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# Simulating impacts, potential adaptation and vulnerability of maize to climate change in India

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**Abstract** Climate change associated global warming, rise in carbon dioxide concentration and uncertainties in precipitation has profound implications on Indian agriculture. Maize (*Zea mays L.*), the third most important cereal crop in India, has a major role to play in country's food security. Thus, it is important to analyze the consequence of climate change on maize productivity in major maize producing regions in India and elucidate potential adaptive strategy to minimize the adverse effects. Calibrated and validated InfoCrop-MAIZE model was used for analyzing the impacts of increase in temperature, carbon dioxide ($CO_2$) and change in rainfall apart from HadCM3 A2a scenario for 2020, 2050 and 2080. The main insights from the analysis are threefold. First, maize yields in monsoon are projected to be adversely affected due to rise in atmospheric temperature; but increased rainfall can partly offset those loses. During winter, maize grain yield is projected to reduced with increase in temperature in two of the regions (Mid Indo-Gangetic Plains or MIGP, and Southern Plateau or SP), but in the Upper Indo-Gangetic Plain (UIGP), where relatively low temperatures prevail during winter, yield increased up to a 2.7°C rise in temperature. Variation in rainfall may not have a major impact on winter yields, as the crop is already well irrigated. Secondly, the spatio-temporal variations in projected changes in temperature and rainfall are likely to lead to differential impacts in the different regions. In particular, monsoon yield is reduced most in SP (up to 35%), winter yield is reduced most in MIGP (up to 55%), while UIGP yields are relatively unaffected. Third, developing new cultivars with growth pattern in changed climate scenarios similar to that of current varieties in present conditions could be an advantageous adaptation strategy for minimizing the vulnerability of maize production in India.

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## 1 Introduction

The inter-governmental panel on climate change has projected that the global mean surface temperature is predicted to rise by 1.1–6.4°C by 2100 (IPCC 2007). Increasing atmospheric temperatures and carbon dioxide along with uncertainties in annual precipitation will have an adverse affect on Indian agriculture (Aggarwal 2008). Among the cereal crops, maize (*Zea mays* L.) occupies an important place in Indian agriculture due to its large production potential and utilization as food, feed and industrial raw material. Currently it ranks the third among the most important food grain crops in India, next to wheat and rice. Maize is grown in a wide range of environments, extending from extreme semi-arid to sub-humid and humid regions in Kharif (monsoon) and rabi (winter) seasons. The Indian maize production has expanded over the past few years to about 6.29 million ha (3.6% of the gross cropped area) mainly due to increasing demand for feed from livestock and poultry sectors. In India, demand for maize in next 12 years (by 2020) is projected to rise to 26.2 million tons from current level of 15.1 million tonnes (ASSOCHAM 2008) due to increasing demand for chicken feed and industrial purposes. To meet these targets, it is important to sustain the current high growth rates in maize production. However, impending challenge from climate change could make this a tougher task. Hence it is imperative to assess the impacts of climate change on maize productivity. Simulation analyses indicated impact of climate change and climatic variability on maize production in different regions of world, viz., Africa and Latin America (Jones and Thornton 2003), North America (Tubiello et al. 2002), Europe (Wolf and Van Diepen 1995). However, relatively a little is understood on the impact of climate change on maize productivity in India and about the likely performance of crop in winter season where it is gradually gaining importance in many part of the country. The benefits of rainfall, and agronomic adaptation practices influencing monsoon and winter season maize yields in climate change scenarios and the adaptation strategies required to mitigate its impacts are also little understood.

Rise in temperature and changes in rainfall influence maize yield as it is relatively a less hardy plant than other C4 plants like sorghum. Several studies have revealed the temperature sensitivity of maize. High temperatures hastened the crop phenology, doubling temperature variability can reduce the maize yields up to 50% (Wheeler et al. 2000), the net photosynthetic rates reduce when temperatures goes beyond 38°C (Crafts-Brandner and Salvucci 2002; Sage and Kubien 2007), altering dry matter partitioning (Lafitte and Edmeades 1997), increasing pollen sterility up to 50% in high temperature (Aylor 2004) and grain filling rate while decreasing grain number and (Cantarero et al. 1999). Increase in ambient temperature accelerate crop's rate of development, allowing maize to complete its phenological life cycle in shorter period of time with adverse impact on other important crop physiology.

In India, monsoon season (June–September), which receives majority of annual rainfall through south-west monsoon, is the major maize cropping season. Rain fall influences maize growth during monsoon season by influencing soil moisture availability even though its influence on winter season maize is negligible as it is predominantly irrigated crop. Another factor which influences crop production is atmospheric $CO_2$ concentrations. Even though, increase in ambient $CO_2$ does not have significant direct effects on C4 (C4 carbon fixation pathway) photosynthesis of maize crop (Leakey et al. 2004, 2006), increase in ambient $CO_2$ leads to higher water use efficiency in water stress conditions and there by directly influences dry matter production and grain yield (Leakey et al. 2004).

All these interactions were studied in the current simulation analysis using InfoCrop-MAIZE, a generic crop simulation model which can integrate the climate change parameters along with the varietal coefficients and crop management under Indian subcontinent conditions. The model has been calibrated and validated for various crops vis., wheat (*Triticum aestivum* L.) (Aggarwal 2008), rice (*Oryza sativa* L.) (Krishnan et al. 2007), cotton (*Gossypium spp* L.) (Hebbar et al. 2008), potato (*Solanum tuberosum* L.) (Singh et al. 2005), coconut (*Cocus nucifera* L.) (Naresh Kumar et al. 2008). The model has earlier been used to study the impacts of climate change on wheat (Aggarwal and Swaroopa Rani 2009), rice (Krishnan et al. 2007), soyabean (Mall et al. 2004) and coconut (Naresh Kumar and Aggarwal 2009). In these analysis, climate change is projected reduce the yields of wheat, rice, monsoon maize and soybean with varying degrees, while coconut production is likely to increase in west coast of India.

Keeping in view of the current gap in knowledge on impacts of climate change on maize production in India and required strategies for making maize cultivation more resilient to climate change, a simulation analysis was carried out. The objectives of the present study, therefore, are to (1) calibrate and validate InfoCrop-MAIZE model to three different agro-climatic zones, (2) assess the impact of gradual change in atmospheric temperature, carbon dioxide rise and change in rainfall on maize yield, (3) assess the impact of climate change scenarios on maize yield and to 4) elucidate potential low- or no-additional cost adaptation strategies to reduce the adverse effects of climate change. Deriving agronomic strategies include possible change in sowing dates and suitable variety in changed environments, which are considered as adaptation options in the present study.

