PAPER

Impact of climate change on productivity of food crops: a sub-national level assessment for India

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Abstract

Climate change is considered as a potential threat to sustainability of agriculture in India. Considering the importance of agriculture in the pursuit of the India’s development objectives, including the Sustainable Development Goals of the United Nations, understanding possible impacts of climate change on productivity of major food crops in the country assumes importance in developing appropriate policies and programmes for agricultural technology development and transfer in general and for climate change adaptation in particular. Such an understanding at a scale where most of the development planning is done will be more useful in policy planning. This paper analysed climate change impacts at district level for major food crops using the district level climate projections for two time periods viz., mid-century (2021–2050) and end-century (2071–2098). Yields of most crops are projected to decrease in a majority of districts during mid-century period. The yield impacts are deeper and wider during end-century period. The yield impacts are relatively smaller and even positive in case of rapeseed & mustard and soybean. Some of the policy implications emerging from this study are: (i) Efforts are to be targeted and prioritized in the districts where the yields are likely to suffer more (ii) Concerns related to abiotic stress, especially those related to heat/temperature stress, need more attention in crop improvement and natural resource management programmes and (iii) Considering the dimension of climate change along with other bottlenecks to sustainable agriculture in the research and development process is a desirable way of mainstreaming climate change in to economic development programmes.

Introduction

Indian agriculture has witnessed commendable growth since independence (Tripathi and Prasad 2009). The country is among the leading producers of a number of agricultural commodities in the world (Mukherjee et al 2012). However, the productivity levels of various crops are much less compared to other countries as well as the world average (Swaminathan and Bhavani 2013). The productivity levels are also lower than the realizable yields as is evident from the existence of considerable yield gaps (Wani et al 2009). Slower rates of technology adoption and diffusion, resource degradation, rising input costs, volatile output prices are some of the challenges associated with the less than desirable rates of growth in agriculture (Macours 2019). On the other hand, the increasing needs to be met from agriculture require that the productivity and income from agriculture rise faster and sustainably. In any analysis of future of Indian agriculture and food systems, the possible impact of climate change cannot be ignored as climate change is recognized as one of the potent threats to sustainable agriculture, food security and livelihoods of farmers, especially of small and marginal farmers in countries such as India with inadequate adaptive capacity (FAO 2008, Mukherjee et al 2012, Praveen and Sharma 2020).

Climate change is characterized by rising atmospheric temperature, varying rainfall patterns, increasing incidence of extreme events (IPCC 2013). All these will have direct and indirect effect on productivity and
sustainability of agriculture and have implications to technology development and transfer. There have been attempts to understand the possible impacts of climate change through such approaches as physical experimentation (e.g. Vanaja et al 2017, Kannojia et al 2019) simulation modelling (e.g. Pathak and Wassmann 2009, Boomiraj et al 2010, Srivasatava et al 2010, Naresh Kumar et al 2014, Subba Rao et al 2015). Econometric approaches such as Ricardian regression and panel data regression models were also used (e.g. Kumar and Parikh 2001) to understand climate change impacts. The panel data regression, because of its advantages (Deschenes and Greenstone 2007), is increasingly being used in understanding climate change impacts at more disaggregated levels (e.g. Birthal et al 2014a, 2014b, Rama Rao et al 2019). These different approaches have their own advantages and disadvantages in terms of their performance, data and skill needs, scale of analysis, etc. In India, rainfall deficits received more attention than the rising temperature while analysing production or productivity impacts (Jayaraman and Murari 2014). The results from different approaches, when seen together, can potentially lead to useful policy suggestions. With this background, we have attempted in this paper to examine the potential impact of climate change, expressed in terms of changes in monthly temperature and rainfall, on productivity of major food crops in India through panel data regression approach.

This attempt is different from other similar works in the following ways: (i) We used climate variables both in their mean and variability terms (ii) The climate variables were used in more temporally disaggregated terms i.e. monthly climate as against seasonal or annual scales and (iii) district-specific climate projections were used instead of national/regional average projections or some hypothetical changes in temperature and rainfall. Thus, we attempted to estimate district-specific climate change impacts on crop yields which can be more useful in targeting and prioritization of adaptation measures.

Materials and methods

Analytical methods

The analysis was attempted in a panel data regression framework following Deschenes and Greenstone, (2007), Kumar and Parikh (2001), Birthal et al (2014a, 2014b), Singh et al (2020). The process consisted of a two-step process: We first estimated the relationship between climate variables and yield by fitting panel data regression to the historical yield and climate data for the period 1971–2004. We included monthly temperature, rainfall in terms of average and variability and number of rainy days by month. The months during which these crops are generally grown are considered (June to October for rainy season (kharif) crops and October to March for post-rainy season (rabi) crops). Then, we applied the coefficients so obtained to the projected changes in future climate variables to estimate the yield impact.

