Maize yield and leaf area index sensitivity to temperature and rainfall changes under stabilization scenarios in Punjab, India

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Abstract

The study has been performed to understand the climate change impact on the major cereal crop *i.e.* maize in four agroclimatic zones (ACZ) of Punjab *viz.* ACZII (Ballowal Saunkhri), ACZIII (Amritsar, Ludhiana and Patiala), ACZIV (Bathinda) and ACZV (Abohar and Faridkot). The maize yield and leaf area index (LAI) trend was analysed under the current and optimized sowing dates with constant farming practices for stabilization scenarios (RCPs 4.5 and 6.0) during near (2021-2055) and far future (2066-2095). An ensemble mean obtained for temperature and rainfall data from four selected global circulation models (GCMs) *i.e.* CSIRO-Mk-3.6.0, FIO-ESM, GISS-E2R and IPSL-CM5A-MR projected yield decline under the scenarios by 12-40%, 9-43%, 7-57% and 1-95% at respective ACZs. The quantified impact of optimized sowing dates with constant farming practices on maize revealed that higher yields were obtained for mid May to end June at ACZII, early May to end June at ACZIII and early May at ACZV (Faridkot) while LAI observed an increasing trend for both the scenarios and time period. The results indicated that the cv. PMH1 performed well during both the time period while PMH2 performed well during near future only and the maximum yield decline was observed during the far future when emissions would be high. The ACZIV and ACZV (Abohar) were found to be completely unsuitable for maize cultivation in the state. Thus, such climate change studies are important for India where variable weather patterns have been projected and these can be applied for future climate studies under new scenarios.

Abbreviations

ACZ: Agroclimatic Zone
LAI: Leaf Area Index
RCP: Representative Concentration Pathway
GCM: Global Circulation Model
PMH: Punjab Maize Hybrid
NASA: National Aeronautics and Space Administration
IPCC: Intergovernmental Panel on Climate Change
GHGs: Green House Gases
SRES: Special Report on Emission Scenarios
CFCs: Chloroflourocarbon
CO_2: Carbon Dioxide
N_2O: Nitrous Oxide
CH_4: Methane
CERES: Crop Environment Resource Synthesis
DSSAT: Decision Support System for Agrotechnology Transfer
cv. : Cultivar
APSIM: Agricultural Production Systems Simulator
AEWs: Agricultural Extension Workers
CSA: Climate-Sensitive Agricultural Practices
USGCRP: United States Global Change Research Program
SPI: Standard Precipitation Index
DTR: Diurnal Temperature Range
CIMMYT: International Maize and Wheat Improvement Centre
PET: Potential Evapotranspiration
CWR: Crop Water Requirement

Introduction

Climate change is an issue arising worldwide leading to significant changes in the weather pattern, cropping pattern, lifestyle, etc. However, climate change studies in agriculture field holds importance due to the significant role of agriculture in the survival of living beings. The climate change impact studies on the crop growth parameters are being widely done to understand the crop performance and it's response to increase in temperature and rainfall variability in various regions worldwide. Though climate change is not visible but it can surely be experienced at most of the places in the world and it cannot be ignored if it can be seen as extreme temperatures, decreasing rainfall amount and increasing rainfall variation patterns, sea level rise, melting glaciers ultimately leading to devastative effect and catastrophes. Agriculture around the world is projected to experience serious decline in major cereal yields due to global warming which might be between 3 and 16 % by 2080 (Mahato, 2014). Many of the developing countries have an average temperature persisting near or above crop tolerance levels which would cause an average decline of 10-25% in agricultural productivity by 2080s while an increase in CO_2 levels to 550 ppm would increase the rice, wheat, legumes and oilseeds by 10-20%. Similarly, a 1°C temperature rise may reduce the yields of wheat, soybean, mustard, groundnut and potato by 3 - 7% which would be higher under rising temperatures (Birthal *et al.*, 2014). The studies show that though a minimum temperature rise would have a favourable impact on most crops but this was not able to compensate the negative impact of rising maximum temperatures. Similar impact was observed with rainfall which was unable to avoid the negative impact of rising temperatures. Maize is a global cereal crop sensitive to weather changes and an important part of the global food cycle. Global studies on climate change impact and mitigation strategies for the same have been introduced and evaluated in different regions of the world and a recent NASA study published by Jaegermeyr *et al.* (2021) reports the climate change impact to be a major setback for maize and wheat production during early 2030s under high greenhouse gas emissions. The quantitative evaluation projects the maize crop yield decline by 24% and potential wheat growth decline by about 17%. These projected changes in yield can be contributed to temperature rise, rainfall pattern shifts and elevated carbon dioxide concentrations under anthropogenic greenhouse emissions. These studies are done using crop simulation models which are able to create ideal crop environment for future scenario studies. The studies have been performed worldwide to understand the future impacts of climate change scenario on major cereal crops and how could these be avoided using adaptation and mitigation strategies. A study conducted on climate change impact on maize yield in Iowa showed that despite the range of predicted amount of warming being wide and large changes in summer precipitation, the simulations showed a significant decrease in maize yields from late