## 2 Methods

### 2.1 Model description

InfoCrop is a generic crop growth model that can simulate the effects of weather, soil, agronomic managements (including planting, nitrogen, residue and irrigation) and major pests on crop growth and yield. (Aggarwal et al. 2006). The model was adapted for maize and its coefficients were based on literature review, our own past experiments, and published models such as Ceres-Maize (Ritchie et al. 1986) and MACROS (Penning de Vries et al. 1989). The model considers different crop development and growth processes influencing the simulation of yield. The total crop growth period in the model is divided into three phases viz., sowing to seedling emergence, seedling emergence to anthesis and grain filling phases. The model requires various varietal coefficients viz, thermal time for phenological stages, potential grain weight, specific leaf area, maximum relative growth rate, maximum radiation use efficiency. Apart from these, model requires crop management inputs viz., time of planting, application schedule and amount of fertilizer and irrigation, soil input data such as soil pH, soil texture, thickness, bulk density, saturated hydraulic conductivity, soil organic carbon, slope, soil water holding capacity and permanent wilting point. Location wise daily weather data (Solar radiation, maximum and minimum temperatures, rainfall, wind speed, vapour pressure) are also required to simulate crop growth and yield.

In InfoCrop, crop development and growth processes and change in temperature, $CO_2$, and rainfall are simulated in the following ways:

1. The total development of a crop is calculated by integrating the temperature-driven development rates of the phases from sowing to seedling emergence, seedling emergence to 50% anthesis and storage organ filling phases. The rate of development is linearly related to the daily mean temperature above base temperature (8°C) up to the optimum temperature (28°C) and above optimum temperature, the rate decreases till maximum temperature (40°C) (Cutforth and Shaykewich 1990; Steck et al. 2008). Therefore, depending upon the temperature thresholds of a crop, in this case maize, temperature increase generally accelerates phenology and hence, crop duration including that of grain filling period is reduced.
2. Dry matter production is based on simulation of daily rates of photosynthesis, respiration, carbohydrate partitioning and photosynthetic area. Gross canopy photosynthesis is calculated depending on the distribution of light within the canopies, the radiation absorbed by the canopy and photosynthesis light response curve of leaves. Photosynthesis is affected by temperature, $CO_2$, leaf nitrogen content and water stress, thus influencing the radiation use efficiency of crop. Carbon dioxide concentration has no direct influence on photosynthesis as maize is a C4 crop. But under water stressed conditions, increase in $CO_2$ indirectly increases photosynthesis and yield by reducing water use and delaying drought stress thorough reduction in stomatal conductance and transpiration rate (Ghannoum et al. 2000).
3. The total amount of carbohydrates available for plant growth each day is calculated by subtracting the carbohydrates used in maintenance respiration from the total gross assimilation. The net dry matter available each day for crop growth is partitioned into plant organs as a crop-specific function of development stage, which is affected by temperature. Total dry weight of the plant organs are obtained by integrating their daily rates of growth over time after considering net losses through senescence.
4. Total photosynthetic area consists of green areas of plant parts such as leaf laminae and surface areas of stems, sheath and spikes. Leaf lamina area changes proportionally with leaf growth rate and non lamina area increases as the crop development progresses. Leaf area is reduced by senescence, tiller mortality, water, N and temperature stresses and post-anthesis mobilization of substrates.
5. Grain yield is largely dependent on source-sink balance. Grain number per unit area is dependent on total dry matter at anthesis. The rate of carbohydrate accumulation in grains is determined by variety, temperature, potential grain filling rate, development stage, potential grain weight and the level of available carbohydrates per grain. Actual rate of grain growth, limited by the potential grain filling rate, is determined by carbohydrates actually available for grain growth.
6. The rate of nitrogen (N) uptake is dependent upon crop N demand, phenological stage, soil N availability, transpiration, rooting depth and soil water status. The potential requirement of N by different plant parts is determined depending on rate of growth and the maximum concentration of N that organ could accumulate. Net N uptake is distributed to root, stem, leaves and spike structures in strict proportion to their relative demand.
7. Temperature influences potential evapo-transpiration. Water stress is determined as the ratio of actual water uptake and potential transpiration. Water stress accelerates phenological development, decreases gross photosynthesis, alters the allocation pattern of assimilates to different organs and accelerates rate of senescence.

8. Adverse temperatures during flowering coinciding with meiosis stage (pollen formation) could significantly increase sterility. In InfoCrop, a part of the storage organ becomes sterile if either maximum or minimum temperatures of the day deviate from their respective threshold values during a short period between anthesis and a few days afterwards. This reduces the number of storage organs available subsequently for accumulating weight. The storage organ start filling up shortly after anthesis with a rate depending upon temperature, potential filling rate and the level of dry matter available for their growth.
9. Influence of rainfall is operated in the model through soil water balance.

## 2.2 Model calibration and validation

For calibration of the model, data from a detailed experiment conducted during the monsoon (June–Sept) and winter (Oct–Feb) season of 1988–91 at the Institute of Agricultural Sciences, Banaras Hindu University, Varanasi (25°18′N, 83°03′E) (Naresh Kumar 1992) was used. In this experiment, maize cultivar Ganga-11 (hybrid) was sown on both seasons (monsoon and winter) and was provided with 6 irrigations for winter crop and 1 to 2 irrigations for monsoon crop. Fertilizer was applied at the rate of 120 N, 60 P and 40 K $Kg.ha^{-1}$. Nitrogen was applied in three splits i.e., 50% of the dose at basal and other half in two splits of equal doses (25%) at 10-leaf stage and at tassel emergence stage. The crop phenology (days to seedling emergence, 50% flowering and physiological maturity), leaf area index (LAI), total dry matter (TDM) and yield apart from other parameters were recorded at various stages of crop growth.