A fixed effect model, as given in (1) is specified:

\[ Y_{it} = \alpha_0 + \alpha_iD_i + \sum \beta_j P_{jit} + \sum \gamma_j Q_{jit} + \sum \delta_j R_{jit} + \sum \eta_j S_{jit} + \sum \theta_j Z_{jit} + \psi t + U_{it} \]  

(1)

Where

- \( Y_{it} \) = Yield of the crop concerned in ith district in year t
- \( D_i \) = Dummy variable for ith cross-sectional unit (district) \( i = 1 \ to \ (k-1) \)
- \( P_{jit} \) = Average temperature during jth month for ith district in tth year
- \( Q_{jit} \) = Rainfall during jth month for ith district in tth year
- \( R_{jit} \) = No. of rainy days during jth month for ith district in tth year
- \( S_{jit} \) = Coefficient of variation in daily average temperature in jth month
- \( Z_{jit} \) = Coefficient of variation in daily rainfall in jth month
- \( k \) = number of cross section units (districts)
- \( j \) = June to November (for kharif crops grown during rainy season) and October to March (for rabi crops, grown during post-rainy season)
- \( U_{it} \) = error term iid \( \sim N(0, 1) \)
- \( \alpha, \beta, \gamma, \delta, \eta, \theta \) and \( \psi \) are regression coefficients

The model included time variable (t) to capture the technological trend (\( \psi \)) that reflects effects of technological changes and other responses that occur over time. District-specific time invariant district specific resources like soil type, soil texture, differences in technology adoption, etc are captured through district dummy variables. The regression coefficients were estimated by Least Squares Dummy Variable Method from a fixed effects panel regression model as the Hausman test (Hausman 1978) rejected random effects model at \( p < 0.05 \).

The yield impacts of climate change were assessed as the difference between the yields obtainable during mid or end century period assuming away climate change and the yields obtainable with changed climate as captured
through the PRECIS-based projections. The former were estimated through extrapolating the technological trend. The yield impact ($\Delta Y_c$) was estimated using the regression coefficients from equation (1) and the projected changes in mean climate variables ($\Delta P$, $\Delta Q$, $\Delta R$, $\Delta S$, $\Delta Z$) for mid- and end-century as given below:

$$\Delta Y_c = \sum \beta_i \Delta P^*_i + \sum \gamma_j \Delta Q^*_j + \sum \delta_i \Delta R^*_i + \sum \eta_j \Delta S^*_j + \sum \theta_i \Delta Z^*_i$$ \tag{2}

The change in climate variables were computed as the difference between the projected mean climate for mid-century or end-century relative to the baseline.

**Data**

The historical time series data on yields of different crops for different districts, at their 1970 boundaries\(^1\), were obtained for the years 1971–2004 from the Department of Agriculture, Cooperation and Farmers’ Welfare, Government of India and various state governments. The study included major food crops covering cereals (rice, wheat, maize, sorghum, pearl millet, finger millet), pulses (pigeon pea, chickpea) and oilseed crops (groundnut, soybean and rapeseed & mustard). These crops accounted for 66.5 per cent of the gross cropped area during 2018–19. The crops were selected considering the importance in food security of the country. Cereals and pulses together are considered as food grains in India. Pulses are major source of protein for Indian population whereas rice and wheat are the two staple food crops in India. On the other hand, oilseed crops are the major dietary component meeting the fatty acid requirements. At present, India is self-sufficient in cereals, nearly self-sufficient in pulses, but imports considerable amount of edible oil. However, the demand for all these crops is likely to increase in future due to rising population and incomes (NITI Ayog 2018). All of these crops except wheat, chickpea and rapeseed & mustard are largely grown during kharif (rainy) season that commences in June. In order to avoid atypical conditions of crop growing that may distort the estimated relationship or coefficients, only those districts having at least a minimum specified area, averaged over 1971–2004, (ranging between 10000 ha in case of finger millet to 20000 ha in case of rice) were included in the analysis. The selected districts accounted for at least 85 per cent of the area under the crop concerned. In case of historical data on temperature and rainfall, the gridded data provided by the India Meteorological Department (IMD) on a daily scale was used to derive the district level data on average temperature and rainfall for the same period.

Two time periods were considered for future climate: mid-century period (2021–2050) and end-century period (2071–2098). The future climate was obtained by using the projections from PRECIS\(^2\) (Providing REnoiral Climates for Impact Studies) regional climate model, which was found to mimic the Indian climate well (Krishna Kumar et al 2011) for SRES A1B\(^3\) scenario and in line with the India’s Second National Communication (MoEF 2012, Rama Rao et al 2016) to United Nations Framework Convention on Climate Change (UNFCCC). This regional climate model, specifically developed for facilitating impact studies, uses the lateral boundary conditions from HadCM3 GCM with the Quantifying Uncertainty in Model Prediction (QUMP) simulations in representing regional climatological features. Further, this involves running 17 QUMP simulations with various combinations of perturbations to the parameters of the model to produce an ensemble. The projections used are an ensemble output of three runs of PRECIS carried out at Indian Institute of Tropical Meteorology, Pune, India with lateral boundary conditions from QUMP simulations for the period 1961–2098. These projections are available at a spatial resolution of $0.44^\circ \times 0.44^\circ$ on a daily scale for the period up to 2098. The yield impacts were reported for mid points of the mid- and end-century periods.

