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Vulnerability of wheat production to climate change in India

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ABSTRACT: The production of wheat, a crop sensitive to weather, may be influenced by climate change. The regional vulnerability of wheat production to climate change in India was assessed by quantifying the impacts and adaptation gains in a simulation analysis using the InfoCrop-WHEAT model. This study projects that climate change will reduce the wheat yield in India in the range of 6 to 23% by 2050 and 15 to 25% by 2080. Even though the magnitude of the projected impacts is variable, the direction is similar in the climate scenarios of both a global (GCM-MIROC3.2.HI) and a regional climate model (RCM-PRECIS). Negative impacts of climate change are projected to be less severe in low-emission scenarios than in high-emission scenarios. The magnitude of uncertainty varies spatially and increases with time. Differences in sowing time is one of the major reasons for variable impacts on yield. Late-sown areas are projected to suffer more than the timely-sown ones. Considerable spatial variation in impacts is projected. Warmer central and south-central regions of India may be more affected. Despite CO_2 fertilization benefits in future climate, wheat yield is projected to be reduced in areas with mean seasonal maximum and minimum temperatures in excess of 27 and 13°C, respectively. However, simple adaptation options, such as change in sowing times, and increased and efficient use of inputs, could not only offset yield reduction, but could also improve yields until the middle of the century. Converting late-sown areas into timely-sown regions could further significantly improve yield even with the existing varieties in the near future. However, some regions may still remain vulnerable despite the adaptation interventions considered. Therefore, this study emphasises the need for intensive, innovative and location-specific adaptations to improve wheat productivity in the future climate.

KEY WORDS: Impacts · Adaptation · Irrigated system · Indo-Gangetic plains · Wheat · Adaptation · Agriculture · Climate change

1. INTRODUCTION

With the threat of climate change looming over crop productivity, the most vulnerable regions of the world are the tropics, particularly the semi-arid regions (Parry et al. 2004, Easterling et al. 2007). The 21st century is projected to experience a rise in surface air temperature between 1.8 to 4°C together with frequent warm spells, heat waves, heavy rainfall events and droughts (IPCC 2007a). These climate change related events can affect agricultural production with serious implications on food security (Nelson et al. 2012). In fact, crop production needs to be increased substantially in order to meet the rising demand of a growing population and economy in developing countries (FAO 2012).

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Cereals account for the major share of food grains, and wheat is the most important cereal crop worldwide. Among the 12 wheat mega-environments proposed by the International Maize and Wheat Improvement Center (CIMMYT), Mexico, the Indo-Gangetic plains (IGP) and Central India are the major wheat producing regions in South-Asia (Braun et al. 1996). In India, wheat is the most important staple crop along with rice. From an annual food grain production of 241.6 Mt, wheat contributes ~36% (~85.7 Mt) of the total, covering 29.25 Mha at a productivity of 2.93 t ha^{-1}. It not only provides food for consumers, but it is also a major source of livelihood to millions of farmers. Wheat yield needs to be increased from 2.6 to 3.5 t ha^{-1} within the next 25 yr (Ortiz et al. 2008) to meet the projected increase in demand. However, climate change is projected to reduce crop production by 10 to 40% in India between 2080 and 2100 under current agricultural management, according to studies on global climate change (Rosenzweig & Parry 1994, Fischer et al. 2002, Parry et al. 2004, IPCC 2007b).

Studies conducted specifically on India also project a decline in agricultural production due to climate change, but at varying magnitudes (Aggarwal & Sinha 1993, Lal et al. 1998, Saseendran et al. 2000, Aggarwal & Mall 2002, Mall & Aggarwal 2002, Byjesh et al. 2010, Srivastava et al. 2010, Naresh Kumar 2011, Naresh Kumar et al. 2011, 2012, 2013). An increase in temperature by 1°C is projected to reduce wheat production in India by 4 to 5 Mt, even after taking CO_2 fertilization into account (but not including benefits from other potential adaptation measures) (Aggarwal 2008). Furthermore, a reduction of ~19 and ~27.5 Mt of wheat is projected following a rise in temperature of 3 and 5°C, respectively (Aggarwal & Swaroopa Rani 2009). Wheat contributes ~21% of the world's total food grains, and ~81% of wheat consumed in developing countries is produced and utilized within the same country (CIMMYT 2005). Hence, it is essential to assess the gains due to possible adaptation strategies in addition to quantifying the impacts. Such analysis is aimed to provide information on the vulnerability of wheat-growing areas and to help prepare against the adverse impacts of climate change.

Climate change affects crops mainly through elevated CO_2, temperature increase and change in rainfall. In India, wheat is grown during the winter season. The sowing starts in November, and crop is harvested by the early half of April. Since more than 85% of the wheat land area is irrigated, the influence of rainfall is not significant. But elevated CO_2 levels increase grain yield due to an increase in leaf area duration, straw yield, number of ears per m^2 and kernel weight (Rawson 1995, Pleijel et al. 2000). The reported gain in yield has ranged from 17 to 19% at 550 µmol CO_2 mol^{-1} to ~31% at 700 µmol CO_2 mol^{-1} (Amthor 2001, Tubiello et al. 2007, Chakrabarti et al. 2012).

Heat stress is considered to be the major climatic factor affecting wheat yield in the IGP region of India (Ortiz et al. 2008). A substantial area is under late- and very late-sown conditions (until the third week of December), exposing the crop to heat stress. This results in considerable yield reduction in central and eastern India. The crop is sensitive to high temperature (Rawson & Bagga 1979, Rawson 1992, Porter & Gawith 1999, Ortiz et al. 2008), which affects photosynthesis (Blum et al. 1994, Pushpalatha et al. 2008), growth and development (Porter & Gawith 1999), number of grains (Rawson & Bagga 1979) and grain yield (Asseng et al. 2011). Wheat crops exposed to temperatures >34°C have significantly low yields because of accelerated senescence (Asseng et al. 2011, Lobell et al. 2012). The optimum temperature range is 17 to 23°C during the entire growth period, with maximum temperatures not exceeding 37°C (Porter & Gawith 1999). Temperature optima are ~22°C for vegetative development and 21°C for reproductive development, while ~35.4°C is the maximum limit for grain filling (Porter & Gawith 1999). Temperatures >31°C just before anthesis induce pollen sterility and reduced grain number and yield (Ferris et al. 1998). In March 2004, high temperatures in the IGP hastened crop maturity, reducing wheat production by 4 Mt (Samra & Singh 2004). Lobell et al. (2012) reported wheat yield reductions of up to 20% in certain pockets of the IGP, due to a 2°C increase in seasonal temperature. On the other hand, low temperatures can be problematic for seed set. Projected increases in temperatures and frequency of weather extremes (IPCC 2007a) could therefore significantly constrain wheat production in a future climate.

Considering the importance of wheat to India's food security, it is imperative to understand the spatial and temporal magnitudes of climate change impacts on the crop at a regional level. Several low-cost technologies can reduce the negative impacts of climate change (Easterling et al. 2007). These adaptation strategies include improved varieties (Braun et al. 1996, Chapman et al. 2012) and improved or altered agronomy (Easterling et al. 2003, Ingram et al. 2008) including efficient input use. A recent analysis on irrigated and rainfed-rice in India showed that such adaptation can significantly reduce the negative impacts of climate change (Naresh Kumar et al. 2013). There is no such assessment available for wheat. The present study was carried out to provide this information in order to help plan adaptation strategies. The aims were (1) to quantify the impacts on wheat yields at a regional level, and (2) to quantify the adaptation gains and identify the vulnerable regions for wheat production in a future climate.

