervention strategies include carbon dioxide removal and solar climate intervention, or solar radiation modification (SRM). SRM is the intentional manipulation of the planet's radiative budget to offset anthropogenic warming and may be necessary to avoid the harms of exceeding the 1.5°C target (Crutzen, 2006; Irvine et al., 2019; Lawrence et al., 2018; MacMartin et al., 2018). However, while these studies suggest that SRM could indeed help prevent the worst of the warming, it will certainly come with side effects that need to be considered. One of the main impacts of concern is the change in precipitation patterns. Past studies have found SAI to lead to shifting precipitation regimes and drying of monsoon regions (Bal et al., 2019; Bala et al., 2008; Bhowmick et al., 2021; Kravitz et al., 2017; Robock, 2020; Robock et al., 2008; Simpson et al., 2019; Tilmes et al., 2013).

Stratospheric aerosol intervention (SAI) is one proposed SRM scheme, inspired by the effects of large volcanic eruptions, that proposes to inject sulfate aerosols into the stratosphere to reflect incoming solar radiation. Here we investigate one possible implementation strategy, which includes a feedback algorithm to determine the annual SO_2 injection amount and locations to maintain the global mean temperatures at 1.5°C above preindustrial levels, despite greenhouse gas concentrations matching SSP2-4.5 (J. Richter, Visioni, Macmartin, Bailey, et al., 2022). This scenario differs from past experiments with its moderate injection strategy, while many others have utilized SSP5-8.5 or doubled or quadrupled CO_2 as the background scenario with equatorial injections to offset all of the warming (Bal et al., 2019; Bala et al., 2008; Kravitz et al., 2017; Simpson et al., 2019; Tilmes et al., 2013). The benefits and risks of SAI have been enumerated (Robock, 2020), but many of the impacts are still underexplored. One crucially underexplored impact is the effect SAI could have on agriculture.

1.3. Agriculture in India

Agriculture is a vital industry in India. As of 2016, India ranked first in the world in terms of total cropland area, at about 170 million hectares (FAO, 2020a). Agriculture employs 45% of its labor force and accounts for 15% of the national gross value added (India's Ministry of Statistics and Programme Implementation, 2023). India is the world's largest producer of pulses and the second-largest producer of rice, wheat, sugarcane, cotton, groundnuts, fruits, and vegetables (FAO, n.d.), generating $50.21 billion in total agriculture exports in 2022 (Ministry of Commerce & Industry, 2022).

A 2021 report by the USDA Foreign Agricultural Service states that India is particularly vulnerable to climate change due to its economy's large reliance on agriculture and the large portion of non-irrigated cropland (Rosmann & Singh, 2021). They note that monsoon season crops (kharif crops), such as rice, are more sensitive to changes in precipitation, while winter (rabi) crops, such as wheat, are more sensitive to increasing temperatures. Under a scenario like SSP2-4.5, the probability of below-average wheat yields could increase by up to 15% (Zachariah et al., 2021). With ever-shortening winters, wheat is already being exposed to harmful warmer temperatures in February and March, which usually coincides with the temperature-sensitive reproductive and ripening stages of growth, and in the fall when it is sown (Sharma et al., 2020). These rising temperatures also make it increasingly difficult and dangerous for farmers to cultivate and harvest their crops. Wheat will also be affected by reduced irrigation capacity due to variable rainfall and reduced glacial melt under global warming (Rosmann & Singh, 2021). Rice would be negatively affected by rising temperatures as well. In Uttar Pradesh, the second largest rice producing state in India, rice yields would decrease under SSP2-4.5 and SSP5-8.5 even under irrigated conditions due to higher temperatures (Singh et al., 2024). While some crops, like pulses and chickpeas, may benefit from projected climate change, wheat and irrigated rice yields are predicted to decline by 6%–25% and 8% by 2100, respectively (Rosmann & Singh, 2021).

1.4. Agroclimatic Indices

This study utilizes agriculturally relevant climate indices to assess the potential impact to rice and wheat production. These kinds of metrics have been used in numerous studies to investigate trends, mechanisms, and impacts of climate on agricultural production (Chou et al., 2021; Mathieu & Aires, 2018; Rani et al., 2022; Sharma et al., 2020; Sun et al., 2016; Vogel et al., 2019; Zeleke et al., 2023; Zhao et al., 2022; Zhu & Troy, 2018). These kinds of indices offer several advantages. Agroclimatic indices tend to rely on daily data to capture extremes that are often obscured by monthly averages (Zhang et al., 2011; Zhao et al., 2022). Monthly or seasonal mean temperature or precipitation may appear appropriate or beneficial to a crop, but even one day of extreme heat, freezing temperatures, damaging winds, or heavy rain can damage crops, impacting the final quantity and/or quality. There are also many complex interactions that occur on short timescales within a plant based on its atmospheric, hydrological, and pedological environment, as well as management choices by the farmers. This makes accurately modeling crop yields and determining the cause of crop failures or damage a challenge (Zhao et al., 2022). Agroclimatic indices offer a way to quantify the exposure of crops to certain stressors (Zhu & Troy, 2018), which allows local users or subject experts to then consider the potential impacts on their own field or region. They can also serve to investigate the reasons for crop improvement or failure, offering a useful tool for assessing the potential impacts and mechanisms behind changes under climate change and climate interventions.

Given the importance of rice and wheat production in India, the declines in production already being witnessed, and the risk of SAI disrupting the precipitation patterns in an already vulnerable region, it is of vital importance to assess SAI's potential regional impacts on the economy, livelihoods, and food security of the most populous country on Earth. This study assesses the potential impacts of SAI on these crops by using agroclimatic indices during the main growth stages of rice and wheat in India. It utilizes one of the latest and most policy-relevant SAI experiments, ARISE-SAI-1.5, to explore whether SAI could ameliorate the stresses on agricultural production in India or worsen them.

2. Methods

2.1. Model and Experiments

This study utilizes the climate model output of the SSP2-4.5 and ARISE-SAI-1.5 experiments simulated by the Community Earth System Model (version 2) with the Whole Atmosphere Community Climate Model (version 6) (CESM2-WACCM6) (Danabasoglu et al., 2020). The WACCM6 model boasts major advancements in stratospheric as well as aerosol modeling (Danabasoglu et al., 2020; Gettelman et al., 2019) with a horizontal resolution of 0.95° × 1.25° and 88 vertical levels (Danabasoglu et al., 2020). Improved chemistry models allow the WACCM6 model to prognostically determine features like stratospheric aerosols, which greatly improved its ability to model high-latitude climate variability and stratospheric processes (Danabasoglu et al., 2020; Gettelman et al., 2019) of particular importance for research on SAI. We also include crop production output from the Community Land Model version 5 Crop model (CLM5crop) (Lombardozzi et al., 2020) that simulated the ARISE-SAI-1.5 scenario. CESM2 is the only Earth system model with a coupled crop model allowing for feedbacks between agriculture and climate (Clark et al., 2023). For more details on crop model simulations, refer to Clark et al. (2023).