The district level climate variables were derived by constructing Thiessen polygons around the grid points which were then overlaid on the district boundary map in a Geographical Information System (GIS) environment. The district level estimates for rainfall related variables were derived as a weighted average with the proportion of the areas of polygons resulting from intersections of district boundary and Thiessen polygons as weights. In case of temperature related variables, simple averages, as spatial variability is relatively less (Attri and Tyagi 2010), of the values of the grid points lying within the district boundaries were used to derive district level estimates.

\(^1\) In India, state governments reorganize districts by creating new districts for administrative convenience and hence the number of districts change over time. In order to build time series data, only those districts that existed in 1970 were considered. Wherever required, data were mapped to those districts by apportioning of data.

\(^2\) PRECIS—Providing Regional Climates for Impact Studies—is a regional climate model that downscales large scale climate projections to regions of interest at a resolution of 25 to 50 KM.

\(^3\) This scenario assumes a future characterized by rapid economic growth, low population growth and introduction of new and more efficient technology. Though climate projections based on CMIP-5 group of GCMs are now available for different Representative Concentration Pathways, the regional projections of the same, at a scale suitable for impact assessment, are not available for India.
Results and discussion

Baseline climate
The baseline climate, as derived from the IMD gridded data set for the period 1971–2004 is presented in table 1. The average temperature of the country ranged from 17.75 °C in January to 30.51 °C in May. The spatial variation in temperature was found to be highest in January with a coefficient of variation of 22%. July was found to be the wettest month with a mean rainfall of 317 mm and January the driest month with 14 mm of rainfall. December and August month experienced highest (264%) and least (64%) variability in rainfall.

Climate projections
Climate projections as obtained from the PRECIS regional climate model are expressed in terms of changes in rainfall and temperature. Figure 1 shows that the average temperature is projected to increase by 1.4 to 2.3 °C during mid-century period and by 3.0 to 6.0 °C during end-century period. During mid-century, rise in temperature is relatively higher in many districts of Rajasthan, Madhya Pradesh, Maharashtra, Karnataka, Jammu & Kashmir, Himachal Pradesh, Bihar and West Bengal. During the end-century, most of the districts in

Table 1. Baseline climate variables (1971-2004).

| Variable               | Minimum | Maximum | Mean  | CV (%) |
|------------------------|---------|---------|-------|--------|
| Average temperature (°C) during |         |         |       |        |
| June                   | 21.35   | 36.17   | 29.94 | 9      |
| July                   | 18.64   | 34.71   | 28.02 | 7      |
| August                 | 15.90   | 32.54   | 27.47 | 6      |
| September              | 20.37   | 31.69   | 27.29 | 6      |
| October                | 16.16   | 30.92   | 25.74 | 7      |
| November               | 12.00   | 27.76   | 22.15 | 11     |
| December               | 7.53    | 27.73   | 18.67 | 18     |
| January                | 6.33    | 31.29   | 17.75 | 22     |
| February               | 7.40    | 33.39   | 20.16 | 19     |
| March                  | 10.76   | 33.00   | 24.41 | 13     |
| April                  | 15.72   | 34.68   | 28.45 | 10     |
| May                    | 19.04   | 37.08   | 30.51 | 10     |

Rainfall (mm) during

| Variable   | Minimum | Maximum | Mean  | CV (%) |
|------------|---------|---------|-------|--------|
| June       | 0       | 1804    | 195   | 99     |
| July       | 0       | 2146    | 317   | 74     |
| August     | 0       | 1723    | 285   | 64     |
| September  | 0       | 1127    | 188   | 75     |
| October    | 0       | 1094    | 86    | 114    |
| November   | 0       | 804     | 32    | 221    |
| December   | 0       | 784     | 15    | 264    |
| January    | 0       | 450     | 14    | 172    |
| February   | 0       | 528     | 18    | 163    |
| March      | 0       | 611     | 21    | 188    |
| April      | 0       | 885     | 40    | 177    |
| May        | 0       | 1295    | 73    | 155    |