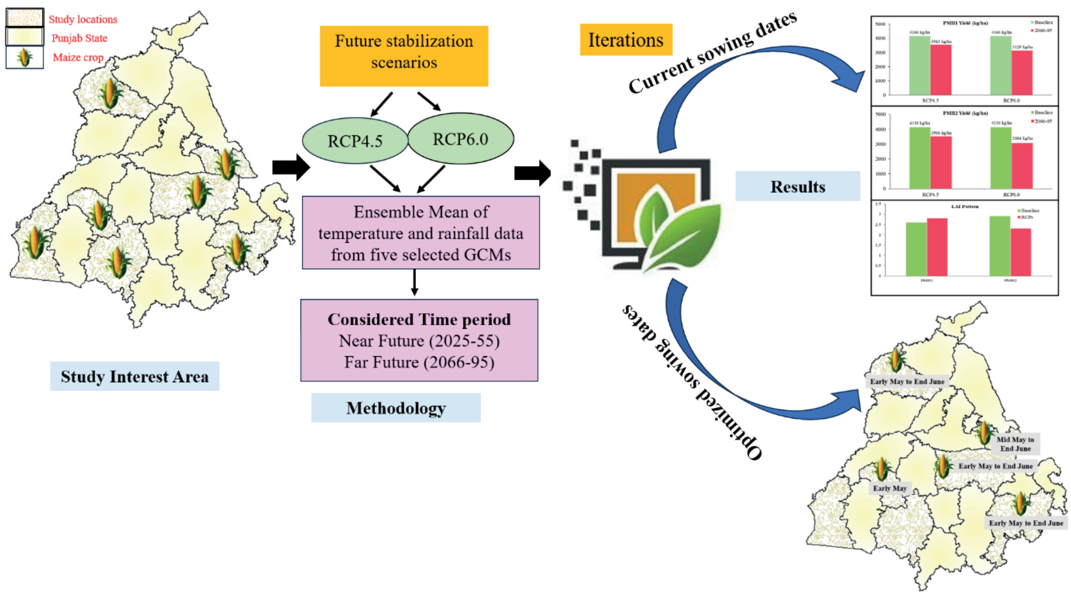

Fig. 1 - Graphical abstract

20th century to mid and late 21st century by 15-50%. The warm season average air temperature and precipitation influenced the state yield so much that even after removing the influence of moisture stress on crop growth in the model would lead to maize yield decline by 10-20% during the end 21st century. Though under optimum climate change scenarios, the societies have enacted ambitious efforts to limit temperatures, but still the global agriculture faces a new climate reality where Jaeger *et al.* (2014) shows that due to interconnectedness of the global food system, impact in one of the region's breadbasket would have a global impact.