The InfoCrop-MAIZE model was calibrated satisfactorily to the growth parameters of cultivar Ganga-11. The simulated phenology of crop matched with that of observed values. Experimental data indicated that this cultivar takes 57 and 110 days to 50% flowering and 89 and 160 days for physiological maturity during monsoon and winter, respectively. Simulated values were in close agreement with these. The LAI at different times also match with the observed values during various stages of crop growth indicating satisfactory model performance regarding canopy development and senescence. The simulated TDM (12 $Mg.ha^{-1}$) was slightly higher than that of observed values (11 $Mg.ha^{-1}$). This is expected as model did not take other stresses like biotic stresses into consideration. However this variation in total dry matter is less than 10 per cent. Consequently, simulated grain yield (4.7 $Mg.ha^{-1}$) was found to be matching the observed yield (4.5 $Mg.ha^{-1}$). The above results indicated that model is able to simulate maize phenology, growth and yield with acceptable precision.

For validation, data sets of experiments from various sources were used (Table 1). Validation of model was done using data sets on phenology, LAI, TDM and grain yield from other experiments conducted in different locations of India (A.I.C.R.P 1997, 1998a, b, 1999). For judging the performance of model, validation results on major crop growth parameters such as phenology, maximum LAI ($LAI_{max}$) during crop growth and grain yield were tested using statistical parameters viz., mean bias error (MBE), root mean square error (RMSE), model efficiency (ME) as per the standard procedure described by Kabat et al. (1995).

The calibrated model was validated for different cultivars and for various management and soil conditions. Varietal coefficients were used to suit the model to a changed variety. These included thermal time coefficients for emergence to 50% flowering period (ranged from 1,100 to 1,400), initial specific leaf area (0.002–0.0024 $m^2.g^{-1}$), potential grain weight (260 to 330 $mg.grain^{-1}$) and nitrogen percentage in grain (1.1. to 1.54). Results indicated model's ability to simulate the phenology, LAI, TDM and yields of different maize cultivars. Simulated and observed phenologies (days to anthesis and physiological

**Table 1** Details of the experiments used for model validation of InfoCrop-MAIZE

| Location | Lat. (oN) | Long (oE) | Altitude m aMSL | Year of experiment | Soil type | Experiment | Crop variety | No. of treatments | Fertilizer | Data source | Maximum temperature range (°C) | Minimum temperature (°C) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Varanasi | 25.33 | 83 | 700 | 1989–91 | Alluvial, loamy alluvial | Varietal and fertilizer trial | Ganga-11, Manjari, Vijay, Deccan -103, Hi -starch | 12 | 120 N:26.2 P:33.3 K Kg.ha$^{-1}$ | (Naresh Kumar 1992) | 11.6–44 | 4–30 |
| Varanasi | 25.33 | 83 | 700 | 1989–91 | Alluvial, loamy alluvial | Varietal performance | Ganga-11 | 18 | Nitrogen treatments of 0, 80 120 and 160 Kg N.ha$^{-1}$, and 26.2 P and 33.3 K Kg. ha$^{-1}$ | (Naresh Kumar 1992) | 11.6–44 | 4–30 |
| Pantnagar | 28.66 | 77.2 | 228 | 1997–98 | Alluvial, loamy alluvial | Varietal performance | Ganga-11 | 2 | 120 | A.I.C.R.P Annual Report | 10.7–48 | 1–30 |
| Ludhiana, | 30.9 | 75.8 | 700 | 1997–98 | Alluvial, loamy alluvial | Varietal performance | Ganga-11 | 2 | 80 | A.I.C.R.P Annual Report | 9.2–42.6 | 2–30.2 |
| Kanpur | 26.5 | 80.4 | 126 | 1997–98 | Alluvial, loamy alluvial | Varietal performance | Ganga–11 | 2 | 150 | A.I.C.R.P Annual Report | 15.6–45.3 | 1–26.4 |
| Karnal | 29.7 | 76.9 | 79 | 1997–98 | Alluvial, loamy alluvial | Varietal performance | Ganga-11 | 2 | 150 | A.I.C.R.P Annual Report | 10–43.2 | 2–29.1 |
| Hyderabad | 17 | 78 | 489 | 1998–99 | Sandy loam, red laterite | Varietal performance | Ganga-11 | 2 | 120 | A.I.C.R.P Annual Report | 24.4–43.4 | 6.5–29.2 |
| Patna | 25 | 85 | 49 | 1998–99 | Alluvial, loamy alluvial | Varietal performance | Ganga-11 | 2 | 120 | A.I.C.R.P Annual Report | 28–48 | 3.5–31 |

maturity), $LAI_{max}$ and yield of different experiments matched satisfactorily. Statistical analysis on model performance indicated that it predicted crop phenology with less degree of error ($R^2$=0.961) for days to 50 % flowering and ($R^2$=0.97) for days to physiological maturity (Fig. 1), $LAI_{max}$ ($R^2$=0.73), TDM ($R^2$=0.80) and grain yield ($R^2$=0.85). The values of MBE for $LAI_{max}$ was 0.18 indicating a positive deviation from observed $LAI_{max}$ and hence slightly over estimation of LAI. This also reflected in yield which has a positive bias of about 220 $Kg.ha^{-1}$. However these positive biases are well within acceptable limit. The ME, value of which close to 1 indicates high agreement of simulated values to observed values, is around 0.75. But, the RMSE for LAI was 12% of the mean measured value while that for yield was about 15% of observed mean values; indicating deviations from measured values are around the periphery of acceptable error limits. These deviations are due to wide range of management practices, soil type and weather varying with agro-climatic zone (Table 1). The model has slightly over estimated the LAI and grain yield in poor management situations. However, in India, maize is generally grown under better management conditions (Joshi et al. 2005), particularly in the locations which were considered for impact analysis. These areas, as mentioned earlier, form the major maize producing regions and it is mainly irrigated. Thus, these variations did not significantly influence the impact analysis.