Number of rainy days during

| Variable   | Minimum | Maximum | Mean  | CV (%) |
|------------|---------|---------|-------|--------|
| June       | 0       | 30      | 11    |        |
| July       | 0       | 31      | 18    |        |
| August     | 0       | 31      | 17    |        |
| September  | 0       | 30      | 12    |        |
| October    | 0       | 29      | 6     |        |
| November   | 0       | 29      | 2     |        |
| December   | 0       | 23      | 1     |        |
| January    | 0       | 18      | 1     |        |
| February   | 0       | 24      | 2     |        |
| March      | 0       | 31      | 2     |        |
| April      | 0       | 27      | 3     |        |
| May        | 0       | 31      | 5     |        |

CV is not presented for number of rainy days because of zero values for non-rainy days.
the country, except those on west and east coasts, are likely to experience a temperature rise of 4 °C–5 °C. Rainfall projections indicate an increase in rainfall by more than 5% in a majority of districts in the country during mid-century period. The projected increase in rainfall is even more widespread during end-century with only a few districts in Rajasthan, Telangana, Karnataka and Arunachal Pradesh showing less than 5% increase in rainfall.

Climate coefficients

Kharif crops

The effect of monthly climate represented in the form of average temperature and rainfall is shown in Table 2 for kharif crops. Unlike many studies, we included the variability in temperature and rainfall as regressors considering the importance of variability and extremes on crop productivity. The regression model was found to be a good fit with R² values ranging from 0.48 in case of groundnut to 0.80 for rice.

In case of rice, average temperature during July, September and October was found to have statistically significant negative effect on productivity. The variability in temperature, expressed as coefficient of variation, during July and October had significant negative effect. With respect to rainfall, number of rainy days during

Figure 1. Projected changes in annual rainfall during (A) mid-century and (B) end-century and average temperature during (C) mid-century and (D) end-century.
Table 2. Panel data regression results for kharif crops.

| Variable          | Rice     | Maize    | Sorghum  | Pearl millet | Finger millet | Pigeon pea | Groundnut | Soybean |
|-------------------|----------|----------|----------|--------------|---------------|------------|-----------|---------|
| Time trend        | 31.996** | 23.98** | 9.53**   | 16.98**      | 12.80**       | 1.75**     | 10.15**   | 20.61** |
| Average temperature during |
| June              | 12.93    | 28.08    | 19.62**  | 13.89*       | 28.83         | 0.21       | 15.84     | 31.63*  |
| July              | −29.70** | 10.40    | 19.82*   | 31.19**      | −43.11        | −17.81     | 41.20*    | −24.91  |
| August            | −17.66   | 124.08** | −16.70   | −40.76**     | 6.37          | 11.47      | −31.12    | 80.04** |
| September         | −34.44** | −131.06* | −29.93** | −34.77**     | −22.17        | 2.10       | 4.60      | −67.86**|
| October           | −57.78** | −65.82*  | −35.25** | −36.91**     | −58.67**      | −30.00**   | −50.29**  | −60.47**|
| November          | −12.34   |          |          |              |               |            |           |         |
| Variation (CV) in temperature during |
| June              | −9.48    | −333.53**| 33.96    | 26.27         | −20.60        | 112.88**   | 166.12*   | 130.59* |
| July              | −293.39**| −184.44  | −152.34**| −244.91**    | −56.71        | 87.16      | −164.78   | −42.20  |
| August            | −66.22   | −640.23**| −7.72    | −160.56**    | 4.96          | 267.01**   | −13.54    | −518.69**|
| September         | −89.75   | 59.20    | −37.21   | 14.07         | −22.90        | 199.53**   | −159.61   | 261.83* |
| October           | −228.52**| 19.31    | 9.22     | 2.85          | −244.00**     | −36.43     | 43.15     | −335.20**|
| November          | −55.07   |          |          |              |               |            |           |         |
| Rainfall during   |
| June              | 0.061    | 0.35     | 0.35**   | 0.15          | −0.06         | 0.44**     | 0.00      | 0.40    |
| July              | 0.22     | −0.38**  | −0.01    | 0.03          | 0.01          | 0.02       | 0.25      | 0.05    |
| August            | 0.18     | −0.07**  | −0.08    | 0.00          | 0.01          | −0.17**    | 0.06      | 0.04    |
| September         | 0.13     | −0.11    | −0.17**  | −0.16         | 0.10          | −0.01      | 0.17      | −0.19   |
| October           | 0.18     | −0.51    | −0.01    | −0.08         | 0.05          | −0.18      | 0.15      | 0.08    |
| November          | −0.21    |          |          |              |               | −0.09      |           |         |
| Variation (CV) in rainfall during |
| June              | −0.03    | −0.15    | 0.13     | 0.04          | 0.21          | −0.003     | −0.15     | 0.06    |
| July              | 0.35**   | 1.29**   | 0.19     | −0.09         | 0.14          | 0.43**     | 0.15      | −0.08   |
| August            | 0.05     | −0.03    | −0.21    | −0.39**       | 0.19          | −0.08      | −0.02     | −0.01   |
| September         | −0.38**  | 0.52     | −0.04    | −0.03         | −0.07         | 0.16       | 0.04      | −0.34   |
| October           | −0.07    | −0.01    | 0.04     | 0.06          | −0.04         | −0.14      | 0.21      | −0.10   |
Table 2. (Continued.)