The ARISE-SAI-1.5 experiments (J. Richter, Visioni, Macmartin, Bailey, et al., 2022) reduce the global temperature from that of SSP2-4.5 to 1.5°C above preindustrial by injecting sulfur dioxide gas, which converts to sulfate, into the stratosphere beginning in 2035 using a feedback algorithm (Kravitz et al., 2017; MacMartin et al., 2018) to maintain the mean global temperature, the equator-to-pole temperature difference, and the interhemispheric temperature gradient. The years 2020–2039 serve as the baseline for ARISE-SAI-1.5 because

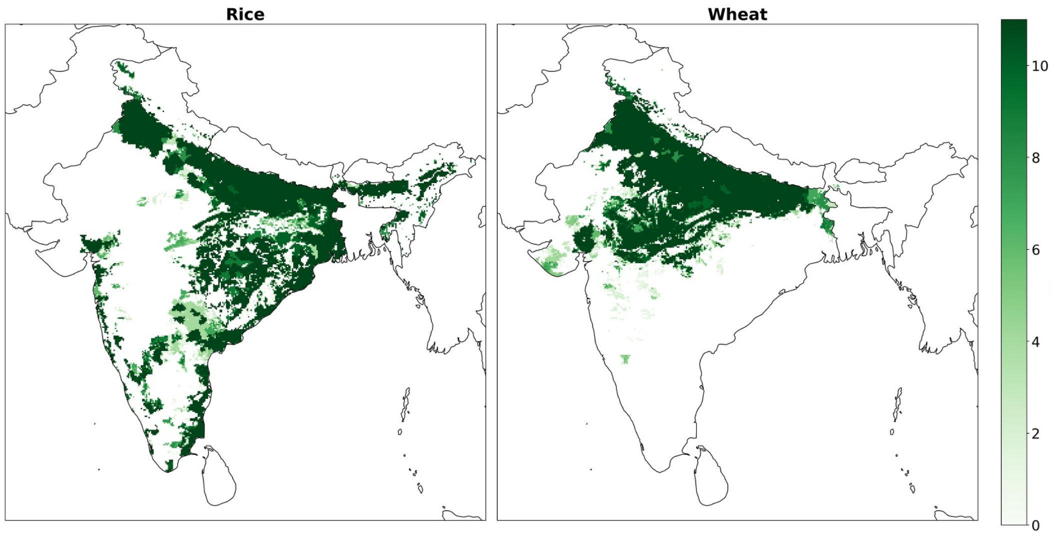

Figure 1. Maps of updated rice and wheat crop area in India from Ray et al. (2019). Maps show the number of years in which a location had a crop area grid cell fraction of at least 0.1 from 2010 to 2020.

that is when the climate system could reach 1.5 K of warming, based on observations of temperature and climate model estimates from CMIP6 (J. Richter, Visioni, Macmartin, Bailey, et al., 2022). CESM2-WACCM6 reaches 1.5 K above preindustrial during the years 2016–2035 (Henry et al., 2023). We define our control period as 2015 to 2034 of the SSP2-4.5 scenario to maximize the difference between the beginning and end of the simulation given the shorter duration. Since the feedback control algorithm maintains average temperature during the years 2020–2039, which represents 1.58 K above preindustrial (Henry et al., 2023), we expect some residual warming compared to our control period. There were 10 ensemble members available for ARISE-SAI-1.5–shortened to ARISE from here on–and five ensemble members for SSP2-4.5 with daily output for maximum temperature, minimum temperature, and precipitation. The years 2050–2069 are selected as the analysis period.

2.2. Crop Seasons

In India, rice and wheat are grown primarily in the eastern half and northern parts of the country, respectively. We created a mask using an updated version of the data used in Ray et al. (2019) to select only the regions where rice and wheat are currently grown by selecting any grid cell in which at least 10% of the grid cell was dedicated to rice or wheat cropland for at least 5 of the 11 years from 2010 to 2020 (Figure 1). The data were then resampled to match the model resolution.

Across those regions, crops are sown on various dates based on the local climate, weather, crop rotation system, and other factors. Rice is typically planted any time from May to August and harvested from September to January. Wheat is usually sown any time from October to December and harvested from February to June (Sharma et al., 2020). We used May 15th as the earliest sowing date and Aug 30th as the latest date for rice, while wheat can be planted from Oct 15th to Dec 31st. To represent the many possible sowing dates in India and test how shifting planting dates could serve as a potential adaptation, starting from the first planting date, the sowing date is incremented by 7 days until the last possible sowing date. This results in 16 planting dates for rice and 12 planting dates for wheat.

This study differs from many others in its treatment of stage-specific stressors. Most impact studies only assess stresses over the entire growing season, but heat stress, cold stress, and moisture stress are not equally damaging across the growth cycle. Certain stages of growth are more or less sensitive to certain weather conditions. For simplicity, the growth cycle of rice and wheat is divided into three stages: vegetative, reproductive, and ripening. For rice, the vegetative stage comprises the germination, seedling, tillering, and stem elongation stages. The reproductive stage includes panicle initiation, booting, heading, and flowering (anthesis). The ripening stage represents the milk, dough, and maturity stage. For wheat, we consider germination, emergence, seedling, crown root stage, tillering, and jointing as the vegetative stage. Reproductive encompasses booting, heading, and

Table 1
Description of Agroclimatic Indices Used in This Study

				Thresholds	
Index	Names	Units	Variable	Wheat	Rice
HD	Hot Days	Days	T-max	>34°C	>35°C
TR	Tropical Nights	Days	T-min	>20°C	>20°C
WSDI	Warm Spell Duration Index	Days	T-max	>23°C	>30°C
CSDI	Cold Spell Duration Index	Days	T-min	<15°C	<20°C
PRCPTOT	Total precipitation	mm	Precipitation	-	-
R5	Dry Days	Days	Precipitation	<5 mm	<5 mm
R20	Very Wet Days	Days	Precipitation	>20 mm	>20 mm
Rx5day	Wettest 5-day Period	mm	Precipitation	-	-
CDD	Maximum consecutive dry days	Days	Precipitation	<1 mm	<5 mm
CWD	Maximum consecutive wet days	Days	Precipitation	>1 mm	>10 mm

flowering (anthesis), and ripening includes grain-filling (milk and dough development) and physical maturity. Generally, the vegetative stages are more sensitive to moisture stresses, the reproductive stages to heat stress, and the ripening stages to extreme precipitation and heat. In reality, the durations of each growth stage are highly variable due primarily to the choice of cultivar and the temperature. Due to the design of this study with fixed length growth stages, we do not capture the effect that high temperatures have on shortening the duration of growth stages in the calculation of the indices (Batts et al., 1996; Mamrutha et al., 2020; Sofield et al., 1977; Tashiro & Wardlaw, 1989; Wardlaw & Moncur, 1995; Yoshida, 1981). The lengths of the three growth stages are chosen to be 65, 35, and 30 days for rice (IRRI, n.d.; Sharma et al., 2020) and 70, 35, and 35 days for wheat (Acevedo et al., 2009).

2.3. Indices

The indices used in this analysis are summarized in Table 1. They are adapted from those developed by the Expert Team on Climate Change Detection and Indices (Karl et al., 1999; Peterson et al., 2001) and those utilized by Zhu and Troy (2018). Indices pertinent and damaging to Indian rice and wheat were chosen from these lists and adapted to this context, seeking to capture changes to extreme heat, heavy rain, and low precipitation periods. Some changes include redefining the warm and cold spell duration indices (WSDI and CSDI). Rather than the 10th and 90th percentiles as thresholds, we utilize the optimal temperature ranges for wheat and rice as defined by the FAO (see values in Table 1). R5 is redefined as the number of days with total precipitation below 5 mm instead of above, and for rice, the maximum consecutive wet and dry day (CWD and CDD) index thresholds are increased to 10 and 5 mm, respectively, to scale with the monsoon season. Indices are calculated over the control period (2015–2034 of SSP2-4.5) and test period (2050–2069) for each growth stage and each planting date for rice and wheat, based on daily minimum temperature, maximum temperature, and total precipitation. Statistical significance for indices is calculated using all five ensemble members for the control period to determine the 95% confidence intervals.