## 2.3 Impact assessment

Using validated InfoCrop-MAIZE model, simulations were carried out for past 25 years (1970–1995) for different locations representing three agro-climatic zones. The period of

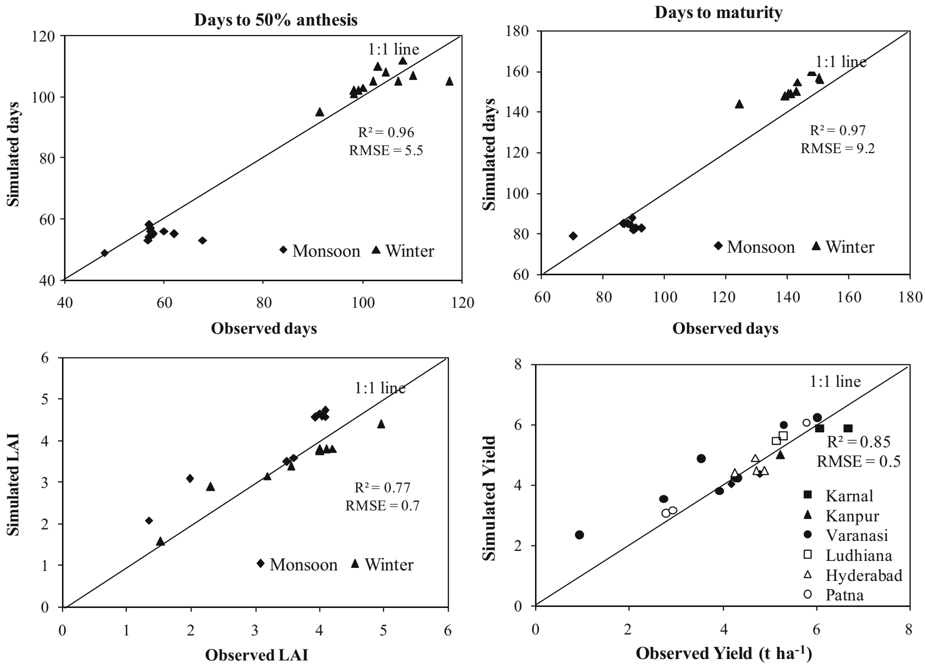

**Fig. 1** Validation graphs of InfoCrop-MAIZE for phenology (50% flowering and maturity). leaf area index (LAI) and yield grown at different management conditions and different locations in India

1960–1990 is the universal baseline years for Global Climate Models (IPCC 1994). Since the data for this exact period was not available, baseline was taken from 1970 to 1995, which largely coincides with the baseline period of GCMs. This period is taken for the reason that the 'difference fields' between baseline (1960–1990) and scenarios (2020, 2050 and 2080) for temperature (maximum and minimum) and rainfall are coupled to the baseline to derive the scenarios. The baseline years were restricted to 1995 and not beyond to avoid artificial increase in the values of climatic parameters in climate change scenarios. Model inputs included daily weather for past years (1970–1995), characteristics of major soil type of the respective region, normal sowing date and crop management as followed by farmers in these agro-climatic zones. With these, model was satisfactorily simulating the average maize yield of a given region. Impact of climate change on grain yield of maize was studied using two approaches. Firstly, fixed rise in temperature (minimum and maximum) and carbon dioxide and change in daily rainfall were used in three factorial matrix combinations. Atmospheric temperature (maximum and minimum) were raised by 1°C, 2°C, 3°C, 4°C and 5°C. Carbon dioxide was raised from 369 (for baseline period-1970 to 1995) to 450 and 550 ppm and rainfall was changed from deficit (−100%) to excess (+100%) in 10% steps. Simulations were carried out after coupling these changes in temperature, carbon dioxide and rainfall to the baseline (25 years) weather data. Such analysis was done for three locations differing in weather and representing important maize growing areas viz., upper Indo-Gangetic plain (UIGP) (represented by Delhi), middle and eastern Indo-Gangetic plain (MIGP) (represented by Patna), and southern plateau (SP) (represented by Hyderabad). These areas varied for crop management practices (Table 1) apart from weather and soil characteristics (Table 2). The chosen areas contribute considerably to the maize production at national level. Simulations were done for popular maize variety Ganga-11, widely grown all over India, in both monsoon and winter crops. In India, maize during monsoon is grown as rainfed crop while during winter it is grown as irrigated one.

An additional analysis was done to assess the impacts of climate change on maize production where HadCM3 (Hadley Centre Coupled Model, version 3) global climate model outputs on temperature (minimum and maximum), and rainfall for 2020, 2050 and 2080 A2a scenarios (IPCC-AR3) were used. The HadCM3 scenario output is widely used for climate change impact assessment. HadCM3 is a coupled atmospheric-ocean general

**Table 2** General weather conditions during cropping seasons (M-monsoon, June–September; W-winter, October–March) of locations under study

| | Upper Indo Gangetic Plain (UIGP) (Delhi) 28.62°N; 77.22°E | | Lower and middle Indo-gangetic plain (MIGP) (Patna) 25°N; 85°E | | Southern Plateau (SP) (Hyderabad) 17.4°N; 78.5°E | |
|---|---|---|---|---|---|---|
| | M | W | M | W | M | W |
| $T_{max}$ (°C) | 34 | 24 | 33 | 26 | 31 | 29 |
| $T_{min}$ (°C) | 26 | 9 | 26 | 11 | 23 | 15 |
| Total rainfall during cropping season (mm) | 548 | 58 | 671 | 42 | 560 | 59 |
| Daily radiation ($\mathrm{MJm^{-2}}$) | 19.52 | 14.54 | 17.49 | 16.12 | 16.39 | 17.31 |
| Soil type | Alluvial | | Alluvial, loamy alluvial | | Sandy loam and red and black soils | |
| Normal sowing window | | Jun–July (M) | | Oct–Nov (W) | | |

circulation and one of the models used for IPCC third and fourth assessment report (2007). The model scenario outputs were coupled to the baseline weather data. The projected carbon dioxide levels as per Bern CC model (Kirchhoff et al. 2001) for these scenarios were also included in the model for simulations. As per this model, the atmospheric $CO_2$ concentrations are projected to be 414, 522 and 682 ppmV for A2 2020, 2050 and 2080 scenarios, respectively. All other simulation conditions were maintained as explained earlier. To express the impacts on yield, the net change in grain yield in climate change scenarios was calculated and expressed as the percentage change from baseline mean.

### 2.4 Adaptation and vulnerability analysis

Two low cost options, independently and in combination were tested as adaptation strategies to assess the adaptive capacity of maize to climate change. These are 1) use of short (75–80), medium (95–100) and long duration (105–110 days to maturity during monsoon and about 20–25 days more in winter season) and 2) change in sowing time which includes early as well as late sowing relative to normal sowing time. Normal sowing time of monsoon crop is generally determined by onset of rainfall while the crop performance depends on rainfall distribution and atmospheric temperature during crop growth period. Series of sowing dates and varieties were input into the model and it was run for baseline years and also for climate change scenarios to identify most suitable adaptation combination. The combinations, which gave highest yield in each scenario, were taken as the best suitable adaptation option. In all, more than 2.5 million simulations were carried out for this entire analysis. The net yield gain is expressed as the relative change from the mean baseline yield. The net vulnerability on maize even after adaptation in respective scenario was obtained as $\text{Net vulnerability(yield loss(\%), even after adaptation, from baseline)} = \text{Yield gain after adaptation(\%)} + \text{Impact(yield loss due to climate change, \%)}$ In situations where climate change is likely to benefit the maize, net vulnerability values represent net positive impacts maximized with additional adaptation measure.

