South India projected to be susceptible to high future groundnut failure rates for future climate change and geo-engineered scenarios

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Abstract

With an increase in global mean temperature predicted for this century accompanied by more frequent extremes, will farming communities need to brace for increased crop failures and hardship? Solar dimming climate geoengineering has been proposed as a possible solution to combat rising global temperature but what effect will it or other climate related adaptation have on crop failures? We performed a crop modelling study using future climate and geoengineering projections to investigate these questions. Our results indicate that groundnut crop failure rates in Southern India are very sensitive to climate change, and project an increase of approximately a factor of two on average over this century, affecting one out of every two to three years instead of one in every five years. We also project that solar dimming geoengineering will have little impact on reducing these failure rates. In contrast, the projections for the rest of Indian regions show decreasing failure rates of 20-30%. In this research, we indicate why south India is more susceptible than the rest of the country and show that neither Solar dimming geoengineering nor reducing heat or water stress are able to fully counteract the increase in failure rates for this region. Thus our modelling projections indicate the potential for a grountnut crop failure crisis for the South India.

1 Introduction

According to the latest IPCC report, our Earth's globally averaged surface temperature is likely to continue to follow a warming trajectory that could have serious consequences for socio-ecological systems during this century (Bindoff *et al* 2013). A recent global meta-analysis of projected climate impacts on food production highlighted that our understanding is limited (Challinor *et al* 2014, Campbell *et al* 2016, Challinor *et al* 2018). Challinor *et al*. (2014) concluded that projected climate change would, on average, reduce crop production stability. In addition, with future climate we can expect more frequent extreme weather compared to the past (IPCC, 2012). Increasing frequency and strength of extremes will affect crop failure rates, and it highlights the importance of assessing potential consequences for a wide range of crop types and climate scenarios (Challinor *et al* 2010, Hansen *et al* 2012, Parkes *et al* 2015, Gaupp *et al* 2019, Mehrabi and Ramankutty 2019).

Future food production and crop stability will be, to some degree, determined by our collective impact on the climate system. Approaches using one or more of mitigation, adaptation, geoengineering or 'business as usual' will all lead to different radiative forcing and global warming pathways. These pathways also lead to different food-stability and economic futures (Lobell *et al* 2008, Porter *et al* 2014, Harding *et al* 2020). Adaptation is a viable option to deal with the effects of climate change on food production (Kravitz *et al* 2013, Yang *et al* 2016) but, equally, mitigation is also important to address increasing temperature and changing rainfall patterns that can affect plant growth. It is also prudent to investigate the value of climate geoengineering as a possible strategy to restore our climate if necessary in the extreme. There are numerous geoengineering approaches and implementation strategies and some of these have been modelled in studies such as Kravitz *et al.* (2011). The GeoMIP project evaluated the potential of climate geoengineering to restore future globally averaged temperature to current levels. Although, recent studies have examined the effects of geoengineering on local and regional hydrology (Kravitz *et al* 2013, Bal *et al* 2019, Irvine *et al* 2019), few studies have assessed the geoengineering consequences for crops.

In this paper, we focus on the effects of extremes of predicted climate change and geoengineered climate on groundnut failure rates (i.e. frequency of very low yielding years). We hypothesise that crop failure rates will increase in frequency over this century relative to historical failure rates. This is expected due to expected increased mean temperature and more frequent extremes of temperature and precipitation predicted for this century. Although increasing precipitation can lead to higher yields, it is anticipated that extremes will be detrimental for crop yields and lead to an increase in failures. A further hypothesis is that geoengineering will moderate the failure rates by reducing the severity of climate change and associated extremes. Knowing whether crop failures are likely to change with future climate change needs to be understood for future planning by farmers and their communities (Parkes *et al* 2015). We chose groundnut as the crop to study as it is strongly dependent on the monsoon which is likely to alter for future climates (Kravitz *et al* 2013, Akram *et al* 2018, Halder *et al* 2020) and because groundnut is an important cash crop for the Indian population (Talawar 2004 and Singh *et al* 2014b; Supplementary Text S1).