| Variable          | Regression coefficient |
|-------------------|------------------------|
|                   | Rice | Maize | Sorghum | Pearl millet | Finger millet | Pigeon pea | Groundnut | Soybean |
| November          | 0.20 |       |         | 0.06         |               |           |           |         |
| Rainy days during |      |       |         |              |               |           |           |         |
| June              | 2.02 | 5.78  | 2.20    | 1.44         | 6.76          | 6.21**     | 2.51      | 6.22    |
| July              | 0.82 | 11.47**| 3.10    | 1.19         | 0.92          | 5.74**     | 11.01**   | 2.71    |
| August            | 4.94**| 7.43  | 1.51    | 3.32         | 9.41**        | 3.59@      | 4.37      | 1.75    |
| September         | 5.35**| 9.96  | 4.08**  | 5.04**       | 0.34          | 5.39*      | 2.97      | 2.14    |
| October           | 0.65 | 2.96  | 1.02    | 1.63         | 1.93          | 0.46       | 5.85      | 8.50    |
| November          | 22.96|       |         | 1.93         |               | 5.85       |           |         |
| R²                | 0.80 | 0.75  | 0.58    | 0.69         | 0.65          | 0.75       | 0.48      | 0.67    |
| No. of districts  | 219  | 137   | 172     | 132          | 25            | 81         | 66        | 63      |
| No. of observations | 7446 | 4658  | 5848    | 4488         | 850           | 2754       | 2244      | 2142    |

**, *, and @ indicate significance at 1, 5 and 10 per cent, respectively. Standard errors are not presented for want of space. The coefficients of most of the district dummies (not presented here) are statistically significant indicating presence of district specific effects.
August and September had a significantly positively relationship with yield. The coefficient with respect to time was found to be about 32 kg/ha over the period 1971–2004 due to such factors as changes in technology, input use including irrigation, etc.

The maize yields were found to be adversely affected by average temperature during August and September which coincide with critical growth stages of the crop, normally sown during June and July. Temperature variability during June and August was found to be negatively influencing yield, probably due to sensitivity of seed germination and establishment which are known to be affected by low rainfall and high temperature (Heloisa et al 2019). Rainfall during July and August showed statistically significant influence on maize yields negatively. The coefficient with respect to time was 24 kg/ha.

In case of sorghum, yield was found to be positively affected by the average temperature during June and July. However, temperature during September and October showed an adverse effect as this period overlaps with reproductive and maturity stages of the crop. Rainfall in the months of June and September showed positive and negative effects, respectively. The crop is sown in the month of June with the onset of the monsoon rains and any delay in sowing causes decline in yields (Sharma 2014). Also, high rainfall during the reproductive stage attracts higher pest and disease incidence. Further, variation in temperature in the month of July was found to have adverse effect on yield. The coefficient with respect to time was significant at 9.5 kg/ha. The model explained about 58 per cent of the variability in yields.

In case of pearl millet, the model explained 69 per cent of the variation in yield. The regression coefficients showed that yield increased by about 17 kg per year. Both mean levels and variability in monthly temperature were found to affect yields of pearl millet. However, average temperature during August, September and October, and variability in temperature during July and August showed significant negative effect on yield. The yield was also adversely affected by variability in rainfall in the month of August.

In case of finger millet, grown only in a few states, the coefficient with respect to time was found to be 13 kg/year. The crop yield was found to be highly sensitive to average temperature during October. Number of rainy days during June and August were found to have significantly positive effects on the yield.

Among pulses, pigeon pea is the most important crop grown largely during kharif season. The coefficient related to time was found to be low at 1.75 kg/ha indicating slow growth. The crop yields were found to be negatively sensitive to temperature during October which coincides with flowering and pod setting. The crop is also known to be sensitive to distribution of rainfall which is reflected in the positively significant relationship with rainy days during the months of June, July, August and September. The model accounted for 75% of variation in crop yield.

The yields of groundnut were found to be sensitive to temperature during July and October. Temperature variation during June and number of rainy days during July were other climate variables with a statistically significant relationship. The coefficient with respect to time was found to be about 10 kg/ha.

Soybean, which has risen to prominence during the last few decades, yields were found to be significantly influenced by average temperature during June, August, September and October. Variation in temperature during most of these months were also found to be important with significant coefficients. The model accounted for 67% of variation in the yield.