The main limitations in this simulation analysis are 1) while extrapolating to a larger area it is assumed that the soil has similar textural property and fertility condition 2) simulation of impact of pest and disease on crop production is not considered 3) even though change in variety and sowing dates are used as adaptation strategies, future technology growth is not considered in comprehensive manner.

## 3 Results

### 3.1 Analysis on impact of climate change on maize yield

As indicated earlier, impact analysis was done with two approaches viz., 1) impact of rise in temperature and carbon dioxide with fixed increase over baseline values; and changes in rainfall ranging from −100 to +100% at 10% interval 2) impact of climate change (HadCM3 A2 a 2020, 2050 and 2080 scenarios) coupled to baseline values.

#### *3.1.1 Impact of fixed rise in temperature, $CO_2$ and change in rain fall*

*Monsoon crop* Results of simulation analysis indicate that maize yields in monsoon season adversely affected due to rise in atmospheric temperatures in all three regions (Fig. 2a). Grain yield decreased with each degree rise in atmospheric temperature. However, the rate

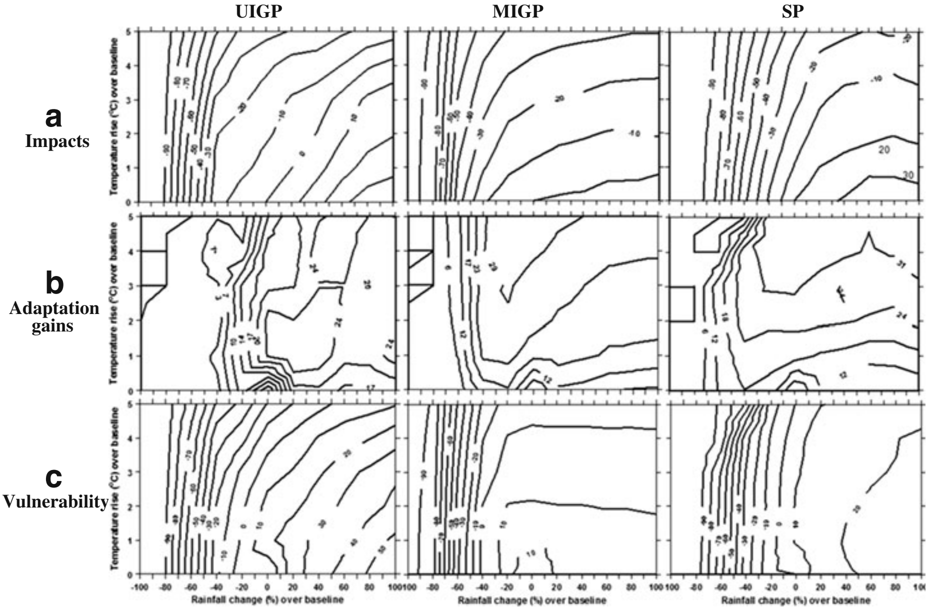

**Fig. 2** Impact, adaptation gains and net vulnerability of monsoon maize crop in three distinct agro-climatic zones of India. UIGP—Upper Indo-Gangetic plains, MIGP-Mid-Indo-Gangetic plain and SP—Southern plateau

of decrease varied with location. The mean baseline yield of rainfed maize crop is about 2 Mg ha$^{-1}$ in UIGP, where the projected yield loss is up to 7, 11, 15, 22, and 33% relative to base line yields with 1, 2, 3, 4, 5°C degrees rise in atmospheric temperatures. However, a 20% increase in rainfall is projected to offset the yield loss due to 1°C rise in temperature. Similarly, a 30% increase in rainfall is predicted to offset the adverse impact of 2°C rise in temperature. In MIGP region, yield reduction of about 8–35% with 1–5°C rise in atmospheric temperature is projected. In this region, increase in rain fall is likely to offset the temperature rise upto 0.75°C and any increase beyond this temperature will adversely impact the yields, in spite of increase in rainfall. The SP region also projected to experience adverse impact with −10, −15, −23, −27 and −35% reductions from the baseline yield levels at each 1°C rise in temperature. A 10% increase in rain fall will offset the reduction in yield due to 1°C rise in temperature in this region.

Even though maize is a C4 plant, increase in carbon dioxide is projected to benefit the crop yield ranging from 0.1 to 3.4% at 450 ppmV and 0.6 to 7.2% at 550 ppmV. The benefits are projected to be high in mild water stress conditions, but they are likely to reduce in severe water stress situations (Table 3). The yield gains due to increase in atmospheric $CO_2$ concentration is projected to be more in SP regions (low rainfall area) followed by UIGP and MIGP regions.

*Winter crop* Maize crop during winter is provided with assured irrigation and thus yields about 1.5 times more than that of monsoon crop. Winter maize grain yield reduced with increase in temperatures in SP and MIGP, but in UIGP rise in temperatures up to 2.7°C is likely to improve the maize yields. However, further increase in temperature is projected to reduce grain yields and the reductions are likely to be more than those at MIGP and SP (Fig. 3a). In UIGP, this

**Table 3** Influence of atmospheric carbon dioxide concentration on maize yields in rainfall deficit conditions during monsoon season

| Rainfall deviation from the normal (%) | UIGP | | MIGP | | SP | |
|---|---|---|---|---|---|---|
| | Levels of carbon dioxide concentration (ppmV) | | | | | |
| | 450 | 550 | 450 | 550 | 450 | 550 |
| 0 | 0.1 | 1.1 | 0.7 | 0.6 | 0.4 | 1.9 |
| −10 | 0.3 | 3.3 | 0.5 | 1.2 | 1.3 | 3.0 |
| −20 | 0.3 | 3.3 | 0.9 | 1.5 | 3.4 | 7.2 |
| −30 | 0.9 | 5.9 | 1.2 | 1.8 | 1.1 | 4.5 |
| −40 | 1.5 | 6.2 | 1.2 | 2.3 | 0.4 | 3.7 |
| −50 | 1.4 | 6.6 | 1.1 | 4.1 | 0.1 | 0.1 |

beneficial effect with rise in temperature is projected to be more up to 2°C rise (13% increase over current yields). In this region, yield will improve with 2°C in spite of reduction in rainfall. In the event of further increase in temperature to about 2.7°C, the reduction in yields can be offset only if rainfall is increased or more irrigation is provided. With temperature rise crop experiences more towards optimal temperature during grain development benefitting grain number. Relatively low temperature during grain filling period required more days to satisfy thermal time requirement. However, in both MIGP and SP, where the average maximum temperatures during winter crop season are relatively higher (Table 2), any increase in temperature can cause reduction in yield.