2. MATERIALS AND METHODS

2.1. Simulation analysis using InfoCrop

In this study, irrigated wheat for timely-, late- and very late-sown conditions were considered. To carry out the analysis, InfoCrop-WHEAT model was used due to its suitability for simulating the growth, development and yield of wheat in sub-tropical and tropical conditions such as in India. InfoCrop is a generic crop growth model that can simulate the effects of weather, soil, agronomic managements (planting, nitrogen, residue and irrigation), and major pests on crop growth and yield (Aggarwal et al. 2006). The model dynamically simulates different growth and development processes of a crop. The total crop growth period in the model is divided into 3 phases: (1) sowing to seedling emergence, (2) seedling emergence to anthesis and (3) the storage organ filling phase. The model requires various coefficients such as thermal time for phenological stages, potential grain weight, specific leaf area, maximum relative growth rate and maximum radiation use efficiency. Crop management inputs include time of sowing, application schedule, and the amount and type of fertilizer and irrigation. Soil input data include pH, texture, layer-wise thickness, bulk density, saturated hydraulic conductivity, organic carbon, slope, water holding capacity and permanent wilting point. Location-specific daily weather data (solar radiation, maximum and minimum temperatures, rainfall, wind speed and vapour pressure) are also required to simulate the crop performance. The details on the simulation framework of temperature, CO_2, and rainfall effects on crop growth and development have been described earlier (Aggarwal et al. 2006, Srivastava et al. 2010, Naresh Kumar et al. 2011).

The InfoCrop-WHEAT model was calibrated and verified for Indian varieties (Aggarwal & Kalra 1994, Aggarwal 2003, Aggarwal et al. 2006, Aggrawal & Swaroopa Rani 2009). The model was able to capture the year-to-year variation in dry matter (mean ± RMSE: 9.9 ± 0.55 t ha^{-1}) and grain yield (4.7 ± 0.21 t ha^{-1}) of the experiments (Aggarwal et al. 2006). The model performance indicators, such as RMSE, model efficiency, agreement index and bias (Wallach et al. 2006), indicate that the model could adequately simulate the phenology and grain yield (Fig. 1a–c) of different varieties sown in timely-, late- and very late-conditions, as well as for different locations (Table 1). This calibrated and verified model was used for simulating the yield during the baseline period (1969–1990) and for assessing the future climate impact on (1) timely-sown (2) late-sown and (3) very-late sown irrigated crops with and without-adaptation.

2.2. Processing of input data

2.2.1. Weather

The Indian Meteorological Department (IMD) supplied daily gridded (1° × 1°) data on rainfall, minimum and maximum temperatures. Based on the availability of observed weather data for all grids across India, we used the 1969 to 1990 period data coinciding with the baseline period (1960 to 1990) of climate models. These data were converted to InfoCrop weather file format using custom made software. Files for 22 yr (1969 to 1990) for each grid were prepared and served as the observed data for the baseline period. Solar radiation was calculated based on the Hargreaves method (Hargreaves 1994), which is reported to be the best suited for Indian conditions (Bandyopadhyay et al. 2008). The potential evapotranspiration was calculated by the Priestley–Taylor method.

2.2.2. Soil data.

Data on soil parameters such as texture, water holding characteristics, bulk density, soil pH, and depth of 3 soil layers were adopted from the soil database of the National Bureau of Soil Science and Land Use Planning (NBSSLUP) and Harmonized World Soil Database (HWSD) v1.1 (FAO/IIASA/World Soil Information–ISRIC/ISSCAS/JRC 2009). The HWSD v1.1 is a 30′ raster database with more than 15 000 different soil mapping units containing information within the 1:5 000 000 scale world soil map. The NBSSLUP data base is at a 1:250 000 scale providing soil series information for 60 agro-ecological sub-regions of India. The characteristic data of major soil type in a grid (1° × 1°) were extracted using GIS tools and entered into the model. The pedo-transfer functions were used to derive the hydraulic characteristic coefficients.

2.2.3. Varietal coefficients

The coefficients of dominant wheat varieties in different regions of India were taken from the published literature (Aggarwal & Kalra 1994, Aggarwal 2003, Aggarwal et al. 2006, AICW&BIP 2012). Grids covering a region with similar type of dominant cultivars had similar varietal coefficients. The performance of short-, medium- and long-duration varieties sown in timely-, late- and very late-conditions, respectively, was simulated and the combination that gave the highest grain yield was taken for the baseline and impact assessment.

2.2.4. Management.

In order to mimic the situation in farmers' field conditions, the crop was provided with variable doses of fertilizers for timely (120 kg N ha^{-1}) and late (100 kg N ha^{-1}) sown conditions. Half of the nitrogen was applied as urea at the time of sowing and the remaining half at crown root initiation (CRI; 20 to 25 d after sowing) stage. In addition to a pre-sowing irrigation, 5 irrigations (50 mm each) were provided at the CRI, jointing, flowering, milk and late grain-filling stages of the crop. It was assumed that the crop was maintained free of pest and disease infestation.

2.3. Estimating impact of climate change

2.3.1. Estimating baseline yields

Simulations were run for each of the sowing times for 21 yr (sowings in 1969 to 1989 and harvests in 1970 to 1990) using the IMD gridded data, resulting in 21 yr averaged yields per grid. District-wise yield was obtained as a sum of the weighted yield from each grid fraction in the district. This was the baseline yield of a district for the respective sowing condition. State-level yield was calculated separately for timely-, late- and very late-sown crops for the respective state based on simulated yield of its districts. About half of the wheat area was considered to be under late- and very late-sown condition in north-