### Rabi crops

Wheat, chickpea and rapeseed & mustard are the important food crops grown during rabi season. The model accounted for 56 to 86% of variation in productivity in these crops (table 3). The crop yields were regressed on temperature related variables from October to March and rainfall related variables for October only as the rainfall during post-monsoon season is scanty. Most of the rabi crops are grown under irrigated conditions. Though these crops are sown from November onwards, the residual soil moisture is an important determinant of crop yield during rabi season. Crops like wheat are also known to be sensitive to night/minimum temperature. The yields of all the three crops were found to be significantly influenced by both average and variation in temperature. The coefficient with respect to time was about 39, 10 and 12 kg per year in case of wheat, chickpea and rapeseed & mustard, respectively.

### Impact of climate change on yield levels

The impact of climate change on crop yields, estimated as the difference between the projected yields with and without climate change, are presented in table 4. It can be seen from the table that the yield impacts are more conspicuous during the end-century period as the change in temperature is more towards the end of the century. The yield impacts are higher in case of maize whose yields are likely to be lower by about 113 kg/ha, 6 per cent of the baseline yields, in the projected climate compared to those obtainable in a no climate change situation. The yield reduction is likely to be smaller in case of sorghum, chickpea and pearl millet (0.2 to 3.6% relative to baseline) during the mid-century period. However, yields of crops such as soybean (11.2%), groundnut (14.8%)...
are likely to increase due to climate change. Such positive impacts of climate change are also reported by Government of India (2008) and Lal et al (1999). The yields are likely to decrease by larger extent driven by the steeper rise in temperature, and are reflected in the projected decrease of rice yield by about 460 kg/ha (23.7%), maize (397 kg/ha, 21.1%), soybean (337 kg/ha, 33.7%), wheat (302 kg/ha, 11.4%), pearl millet (274 kg/ha, 30.5%). Groundnut and pigeon pea yields are likely to increase due to climate change. It is to be noted here that the yields will still be higher than the current yields provided the technological trend continues into the future. Whether this trend will persist into future will depend on how the processes of technology development and transfer evolve taking into consideration the climate change. In general, results from simulation studies show

| Variable | Wheat | Chickpea | Rapeseed and mustard |
|----------|-------|----------|----------------------|
| Time trend | 39.16** | 9.80** | 12.40** |

** and * indicate significance at 1 and 5 per cent, respectively. Standard errors are not presented for want of space. The coefficients of most of the district dummies (not presented here) are statistically significant indicating presence of district specific effects. CV in rainfall and number of rainy days were not included in regression of wheat and chickpea yields as these crops are generally sown in latter part of October or early November.

| Impact of climate change on crop yields during mid-century (2021–2050) and end-century (2071–2098) periods. |
|-------------------------------------------------------------|
| Crop | Impact of climate change on yield (kg/ha) |
|------|------------------------------------------|
| Rice | −81 (4.2) | −460 (23.7) |
| Wheat | −45 (1.7) | −302 (11.4) |
| Maize | −113 (6.0) | −397 (21.1) |
| Sorghum | −1.8 (0.2) | −219 (29.0) |
| Pearl millet | −25 (2.8) | −274 (30.5) |
| Finger millet | −45 (3.6) | 196 (15.9) |
| Pigeon pea | 99 (14.9) | 20.1 (3.0) |
| Chickpea | −18 (2.3) | −151 (19.3) |
| Groundnut | 152 (14.8) | 36 (3.5) |
| Soybean | 107 (11.2) | −337 (35.2) |
| Rapeseed & mustard | 45 (4.4) | 103 (10.0) |

Values in parentheses indicate per cent change from baseline.
considerable adverse impacts of climate change on crop yields when no adaptation is considered (Aggarwal et al 2022). These models also show significant benefits of selected adaptation options in protecting or sometimes even increasing crop yields. For example, rice yields are projected to decrease by 4%, maize yields by 3 to 18% and pigeon pea yields by 3 to 38% depending on location, variety and climate change scenario considered.

Climate change is characterized by slowly and gradually changing temperature, rainfall and other climate variables and increasing incidence of extreme events. Likewise, climate change adaptation has two main components: autonomous adaptation and planned adaptation. The agricultural technology development process implicitly addresses the ‘gradual’ part of climate change as the technologies are developed and evaluated in the evolving climate. The technological trend implicitly captures such autonomous adaptation. More focus is needed to give an explicit attention to the climate, especially to the increasing incidence of extreme events, in the technology development process so that the yield enhancing effects of technological change outweigh the negative yield effects of rising temperature and varying rainfall patterns. Also, historically rainfall deficits received more attention in terms of understanding and dealing with productivity and production declines whereas heat stress, captured as rising temperature, is emerging as a major yield determinant. Accordingly, breeding for crop varieties with heat stress tolerance has to receive adequate attention.

**District level climate change impacts**

**kharif crops**

As crop production and climate change are spatially variable, the impacts of climate change on crop yields also vary across space. An attempt is made to bring out such spatially disaggregated yield impacts so that the agricultural research and development processes can be better targeted and prioritized.