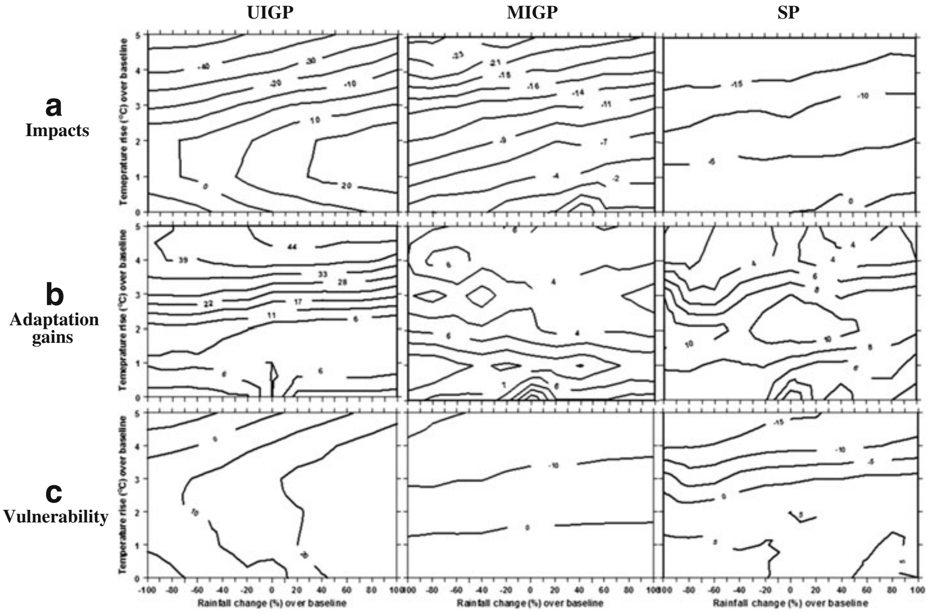

**Fig. 3** Impact, adaptation gains and net vulnerability of winter maize crop in three distinct agro-climatic zones of India. UIGP—Upper Indo-Gangetic plains, MIGP-Mid-Indo Gangetic plain and SP—Southern plateau

In UIGP, rise in temperatures beyond 2.7°C caused reduction in yield mainly due to reduced number of grains. This limited the gains in spite of increase in GFD and individual grain weight. Further increase in temperature resulted in yield reduction from current yields. In UIGP, GFD was found to increase with rise in temperature because of current lower temperature during winter. While the rise in temperature prolonged GFD significantly at UIGP than at MIGP, it actually reduced at SP. In all locations flowering hastened due to increase in temperature.

### *3.1.2 Impact of climate change scenarios on maize yield*

The climate change scenario outputs of HadCM3 model on minimum and maximum temperatures and rainfall; $CO_2$ concentrations as per Bern CC model for 2020, 2050 and 2080 were coupled to InfoCrop-MAIZE model. This approach was followed because of reported spatio-temporal variations in climate change scenarios (IPCC 2007).

*Monsoon crop* The analysis indicates that in UIGP region climate change is projected to insignificantly affect the productivity of monsoon maize crop in 2020, 2050 and 2080 scenarios (Fig. 4a). This is mainly due to projected increase in rainfall during crop season, which will provided scope for improved dry matter production and increase in grain number. This implies that the maize crop may benefit from additional availability of water in spite of increase in temperature and related reduction in crop duration by 3–4 days. On the other hand, in MIGP, maize is likely to suffer yield loss in future scenarios. The loss from current yields is projected to be ~5%, ~13%, ~17% in 2020, 2050 and 2080, respectively. In SP, monsoon season crop is projected to lose grain yield by 21% from current yields due to climate change by 2020 and 35% by 2050 and later. Projected rise in day time temperature during monsoon is higher in SP and MIGP as compared to UIGP region, even though minimum temperatures are projected to rise almost similarly in these locations. Apart from this, rainfall is projected to increase in UIGP while it is likely to change in MIGP. Thus, the spatio-temporal variation in existing climatic conditions and projected changes in temperature and rainfall would bring about differential impacts on monsoon maize crop in India.

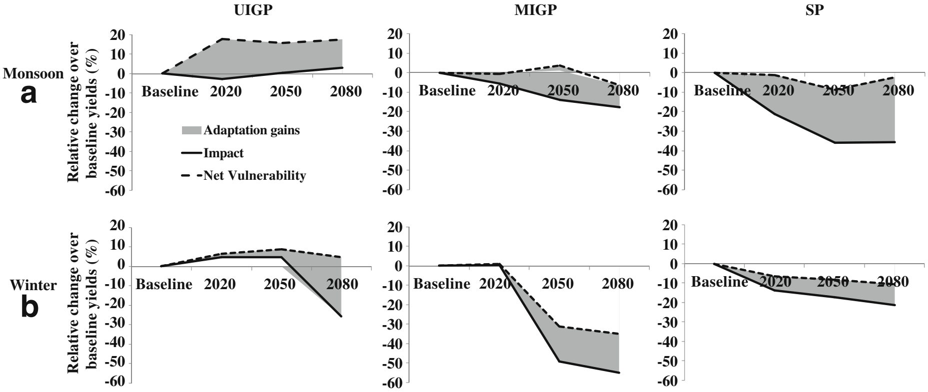

**Fig. 4** Impact, adaptation and net vulnerability of maize yield to 2020, 2050 and 2080 HadCM3 scenarios. (UIGP—Upper Indo Gangetic plain; MIGP:—Middle and lower Indo Gangetic Plain; SP:—Southern Plateau)

*Winter crop* As far as maize crop grown in winter is concerned, yield gains are projected be ~5% over current yield in 2020 scenario at UIGP and this benefit is likely to remain till 2050 (Fig. 4b). However, in 2080 scenario, yields are projected to be reduced by 25% from current yields. Winter maize in MIGP, currently a high yielding zone, is projected to suffer in post 2020 scenario. The reduction in yield is likely to be to the tune of ~50% by 2050 and about 60% by 2080. In SP region, yields are projected to decline by about 13% in 2020, 17% in 2050 and 21% in 2080. In these areas winter maize is well irrigated and thus variation in winter rainfall, which even other-wise is low, is less influential. The projected rise in temperature during winter crop season is more in UIGP in 2020 and 2050 than in MIGP and SP, particularly during later part of crop growth.