2 Methods

2.1 CMIP5 and GeoMIP meteorological data

Our study used a combination of climate prediction data and crop modelling to predict groundnut yields and evaluate the frequency of crop failure rates for future climate. The climate model data used are from the CMIP and GeoMIP studies (Taylor *et al* 2012, Kravitz *et al* 2011). The CMIP provides projections of future climate making various assumptions about emissions for the future, resulting in radiative forcing ranging from approximately 2.6 to 8.5 W/m2 by the year 2100. The different emission scenarios are referred to as representative concentration pathways (RCPs). We chose to use the RCP4.5 which is an intermediate scenario of climate change. In addition to the CMIP climate projections being a frequently used set of climate projections, including for the IPCC, the additional benefit for this work is that the GeoMIP project uses the CMIP RCP4.5 as the basis for its geoengineering simulations. GeoMIP is an international study that focused on understanding the effects of geoengineering on modelled future climate. GeoMIP focused on radiation management of geoengineering through, for example, the introduction of additional stratospheric aerosol, which was considered in this study. Thus, in this research, by running crop models using GeoMIP and CMIP RCP4.5, both for historical periods and future climate, we were able to isolate both the impacts of geoengineering and climate change on our crop projections and failure rates.

India's summertime precipitation levels depend significantly on the South-Eastern monsoon so we selected a climate model that was effective at modelling this complex system. We used the Beijing Normal University Earth System Model (BNU-ESM) as it scored well compared to analysis of the historical meteorological trends for the region, has realistic spatial distributions of precipitation for the summer Indian monsoon, and performed well compared with other GCMs participating in CMIP5 according to a quantitative assessment of a variety of key variables (mean temperature, total precipitation, wet day frequency, and diurnal temperature range, see Supplementary Text S2) (Ramirez-Villegas 2014, Sabeerali *et al* 2013).

The CMIP5 project (Taylor *et al* 2012) provided data for historical (HIS) and RCP 4.5 simulations, and the GeoMIP project (Kravitz *et al* 2013) provided data for G3 climate geoengineering results. From the GeoMIP study, we used the G3 implementation of solar dimming as it is considered a realistic geoengineering scenario based on injection of SO_2 into the stratosphere at a constant rate forming aerosol and was designed to compensate for the annual radiative forcing of the RCP 4.5 scenario. In the simulations, the geoengineering was implemented early this century (by 2020) and lasted for 50 years. After the geoengineering intervention was ceased, climate simulations were extended to the end of the 21st century (2099).

2.2 Crop simulation design and data analysis

The General Large-Area Model for annual crops (GLAM) was used in this study to simulate the groundnut crop. It is a process based model designed to take advantage of the large-scale relationships between climate and crop yields (Challinor *et al* 2004). Details about the crop model and crop simulation design can be found in the Supplementary text (see S2 and S3). The GLAM model was designed to model crops at the scale of the resolution of GCMs so no downscaling was necessary.

The crop failure rates were determined according to Challinor *et al.* (2010) as the percentage of harvests failing for a specified time period. A failed harvest was defined as a yield below a set threshold. Here, we use a relatively conservative threshold of one standard deviation below the historical mean for each grid, indicative of moderate crop failures (Challinor *et al* 2010, Parkes *et al* 2015) and evaluated the consistency of results with larger (i.e. 1.5 x standard deviation) and smaller thresholds (i.e. 0.5 x standard deviation). For the historical simulation, we computed failure rates over the period 1966-1990 and for the future simulations we computed failures for the period when geoengineering is first applied (2020) until ending in 2099, totalling 80 years. Crop failures were calculated individually using grid-cell yields and failure thresholds and were used to depict spatial variability in the boxplots. These results were then used to determine mean national and regional failure rates (for each of the four groundnut growing zones) by aggregating the grid-cell failure rates.

3 Results

3.1 Projected changes in regional climate

For future climate change, it is anticipated that the Asian monsoon will alter with or without geoengineering (Kravitz *et al* 2013). Fig. 1 shows projected changes to temperature and precipitation for the period June-July-August-September (JJAS), during which 80 % of the groundnut crop in India is cultivated. In the figure, the geoengineering intervention is also included (i.e. acting between years 2020 and 2069) and the subsequent years without geoengineering until 2099 (totalling 80 years). For the geoengineering results, we note that the mean temperature in a number of regions of India (especially North and South India) are reduced as expected for the geoengineering scenario (G3, Fig. 1c) compared to the global warming scenario (RCP 4.5, Fig. 1b).