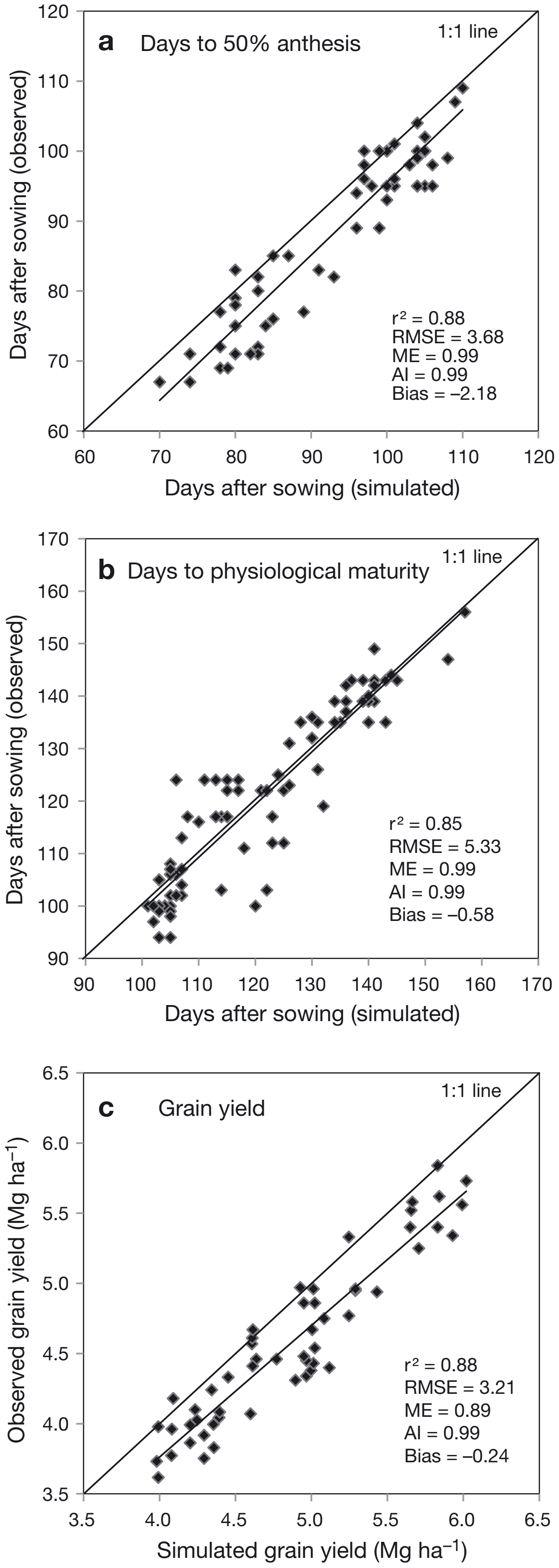

Fig. 1. Verification results of InfoCrop-WHEAT model for (a) days to 50 % anthesis, (b) days to physiological maturity and (c) grain yield. ME: model efficiency, AI: agreement index. See Table 1 for details of data source

west and central IGP, compared to ~18% of the area in eastern IGP and ~40% in Central India. State-level yield, obtained from total production and area, were then up-scaled to national level to obtain the national-level yield for timely-, late- and very late-sown conditions. Additionally, the consolidated yield at the national level was calculated by taking state-level weighted yield under each sowing condition.

2.3.2. Simulating yields in future scenarios

To simulate the impact of climate change on wheat yield, the climate outputs of a global climate model (GCM; MIROC3.2.HI, Atmosphere and Ocean Research Institute, Japan; National Institute for Environmental Studies, Japan; Frontier Research Centre for Global Change, Japan) and a regional climate model (RCM; PRECIS: Providing Regional Climates for Impact Studies, which included the Hadley Centre Climate Model [HadCM3] as the GCM) were used. They are found to suitably simulate Indian climatic conditions (Rupa Kumar et al. 2006, Das et al. 2012), and PRECIS is extensively used in climate change studies in India (INCCA 2010, NATCOM 2012). Climate data of the MIROC3.2.HI model for A1b and B1 emission scenarios, and those of the PRECIS model for A1b, A2 and B2 emission scenarios for 2050 and 2080 were used. The spatial resolution of MIROC3.2.HI is 1.125° × 1.125° and that of PRECIS is 0.44° × 0.44°. Since the observed weather is in 1° × 1° resolution, the GCM and RCM outputs were rescaled to 1° × 1° resolution for comparison and up-scaling of the crop model outputs. Climate scenarios were derived using the climate model projected changes in monthly temperatures (minimum and maximum) and rainfall for 2050 and 2080 following the formulae given below.

Table 1. Details of the data base used for the calibration and validation of InfoCrop-WHEAT. Locations: given represent >90% of wheat area in India. a.s.l.: above mean sea level. IVT: initial varietal trial; TS: timely sown; LS: late sown; VLS: very late sown. Data source: AICW&BIP (2012) and Chakrabarti et al. (2011)

Location	Latitude (°N)	Longitude (°E)	Altitude (m a.s.l.)	Crop season and year	Soil type	Experiment, treatment	Wheat variety	Number of treatments used for comparing with simulated values
Ludhiana	30.9	75.5	242	Nov–Dec 2000, 2002, 2003	Sandy loam	IVT, TS	HD-2687, K-9107, HUW-468	9
Karnal	29.7	76.8	235	Nov–Dec 2000, 2002, 2003	Sandy loam	IVT, TS	HD-2687, K-9107, HUW-468	9
Karnal	29.7	76.8	235	December 2000, 2001	Sandy clay loam	IVT, LS,VLS	PBW-435, UP-2425, HD- 2643, HP-1744, DL-788-2, WR- 251, WR- 544, Raj - 3765, PBW-373	18
Delhi	29	77.5	228	Nov–Dec 2000, 2002, 2003	Sandy Loam	IVT, TS, LS	HD-2687, PB-W373	9
Delhi	29	77.5	228	Oct–Jan 2005, 2006	Sandy loam	IVT, TS, LS,VLS	HD-2733, HUW-468, HD-2851, PBW-343, HDR-77, HD-2936, HI-8498	35
Hisar	29	75.7	200	Nov–Dec 2000, 2002, 2003	Sandy loam	IVT, TS	HD-2687, K-9107, HUW-468	6
Pantnagar	29	79.5	344	Nov–Dec 2000, 2002, 2003	Sandy loam	IVT, TS	HD-2687, K-9107, HUW-468	6
Faizabad	26.8	82.1	1200	Nov–Dec 2003, 2004	Sandy loam	IVT, TS	HD-2687	1
Varanasi	25.2	82.3	81	Nov–Dec 2000, 2002, 2003	Sandy loam	IVT, TS	HD-2687	6
Ranchi	23.3	85.3	654	Nov–Dec 2000, 2002, 2003	Sandy loam	IVT, TS	HD-2687	6
Jabalpur	23.1	79.9	411	Nov–Dec 2000, 2002, 2003	Clay loam	IVT, TS, LS	HI-8498, GW-347	3
Indore	22.7	75.8	553	Nov–Dec 2000, 2002, 2003	Loamy clay	IVT, TS	HI-8498, GW-347	3

For temperature,

$$T_S = T_{OB} + T_D \quad (1)$$

where T_S = scenario temperature, T_{OB} = IMD gridded daily temperature, T_D = daily change in temperature. Monthly change in temperature (T_{Ddmi}) is linearly interpolated to get the T_D. T_{Dmi} = monthly temperature in scenario minus monthly temperature in baseline.

For rainfall,

$$R_S = R_{OB} \times (1 + R_D) \quad (2)$$

$$R_D = (R_{Smi} - R_{Bmi}) \div R_{Bmi} \quad (3)$$

where R_S = scenario rainfall, R_{OB} = IMD gridded daily rainfall, R_D = relative change in rainfall, R_{Smi} = monthly rainfall in scenario, R_{Bmi} = monthly rainfall in baseline.

A major advantage of this method is that it overcomes the bias of the climate model for baseline weather. To coincide with the climate model baseline period (1960 to 1990), we used observed data for 1969 to 1990. The carbon dioxide level for each scenario (522, 523, 482 and 473 μmol mol^{-1} for year 2050 and 639, 682, 530 and 552 μmol mol^{-1} for year 2080, for scenarios A1b, A2, B1 and B2, respectively) was also included in the crop model for simulations. All other simulation conditions were maintained as explained earlier. Based on the simulated yield for the future scenarios, district yield was calculated as in the case of baseline yield assuming that the crop land area in each district remains the same in the future.

The impact of climate change on yield was calculated using the following formula:

$$Y_d = \frac{\left(Y_s\left(\frac{Y_c}{Y_b}\right) - Y_b\left(\frac{Y_c}{Y_b}\right)\right) \times 100}{Y_b\left(\frac{Y_c}{Y_b}\right)} \quad (4)$$

where Y_d = yield deviation in a climate scenario, Y_s = mean simulated yield in a climate scenario, Y_c = mean observed yield for 2000–2007, Y_b = mean simulated baseline yield.