## 3.2 Analysis on adaptation strategies and net vulnerability

### *3.2.1 Monsoon crop*

Climate change impact on monsoon maize yield is projected to be negative in MIGP and SP regions. To minimize the temperature rise mediated yield loss, simulations were carried out with varieties having various vegetative durations at normal sowing date and in combination with change in sowing date (Aggarwal 2008). In this approach, the vegetative duration of variety was restored in changed scenarios to that of current vegetative duration. In UIGP early sowing (1–2 weeks from normal date of sowing) of variety with days to flowering similar that of current variety, can be a better adaptation option. This provides the opportunity for the crop to experience relatively lower temperatures during grain filling period. On the other hand in SP and MIGP, sowing 2–3 weeks after onset of monsoon will benefit crop in future climate change scenarios.

Adaptation gains in 'fixed' temperature rise scenarios up to 1–2°C rise are almost similar in UIGP, MGIP and SP regions with about ~17% gains at 1°C rise and about 24% at 2°C rise with respect to current yield levels (Fig. 2). Adaptation gains further improved if the rainfall is increased even at a temperature rise of 3°C and beyond. In instances where temperature rise is beyond 3°C, gains due to adaptation strategies are higher in SP followed by at MGIP and UGIP. Results indicate that adaptation gains are higher in conditions where stress is within manageable limits, whereas adaptation gains reduced in the event of significant deficit (−40 to −50%) in rainfall.

Analysis on net vulnerability (a net output of climate change impacts and adaptation gains) of monsoon maize productivity to climate change indicated that in UGIP, adaptation strategies can offset the yield loss due to a 25% reduction rainfall and an increase in temperature up to 3°C, thus causing no net vulnerability of maize (Fig. 2). In fact in the event of increase in temperature up to 2.5°C and any increase in rainfall in UGIP will benefit the crop and adaptation strategies provide additional yield advantage. For instance, a 2°C rise in temperature and 20% increase in rainfall will provide 20% yield advantage. After adaptation gains, the net vulnerability in MIGP is zero even if rainfall deficit is up to 40%, but the increase in rainfall likely to provide a 10% yield advantage up to 2°C rise. However, further increase in temperature may reduce the yield advantage even if rainfall is increased. On the other hand, in SP region the net vulnerability of maize is zero even if a 10% reduction in rainfall is coupled with temperature rise. Any reduction in rainfall beyond this will cause the net vulnerability of maize productivity (a 30% reduction in rainfall causes 10% net vulnerability of production). The yield reduction is due to water stress caused by increased temperature driven evaporative demand, which directly hampers crop physiological function viz., gross photosynthesis, assimilate allocation pattern and hasten senescence. The monsoon temperatures are higher in UIGP than in SP and MIGP. Monsoon maize is projected to be vulnerable to climate change in all the studied location with reduction in rainfall. The net vulnerability of maize crop varied from +50% to crop failure in various scenarios of temperature rise up to 5°C and change in rain fall. If the rainfall deficit is more than 40–50% the crop fails due to severe water stress.

Under climate change scenarios of HadCM3, monsoon maize crop in UIGP region is likely be benefitted and thus the crop is not vulnerable (Fig. 4). Adaptation strategies mentioned earlier likely to further increase these gains by ~17%. Similarly, maize in SP and MIGP areas is also projected to be not vulnerable in future scenarios as adaptation strategies offset the adverse impacts. Since, increase in rainfall causes less rise in temperature apart from helping in exploiting the adaptation benefits, the monsoon maize production is less vulnerable to climate change.

### *3.2.2 Winter crop*

Since winter crop is irrigated and well managed, adaptation gains are low compared to those in monsoon crop (Fig. 3). However, maize in UIGP is likely to experience a benefit due to temperature rise (~6% at 1°C rise to ~44% at 5°C). The net vulnerability of maize crop is zero even with an increase in temperature up to 3°C. However, an increase in temperature beyond this will cause winter maize vulnerable (by ~10% reduction relative to current yields). The MGIP and SP regions have very less adaptation gains which are about 6–10%. However, maize in these regions is sensitive to rise in temperature. Any increase of 1.5°C and beyond in temperature likely to result in maize productivity becoming vulnerable to climate change in MGIP region. On the other hand, increase in temperature beyond 2°C is projected to cause such effects in SP region. The adaptation strategies in climate change scenarios indicated that sowing window may be expanded in MIGP area.

Analysis indicated that in climate change scenarios of HadCM3, the winter maize crop in UIGP region is projected to gain and these positive impacts of climate change can be further improved by adaptation strategies by about 6% in 2020, 11% in 2050 relative to current yields (Fig. 4). However, these benefits are projected to reduce post 2050 scenario. On the other hand, maize in MGIP region is projected to be very sensitive to climate change. Even though maize yields are likely to be similar up to 2020 but there after crop is projected to suffer severely. Even with adaptation (a gain of 10–15%) the net vulnerability of productivity is to the tune of 28% in 2050 to 35% in 2080. In SP region, adaptation gains are projected to offset half of yield loss leaving maize vulnerable by about 6% in 2020, 8% in 2050 and 10% in 2080.