The climate change studies can be easily performed using projection data available through Global Circulation Models (GCMs) which have constantly shown improvement and are being used in multimodel ensemble form for reliable results. As per IPCC (2014) reports the GCMs are an efficient tool for various climate aspects like atmospheric and oceanic temperatures, precipitation, wind, clouds, ocean currents and sea-ice content and these are extensively tested against the historical observations. The representative concentration pathways (RCPs) are a clear description of the four different pathways of the 21st century which include the GHGs emissions and atmospheric concentrations, air pollutant emissions and land use. These concentration pathways have been built by using integrated assessment models (IAMs) as input to different climate model simulations thus projecting consequences for the climate system. These climate projections are evidently and frequently used for climate change studies along with its impact and adaptation assessment. These models simulate and provide temperature (maximum and minimum) and rainfall predictions which can be efficiently utilized in climate change studies. These simulated meteorological data is available for four future climate scenarios *i.e.* RCP 2.6, RCP 4.5, RCP 6.0 and RCP 8.5. Amongst the four scenarios RCP 2.6 is considered as the extremely low emission scenario, RCP 4.5 and RCP 6.0 are considered as the stabilization scenarios and RCP 8.5 as the extremely high emission scenario. The RCPs have an edge over the Special Report on Emission Scenarios (SRES) used previously as they cover a wider range and represent scenarios with climate policy. The RCP 4.5 is the low intermediate scenario that addresses the research directed towards understanding the consequences resulted under reduced GHGs intended to stabilize the radiative forcing in 2100. This is also known as the mitigation scenario as none of the transformations would help meet targets without any mitigation action on the GHG emissions (Thomson *et al.*, 2011). As described in a study by Nazarenko *et al.* (2015), the intermediate scenario, RCP 6.0 observed large increase in the CO_2 and N_2O concentrations by 82 and 0.02 ppm, respectively between 2100 and 2150 while a compensatory decline was observed in other greenhouse gases like CH_4, CFCs and other trace gases to maintain a radiative forcing at about 6.0 W m^{-2}. In RCP 6.0, a continuous increase of radiative forcing causes an increase in energy imbalance to 2100 while gradual imbalance decrease in RCP 6.0 scenario is visible followed by a strong decrease in CH_4, CFCs and other trace gases. These temperature and rainfall projections available from GCMs are used as an input in the crop simulation models to simulate yield and other growth parameters.

The following study has been performed keeping in mind the agricultural state of India *i.e.* Punjab where weather patterns have observed changes and are predicted to variate under future climate scenarios. Thus, a critical study on yield and LAI pattern under current and future optimization of sowing practices were analysed for the common maize hybrids (PMH1 and PMH2) prevalent in the state under the two intermediate scenarios (RCPs 4.5 and 6.0) during near and far future using crop simulation model (CERES - Maize v 4.7.5) for four agroclimatic zones of the state. The state experiences weather variation within the state thus, different locations under different agroclimatic zones with available observed meteorological data were selected. The study compares the performance and results obtained from Ensemble mean of four selected GCMs (current study) and Ensemble of seventeen GCMS (previous studies). Previously, the crop simulation studies under RCP scenarios were performed using the ensemble of the seventeen available GCMs in the MarkSim generator (Kothiyal *et al.*, 2023, Kothiyal *et al.*, 2023a, Kothiyal *et al.*, 2023b) while study on the ensemble mean of the selected GCMs (Kaur, 2020) remained untouched. The research highlights on the minute differences that might be noticed while studying the impact on crop yield from ensemble mean of different GCMs.

Materials and methods

Study Location

The study was conducted in the Punjab state of India which has highly variable rainfall pattern over total land area of 50,362 km^2. Due to these variations over a small area, different agroclimatic zones (ACZ) were selected *viz.* ACZII (Ballowal Saunkhri), ACZIII (Amritsar, Ludhiana and Patiala), ACZIV (Bathinda) and ACZV (Abohar and Faridkot, Supplementary Fig. 1).