The observed yield for the period 2000 to 2007 was used for expressing the yield deviation as shown in Eq. (4). Grid values were used for mapping the impacts in the study region in the GIS platform. Yield deviation in future climate scenarios (2050 and 2080) were also plotted against the current seasonal mean minimum and maximum temperatures for the wheat growing period.

2.4. Simulating adaptation gains in future scenarios

Several low-cost and easy-to-adopt adaptation options were tested independently or in combination to assess the adaptive capacity of the wheat crop to climate change. These strategies included (1) the use of improved varieties: short-, medium- and long-duration varieties with high temperature stress tolerance; (2) change in sowing time: advanced or delayed by 1 wk for late- and very late- sowing window, advanced or delayed by 10 d for current optimal sowing window; (3) rescheduling the time of irrigation to suit the phenological stages in future climates, and extra split application of nitrogen (i.e. 50% as basal, 25% at CRI stage and 25% at jointing period, 45 to 60 d after sowing); and (4) without 25% additional nitrogen. The combination that gave the highest yield in each grid or scenario was taken as the best suitable adaptation option. The yield deviation from mean baseline yield was expressed as in Eq. (4).

The vulnerability in a specific scenario was obtained using the following formula:

Vulnerability (yield reduction from baseline even after adaptation) = Impact (yield reduction due to climate change) − Adaptation gain (5)

In instances where impact on yield is positive, simulations were run for similar adaptation strategies to quantify additional benefits to represent net preferable impacts maximized with additional adaptation measures. In all, about 5.15 million simulations (21 yr × [8 scenarios + baseline] × 220 grids × 3 sowings × 8 varieties × 5 rescheduled sowing dates, plus 0.71 million simulations for rescheduling of nitrogen and irrigation, and for 25% additional nitrogen) were carried out for this entire analysis.

3. RESULTS AND DISCUSSION

3.1. Quantification of impacts

The yield of timely-sown wheat is projected to reduce by ~6 and 15% by 2050 and 2080, respectively. However, in late- and very late-sown conditions, yield is projected to decrease ~28 and ~45%, respectively, in 2050, and by ~35 and 52%, respectively, by 2080. The magnitude of projected impacts is slightly higher in GCM-derived climate scenarios than in those derived using RCM scenarios (Fig. 2). The projected increase in minimum and maximum temperatures by 2080 for Indian regions is higher by 0.4 and 1°C, respectively, in MIROC3.2.HI projec-

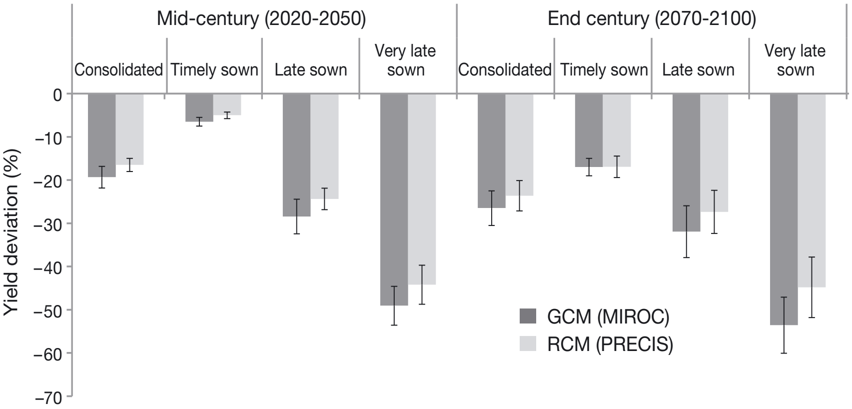

Fig. 2. Impact of climate change on wheat yield (percent deviation from mean yield between 2000 and 2007) in India for mid- (up to 2050) and end of century (2080) climate scenarios of a global (MIROC3.2.HI) and a regional climate model (PRECIS). Bars: 21 yr mean impact on all wheat growing areas in India for A1b, A2, B1 and B2 emission scenarios. Consolidated: weighted impacts on timely-, late- and very late-sown wheat. Timely-sown: as per the recommended date of sowing in different regions; late sown: 15 d delay (as compared to the recommended date); very late sown: 1 mo delayed

tions than those by PRECIS, regardless of emission scenarios. On an all-India scale, in the consolidated impacts, considering timely-, late- and very late-sown conditions, the projected yield reduction is ~23 % by 2050 and ~25 % by 2080.

3.2. Regional impacts and uncertainty assessment

Among the wheat-growing regions (Fig. 3a), the impact of climate change on yield is projected to vary spatially, and with climate and emission scenario (Fig. 3b,c). By 2050, wheat yield in north-western IGP (NWIGP), consisting of the states of Punjab and Haryana, is projected to decrease 8 to 22 %, with a greater reduction in Haryana. The initial gains in productivity due to climate change in this region (Fig. 4) may taper at a later period of this century. In the central IGP (CIGP) region, yield in Uttar Pradesh (UP) is projected to be reduced by ~24 %. A similar yield reduction is projected for West Bengal in eastern IGP (EIGP). In the IGP region, climate change impact on wheat yield is projected to be more in Haryana, Uttar Pradesh, Bihar and West Bengal. In the warm central zone (CZ), yield reduction is projected to be ~25 % in Rajasthan and Madhya Pradesh, which are the major wheat producing states in this zone. In the warmest south-central zone (SCZ), where wheat area is much less, yield is projected to reduce ~42 % in Maharashtra and Andhra Pradesh. For 2080, the projected yield reduction in these regions is even higher, especially in the above mentioned states in each region (Fig. 3b). Among all major zones of wheat cultivation, higher yield reduction is projected for central and south-central zones (Fig. 3c & 4). Wheat yield is projected to reduce the most in scenario A2, followed by A1b, B1 and B2 emission scenarios; though only a single GCM is considered for each emission scenario. The uncertainty of impacts, in general, is higher towards the end of the century, with spatial variation in all zones. Generally, the uncertainty of projected impacts on wheat yield is about 10 %, but it is significantly higher in central and south-central zones (Fig. 3c) and least in CIGP.

3.3. Adaptation to climate change

Adjusting the time of sowing within the timely-, late- and very late- sowing windows is projected to minimize yield reduction from ~23 % (impact, without adaptation) to ~17 % in 2050 even with existing varieties under improved nutrient and irrigation management and with higher dose of nitrogen fertilizer (25 % higher than the dose currently applied by farmers) (Fig. 5a). In addition, by growing improved varieties, projected yield reduction may be minimized to ~9 % in 2050 and to ~13 % in 2080. In order to sustain the yield in future, timely sowing of improved wheat varieties across India along with better management (nutrients and irrigation) and application of higher dose of nitrogen fertilizer is essential. By doing so, the impacts can be offset (~2 % increase) (Fig. 5b) up to 2050. Even if all the above mentioned strategies are employed together, the wheat production in India by 2080 is projected to still reduce by ~5 %.

