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Crop yields in a geoengineered climate

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Crop models predict that recent and future climate change may have adverse effects on crop yields[1,2]. Intentional deflection of sunlight away from the Earth could diminish the amount of climate change in a high-CO_2 world[3–6]. However, it has been suggested that this diminution would come at the cost of threatening the food and water supply for billions of people[7]. Here, we carry out high-CO_2, geoengineering and control simulations using two climate models to predict the effects on global crop yields. We find that in our models solar-radiation geoengineering in a high-CO_2 climate generally causes crop yields to increase, largely because temperature stresses are diminished while the benefits of CO_2 fertilization are retained. Nevertheless, possible yield losses on the local scale as well as known and unknown side effects and risks associated with geoengineering indicate that the most certain way to reduce climate risks to global food security is to reduce emissions of greenhouse gases.

Climate variations affect food production in complex ways. The most direct impacts stem from the dependence of crop yields on climate variables such as precipitation and temperature. Studies have estimated that global yields for key crops have been adversely affected by recent changes in these variables[2,8] and that they will continue to be so under a range of future climate projections[9,10]. The impact of climate change on yields varies widely across regions. Positive effects are projected in some areas, whereas strong detrimental effects are projected for highly vulnerable regions[9,11], with negative consequences on food security[12].

Recent climate change observations as well as future climate projections are characterized by an increase in global mean temperature. At least on a global mean basis, this warming could potentially be counteracted by intentionally deflecting sunlight away from the Earth, a form of geoengineering known as solar-radiation management[13] (SRM). SRM schemes aim to stabilize global mean temperatures, despite the increasing atmospheric CO_2 concentrations, by reducing the amount of solar insolation absorbed by the Earth, for example, by injecting scattering aerosols into the atmosphere. In climate models, these schemes have been simulated to be able to fully compensate warming at the global mean[3–6]. However, these schemes are expected to alter regional climate and to have substantial effects on climate variables other than temperature, such as precipitation. Therefore, concerns have been raised that SRM will pose risks to food security[7]. In light of uncertainties about climate sensitivity and the existence of climate tipping points, it has been suggested by some members of the scientific and political communities that SRM may have the potential to reduce the risks associated with greenhouse-gas emissions, with some going so far as to present SRM approaches as an alternative solution to emission reductions[13]. These considerations make assessments of benefits and risks of geoengineering imperative, yet such assessments are only just beginning to emerge.

Here, we combine climate-model simulations with models of crop-yield responses to climate to assess large-scale changes in yields and food production for SRM scenarios. Our study thus investigates an important risk of geoengineering and contributes to an integrative assessment of all risks that will be needed to judge the suitability of SRM in averting the negative consequences of climate change. However, it does not address other potentially important effects of geoengineering.

We carry out three global climate simulations: a climate similar to today's with an atmospheric CO_2 concentration of about 400 ppm (control); a climate at doubled atmospheric CO_2 concentration ($2 \times CO_2$), as is, for example, projected for scenarios of strong economic growth within this century[14]; and a climate at doubled atmospheric CO_2 concentration but with sulphate aerosol concentrations increased in the model stratosphere sufficient to stabilize global mean temperatures at control levels (SRM). The simulations show the typical pattern of SRM with tropical overcooling and substantial changes in regional precipitation (Fig. 1). On the basis of the simulated changes in temperature and precipitation, we estimate changes in yields and production for key crops using published regressions of historical weather and yield data[2]. To account for uncertainties in the yield–weather relationships, we double and halve the sensitivity of yields to temperature and precipitation changes (Supplementary Figs S13 and S14). Although this affects the magnitude of simulated yield and production changes, the sign of the response, in particular the averted yield losses under SRM as compared with $2 \times CO_2$, does not change. The crops that are considered are wheat, maize and rice, which together directly provide nearly half of the calories consumed by humans and also contribute a major fraction of the calories consumed by livestock[15]. Furthermore, we account for the effects of an increased atmospheric CO_2 concentration, which has been shown in field and laboratory studies to enhance crop yields (Methods). Climate models have simulated an increase in global plant productivity under SRM (ref. 16), but the combined effect of CO_2 and climate changes under SRM on crop yields remains unclear.