Global Circulation Models (GCMs)

GCMs provide temperature (maximum and minimum) and rainfall predictions using seventeen models available at the "Marksim Weather Generator". These predictions can be downscaled and bias corrected for further applications using individual GCM or their ensemble. The seventeen GCM output were downscaled and bias corrected for the different agroclimatic zones using different bias correction techniques (Kaur, 2020). Amongst the seventeen GCMs, an ensemble of the predictions obtained for the time period (2010 - 2095) from four selected GCMs *i.e.* CSIRO-Mk-3.6.0, FIO-ESM, GISS-E2R and IPSL - CM5A - MR (Supplementary table) for two stabilization scenarios (RCP 4.5 and RCP 6.0) were used as weather input files in crop simulation model.

Crop simulation model (CSM)

The meteorological data as obtained from the GCMs and bias corrected for temperature and rainfall pattern was used as weather input for running the largely applicable simulation mode *i.e.* Decision Support System for Agrotechnology Transfer (DSSAT) Crop Environment Resource Synthesis (CERES-Maize model (v 4.7.5)) for predicting crop growth of two maize cultivars *i.e.* PMH1 (long duration maize hybrid) and PMH 2 (short duration maize hybrid) under the two stabilization scenarios (RCP 4.5 and RCP 6.0) during near century (2025 - 54) and far century (2066 - 95). The CERES-Maize model was sensitized, calibrated and validated for the crop growth parameters (anthesis, maturity, grain yield and LAI) before its further application for simulating future performance of the cultivars (Kothiyal *et al.*, 2022).

Yield Assessment

The simulations for the crop yield and LAI assessment was performed for a period of 70 years (2025-2095) using the ensemble predicted meteorological data for the current sowing window (end May to end June) and optimized sowing window (early May to mid July). The percent yield changes and LAI deviations from the baseline were evaluated using deviation% (Eq. 1) and deviation (Eq. 2), respectively which quantified the increase/decrease in the yield and LAI of maize crop. The baseline for the yield and LAI was evaluated using the 11 year period (2010 - 2021) simulated yield for the current sowing window while the baseline for the optimized sowing dates and LAI was considered as early June which was validated as per the study (Kothiyal *et al.*, 2022) for maize cultivars. The deviations were evaluated for the current and future optimized sowing dates and LAI using their respective baseline.

The maize yield and LAI deviations under the current sowing window for the two stabilization scenarios during the near and far century was depicted using the box and whisker plot while the future optimized sowing window was represented using the combination of region map and bar charts. Further, the LAI deviations under future periods were depicted using the radial graphs which showed clear deviation values and patterns. The deviations for the current and future were evaluated using the consistent agronomic practices considered during the study period.

$$Deviation\% = \frac{(Predicted\text{-}Baseline)}{Baseline} * 100 \text{ (Eq. 1)}$$

$$Deviation = Predicted\text{-}Baseline \text{ (Eq. 2)}$$

Results

An average of the yield and LAI deviation values for both the scenarios has been done on cultivar and time period basis.

Yield and LAI deviations under the current sowing window of maize crop

Agroclimatic zone II (Ballowal Saunkhri)

The cv. PMH1 observed a yield decline ranging 18 - 22% under end May and early June and yield increase ranging 12 - 25% during the near future under mid and end June while a significant decline of 8 - 33% was observed under the far future scenario (Supplementary Fig. 2a). Similarly, for cv. PMH2 the yield decline was

Details of the selected GCMs used in evaluating the ensemble mean for the crop model

Sr. No.	Model name	Institutions	Resolution (degree)
1.	CSIRO-Mk 3.6.0	Commonwealth Scientific and Industrial Research Organization and the Queensland Climate Change Centre for Excellence	1.875×1.875
2.	FIO-ESM	The First Institute of Oceanography, SOA, China	2.812×2.812
3.	GISS-E2R	NASA Goddard Institute for Space Studies	2.0 x 2.5
4.	IPSL-CM5A-MR	Institute Pierre-Simon Laplace	1.2587×2.5