3.4. Vulnerability of the wheat crop to climate change

The magnitude of impact, adaptation gains and therefore that of vulnerability are projected to vary with emission scenario, adaptation option and region in future climates (Figs. 6 & 7). Climate change is projected to cause 3 basic types of impacts (Fig. 7). Category (1) includes regions that are projected to be

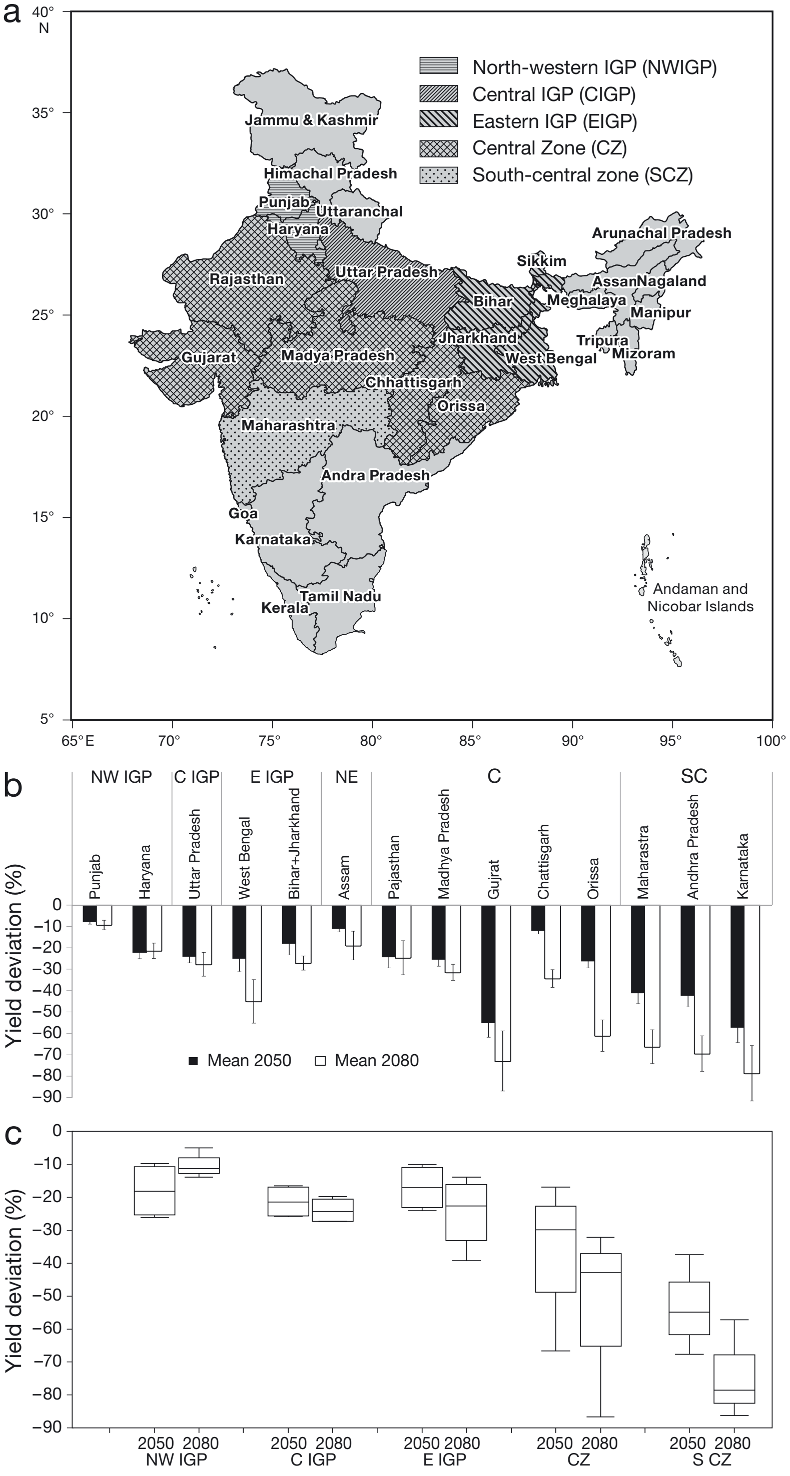

Fig. 3. (a) Wheat-growing-regions. (b) Climate change impact on wheat yield (percent deviation from mean yield between 2000 and 2007) in different regions of India (covering several states). Mean impact for 2050 and 2080 in different states of a region. (c) Extent of uncertainty among different emission scenarios (A1b, A2, B1 and B2) in global MIROC3.2.HI and regional PRECIS climate models for 2050 and 2080 in different regions of India. Horizontal line within a box: median value; error bars: standard error. IGP: Indo-Gangetic Plain; C: central. CZ: central zone

adversely affected by climate change, but can gain yield (over current yield) in future climate with adaptation as mentioned above. Most of the wheat areas in IGP fall in this category (Fig. 6). Category (2) consists of regions such as central and south-central zones that are to be adversely affected and remain vulnerable despite adaptation gains (Figs. 6 & 7). Category (3) consists of areas where climate change may increase yield in the near future, but may decrease in the later part of the century (Figs. 6 & 7). Adaptation in these areas can increase the positive effects. Parts of Punjab and Haryana fall in this category.

The analysis also indicates that adaptation gains with timely sowing may not be uniform in all wheat regions, because of differential impacts and relative area under late- and very late-sown conditions (Fig. 8). Combining timely sowing of wheat with other adaptation measures that have been mentioned in this study is projected to improve yield up to ~18 % in different states by 2050 (Fig. 8a). However, these projected benefits may reduce to ~15 % in 2080 (Fig. 8b). Regions with projected yield reduction of ~20 to 30 % may gain substantially by adopting timely sowing of wheat.

3.5. Seasonal mean minimum and maximum temperatures in relation to wheat yield

Yield reduction is projected to be less in areas with current mean seasonal minimum temperatures of 10 to 12°C than those having >12°C, such as in parts of EIGP, central and south-central India (Fig. 9a). In various emission scenarios, projected increase in mean seasonal minimum temperatures in these regions is by ~1.5–2°C in 2020, ~2.5–4°C in 2050 and 4–6.5°C in 2080. Even though a similar or slightly higher increase in temperature is projected for the NWIGP region, the projected impacts are less, due to current lower mean seasonal minimum temperatures of ~7 to 10°C (Fig. 9a). Seasonal mean