Our approach should be seen as a first-order estimate of the impacts of SRM on crop yields. To cover the full range of uncertainties, future studies should be carried out that employ a wider range of crop and climate models. Furthermore, the regression model was trained on historical weather variations, yet modelled climate changes, in particular temperature changes in the $2 \times CO_2$ scenario, may go beyond this range at specific locations. However, we find for all scenarios and crops that less than 1% of the land area exhibits changes in climate that are outside the 90th percentile of the temperatures used to train the model (Supplementary Table S1). Moreover, although regression models capture some aspects of adaptation, they do not account for changes such as adding irrigation, switching crop choice, or the development of new cultivars, all of which could alleviate the

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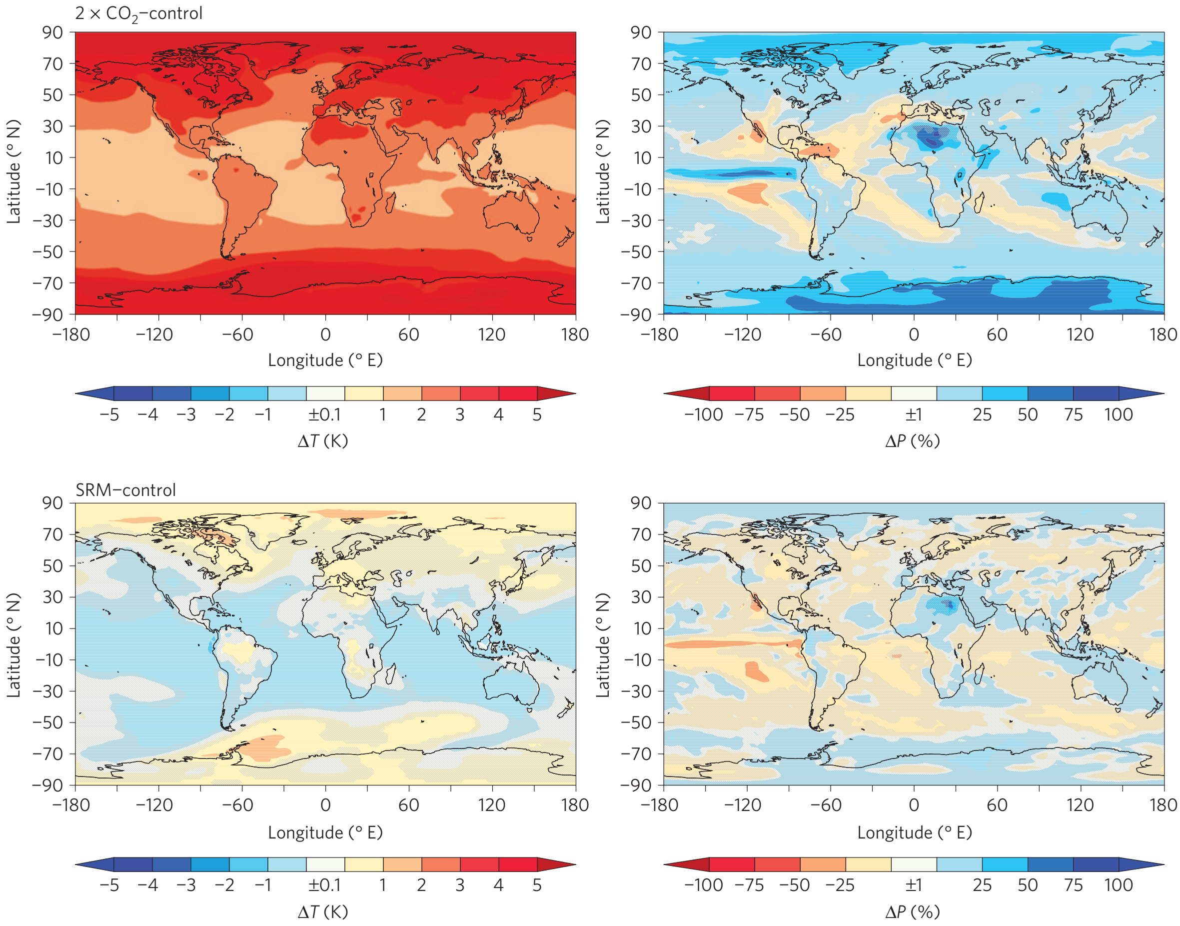