Hot days are defined for wheat as those above 34°C, above which senescence occurs leading to decreased photosynthetic rates (Al-Khatib & Paulsen, 1999; Lobell et al., 2012), and above 35°C for rice above which spikelet sterility occurs leading to reduced grain number and yield (Matsui et al., 1997; Sakai et al., 2022; Satake & Yoshida, 1978; Wassmann et al., 2009). Tropical nights are ideal for rice but can be detrimental to wheat (García et al., 2016; Prasad et al., 2008; Sridevi & Chellamuthu, 2015; Su & Kuo, 2023). When nighttime temperatures exceed 20°C around anthesis, grain-filling is shortened, spikelet fertility is reduced, and grain size and number decrease (García et al., 2016; Prasad et al., 2008). WSDI and CSDI, which count the number of days contributing to warm or cool spells (at least 5 consecutive days above or below the threshold), indicate when a crop could be performing sub-optimally. One or 2 days above or below their optimal range will not kill the plant, but if conditions are consistently outside of the optimal range, subpar yield results can be expected (Sridevi &

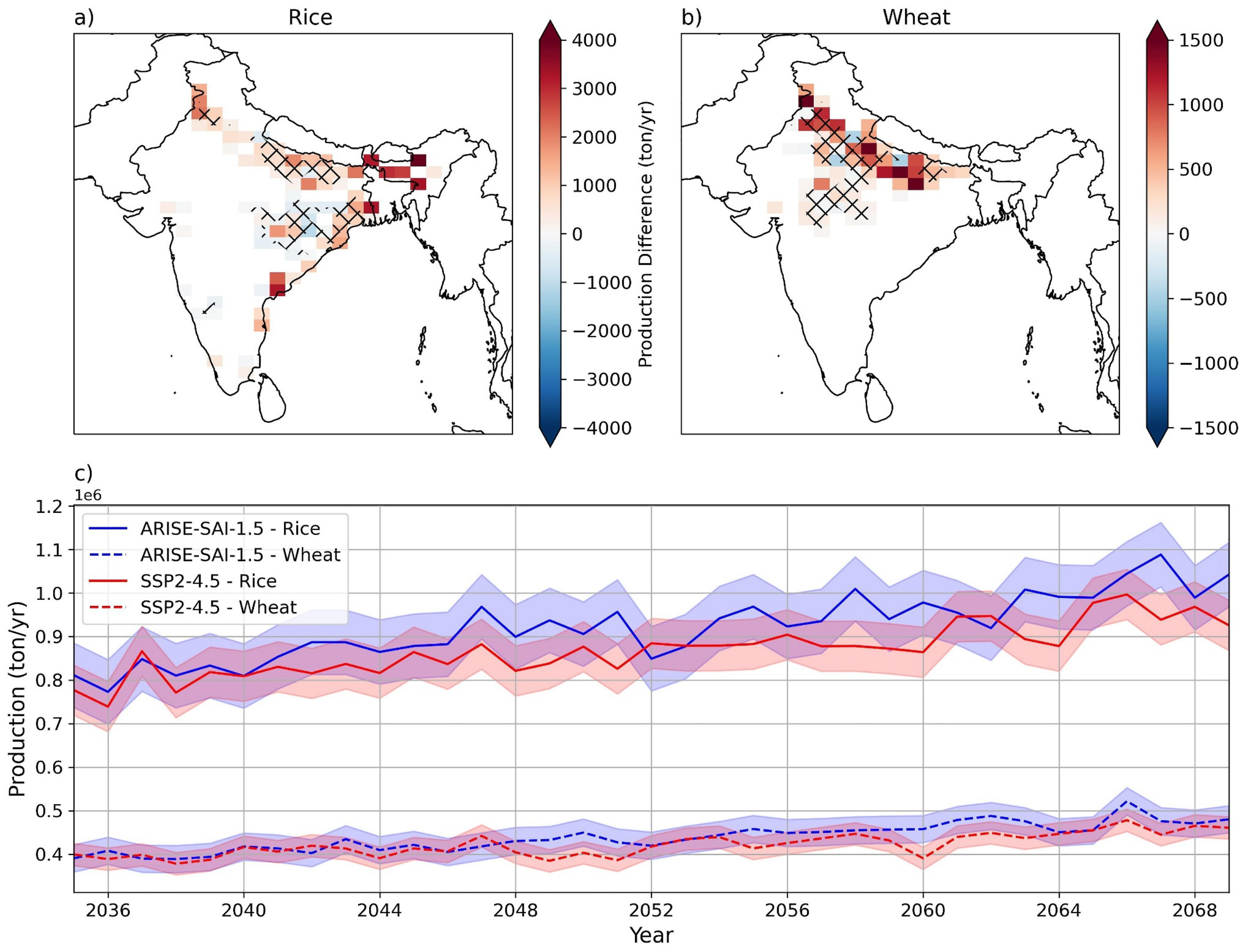

Figure 2. Production differences (yield times crop area) in millions of tons per year between ARISE-SAI-1.5 and SSP2-4.5 from CLM5crop. Rice (a) and wheat (b) production are averaged over 2050–2069. Hatches indicate the difference between the two experiments is insignificant. Total Indian rice and wheat production time series (c). Shading represents the range corresponding to one standard deviation.

Chellamuthu, 2015). This can cause grain filling to be stifled or rushed, affecting the final size of the grain and reducing yield (Sofield et al., 1977; Tashiro & Wardlaw, 1989; Wardlaw & Moncur, 1995; Yoshida, 1981).

The amount of total precipitation received by crops during their life cycle is very important, especially for rainfed rice, but its distribution is even more important (Sridevi & Chellamuthu, 2015). For example, a month's worth of water over a couple of days is worse for the crop than slightly deficient rainfall but steadily distributed over a month (Sridevi & Chellamuthu, 2015). The other precipitation indices can indicate how evenly distributed the precipitation is and how moisture levels may be impacted. Especially during ripening and harvesting, moist conditions can encourage pest or disease outbreaks, and soaked soils can cause plants to fall or make harvesting difficult (Shah et al., 2017). Heavy rainfall can directly damage crops, limit nitrogen availability, or interrupt pollination (Fu et al., 2023). Extended dry periods can be beneficial during some stages but harmful during others. Similarly, many wet days in a row can indicate ample moisture available to the crops or lead to waterlogging and certain pests or diseases.

3. Results

Results from CLM5crop show that ARISE leads to more total rice production in India when averaged across 10 ensemble members (Figure 2c). For wheat, there is also improvement but minimal. However, when considering the standard deviation across ensemble members, the overlap suggests that differences for both wheat and rice are

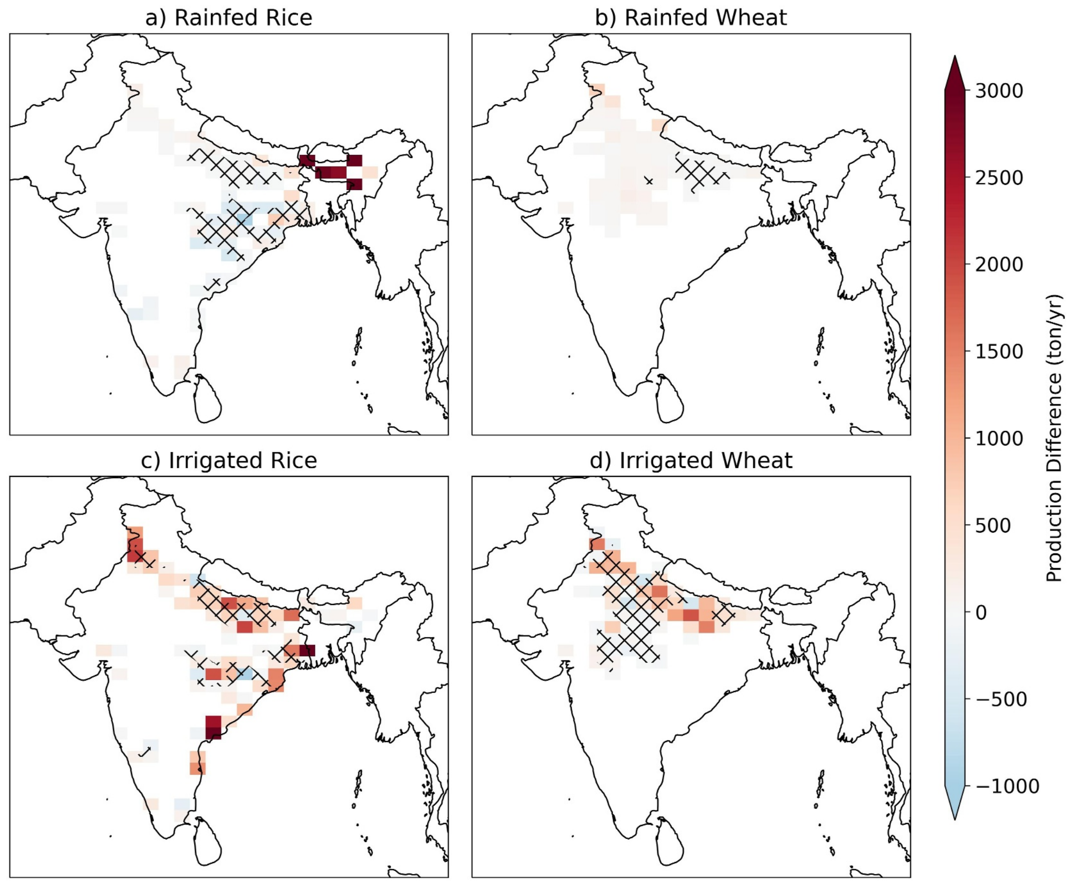

Figure 3. Production differences (yield times crop area) between ARISE-SAI-1.5 and SSP2-4.5 from CLM5crop. Increases indicate ARISE-SAI-1.5 leads to more production than SSP2-4.5. Rainfed rice (a) and wheat (b) and irrigated rice (c) and wheat (d) production are averaged over 2050–2069. Hatches indicate the difference between the two experiments is insignificant.