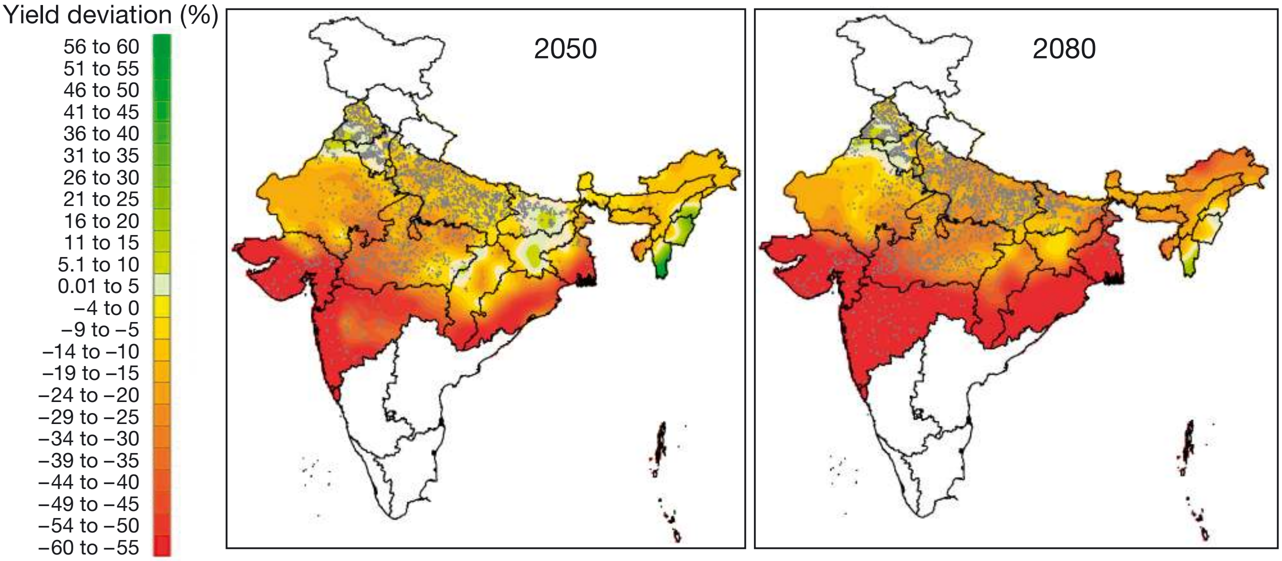

Fig. 4. Spatial variation in impact of climate change on timely-sown wheat yield in India for 2050 and 2080. Ensemble average of emission scenarios. Dots: 10 000 ha of wheat area

maximum temperatures in wheat growing areas in India also vary significantly from 23–25°C in the NWIGP to 29–30°C in the EIGP region (Fig. 9b). The central and south-central regions are even warmer at 28 to 31°C. In fact, yield levels are significantly negatively correlated with the current seasonal mean minimum temperatures in the range of 12 to 18°C (Fig. 9c) and with mean maximum temperatures of 21 to 31°C (Fig. 9d). The projected increase in mean seasonal maximum temperatures varies 1–1.5°C in the IGP to ~1.75°C in central India. However, less warming of up to 1°C by 2020 is projected for the north-eastern states. In 2050, the projected warming in the IGP region is ~3 to 4.5°C for seasonal minimum temperatures and ~1.75 to 4°C for seasonal maximum temperatures, with a relatively higher increase in the NWIGP. A rise of 2–3.5°C and 3.5–4°C in seasonal maximum and minimum temperatures, respectively, is projected for central and south-central India. Such projected warming, beyond the upper limit of optimal temperatures, may constrain wheat productivity. By 2080, large areas under wheat cultivation are projected to have mean seasonal minimum and maximum temperatures that are higher by 4–6°C and 3–6°C, respectively. A greater warming in the NWIGP and in central India is projected. Increases in temperature are projected to cause yield reduction at an accelerated pace towards 2080 (Fig. 9e,f). Therefore, for wheat cultivation, future temperatures may play a major limiting role for higher productivity particularly in areas with current high seasonal mean maximum temperatures, such as Central India. Wheat yields are projected to decrease in areas with mean seasonal maximum and minimum temperatures in excess of 27 and 13°C, respectively, in spite of CO_2 fertilization benefits.

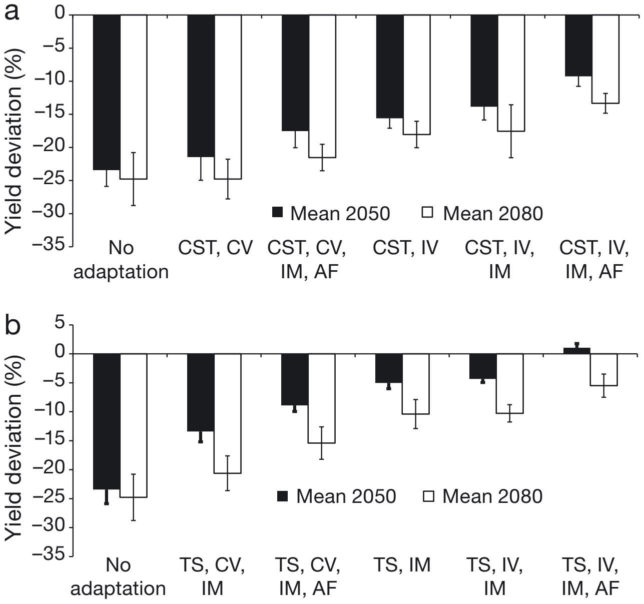

Fig. 5. Overall impact with and without adaptation on wheat yield (a) adjusting the sowing time within timely-, late- and very late-sown conditions and (b) for adjusted timely sowing of wheat in all regions in India for 2050 and 2080. Negative adaptation gain values: vulnerability. Impacts in both cases are as per the current ratio of area under timely-, late- and very late-sown conditions. Error bars: standard error; CST: change in sowing time; CV: current variety; IM: improved management; AF: additional fertilizer; IV: improved variety; TS: timely sown

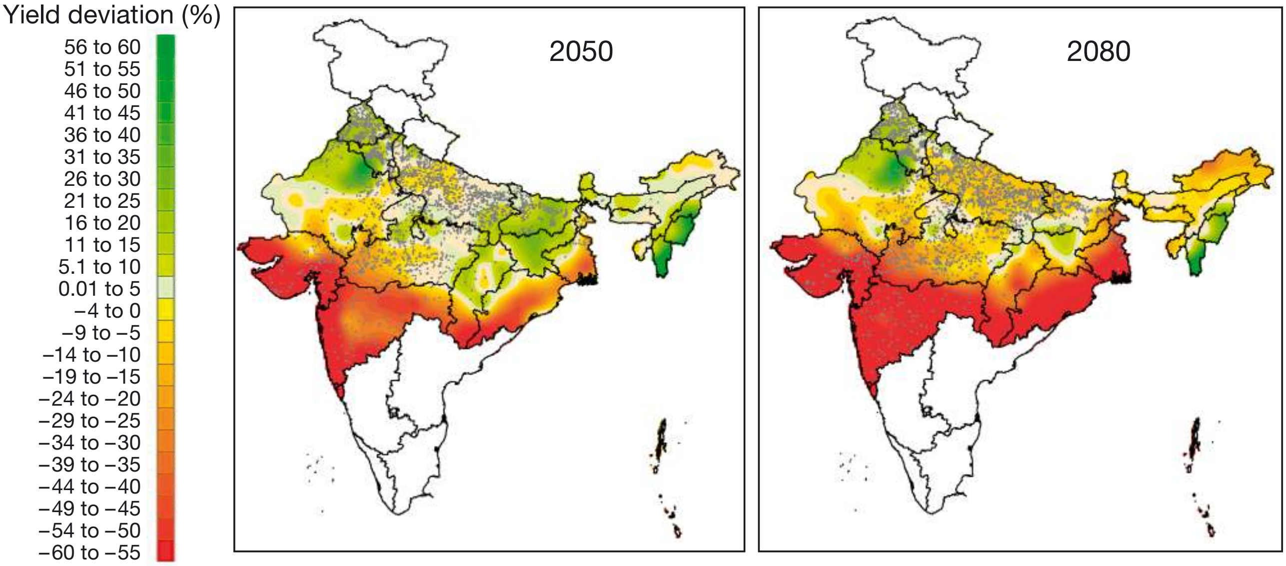

Fig. 6. Spatial variation in vulnerability (after adaptation) of timely-sown wheat yield to climate change in India for 2050 and 2080. Areas in red: vulnerable even after adaptation. Ensemble average of emission scenarios. Dots: 10 000 ha of wheat area

The projected differential impacts on wheat yield in different emission scenarios are mainly due to variations in concentrations of atmospheric CO_2 and rise in temperatures. While a rise in atmospheric CO_2 is projected to benefit the wheat crop, the magnitude of the benefit may depend on the trade-off with reduction due to a rise in temperature. The uncertainty in the magnitude of impacts on wheat yield is significantly high in central and south-central zones, while least in CIGP. This may be due to (1) less variation in projected temperature rises among the emission scenarios for CIGP, and (2) wide variations in the current and projected growing season temperatures in the central zone spread between 20–28° N and 65–86° E, covering several states, the largest among the zones that have been considered. In addition, change in rainfall amount, intensity and distribution may influence wheat crop in limited irrigation farms. Current winter season rainfall in wheat growing regions is up to 100 mm. The PRECIS and MIROC 3.2.HI scenarios project a 5 to 10 % increase in winter rainfall in parts of north eastern states and central India by 2050.