$2 \times CO_2$−control

SRM−control

Figure 1 | Simulated climate change. Change in annual mean temperature (*T*, left-hand panels) and relative change in precipitation (*P*; right-hand panels), compared with the control climate, of the $2 \times CO_2$ simulation (top) and the SRM simulation (bottom), for the CAM3.5 model. See Supplementary Table S2 for global and land averages and Supplementary Fig. S2 for precipitation changes in absolute values. Hatched areas are regions where changes are not statistically significant at the 5% level using Student's *t*-test.

negative impacts of future climate change on yields[9]. However, large uncertainties remain concerning the level of deployment, efficacy and sustainability of adaptive practices, especially in less-developed countries. More explicit consideration of adaptation and technological change would probably diminish the adverse effects of inadvertent climate change on yields and thus could diminish the predicted yield differences between the $2 \times CO_2$ and SRM scenarios, but is unlikely to change the sign of response.

In the simulation using $2 \times CO_2$ relative to the control climate, global crop yields and production exhibit small negative (maize) or positive changes (wheat, rice), which are a net result of the detrimental influences of climate change and the beneficial influences of CO_2 fertilization (Table 1). This is consistent with previous studies of $2 \times CO_2$ scenarios[9]. Warming, rather than precipitation change, causes most of the climate-induced yield reductions, in part because precipitation effects in individual regions are cancelled out when averaged over latitude bands. Warming has large detrimental effects on maize and wheat at most latitudes, whereas rice may benefit from higher temperatures and an extended growing season, particularly at high latitudes (Fig. 2). Heat and drought stress explain yield decreases at low latitudes[9]. CO_2 fertilization largely compensates for the climate-induced global yield losses for maize and leads to yield increases for wheat and rice, although this depends on the assumed fraction of radiative forcing from CO_2 and the responsiveness of crops to increased CO_2 (Supplementary Figs S9 and S10).

In the scenario using SRM relative to the control climate, global yields and production are simulated to increase for all three crops, at the global mean and across all latitudes (Table 1, Fig. 2). This increase is primarily due to the effects of CO_2. In contrast, climate-induced yield changes are small across all latitudes and within ±1% at the global mean, with precipitation changes being of similar importance to temperature changes. Although small negative impacts on yields are simulated for some latitudes for climate change in the SRM case, these are usually smaller than in the $2 \times CO_2$ case.

Our simulations overall indicate that SRM could lead to an increase in global yields relative to what would be achieved under a $2 \times CO_2$ climate (Table 1). Substantial yield losses with SRM relative to $2 \times CO_2$ are found only for rice growing at high latitudes, where the limits of low temperatures are no longer alleviated (Fig. 3a). Similarly, the production of maize, wheat and rice is generally higher under SRM than under the $2 \times CO_2$ climate (Fig. 3b). In particular, the large production losses that are found under the $2 \times CO_2$ climate for the extensive maize-growing regions at the northern mid-latitudes are averted. The losses in rice yields with SRM as compared with the $2 \times CO_2$ climate are not reflected in production losses, as yield changes occur in regions that are not growing a substantial amount of rice at present. Production losses could be more substantial in these regions if we had taken into account the fact that the extent of crops may alter with climate change.

Although we find in our model simulations that SRM increases yields and production compared with the $2 \times CO_2$ climate at the global mean, gains and averted losses are not uniformly distributed, as shown in the maps of Supplementary Fig. S5. Moving from a $2 \times CO_2$ to an SRM climate will probably alter market shares

Table 1 | Global changes in yields and crop production.

	$2 \times CO_2$ minus control		SRM minus control		SRM minus $2 \times CO_2$	
	Yield	Production	Yield	Production	Yield	Production
Maize	−3	−29	11	57	14	86
Wheat	6	46	26	145	21	99
Rice	19	122	28	147	8	25

Differences in global mean yield (percentage) and global production (million tons) between $2 \times CO_2$ and control climate, between SRM and control climate and between SRM and $2 \times CO_2$ climate.