The geoengineered case shows a mean seasonal decrease in precipitation for India as a whole. We see regionally that in particular the precipitation in the Central and Eastern India are below the historical levels (see Fig. 1e and 1f) whereas the other regions increased. Similarly, we note important regional differences in projections of inter-annual variability for precipitation and highlight that there is similarity in results for RCP 4.5 and G3 scenarios (Fig. 1g, 1h and 1i). With decreased precipitation, one might expect reduced mean yields and increased crop failure rates. In the following sections, we concentrate on the groundnut crop failure frequencies for these climate scenarios outlined above.

3.2 Crop failure projections

Figure 2 illustrates the results of the model simulations for groundnut crop failures. All of the plots in Fig. 2 have been derived from aggregating the grid-scale results weighted by the production (the production for each region is given in Table S4). We found that for India the crop failures for South India contrast strongly with the rest of the study region (See Fig. S1) further north (north of about 18° latitude). South India showed a very large percentage increase in the failure rates of 198% (33 percentage points, pp) and 166% (27 pp) for RCP and G3 relative to the HIST period, respectively. In contrast, the failures are reduced for the regions of Eastern, Central and Western India (zones 1-3), especially for zones 1 and 3. Zone 1 failures are reduced by 39% (7 pp) and 23% (4 pp) for RCP and G3, respectively, and zone 3 failures are reduced by 64% (11 pp) and 45% (7 pp) for RCP 4.5 and G3, respectively.

All zones were tested to determine if the production weighted yields were statistically different for RCP and G3 relative to the HIST results by applying both the Student-T and Kolmogorov Smirnov (KS) tests for the period between 2020 and 2099 using a 95% confidence level (Table S5). Both results were requried to be statistically significant in order to consider a zone or zones to be statistically significant. The result for the national scale was determined not to be statistically different for RCP and G3 relative to HIST and so was not shown. However, statistical significance between RCP/G3 and HIST were found for all zones 1-4 individually and also when zones 1-3 were combined (production weighted failures were aggregated at the grid-scale level to obtain the results, shown in Fig. 2). So South India (zone 4, Fig. 2) was predicted to undergo approximately a two-fold increase in failure rates with climate change. North of this, the combined Eastern, Central and Western regions showed an opposing 32% (6 pp) reduction in failure rates for RCP relative to HIST and an 18.5% (3.5 pp) reduction in failure rate for G3 relative to HIST. Although the same trend shown in the national plot is seen in three out of the four growing zones (western, central, and eastern India), the whole-India failure rate masks important spatial variations, especially for south India.

In addition to the production weighted failures shown in Fig. 2, we were also interested in the distribution of grid-specific failure rates as shown in Fig. 3. Fig. 3 shows box-whisker plots which include all grid failures and shows the degree of variability within regions at the highest resolution undertaken in the study. It is evident that there is a significant contrast in the results of South India compared to the three regions to the north. South India exhibited the largest variabilitiy in failure rates, by far, for both of the future scenarios when compared to historical. Thus, whilst the country and regional results exhibit a fairly consistent picture, the significant spatial variability of crop failures under global warming and geoengineered climate suggests it is necessary to take grid-specific yields into account when assessing and communicating potential impacts. This highlights the need for an adequate resolution for simulating crops (Baron *et al* 2005, Angulo *et al* 2013) nd also appropriate specification of crop failure thresholds. We show in Supplementary S5-8 that the trends exhibited in our results remain consistent when using alternative specifications of the failure thresholds including 0.5 and 1.5 times the standard deviation.