potentially insignificant. Indeed, over most of India, the 2050–2069 averaged differences between ARISE and SSP2-4.5 are statistically insignificant (Figures 2a and 2b). However, when isolating rainfed rice and wheat (Figures 3a and 3b), there are a few locations with large and significant increases in production, such as northeast India near Assam for rice and northern India near Himachal Pradesh for wheat. Irrigated rice and wheat results are largely insignificant, but there are scattered locations with improvements under ARISE. Given that conditions are typically hotter than optimal in India, the reduction in temperature should indeed improve yields. When normalizing for total production under SSP2-4.5 (Supplemental Figure 1 in Supporting Information S1), we find small reductions in rainfed rice production in southwestern India and large relative increases in northwestern India. When normalized, rainfed wheat has relatively large increases for nearly all growing areas, not just near Himachal Pradesh.

3.1. Rice

To understand these production results, we turn to the selected agroclimatic indices. Many of the indices proved inconsequential due to minimal changes or similar patterns of change to other indices. All results can be found in the supplementary material. The most salient results are shown in the main text. For temperature, ARISE maintains values near the reference period levels for nearly all four indices and all three growth stages (see results for HD in Figure 4). The residual warming is likely explained by the choice in control period as discussed in the Methods section. Under SSP2-4.5, parts of southern India experience 15 or more additional days above 35°C during the vegetative period. While this stage is not particularly sensitive to heat (Sánchez et al., 2014; Sridevi & Chellamuthu, 2015), the contrast between SSP2-4.5 and ARISE is sizable, and the heat could still impact workers. These temperature results would suggest rice yields across India should increase under SAI. Although the crop

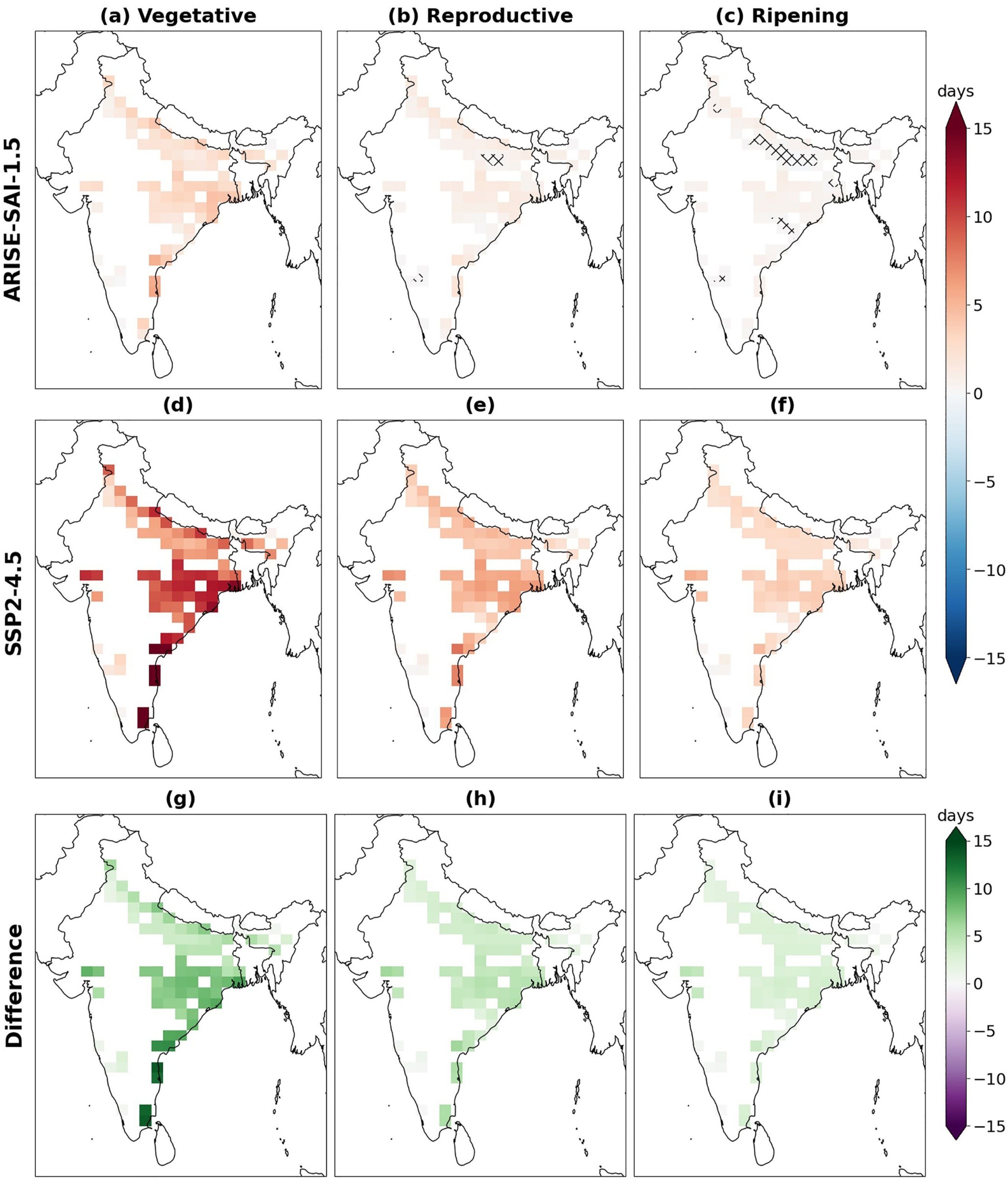

Figure 4. Difference between 2050–2069 and 2015–2034 agroclimatic index HD during the rice vegetative, reproductive, and ripening stages. Positive changes indicate an increase compared to the control period. Hatching indicates results are statistically insignificant at the 95% confidence level. The differences (g–i) show SSP2-4.5 minus ARISE, such that green represents warmer conditions under SSP2-4.5 compared to ARISE.