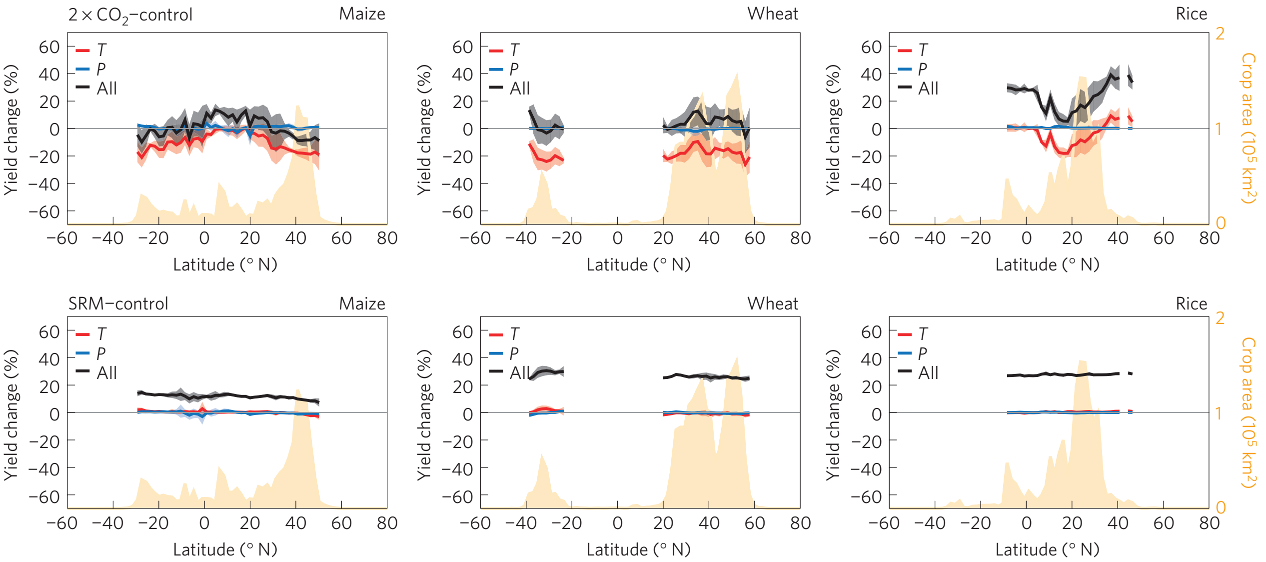

Figure 2 | Yield changes for $2 \times CO_2$ and SRM simulations. Relative changes in yields for maize, wheat and rice, compared with the control climate, of the $2 \times CO_2$ simulation (top panels) and the SRM simulation (bottom panels); for changes in temperature (T), precipitation (P) and combined changes in both of these factors plus CO_2 fertilization (All), for the CAM3.5 climate model. Vertical lines are latitudinal mean values for all of the land area, shown for latitudes with more than 5,000 km^2 of respective crop area. The shaded horizontal band indicates one standard deviation across longitudes of each latitude. The beige histogram indicates the latitudinal sum of the crop area. See Supplementary Figs S5–S8 for maps.

and the ranking of top producers. Even when we compare SRM with the control climate, specific regions may gain or lose crop productivity to different extents, as regional climate may change even with the stabilization of global mean temperatures (Fig. 1). Similarly, although our model simulations may refute concerns of threats by SRM to food security in large regions (latitudinal bands), individual small regions may exhibit larger changes in yields, which may pose a risk to local food security if subsistence farming prevails and adaptation is not possible. Although temperature effects play a larger role in averting global yield losses in the SRM compared with the $2 \times CO_2$ scenario, the effect of precipitation changes on yields has substantial regional variation (Supplementary Figs S6–S8). An important point is the weakening of the Asian monsoon that has been predicted to pose substantial risks to food security. Although our model simulations show precipitation decreases of about 10% or 0.8 mm d^{-1} (from the CAM3.5 model[21]) and 14% or 1.0 mm d^{-1} (from the HadCM3L model[27]) over this region during the summer, which is of comparable magnitude to previous studies[5,6], yield reductions from $2 \times CO_2$ to SRM are only a few per cent when based on the crop model used in this study[2] and are partly (maize) or fully (rice, wheat) offset by the beneficial effects of the averted increase in temperature. As climate projections are more uncertain on a regional than global scale, multiple-model ensemble studies should be carried out to better characterize the effect of SRM on a local to regional scale.