3.3 Adaptation potential

From the numerous possible adaptation approaches (Howden *et al* 2007, Challinor *et al* 2014), we considered two climactically important strategies: (1) reduction of water stress through irrigation and water management adaptation and (2) reduction of heat-stress through use of adapted germplasm (see Supplementary Test S4). We implemented idealised scenarios showing the maximum effect of these strategies, for illustration. The results showed that water stress adaptation is very effective for most of India as it reduces the future crop failure rates for Eastern, Central and Western India by 95% (20 pp) or more at the grid-scale level (Fig. 4), while avoiding almost all of the regional and national-level crop failures (values near zero so figures not shown). For South India, adaptation to water stress was also effective at regional scales but to a lesser degree than elsewhere, and it was found that large variability was noted at the local scale (grid cell). We note that in addition to water stress adaptation leading to increased mean yields and reduced interannual yield variability (hence sustantically or completely reduced crop failures), it also led to reduced spatial variations in crop failures, thus in general leading to much greater spatio-temporal yield stability for most of India (Fig. 4). Conversely, adaptation to heat stress was largely ineffective, with negligible effects at the local scale (grid cell) (Fig. S4).

4 Discussion

4.1 Crop processes and projected changes in failure rates

One of the main advantages of using the GLAM model (Challinor *et al* 2004) was that it is a process based crop model so enables analysis of the underlying reasons for changes to crop failure rates. To highlight the underlying reasons, first we highlight that the definition of crop failures was based on the historical mean and standard deviation (see Sect. 2.2), so future crop failures depend on changes in both projected mean yields and yield variability relative to historical. RCP4.5 climate change predictions for India indicate temperatures will increase along with increased CO_2 levels; however, precipitation is less well understood, with some areas increasing and other areas decreasing.

Increased CO_2 levels and reduced water stress both acted to reduced failure rates; whereas, the effects on failures due to temperature is complicated by the fact that the definition of failures depends on the historical temperature. It is important to note that in the GLAM model there is a cardinal temperature for crop development, T_o, and the temperature the crop experiences relative to T_o largely determines the rate of crop development, which determines growth duration and, in turn, determines the time intercepting sunlight, amount of water transpired and hence yield (Wheeler *et al* 2000, Porter and Semenov 2005). For groundnut, T_o is 28 ºC (Singh *et al* 2014, Challinor *et al* 2004) and, therefore, if the crop experiences temperatures at the cardinal temperature T_o then the crop will develop through the growth stages quickly but this means a shorter growth period and thus less yield. If the historical temperature is, on average, either side of T_o then there will be greater yield but, importantly, if the historical is on the lower (higher) temperature side of T_o and temperature increases with climate change then the yield will decrease (increase). Thus, it is critical for the crop yield as to which side of T_o the historical mean temperature resides.

In Fig. 1, we identified with stippling the regions where the historical mean temperatures were less than the cardinal temperature of 28 ºC. With climate change, temperatures in India are predicted to be 0.5-1.5 ºC higher (both RCP4.5 and G3 scenarios) than the historical mean, so the regions identified with stippling with climate change will tend towards the cardinal temperature, resulting in a faster development rate for crops relative to historical rates and thus will be projected to have lower mean yields and higher failure rates in the future. This is one of the main reason why South India (zone 4) has projected increases in failure rates in this study. Another important factor that contributed to the projected increased occurrences of failures for the south is the presence of increased interannual variability of precipitation, which is shown in Fig. 1 g-i to have a distinct increase for South Indian in the future relative to historical. The increased interannual variability in precipitation will further increase failure rates.

In contrast to South India, the Eastern, Central and Western regions mean historical temperatures are above the cardinal temperature of 28 ºC and so climatically increased temperatures from global warming act to increase the temperature relative to the cardinal temperature and this increases the duration of growth stages and hence yields, resulting in decreased failures. This is also amplified by reduced interannual precipitation variability which also acts to decrease failures.

4.2 Implications of projected changes in failure rates at national and regional scales

South India is the second largest groundnut producing region of India, and our results predict failure rates to greatly increase for this region relative to historical values for both RCP 4.5 and G3. For RCP 4.5, the increase is predicted to be 198 % (33 pp) and for G3 the increase is predicted to be 166 % (27 pp). Increased failure rates could be very detrimental to groundnut farmers income stability (82 % of groundnut production is used for edible oil production; Mehrotra, 2011) and the wellbeing of farmers and farming communities (discussed below). In contrast, for the Eastern, Central and Western regions (latitutes higher than about 18° N**)** the crop failures are projected to decrease by 20-30%. In all regions, geoengineering was projected to have failures rates between RCP and HIST, and usually much closer to RCP.