The impact of climate change on crop yields computed as the difference between the projected yields with and without climate change and expressed as per cent change relative to baseline are presented in figures 2–4. The yields of rice are projected to decline by more than 25% in eight districts and by up to 25 per cent in 118 districts of the country during the mid century. The yields will be lower by more than 25 per cent in 79 districts during the end century period because of the projected steeper change in climate. At the current extent of area under the crop, these yield declines will mean a production loss of more than 100 thousand tonnes in 10 districts during the mid century and in 59 districts in end century. In case of maize, out of 137 districts growing the crop, yields are likely to decline in 112 districts during mid century and increase in 25 districts. However, all 137 districts are likely to witness a decline in yield during the end century period which will lead to a reduction in production by more than 25000 tonnes in 26 districts.

Sorghum yields are projected to decline by more than 25 per cent in 5 and 72 districts during mid- and end-century periods, respectively. The projected change in temperature and rainfall are likely to increase sorghum yield in 115 out of 172 sorghum growing districts during mid-century. These yield changes may lead to a production loss of more than 25000 tonnes in end-century period in 72 districts. Pearl millet was grown in 132 districts in the country. Climate change is likely to reduce yields by more than 25 per cent in 12 districts and increase yields in 66 districts during mid-century. The yields are estimated to decline in all the districts during the end-century period leading to a loss of production by more than 25000 tonnes in 64 districts during end-century period. In case of finger millet, the number of districts that are likely to see decline in yields increased from 16 during mid-century to 21 during end-century. Production declines can be observed in 16 and 21 districts, respectively in mid- and end-century. A few districts are also likely to see an increase in yield by more than 25 per cent during both periods.

Yields of pigeon pea are likely to be negatively affected by climate change in 13 and positively in 68 districts during the mid-century. Positive impacts are likely to be realized in 39 districts during end-century with 42 districts likely to suffer yield decline. These yield changes translate into production loss of more than 10000 tonnes in 13 districts during mid-century. In case of groundnut, positive yield impacts are likely in 44 of 66 districts during mid-century and 24 districts during end-century. Production gains (loss) are expected in 44 (22) districts during mid-century and end-century. Soybean yields may be affected by more than 25 per cent in 39 of 63 districts during the mid-century with production losses exceeding 50000 tonnes in 20 districts. During the mid-century, the yield losses may exceed –25 per cent in one district only though yields are likely to decrease in 14 districts by up to 25 per cent. Yields in fourteen districts during mid-century and four districts during end-century are likely to increase.

**Rabi crops**

Climate change is likely to reduce yield of wheat in 141 out of 204 districts in the country with three districts likely to suffer more than 50 per cent decline during the mid-century. During the end-century, all districts except two may possibly see a decline in yield. Yield in eleven districts are likely to fall by more than 50 per cent. These yield changes at the current area under the crop can cause a production decline exceeding 50000 tonnes during

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mid-century and 49 districts in end-century. In case of chickpea, negative yield impacts are likely in 88 and 187 of 189 districts during mid- and end-century respectively. Production losses are estimated at more than 10000 tonnes in 2 and 35 districts, respectively in mid- and end-century periods. The yield of rapeseed and mustard is likely to be positively affected by climate change in 95 out of 124 districts during mid-century and 121 districts during end-century period. The yields will probably decline by more than 10 per cent in three districts during end-century period. These yield changes will result in a production decline of more than 10000 tonnes in 29 and 3 districts during mid- and end-century period respectively.

Climate change is also associated with changes in rainfall pattern which, if translated into enhanced water availability for irrigation, can moderate the adverse effects of rising temperature. The projected changes in
rainfall patterns present opportunities for rainwater harvesting (Rejani et al 2018) which can be gainfully utilized in management of dry spells and heat stress that the crops are exposed to (Srinivasa Rao et al 2017). A number of technologies related to crop management, natural resource management, livestock management and institutional arrangements are being demonstrated in different parts of the country (Srinivasa Rao et al 2016) to deal with climate variability and change. Such attempts to develop and deliver climate resilient agricultural technologies together with the realized extent of climate change will determine the impact on yields.

The analysis showed that crop yields are likely to be adversely affected by changing climate and the impacts vary among crops and across districts. The differences in crop varieties, access to irrigation and other technologies cause differential impacts on yield. For example, rice is cultivated largely under irrigated conditions

Figure 3. District-level impact of climate change on yield and production finger millet (E1)–(E4), pigeon pea (F)–(F4), groundnut (G1)–(G4) and soybean (H1)–(H4) during mid-century (2021–2050) and end-century (2071–2098).
in northern, western and southern parts of the country while it is grown under rainfed conditions in eastern regions. The climate change impacts on crop yields are both direct and indirect. The direct impacts operate by affecting physiology and growth of plants, by altering the length of crop growing season (Raza et al 2019). Different crop species respond differently to climate change. For example, the physiological processes of anthesis and pollination are adversely affected by rising temperature in case of rice, and wheat (Debaeke et al 2017). In general, C4 plants (e.g. maize, sorghum) are more benefited by rising concentrations of carbon dioxide which is a key feature and determinant of climate change (da Silva et al 2020). The yield impacts are also mediated through the changes in availability of water and incidence of insect pests and diseases (Pareek et al 2017).