Our study focuses on the impacts on crop yields of changes in temperature, precipitation and the atmospheric CO_2 concentration. We did not consider the diverging consequences of SRM and $2 \times CO_2$ for other climate variables, most notably solar radiation. In wet climates with low radiative heat load on plants, the net primary productivity of vegetation, including crops, generally decreases with a reduction of solar insolation[17]. No detrimental effect of reduced radiation on productivity is found when crops are limited by water, as often occurs in semi-arid regions. Assuming a global linear scaling of yields with solar-radiation reduction would imply yield decreases of 2.2%, which is of similar magnitude to the yield gains of maize and wheat under SRM compared with $2 \times CO_2$ climate in the tropics, but is substantially smaller than yield gains at other latitudes and at the global mean. Apart from reducing insolation, scattering aerosols increase the fraction of diffuse radiation. Increases in diffuse light were found in observational and modelling studies to increase net primary productivity[18], owing to a reduction in shading and light saturation[19]. Increased diffuse light may therefore further offset the potential detrimental effects of reduced insolation. Overall, therefore, changes in insolation and diffuse fraction with SRM will probably have a smaller effect on yields than climate and CO_2 and will act in the direction of higher expected benefits from SRM.

As the accelerating rate of increase in atmospheric CO_2 over the past decades has revived the idea of attempting to offset some climate change by SRM, a comprehensive evaluation of its environmental and socioeconomic consequences is needed. Here, we have estimated the impact of SRM on global crop yields for a widely discussed scheme of SRM, modifying the stratospheric aerosol concentration[13]. We do not find substantial reductions in

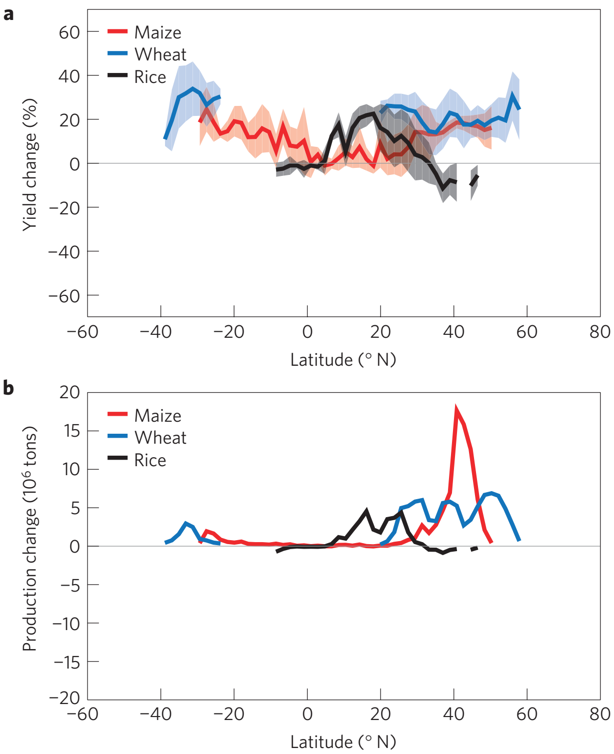

Figure 3 | Gains and losses in yield and crop production by geoengineering. a, Difference in the relative changes in yields of Fig. 2 between the SRM and 2 × CO_2 simulations (combined effects of changes in precipitation, temperature and CO_2 fertilization; latitudinal means). **b**, Difference in production changes (latitudinal sums).

yields by SRM compared to the control climate; on the contrary, the yields and production of maize, wheat and rice increase at the global mean and across most latitudes when SRM is carried out in a high-CO_2 world. This is largely because the changes in climate, in particular temperature, with a doubling of atmospheric CO_2 concentration are substantially reduced by SRM, while the beneficial effect of CO_2 fertilization on plant productivity remains active. We note, however, that an SRM deployment would be unlikely to maintain the economic status quo, as market shares of agricultural output may change with regional climate change. More importantly, geoengineering by SRM does not address a range of other detrimental consequences of climate change, such as ocean acidification[20], which could also affect food security through effects on marine food webs. Finally, SRM poses substantial anticipated and unanticipated risks by interfering with complex systems that are not fully understood. Therefore, although SRM may allow beneficial effects of CO_2 fertilization at a comparatively low level of climate change, the potential for such approaches to reduce the overall risks is still far from established. The safest option to reduce the climate risks to global food security may be to reduce emissions of greenhouse gases.

Methods

We carry out control, 2 × CO_2 and SRM simulations with the climate model CAM3.5 at about 2.5° × 1.9° resolution using a slab ocean model with prescribed ocean heat transport[21], analysing the last 60 of 100 years for each simulation, which show no apparent trend in climate. Temperature stabilization for SRM is achieved by a globally uniform increase in the concentration of stratospheric sulphate aerosol[22]. All simulations are idealized in that they represent a climate state at quasi-equilibrium in which the difference in climate between simulations depends only on the difference in atmospheric CO_2 concentration, whereas in reality climate will evolve transiently and responds to a range of non-greenhouse gases that are not considered here. This idealization aims to clearly isolate the effect of a high-CO_2 world with and without SRM compared with the present-day climate.