## 4 Discussion

The results indicate that any reduction in rainfall from baseline had severe impact on rainfed maize crop resulting in yield reduction. In the event of reduction in rain fall by 30% to 40%, the water stress predominates in crop failure than the rise in temperature. Any increase in rainfall benefitted crop as these regions receive relatively less rainfall during the monsoon crop season. Increase in rainfall neutralized the negative impact of rise in temperature and thus benefiting the crop yield. This relative benefit varied with region, mainly due to variability in climatic conditions. Increase in rainfall causes 1) increased availability of soil moisture reducing water stress at respective crop growth stages and 2) reduction in adverse impacts of high temperature driven increased evapo-transpiration. Water stress accelerates phenological development, decreases gross photosynthesis and alters the allocation of assimilates to different organs and accelerates rate of senescence. Maize, being a C4 crop has comparatively higher radiation use efficiency (Kinry et al. 1989), thus a reduction in solar radiation due to more cloudy days in increased rainfall scenario may not hamper the crop growth and yield. The gains in yield during monsoon season due to rise in atmospheric $CO_2$ concentrations can be attributed to the indirect effect of improved water use efficiency in elevated $CO_2$ conditions mainly in water-stress situations (Leakey et al. 2006).

Low yields at higher atmospheric temperatures were due to considerable reduction in crop duration i.e. days to 50% flowering and grain filling duration (GFD), reduced leaf area index and leaf area duration. The crop phenology reduced considerably with increase in temperature with 16% (days to 50% flowering) and 14% (GFD) reduction at 5°C temperature rise. Higher temperature also affected yield components like weight of grain, test weight and number of grains per hectare causing yield loss. Number of grains per hectare significantly reduced by about 6% at 1°C rise to 32% at 5°C rise in temperature. Currently, it is well documented that grain number is a function of the rate of biomass accumulation at the ear level around flowering (Vega et al. 2001; Borras et al. 2007). At higher temperature range from 25 to 32°C, no increase in grain-growth (Muchow 1990) together with reduction in grain-filling duration reduced yield. Apart from this, increased temperatures hasten leaf senescence particularly during grain filling period (GFP) in major crops (Zhao et al. 2007) including maize, thus limiting the availability of assimilates for grain growth. All these temperature driven physiological phenomena led to reduced yield in temperatures above optimal level. The adverse effects increased exponentially once temperatures increased beyond maximum tolerable level (Jones et al. 1981).

A comparative analysis of data from three locations indicates that in monsoon crop GFD varied from 54% to 62% of duration from seedling emergence to 50% flowering. On the other hand, for winter crop, the corresponding values ranged from 24% to 55%. Rise in temperature benefitted maize crop in locations where this ratio is low presently present and temperature increase prolonged GFD. However, this benefit seems to be nullified if it goes beyond 35%. In this situation other factors such as grain number is becoming a limiting factor. Grain-filling rate had a positive phenotypic correlation with grain weight and was negatively correlated with mid-silking date and effective GFD. Grain number per inflorescence was considered more important than grain-filling rate in influencing grain yield in maize (Wang et al. 1999).

Analysis of results indicate that the total crop duration decreased in all locations due to climate change, however, GFD in UIGP was maintained (in monsoon) or increased (in winter) as that of baseline along with increase in number of grains and grain weight thus resulting in positive impacts at this region. On the other hand, in SP and MIGP, crop duration, GFD, grain number and TDM decreased resulting in negative impact. Overall results from impact analysis indicate that the maize yields are projected to be affected more in the event of reduction or no increase in rainfall as indicated from the fixed temperature rise simulations. However, in HadCM3 model scenarios, the rainfall in many parts of India is projected to increase and this is the major reason for slightly less impact of climate change scenarios compared to 'fixed' temperature rise scenarios on maize grain yield.

Change in variety as an adaptation option for climate change has been explored earlier and found that shorter duration wheat in Austria (Alexandrov et al. 2002) and variety with longer GFP and less vernalization requirement in Great Plains of China (Tubiello et al. 2002) are suitable for reducing climate change impacts. However, in scenarios with high rise in temperature along with reduction in rainfall, short-season cultivars are suggested to be used (van Ittersum et al. 2003) to escape heat and drought stress during GFP. Studies on change in sowing dates as an adaptation option indicated early sowing of photosensitive soybean in Austria (Alexandrov et al. 2002), sugar beet in central Italy (Donatelli et al. 2002) as best adaption options for reducing climate change impacts.

In general, studies in agriculture indicated that the degree of benefits for adaptation are greater with moderate warming (<2°C) and increased rainfall scenarios (Howden et al. 2007) in winter season crop. Globally, several studies on adaptation to climate change impact on crops have been identified. The modifying farming practices have adaptive capacity to minimize the risk of climate change impacts. Introduction of higher yielding, earlier maturing varieties in cold regions, heat/drought/salt tolerant varieties together with improved farm managements viz., altered application of nutrient and irrigation, changing planting date and varieties include socio-economic adaptive management strategy (Cruz et al. 2007). Potential adaptation strategies for maize included sowing in earlier date than the normal and using varieties having high grain filling duration have been identified for Europe (Kapetanki and Rosenzweig 1997), earlier maturing varieties and early planting for western Kenya (Mati 2000) and advancing sowing date and altering irrigation for Argentina (Travasso et al. 2009). Current study reveals that developing new cultivars with growth pattern in changed climate scenarios similar to that of current varieties in present conditions and sowing them on time could be an advantageous adaptation strategy for minimizing the vulnerability of maize production in India. The approach followed in this study can be extended to regional level for assessing the climate change impacts on maize production and adaptation capacity of maize in order to estimate the net vulnerability of maize production in India due to climate change. The results indicate possibility of expansion of maize area in some northern parts of India as it has shown to be beneficial in climate change scenarios. In India, location or regional specific vulnerability analysis becomes essential in view of wide variability with respect to soil type, management and climate.

## 5 Conclusions

Assessing climate change impacts on maize yields is important for elucidating adaptation strategies to reduce the negative impact of climate change for ensuring food security. The effect of temperature rise by climate change is much more important than that of $CO_2$ surge as maize is a C4 crop. Climate change impact study indicates a reduction in productivity of maize in MGIP and SP regions of India during both monsoon and winter seasons. With rise in temperature, reduction in yields is projected to be larger in warmer locations than at other locations. However, in areas with low temperatures during winter (UGIP), the crop is projected to benefit. The combination of variety with vegetative duration as that of current variety and altered sowing date could be a potential adaptation strategy for the future climate change scenarios. Adaptation options varied quantitatively with location and season. Thus, there is a need for breeding cultivars with phenology in changed scenario similar to that of current varieties. Plant breeders should capture the variation in phenology of different maize genotypes while breeding varieties for the future climate change scenarios. In view of the projected net vulnerability of productivity even after these adaptation strategies, other adaptation strategies also need to be developed to minimize the net vulnerability of maize crop in MIGP and SP regions of India.

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