*Ensemble mean of the above selected models has been used in the study

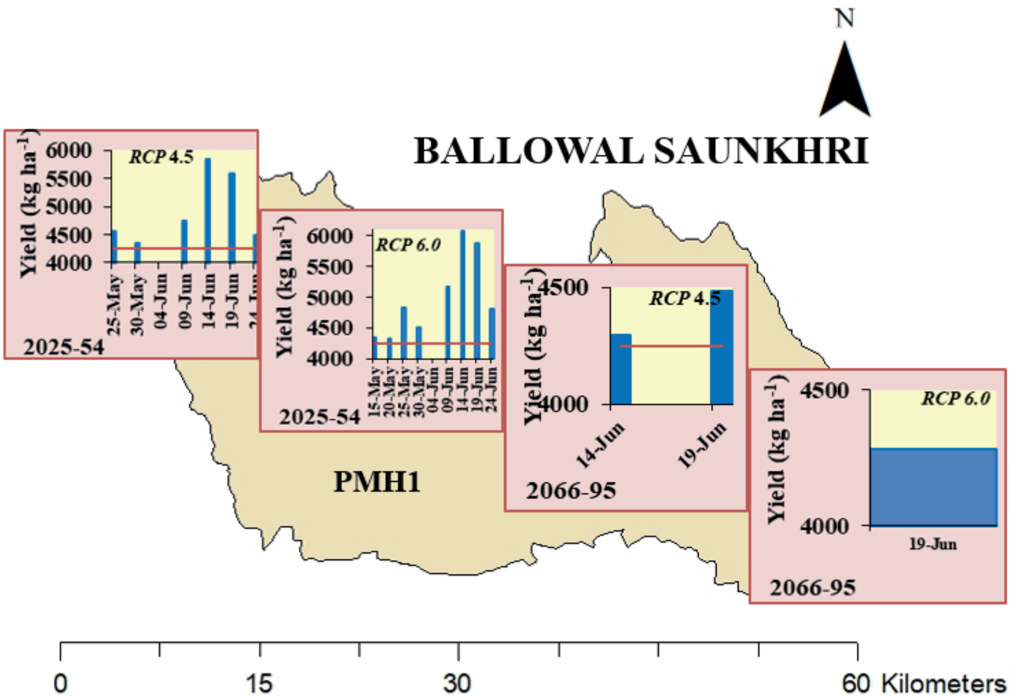

Fig. 1 (a): Adaptive sowing date option for maize cultivar PMH1 under the two scenarios in agroclimatic zone II: Ballowal Saunkhri

observed ranging 24 - 25% under end May and early June and yield increase ranging 16 - 17% for near future under mid and end June while a decline of 17 - 40% was observed for the far future century (Supplementary Fig. 2b). The LAI observed deviation of 0-1 from the baseline for both the cultivars during both the centuries (Supplementary Fig. 2c & d).

The two maize cultivars under stabilization scenarios observed a major decline in yield of 16 - 25% and 12-40% during the near future and far future, respectively. However, the mid and end June observed a significant increase in yield during near future for both the cultivars by 12 - 25%. The yield decline was observed to be higher for PMH2 cultivar and far future time period when emissions would be high. The LAI pattern showed not much significant deviations ranging 0 - 1 for the cultivars.

Agroclimatic zone III (Amritsar, Ludhiana and Patiala)