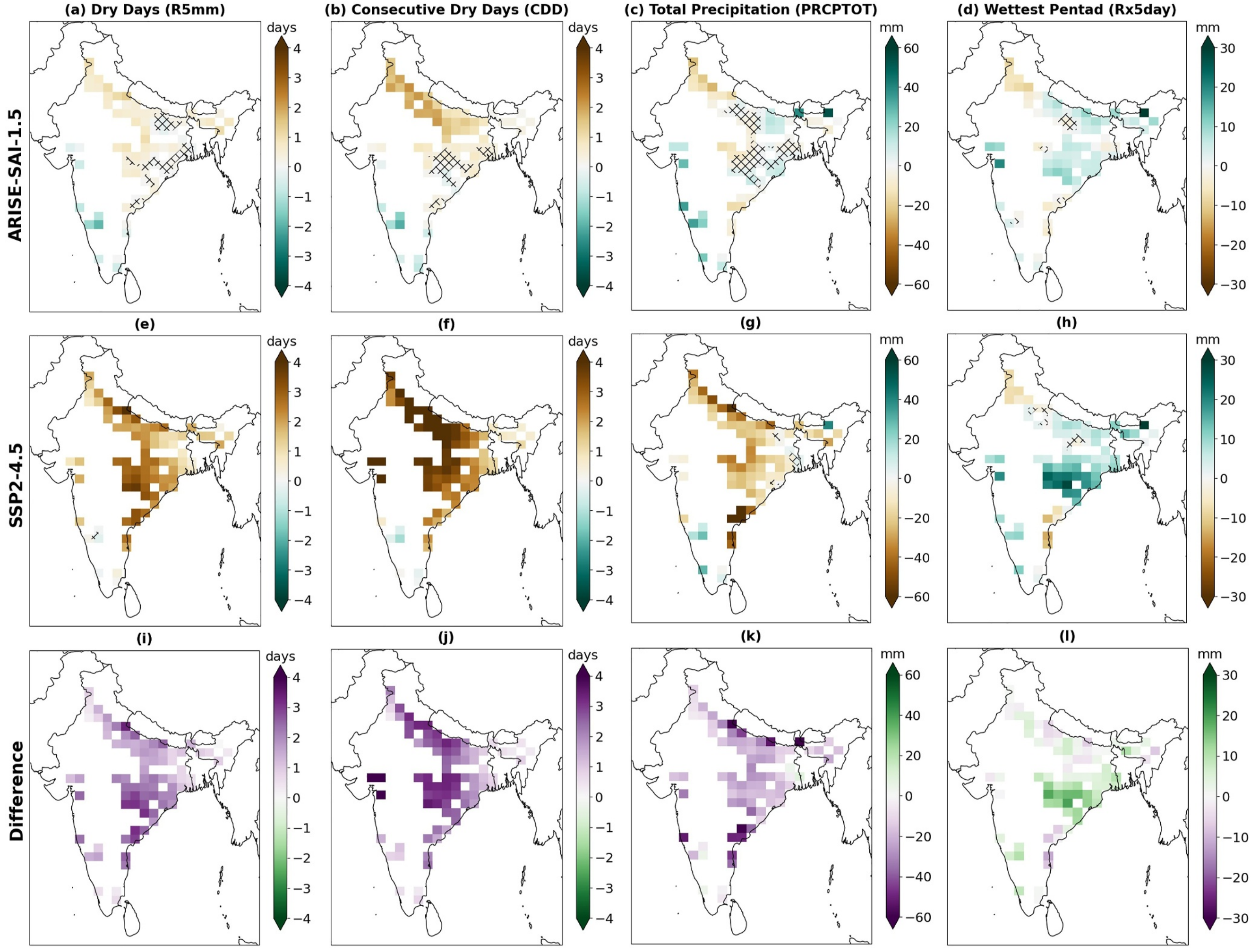

Figure 5. Difference between 2050–2069 and 2015–2034 agroclimatic indices R5, CDD, PRCPTOT, and Rx5 day during the rice vegetative period. Indices are calculated over 16 65-day periods starting in mid-May, then averaged over all ensemble members and all 16 sowing dates. Positive changes indicate an increase compared to the control period. Hatching indicates results are statistically insignificant at the 95% confidence level. The differences (i–l) show SSP2-4.5 minus ARISE, such that green represents wetter conditions under SSP2-4.5 compared to ARISE.

model simulated rice yields increase in most regions under SAI, southwestern India showed reductions in rice production. The temperature difference between ARISE and SSP2-4.5 in this region is smaller than the rest of the country for all three stages. Northeastern India also experiences minor differences in HD between the two experiments, though there is a reduction in warm spells during reproductive and ripening growth (Supplemental Figures 5 and 8 in Supporting Information S1). With minimal temperature benefits, precipitation changes are likely the reason for the production changes in southwest India, while northern India may have benefited from temperature and precipitation changes alike.

For precipitation, we highlight changes in PRCPTOT, CDD, R5, and Rx5 day. For all vegetative results, refer to Figures S2–S4 in Supporting Information S1). During the vegetative period (Figure 5), R5 and CDD decrease, and PRCPTOT increases under ARISE in southwestern India. The precipitation changes under SSP2-4.5 are more complex for this region. PRCPTOT increases in southwestern India, but further north PRCPTOT decreases. This pattern of drying also appears for R5 and CDD, but not Rx5 day. This suggests that under SSP2-4.5 during the monsoon season, southwest India along with most of the rice growing regions experience less evenly distributed rainfall in exchange for more sporadic, heavy rainfall periods. During the vegetative period, receiving enough rain to maintain properly flooded conditions is crucial, but excessive or intense precipitation can cause new crops to fall over or flood (Shah et al., 2017; Sridevi & Chellamuthu, 2015). A shift to more sporadic rainfall should suggest reduced rice production under SSP2-4.5 for this region compared to ARISE. However, what we find in the CLM5-crop output differs from expectations based on the indices. Since we find the opposite in the yield results, it may suggest that the increased rainfall under ARISE comes either too early or too heavily, or some other factor, such as an associated change in cloud cover, could be reducing the yield. The increased yields under SSP2-4.5 must either be a product of potentially harmful changes under ARISE or inconsequential changes to rainfall under SSP2-4.5. In northwestern India, all four indices reveal a decrease in precipitation under ARISE, however, the decreases are much smaller than those under SSP2-4.5. This pattern agrees with the improved yields under ARISE. In northeastern India, changes in all four indices are similar for both experiments, though SSP2-4.5 tends to be drier. This agrees with the increased yields under ARISE.

During the reproductive and ripening stages, changes are similar for most indices in southwestern India (Supplemental Figures 6, 7, 9, and 10 in Supporting Information S1). The index most likely to explain the yield difference was a slightly larger increase in PRCPTOT under SSP2-4.5 compared to ARISE, which could offer another reason for the improved yields under SSP2-4.5. The reproductive stage is known as a temperature-sensitive stage (Ghadirnezhad & Fallah, 2014; Sánchez et al., 2014), especially during anthesis, but it is also important to avoid water stress (Fu et al., 2023; Sridevi & Chellamuthu, 2015). In northwestern India, the pattern of reduced drying under ARISE continued in both stages. In the northeast, precipitation changes were nearly identical during the reproductive and ripening stages, with slightly more rainfall (PRCPTOT and Rx5 day) under SSP2-4.5 during the reproductive stage (Supplemental Figure 7 in Supporting Information S1). This may have been excessive for the plants at that time.

3.2. Wheat

Rainfed wheat in India appears to have benefitted from the temperature reductions under ARISE, especially during the ripening stage, and the increases in precipitation across all stages (see Supplemental Figures 11–19 in Supporting Information S1). Patterns of change during the vegetative period largely follow the other stages, so we focus on the results from the two stages most sensitive to weather and climate change. Wheat production in India is currently threatened by heat extremes in the spring and rising nighttime temperatures (Dubey et al., 2020; Impa et al., 2021). Wheat is most sensitive to extreme heat during its reproductive stage (Porter & Gawith, 1999; Wollenweber et al., 2003). Nighttime temperatures above 20°C and maximum temperatures above 34°C can lead to heat stress in wheat crops.

During the reproductive growth stage, we highlight changes in TR, WSDI, PRCPTOT, and CDD (Figure 6). The ARISE experiment greatly reduces the warming from SSP2-4.5, with many locations experiencing negligible changes in the number of tropical nights or warm spell days. In contrast, SSP2-4.5 on average leads to an additional 6 or more tropical nights in central India and 6 more days of warm spells in the north. For precipitation, we find both experiments lead to increased rainfall, but the increases are highest under ARISE.

During the ripening stage, there are important contrasts between ARISE and SSP2-4.5. Wheat prefers warm and dry conditions during this stage and can be damaged by extreme heat or heavy rain (Lobell et al., 2012; Mamrutha et al., 2020; Prasad et al., 2008; Stone et al., 1995; Vijaya Kumar et al., 2015). Large crop failures have occurred in recent years due to unprecedented heat near the end of the growing season, but under ARISE, it may be possible to reverse this warming trend, offering relief to crops and farmers alike. The number of tropical nights and hot days remains virtually unchanged under ARISE. There are even statistically significant decreases in HD in northern India (Figure 7b), while the warming trend in recent years would continue under SSP2-4.5.