In a recent study by Carleton (2017), evidence is presented linking crop damaging temperatures to increased suicide rates for India. The study used a nationally comprehensive 47 year dataset of India and showed that fluctuations of, primarily, temperature during the growing season significantly affected suicide rates. Carleton (2017) found that temperatures in excess of 20 °C could explain 6.8% of the total upward trend in the national suicide rate. In the Fig. 2C, the geographical heterogeneity in the suicide-temperature response shows that South India is one of the main ‘hot-spots’ in terms of the sensitivity of suicide rate to temperature. This is particularly concerning when compared to our zone 4 panels in Figs. 2 and 3 which predict increasings in failure rates for South India, and that even human intervention by solar dimming climate geoengineering is likely to have little effect on reducing these failures.

Finally, we would like to point out that uncertainties associated with numerical modelling can limit the usefulness of results for decision making (Vermeulen *et al* 2013, Campbell *et al* 2016). In this work, most notably, the use of single climate and crop models can entail potentially significant uncertainty in the study, especially with regards to regional climate projections; however, we have reduced the risk as much as possible by using the BNU-ESM which was noted to have appropriate regional spatial distributions of meteorological variables for the Indian Monsoon (Sabeerali *et al* 2013). We also note that we have not accounted for the farmers' autonomous response to changing climate change aside from through altered planting dates, nor have we accounted for future technological changes (e.g. new machinery, new germplasm, etc.) which are typical of the timescales we have analysed here (Tilman *et al* 2001). However, we did choose an intermediate climate change pathway, RCP 4.5, which may potentially offset these. Our analysis uses state-of-the-art, well-established crop and climate simulation models, and shows a consistent picture for groundnut crop failures under future climate.

5 Conclusion

In this work, we questioned whether farming communities should brace for more crop failures and increased crop instability and whether climate geoengineering might reduce or adversely affect future crop failure rates. We hypothesised that crop failure rates would increase in frequency over this century relative to historical failure rates and that geoengineering would moderate these increases. We find from our results that certain parts of India likely do need to brace for increases in crop failures in coming years with climate change. Most concerning is South India where projections show dramatically increased failures rates of 198 % (33 pp) and 166 % (27 pp) for RCP4.5 climate change and G3 climate geoengineering scenarios, respectively, relative to the historical means. However, the opposite was predicted for Eastern, Central and Western India (in this work defined as North of 18° latitude) which was attributed to the historical mean temperature of this region being below the cardinal temperature for groundnut and thus leading to increased yeilds with climate change and fewer failures. RCP4.5 climate change reduced the groundnut failures by 20 to 30 % and solar dimming geoengineering intervention GeoMIP G3 was predicted in all cases to moderate the failures, resulting in failure rates part-way between the RCP4.5 and historical values.

Our projections indicate that South India can expect to have on average an almost doubling of crop failures for groundnut, with on average one failure every two to three years instead of one every four to five years. Also concerning is that projections for South India showed limited response to reduced heat and water stress or even solar dimming climate geoengineering. Agriclimate projections contain a number of uncertainties but these results suggest South India's groundnut should be the focus of innovative adaptation and farming strategies going forward to combat future climate impacts.

Author Contributions

HY and SD designed the project. HY performed all the GLAM-groundnut simulations. JRV and AJC assisted with calibration. JRV, AJC, SQ and SG assisted with results analysis. HY and SD wrote the paper with all authors providing input.

Acknowledgments

The authors would like to thank the participants of the inter-comparisons CMIP and GeoMIP for making their data available. The project was supported by the National Science Foundation for Young Scholars of China (Grant No.: 41205003). JRV and AJC are supported by the CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS), which is carried out with support from CGIAR Fund Donors and through bilateral funding agreements. For details please visit *https://ccafs.cgiar.org/donors*. The views expressed in this document cannot be taken to reflect the official opinions of these organizations. The authors thank the members of the Climate Impacts Group at the University of Leeds for feedback on some of the results presented here.

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