The cv. PMH1 observed a yield decline ranging 25 - 30% , 4 - 15% and 15 - 21% under end May and early June, respectively at Amritsar, (Supplementary Fig. 3a) Ludhiana (Supplementary Fig. 4a) and Patiala (Supplementary Fig. 5a) while a yield increase ranging 6 - 10%,11 - 23% and 10 - 19% was observed for respective locations during the near future under mid and end June. A significant decline of 9 - 43%, 6 - 37% and 13 - 42% was observed under the far future scenario. Similarly, for cv. PMH2 the yield decline was observed ranging 5 - 36%, 7 - 21% and 10 - 33%, respectively for Amritsar (Supplementary Fig. 3b), Ludhiana (Supplementary Fig. 4a) and Patiala (Supplementary Fig. 5a) under end May and early June and yield increase ranging 2%, 8 - 13% and 8 - 15% for respective locations for near future under mid and end June. A decline of 29 - 51%, 3 - 35% and 10 - 45% was observed for the far future century. The LAI observed deviation of 0 - 1 from the baseline for both the cultivars during both the centuries for all the locations. The two maize cultivars under stabilization scenarios observed a major decline in yield of 15 - 25% and 9 - 43% during the near future and far future, respectively in ACZIII. However, the mid and end June observed a significant increase in yield during near future for both the cultivars by 8 - 23%. The yield decline was observed to be higher for PMH2 cultivar and far future time period when emissions would be high. The LAI pattern showed not much significant deviations ranging 0 - 1 for the cultivars. (Supplementary Fig. 3 c&d and Fig. 4c&d)

Agroclimatic zone IV (Bathinda)

The cv. PMH1 (Supplementary Fig. 6a) observed a significant yield decline ranging 16 - 37% and 31 - 78%, respectively during the near and far future under end May, early, mid and end June. Similarly, for cv. PMH2 (Supplementary Fig. 6b) a significant yield decline ran-

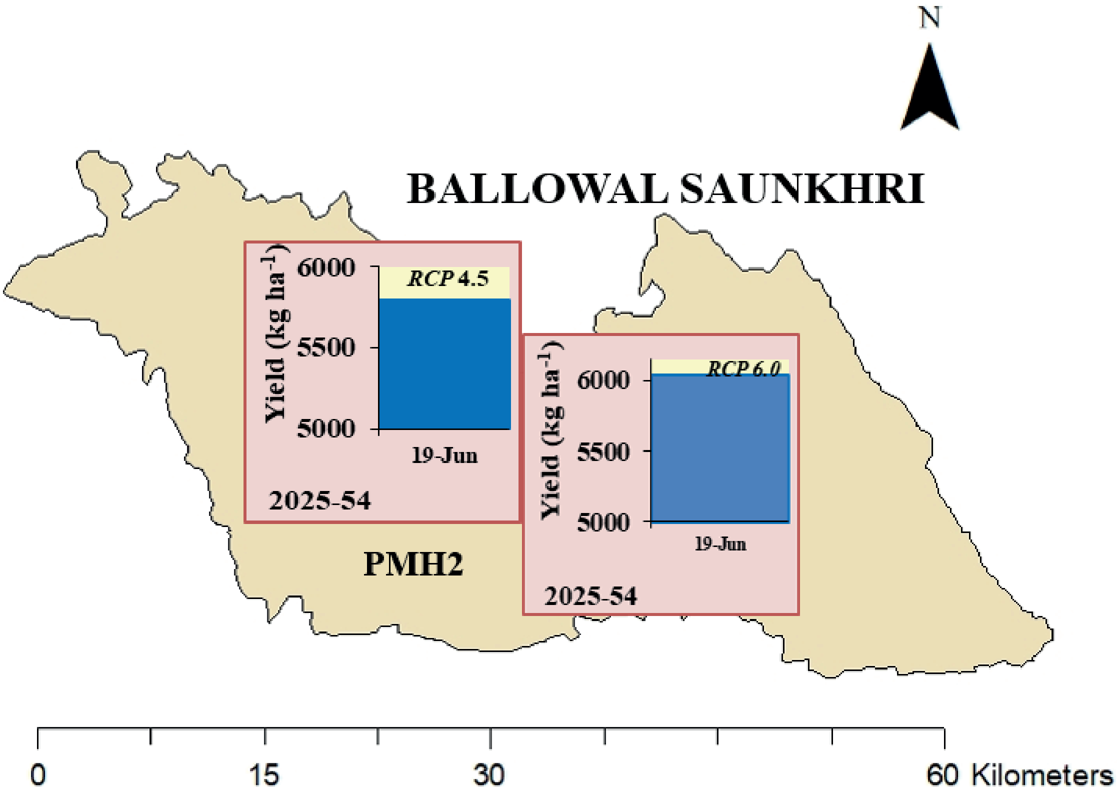

Fig. 1 (b): Adaptive sowing date option for maize cultivar PMH2 under the two scenarios in agroclimatic zone II Ballowal Saunkhri