For precipitation, again, both ARISE and SSP2-4.5 lead to increased rainfall, but ARISE leads to even wetter conditions. The CDD changes under ARISE match the pattern of yield changes quite well. Even though wheat requires warm and dry conditions during this stage, the increased precipitation is not damaging. Winter and spring are dry seasons in India. An additional 4–8 mm of rain on average is not enough to soak the maturing wheat, but it could offer minor relief on irrigation demands in the region.

3.3. Adaptations

We also sought to test whether adaptations like adjusting planting dates would be necessary or beneficial under global warming or SAI. Figure 8 depicts the average index values over the entire rice and wheat growing regions for each potential planting date. For all index results, see Supplemental Figures 20 and 21 in Supporting

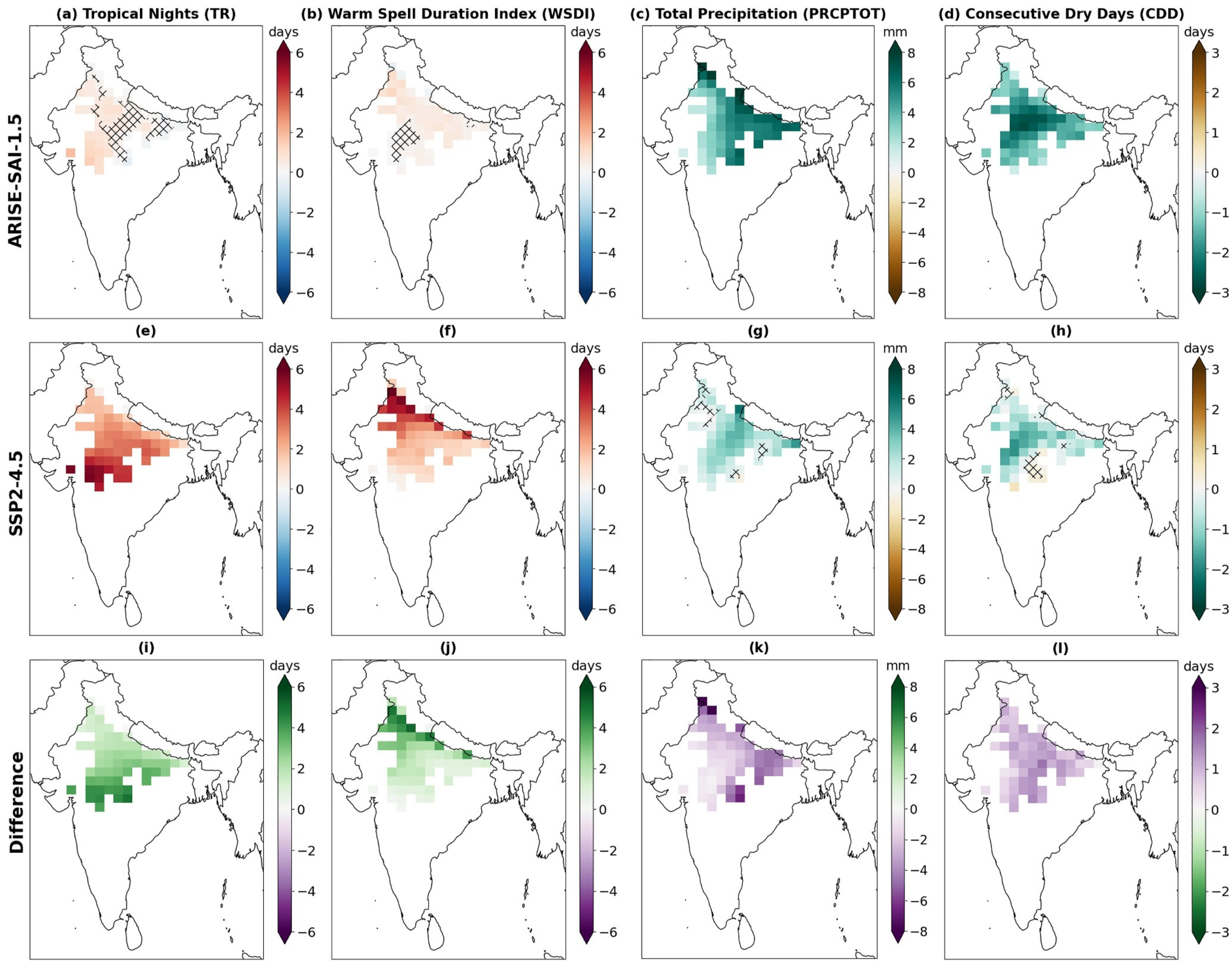

Figure 6. Difference between 2050–2069 and 2015–2034 agroclimatic indices TR, WSDI, PRCPTOT, and CDD during the wheat reproductive period. Indices are calculated over 12 35-day periods starting in late December, then averaged over all ensemble members and all 12 sowing dates. Hatching indicates results are statistically insignificant at the 95% confidence level. The differences (i–l) show SSP2-4.5 minus ARISE, such that green represents warmer (i–j) and wetter (k–l) conditions under SSP2-4.5 compared to ARISE.

Information S1. Here we highlight PRCPTOT, HD, and WSDI. For rice, we find that monsoon rainfall (during the vegetative period) decreases under SSP2-4.5 in the early sowing season. Until July, PRCPTOT is noticeably lower than both the control and ARISE simulations, falling outside of the ARISE and control ensemble spread. This pattern of drying also appears for all other precipitation indices (Supplemental Figure 20 in Supporting Information S1). This suggests a delay and shortening of the monsoon under SSP2-4.5. Those who plant early in the season (May and June) would need to delay planting by a week to receive the typical rainfall. Under ARISE, there is no need for this shift in planting dates.

For temperature, ARISE is much closer to the control values than SSP2-4.5, but there is some residual warming, particularly during the vegetative period for both HD and WSDI. Unlike PRCPTOT, SSP2-4.5 is always higher than the control and ARISE, never rejoining the control values except perhaps during the ripening stage. This means those planting at any point in the season would experience higher than normal temperatures. To plant during similar conditions, one would have to delay by 3 weeks to avoid increased hot days, or about 4 weeks to avoid increased warm spells. But those who plant later in the season, starting in July, would never be able to plant under normal temperatures. To avoid warming during the temperature-sensitive reproductive stage, rice would need to be planted in late July or early August. For early sowing regions to match the current climate for both