For each country in the world, we use estimates of the yield sensitivities of wheat, maize and rice to changes in mean climate (temperature and precipitation) during the growing season based on published regressions of historical weather and yield data[2]. In these regressions, the temperature and precipitation effects on yields are assumed to add linearly. We approximate the direct effects of climate and CO_2 changes on crop production, excluding the effects of market dynamics and management changes, by multiplying our predicted relative yield changes with observed present yields and agricultural areas[23].

As well as the effects of climate, we consider the effects of CO_2 on crop yields. Laboratory and field studies have found that increased atmospheric CO_2 levels enhance plant productivity for C3 (wheat, soy, rice) and, to a lesser extent, C4 vegetation (maize)[24]. In our analysis we include the effect of CO_2 fertilization using yield increases of approximately 27% for C3 and 12% for C4 crops, which are the values used in the Decision Support System for Agrotechnology Transfer (DSSAT) crop models for 2 × CO_2 (ref. 25). These values are at the high end of previous estimates and do not consider interactions of CO_2 fertilization and changes in temperature and precipitation. However, because our main conclusions are based on comparing yields under SRM with those under 2 × CO_2 climate, predicted differences in yield changes between these two scenarios are insensitive to the effect of CO_2 fertilization. This is demonstrated further in our following analysis applying lower and no effects of CO_2 fertilization: although our idealized studies assume that changes in the atmospheric CO_2 concentration are the only climate driver, the same level of radiative forcing can be reached in climate projections at a lower CO_2 level when non-CO_2 greenhouse gases (with overall positive radiative forcing) are also considered. In this case, the effect of CO_2 fertilization will be lower than assumed before[9]. We repeat our analysis of yield changes, reducing the factor for CO_2-driven yield increases to a value that represents the atmospheric CO_2 concentration for a CO_2-equivalent concentration (that is, including non-CO_2 greenhouse gases) of 800 ppm based on the special report on emissions scenarios B2 (SRES B20; which projects approximately 800 ppm by the end of this century[26]). Results for this case are shown for CAM3.5 in Supplementary Figs S9 and S10 (equivalent to Figs 2 and 3) and Supplementary Table S3. Again, our qualitative conclusions, in particular with respect to comparing SRM and 2 × CO_2, are not sensitive towards considering non-CO_2 greenhouse gases. Results for the changes in yields and production excluding the effect of CO_2 fertilization are shown for CAM3.5 in Supplementary Figs S11 and S12 (equivalent to Figs 2 and 3) and for both models in Supplementary Table S3.

To test the robustness of our results with respect to the choice of climate model and SRM scenario, we repeat our analysis using a fully coupled atmosphere–ocean model, HadCM3L (ref. 27). The simulations comprise a pre-industrial control run at 280 ppm, a simulation under 2 × CO_2 at 560 ppm and a SRM scenario at 560 ppm, where the global mean temperature is restored to the pre-industrial value by reducing the solar constant by 2.6%. All simulations are run at about 3.8 × 2.5 spatial resolution for 1,000 years; we analyse the last 100 years, which show no apparent trend in climate. CO_2 fertilization increases yields by 36% for C3 (wheat, rice) and 16% for C4 vegetation (maize), based on the crop model DSSAT. Generally, differences in climate and in yields between scenarios are more pronounced for HadCM3L than for CAM3.5 (compare Figs 1–3 with Supplementary Figs S1, S3 and S4 and see Supplementary Fig. S5 and Tables S2 and S3). However, the spatial pattern of change and differences across crops is very similar on the scale of latitudinal averages; the smaller regional scale differs more, in particular for precipitation effects, as shown in Supplementary Figs S5–S8. All qualitative conclusions drawn in the main manuscript are insensitive towards the choice of climate model.

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Author contributions

K.C. and L.C. provided climate simulations, D.B.L. provided the yield model, J.P. carried out the analyses. All authors contributed to designing the analyses and to writing the manuscript.

Additional information

The authors declare no competing financial interests. Supplementary information accompanies this paper on www.nature.com/natureclimatechange. Reprints and permissions information is available online at http://www.nature.com/reprints. Correspondence and requests for materials should be addressed to J.P.