In near the future, agronomical management can help in overcoming the negative impacts of climate change. However, developing suitable varieties and efficient crop husbandry becomes essential for improving the productivity in the mid- and latter parts of the century. Results also indicate that timely sown wheat is less vulnerable to climate change, and projected negative impacts can be overcome by adaptation. On the other hand, late- and very late-sown wheat yields are projected to decline further in future potential climates. Therefore, there is an urgent need to impress upon farmers the need to undertake timely sowing by adjusting the preceding rice crop transplantation or by adjusting the crop calendar and cropping pattern. Adjusting time of transplantation is one of the suggested adaptation options for rice cultivation in a future climate scenario (Naresh Kumar et al. 2013). Regions that are vulnerable may require more intensive, specific and innovative research and development interventions beyond those tested in this study. Short-duration, heat tolerant, high yielding varieties may be needed for areas with high end season temperatures and water scarcity. Even though the CO_2 response of recent wheat cultivars is relatively less than that of older cultivars, agronomic management can maximize the individual plant performance (Ziska et al. 2004). Availability of nitrogen can significantly influence the response of wheat to high CO_2 concentrations (Cardoso-Vilhena & Barnes 2001) and nitrogen concentration in tissue and grain (Cardoso-Vilhena & Barnes 2001, Kimball et al. 2001). In the present study, the application of 25 % more nitrogen led to higher harvests. Additional quantities of nitrogen and other nutrients may be required to reap the benefits of CO_2 fertilization in poorly fertilized fields or soils with limited fertility. This also helps to maintain the crop C:N ratio and grain protein concentration.

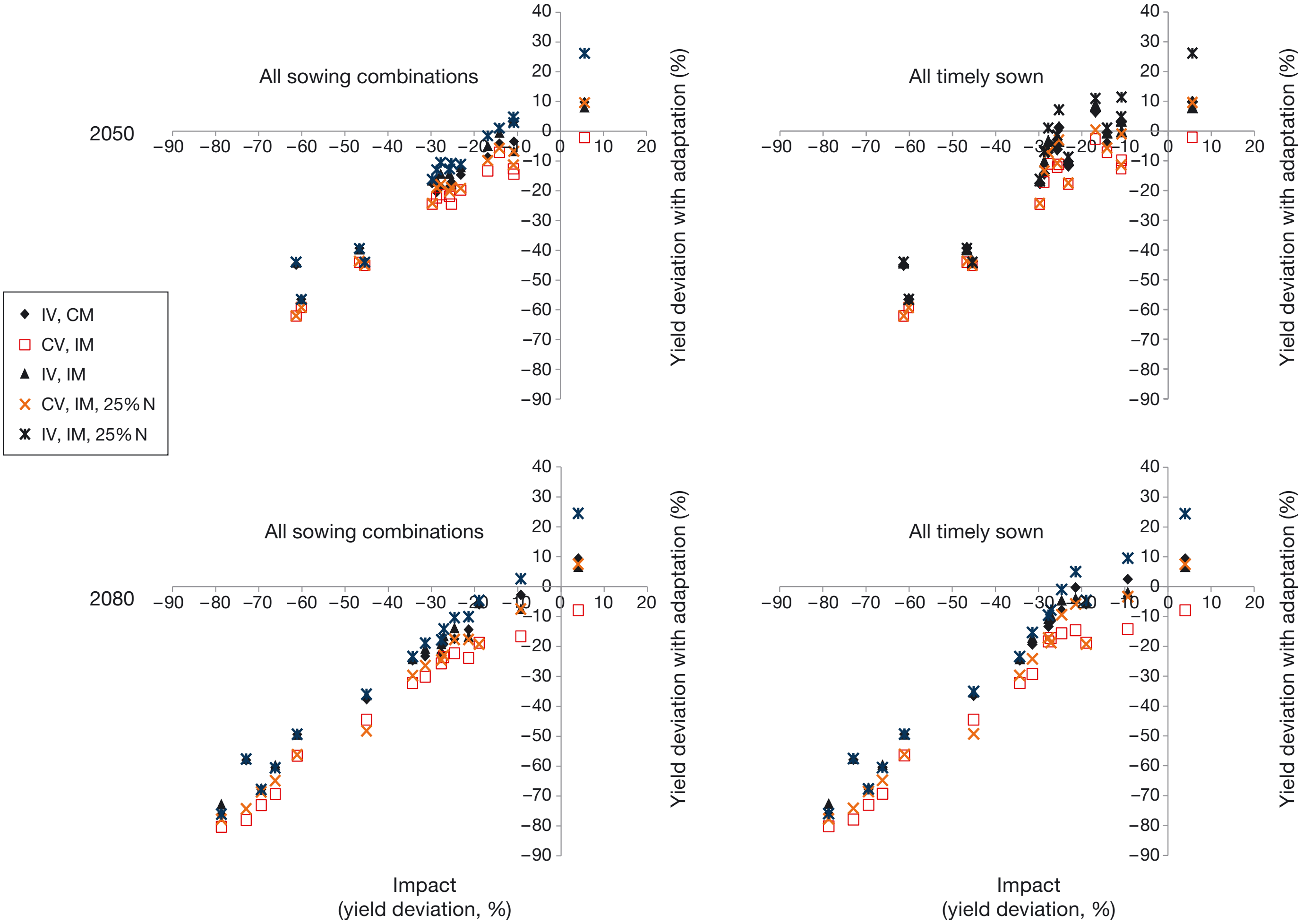

Fig. 7. Vulnerability of wheat yield with variable adaptation gains in regions differentially impacted by climate change in India. Data points: one state. Negative values in *y*-axis: vulnerability of region in spite of adaptation. Positive values: adaptation benefits exceeding negative impacts and providing improvement in yield over mean yield of 2000–2007. IV: improved variety; CM: current management; CV: current variety; IM: improved management; 25 %N: 25 % additional nitrogen