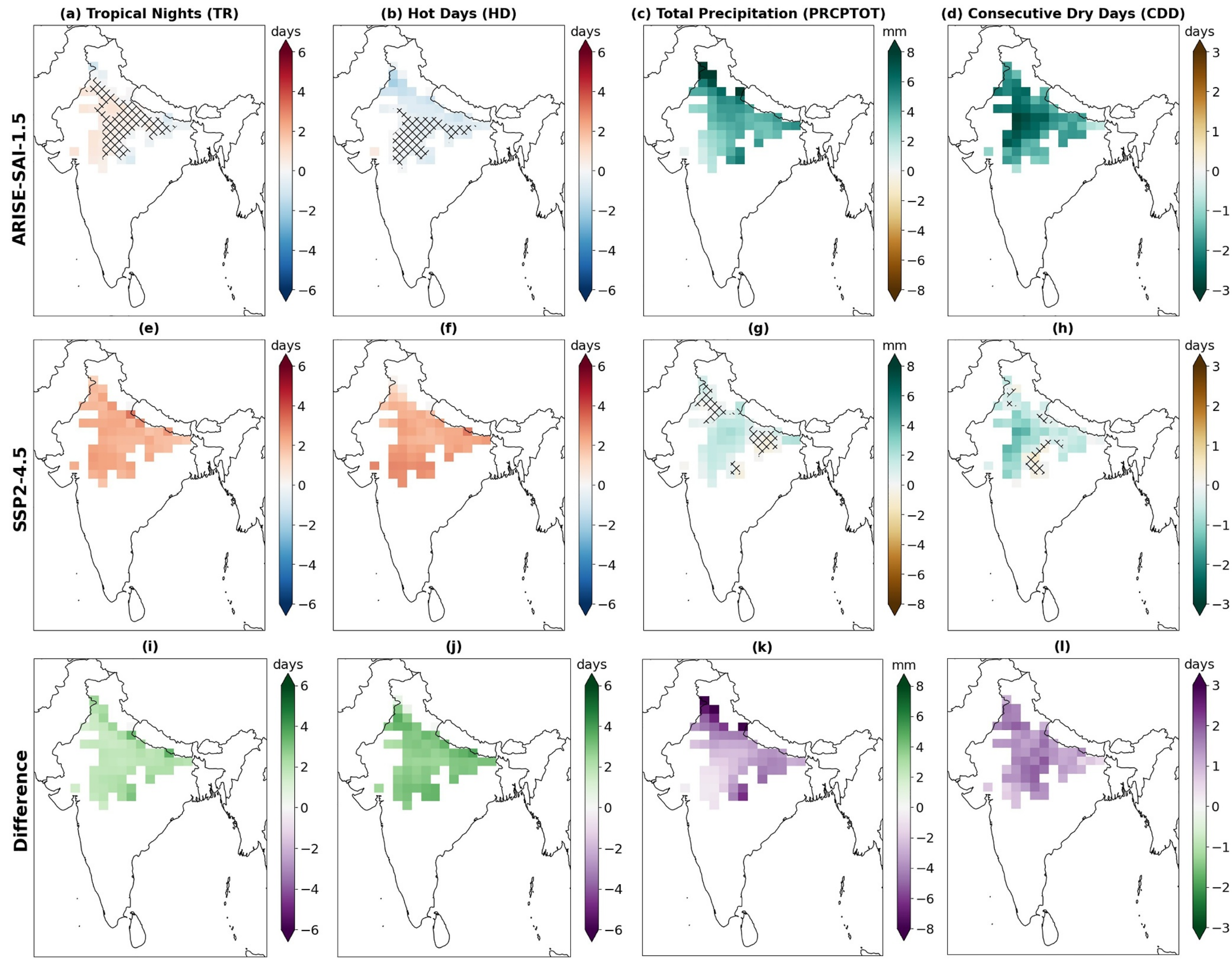

Figure 7. Difference between 2050–2069 and 2015–2034 agroclimatic indices TR, HD, PRCPTOT, and CDD during the wheat ripening period. Indices are calculated over 12 35-day periods starting at the end of January, then averaged over all ensemble members and all 12 sowing dates. Hatching indicates results are statistically insignificant at the 95% confidence level. The differences (i–l) show SSP2-4.5 minus ARISE, such that green represents warmer (i–j) and wetter (k–l) conditions under SSP2-4.5 compared to ARISE.

temperature and precipitation, they would need to delay by 2 months. ARISE, in contrast, does not require such adaptations.

During the winter season for wheat, ARISE cannot prevent the changes in precipitation under SSP2-4.5. However, increased rainfall would likely be a welcomed change during this dry season. ARISE and SSP2-4.5 are nearly identical during the vegetative stage, and during the later two stages, ARISE tends to produce the most PRCPTOT. If normal rainfall conditions are required, there would essentially be no planting date to shift to that could match the control period. For temperature, to avoid warming under SSP2-4.5 during the vegetative stage, early sown wheat would need to be delayed by 1–2 weeks, but after October it would be impossible to avoid increased WSDI. However, this stage is not particularly temperature-sensitive. For the reproductive and ripening stages, one would want to plant 1 week earlier to avoid increased HD, particularly for those who plant in December or November. To avoid increased WSDI during the reproductive stage, early planters would want to plant 2 weeks earlier and still may not be able to avoid all warming. ARISE does not require shifts in the planting dates to avoid heat.

For those farms that plant early in the season and utilize a rice-wheat cropping system (one where rice is planted in the summer followed by wheat in the winter and spring), it might not be possible to delay rice planting to avoid

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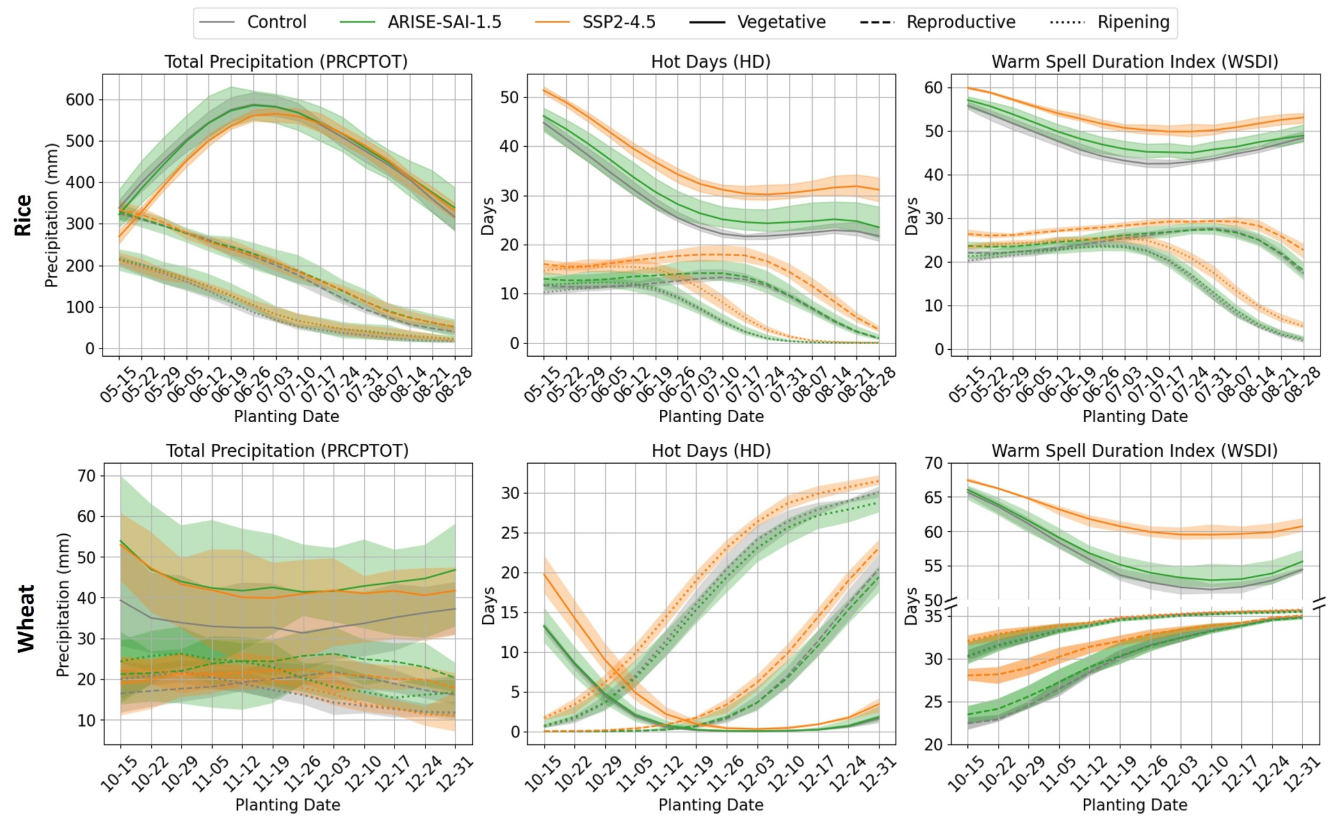

Figure 8. 2050–2069 averages for each index by sowing date over rice and wheat growing regions in India. Shaded regions represent the largest and smallest ensemble member values. The control period (2015–2034) is shown in gray, ARISE-SAI-1.5 in green and SSP2-4.5 in orange. The vegetative period (rice: 65 days; wheat: 70 days) is shown as solid lines, reproductive (rice: 35 days; wheat: 35 days) as dashed lines, and ripening (rice: 30 days; wheat: 35 days) as dotted lines.

drying and heat and still have a successful wheat harvest. Delaying rice sowing by 2 months would then subject wheat to more heat during its sensitive reproductive and ripening stages. It would likely require switching to different seeds that can mature faster to fit within the appropriate climate windows in addition to new sowing dates. However, those who sow rice and wheat later may be able to plant wheat and therefore rice 1–2 weeks earlier without many trade-offs. But the implementation of something like ARISE could eliminate the need for such trade-offs or adaptations.