The projected negative impacts on crop yields have implications to food and nutrition security in India. Though India is self-sufficient in production of rice and wheat, the two major staple food cereals, the demand for these crops is likely to increase considerably in future (Raeboline et al 2019). The demand for coarse cereals such as sorghum, pearl millet and finger millet is also rising owing to their nutritional importance (Davis et al 2019). The demand for maize is also increasing as it has multiple uses (Singh et al 2012). India is the largest producer, consumer and importer of pulses in the world (Shukla and Mishra 2020). Given the predominant incidence of vegetarianism, the importance of pulses to meet the protein needs cannot be over emphasized and short fall in production can have implications to health outcomes (Henchion et al 2017). The declining or stagnant per capita availability of pulses also underscores the need to increase the productivity and production of pulse crops even assuming climate change away (Singh et al 2017). However, if the technology development and dissemination is not slowed down, it is likely that the future yields will be higher than the current yields. A historical growth in performance of agriculture shows that there are periods of slower growth (e.g. 1990s
witnessed considerable slow down in growth in yields of major crops) and faster growth (1970s and 1980s) (Tripathi and Prasad 2009). Most of the demand projections for different crops did not consider the nutrition-diluting effects of climate change. It is important to invest in agricultural research, extension and infrastructure to ensure adequate growth in crop yields to moderate the impacts of climate change. It is to be added here that the production outcomes will depend on the trajectories of technology development and transfer and of temperature and rainfall. Further, as the responsibility of agricultural development in India largely rests with the state governments, information on district level impacts will help decision making on dealing with climate change.

Simulation modelling and controlled experimentation are the most frequently followed approaches to understanding yield impacts. However, these methods are data and resource intensive as they have to be calibrated for different locations and varieties (Lee et al 2012). Also, not all adaptation options can be assessed in these models. On the other hand, econometric approaches, while relatively less data intensive, can complement the outputs of simulation modelling in terms of providing insights at a more disaggregated geographical scale (Nikas et al 2019). However, that these approaches are not based on physiological response of the crop plants and do not consider the carbon fertilization effect is a limitation. The natural adaptation and planned genetic improvement of crop plants through various breeding methods may also influence the impacts of climate change. The uncertainty associated with climate projections and that the present findings are based on downscaled projections are to be kept in mind as are the limitations of econometric modelling while considering these findings. Using an ensemble of projections from more recent climate models such as those belonging to Coupled Model Intercomparison Project (CMIP) – 5 or 6 for estimating and understanding the climate impacts is an area of future research.

Conclusions

The primary role of agriculture in India is to ensure food security to the growing population as well as to secure the livelihoods of those dependent on agriculture. Climate change along with other challenges to agriculture is to be tackled in such a way that the adverse impacts are minimized and positive effects harnessed better. Given that the scope for expansion of sown area is almost non-existent, the required production gains have necessarily to come from productivity gains. This analysis brought out the possible yield impacts on different crops and their distribution across districts which are basic units for development planning and resource allocation in the country. Therefore, efforts are to be targeted and prioritized in the districts where the yields are likely to suffer more.

However, the negative yield impacts do not necessarily mean that yields in future would be lower than the current yields as the technology development process takes care of the ‘gradual change’ part of climate change at least partially which is why the yields of crops show a long-term increasing trend over decades notwithstanding climate change and variability. However, there are periods of slower growth, as those of 1990s, in agriculture. Therefore, there is an increasing need to factor in climate related risks, especially increasing incidence of extreme events, in the process of technology development and transfer. Also, the concerns related to abiotic stress, especially those related to heat/temperature stress, need more attention in crop improvement and natural resource management programmes as those related to variability in climate. The way the technology development and dissemination take place in a changing climatic and socio-economic environment will play a role in determining the actual impacts of climate change in future.

In case of temperature, both historical trends and future projections show conspicuous rise which can directly and indirectly affect crop growth and productivity. However, the trends and projections in rainfall are more spatially variable which have to be better understood for effective technology and policy development. Opportunities for rainwater harvesting should be explored and utilized for managing crop growth and productivity against dry spells. There are several efforts combining technological and institutional interventions in different parts of the country for dealing with adverse effects of climate change and variability. The learnings of such exercises are to be incorporated and followed up in the efforts for scaling out technologies for a more climate resilient agriculture. Considering the dimension of climate change along with other bottlenecks to sustainable agriculture in the research and development process is a desirable way of mainstreaming climate change in to economic development programmes.

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Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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