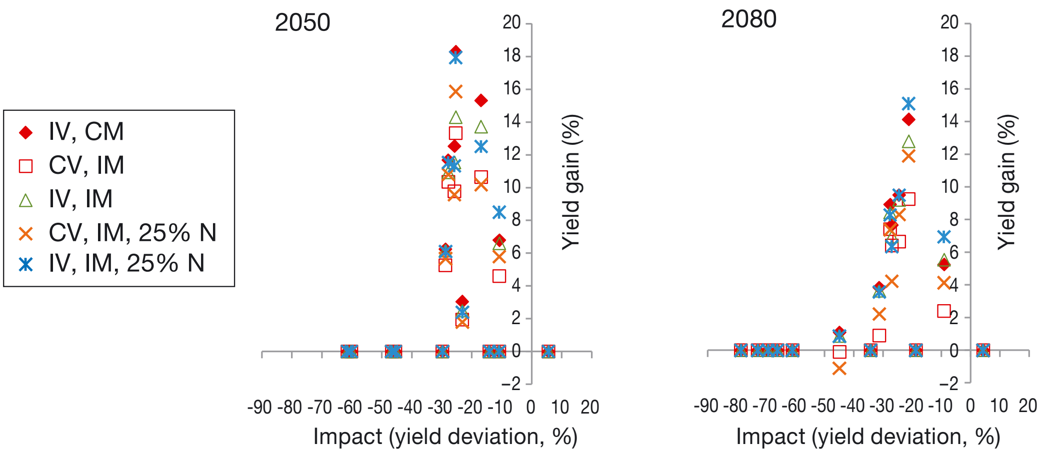

Fig. 8. Additional adaptation gains by timely sowing of wheat as against the adaptation gains by adjusting the sowing time within the normal-, late- and very late-sowing windows in 2050 and 2080. Data points: one state in India. *y*-axis: gain in yield because of timely sowing of wheat (with all other adaptation options inclusive) over the adaptation gains by adjusting the sowing time within the normal-, late- and very late-sowing windows. Change in yield: % deviation from 2000–2007 mean yield

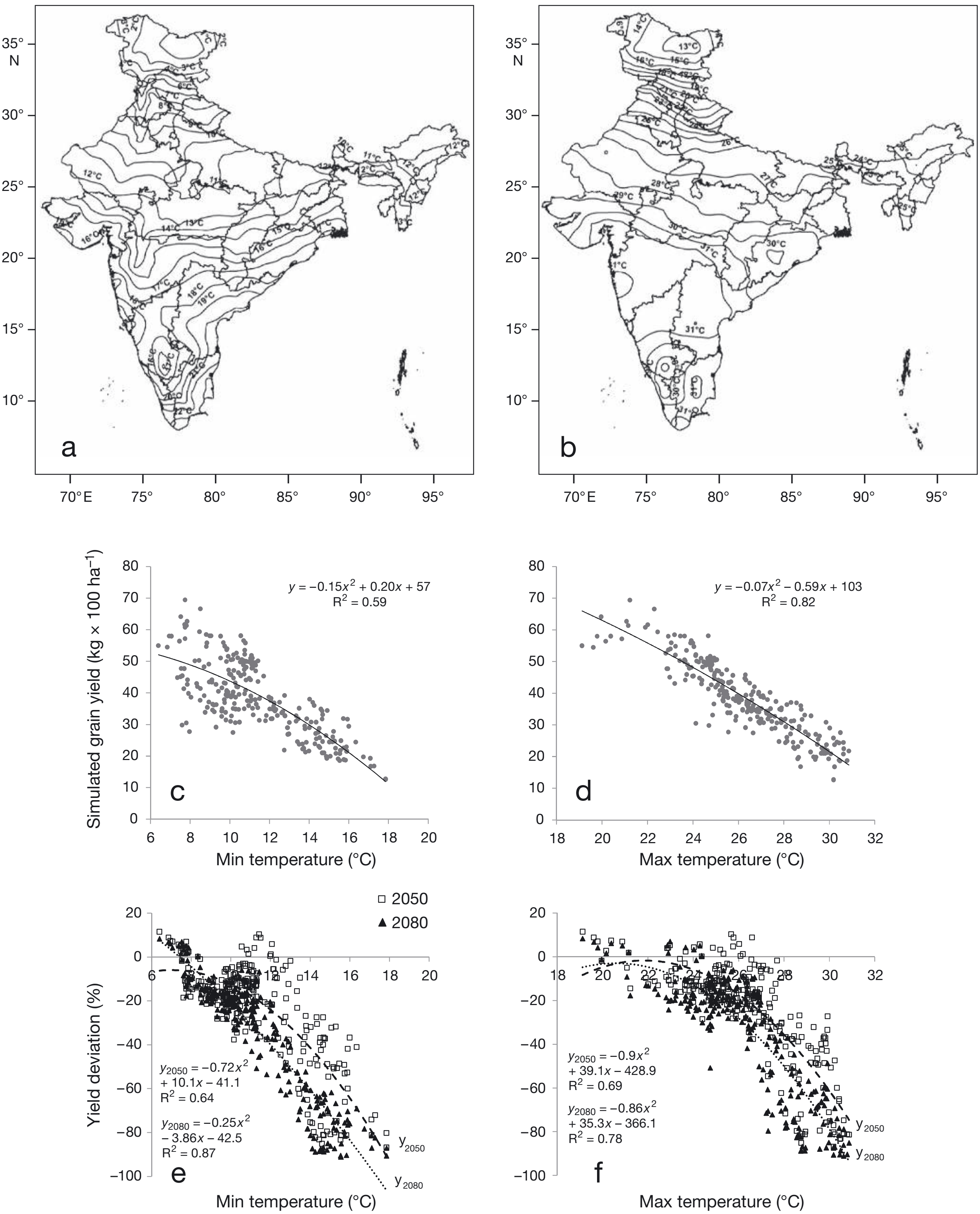

Fig. 9. (a,b) Iso-thermal lines for current mean seasonal (a) minimum and (b) maximum temperatures for the wheat growing period (November to mid-April) in India. (c,d) Simulated grain yield in relation to current growing season (c) mean minimum and (d) mean maximum temperatures. (e,f) Impact of climate change on wheat yield (as percent reduction from mean yield of 2000–2007 at each respective region) in relation to current growing season (e) mean minimum and (f) mean maximum temperatures in 2050 and 2080. Data points: 21 yr yield mean from ensemble of emission scenarios for each grid point (1° × 1°)

4. CONCLUSIONS

The study projects a progressive reduction in wheat yield towards the end of the century due to climate change. Projected impacts are more for late-sown wheat. However, the spatio-temporal variations exist for a wide range of potential of impacts.

Even though the magnitude of impacts vary, the direction of impact is similar in RCM and GCM based assessments. Negative impacts are less severe in the B1 and B2 emission scenarios as compared to the A2 and A1b scenarios. The magnitude of uncertainty has spatial variation and increases with time period.

Adaptation to climate change can reduce the negative impacts. Timely sowing of wheat crop, adoption of improved and heat-tolerant varieties under increased input amount and efficiency regimes can not only offset yield reduction but also result in an increase in yield up to the mid-century. The reduction or complete conversion of areas under late- and very late-sown conditions to timely-sown conditions can significantly improve yield even with current varieties in the near future.

The 3 basic types of influence that are projected as a result of climate change include (1) regions that will be adversely affected by climate change and can gain yield (over current yield) through adaptation strategies; (2) regions that are currently adversely affected, and remain vulnerable despite the adaptation strategies considered in this study; and (3) regions that are projected to gain yield in the near future, for which adaptation can enhance the positive effects. Regions falling in the vulnerable category, even after adopting suggested climate-change adaptation strategies, require more intensive, specific and innovative adaptation options.

Wheat yields are projected to decrease in areas with mean seasonal maximum and minimum temperatures in excess of 27 and 13°C, respectively, in spite of CO_2 fertilization benefits.

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