4. Discussion and Conclusions

We found rainfed wheat and rice yields improve in a world with climate change plus SAI (ARISE) compared to climate change alone (SSP2-4.5). However, there were mostly negligible differences between the two scenarios for irrigated rice and wheat. This suggests as long as sufficient water is provided, rice and wheat could withstand the rising temperatures under SSP2-4.5, at least until the period 2050–2069. For rainfed crops, we found wheat benefitted from the precipitation increases and temperature reductions across all three stages, especially during the reproductive and ripening stages. However, given the similar trend in precipitation changes between the two experiments, we can assume the avoided warming is largely responsible for the production improvements.

Results were mixed for rainfed rice. There were large increases in production in northeast India, and smaller, though still significant changes in northwestern India. Northwestern India seems to have benefited from a reduction in the high temperatures (across all four indices) as compared to SSP2-4.5 during the reproductive and ripening stages in addition to reduced drying (R5, CDD, and PRCPTOT; Supplemental Figures 6, 7, 9 and 10 in Supporting Information S1). Northeastern yields most likely benefited under ARISE from a reduction in warm spells during reproductive and ripening growth (Supplemental Figures 5 and 8 in Supporting Information S1). Precipitation changes in this region were very similar for both scenarios, although ARISE did tend to have wetter conditions. In southwestern India, there is little warming during all three stages even under SSP2-4.5, suggesting precipitation must be driving the decreasing yield changes for rainfed rice. The increased rainfall during the vegetative period should have improved yields under ARISE as it would ensure sufficient rainfall to flood the fields. Instead, the increased precipitation may have been too early or too intense for the region. Increased rainfall under SSP2-4.5 during the reproductive and ripening stages could also explain the improved yields.

When assessing the impact of sowing date on the average climate conditions across the rice and wheat growing regions, under SSP2-4.5, it appears delaying early rice sowing dates by about 1–2 weeks could allow farmers to grow during more typical rainfall conditions, but they would need to delay 1–2 months to achieve both typical rain and temperature. For wheat, while precipitation changes did not vary much between scenarios during the different growth stages, later planting dates led to warmer-than-usual conditions. Rice and wheat production in India are already threatened by variable rainfall and heat extremes (Davis et al., 2019; Dubey et al., 2020; Impa et al., 2021), leading to restrictions on exports in recent years. In locations that follow a rice-wheat cropping system with early sowing dates, it would not be possible to plant rice later and wheat earlier without switching to a faster-maturing rice cultivar. ARISE, however, eliminates the need for changing the crop calendars.

These results suggest that ARISE-SAI-1.5, as modeled by CESM2-WACCM6, would alleviate many of the effects due to climate change during the rice and wheat growing seasons in India. It would be very effective at keeping temperatures similar to the control period during both crop seasons and is even able to maintain precipitation during the rice season. These are unexpected results as past studies with more extreme injection strategies have shown SAI to reduce monsoon rainfall (Bal et al., 2019; Bala et al., 2008; Bhowmick et al., 2021; Kravitz et al., 2017; Robock et al., 2008; Simpson et al., 2019; Tilmes et al., 2013). There could be important implications if a more moderate approach, like those in J. Richter, Visioni, MacMartin, and Dobbins (2022) or Irvine et al. (2019), avoids these disruptions to precipitation while reducing global temperatures. During the dry winter wheat season, both ARISE and SSP2-4.5 created wetter-than-usual conditions, but ARISE tended to be slightly wetter. This, however, is not a harmful change as evidenced by the production results. In India, wheat is commonly irrigated. Yet, with groundwater levels already depleting faster than they replenish (Sishodia et al., 2018), this will not be a sustainable or reliable adaptation for very long. In a future where water supplies become limited, plants will become more susceptible to heat, and precipitation changes will matter more. If winters become wetter, this could ameliorate the pressure on groundwater.

Utilizing stage-specific agroclimatic indices proved helpful for certain questions but unnecessary for other analyses. Many indices showed little fluctuations across the stages. There were rarely sign changes, and the magnitudes did not always differ drastically. It is likely safe to analyze crop season averages, but it was useful to pinpoint early versus late-stage changes. Additionally, while utilizing multiple indices allowed us to understand how the distribution of temperature and precipitation was affected, many followed similar patterns and wound up redundant. The stage-specific indices helped to explain the production changes for wheat and northern Indian rice but were inconclusive for southwestern India. Increased rainfall during the reproductive period may have been more influential than an increase during the vegetative stage, but there could have been some other factor influencing the decrease in that region.

We considered some details other assessments have neglected but still needed to make certain simplifications that are important to consider. For example, there are many varieties of rice and wheat cultivars, and each comes with its own growth stage durations and susceptibility to the thresholds chosen in this study. Not all wheat varieties are as sensitive to temperatures above 34°C or moisture stress, therefore some changes in these agroclimatic indices may have smaller effects on the quantity and quality of the final yield. A second important caveat: the lengths of each growth stage are not fixed in the real world. They are heavily dependent on temperature, and warmer conditions shorten the duration (Batts et al., 1996; Mamrutha et al., 2020; Sofield et al., 1977; Tashiro & Wardlaw, 1989; Wardlaw & Moncur, 1995; Yoshida, 1981). This means under a scenario like SSP2-4.5, the stage lengths would likely shorten by a few days and could affect the crop's exposure to beneficial or damaging weather conditions. Lastly, our models are imperfect. We only use the output of one climate model, and our crop model does not reflect the actual planting dates followed across India or include winter wheat varieties. The model tends to underestimate yields for rice and wheat in India, but there has been recent work to improve planting dates and criteria which could alter the results (Lombardozzi et al., 2020; Rabin et al., 2023).

4.1. Future Work

The impacts of SAI on agricultural production are still a very underexplored field of research. Future work to expand on this study could include increasing the number or complexity of agroclimatic indices assessed, utilizing multiple crop models to compare the impacts on yield and/or quality, and comparing the impacts of other SAI or climate intervention scenarios. Future work could also explore the sensitivity of the results to the choice in stage length and sowing date, reflecting how different cultivars may respond or including realistic planting dates that vary by region. We encourage more climate modeling centers to replicate the ARISE-SAI-1.5 experiment, as did UKESM1 (Henry et al., 2023), to enable multi-model comparisons, or to conduct the new Geoengineering Model Intercomparison Project experiment (Visioni et al., 2024). It deserves further exploration whether other models replicate the reduced impact on monsoonal precipitation observed here under ARISE using CESM2. Lastly, this study only considers the direct effects of temperature and precipitation on crop growth. Including other variables like humidity, soil moisture, cloudiness, sunshine hours, ozone, UV, or conditions favorable to common pests and diseases would help thoroughly assess whether SAI helps or harms agricultural production in India. More studies like these are necessary to make informed decisions should policymakers ever decide to debate deployment.

Data Availability Statement

The code and shapefiles developed for this study are publicly available at https://doi.org/10.6084/m9.figshare.26835754.v4 (Grant, 2024). Model output can be found through the NCAR Climate Data Gateway (Mills et al., 2022) for SSP2-4.5 and ARISE-SAI-1.5 (Y. Richter, 2021) or through the Amazon/AWS Open Data program (J. Richter, Visioni, Macmartin, Bailey, et al., 2022). CLM5crop yield data are available at https://doi.org/10.6084/m9.figshare.24085797.v1 (Clark, 2023).

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