ging 7 - 38% and 24 - 55%, respectively during the near and far future under end May, early, mid and end June was observed. The LAI observed deviation of 0-0.4 from the baseline for both the cultivars during both the centuries. (Supplementary Fig. 6 c, d)

The two maize cultivars under stabilization scenarios observed a major decline in yield of 7 - 38% and 24 - 57%, respectively during the near future and far future. None of the sowing dates observed any yield increase during future century and significant yield decline was observed at the location. The LAI pattern showed not much significant deviations ranging 0 - 0.4 for the cultivars.

Agroclimatic zone V (Abohar and Faridkot)

The cv. PMH1 observed a significant yield decline at Abohar (Supplementary Fig. 7a) and Faridkot, (Supplementary Fig. 8a) respectively ranging 20 - 65% and 1 - 30% during near future while 44 - 95% and 14-51% during far future under end May, early, mid, and end June. Similarly, for cv. PMH2 observed a significant yield decline at Abohar (Supplementary Fig. 7b) and Faridkot, (Supplementary Fig. 8b) respectively ranging 2 - 65% and 6 - 28% during near future while 29 - 89% and 4 - 52% during far future under end May, early, mid and end June. The LAI observed deviation of -1 to 1 from the baseline for both the cultivars during both the centuries at the Abohar (Supplementary Fig. 7c, d) and Faridkot (Supplementary Fig. 8c, d).

The two maize cultivars under stabilization scenarios observed a major decline in yield of 2 - 95% and 1 - 52%, respectively during the near and far future. Though, the end June observed a yield increase in the ACZV but in non-significant measures during near future for PMH1 and PMH2 while the sowing dates *i.e.* end may, mid and end June observed significant decline in yield of the maize cultivars. The LAI pattern showed significant deviations ranging -1 to 1 for the cultivars.

Impact of optimized sowing window on growth parameters of maize cultivars in Punjab

The analyzed growth parameters *i.e.* yield and LAI under current sowing dates and constant farming practices observed significant yield decline at different ACZs of Punjab. Thus, yield and LAI of the two cultivars was simulated for the sowing window *i.e.* early May to mid July at an interval of 5 days using CERES - Maize model with the rainfall and temperature data of ensemble mean as input at each selected location of the four ACZs under the stabilization scenarios (RCPs 4.5 and 6.0). The simulated results in detail have been explained below:

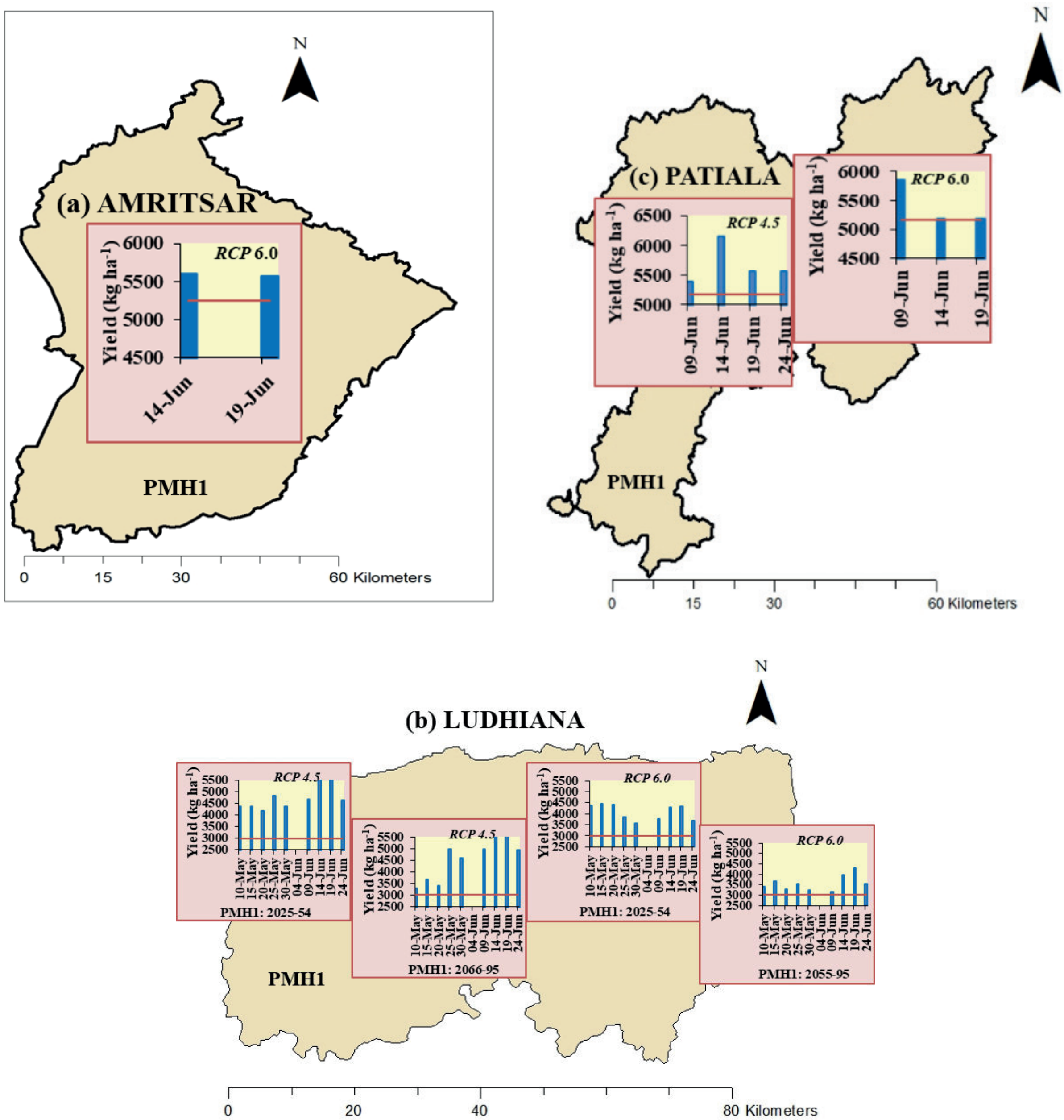

Fig. 2 (a-c): Adaptive sowing date option for maize cultivar PMH1 under the two scenarios in agroclimatic zone III: (a) Amritsar (b) Ludhiana and (c) Patiala

Agroclimatic zone II (Ballowal Saunkhri)

The cv. PMH1 (Fig. 1a), under RCP 4.5 observed higher yields (4345 - 5832 kg ha^{-1}) for sowing window *i.e.* end May to end June and under RCP 6.0, higher yields (4313 - 6074 kg ha^{-1}) for sowing window *i.e.* mid May to end June were observed during near future from the baseline (4246 kg ha^{-1}). Similarly, for far future, the observed yields were higher (4283 - 4483 kg ha^{-1}) for mid June under RCPs 4.5 and 6.0 from the baseline (4246 kg ha^{-1}). The cv. PMH2 (Fig. 1b), under RCP 4.5 observed higher yields (5793 and 6032 kg ha^{-1}) for mid June under RCPs 4.5 and 6.0, respectively from the baseline (5584 kg ha^{-1}) during near future only. The reported LAI changes from the baseline observed an increasing LAI deviation (-0.1 to 0.3) pattern till mid June for both maize cultivars and scenarios during near and far future (Fig. 6a).

A significant yield increment from baseline could be observed in both the maize cultivars during near future scenario for sowing window *i.e.* mid May to end June.

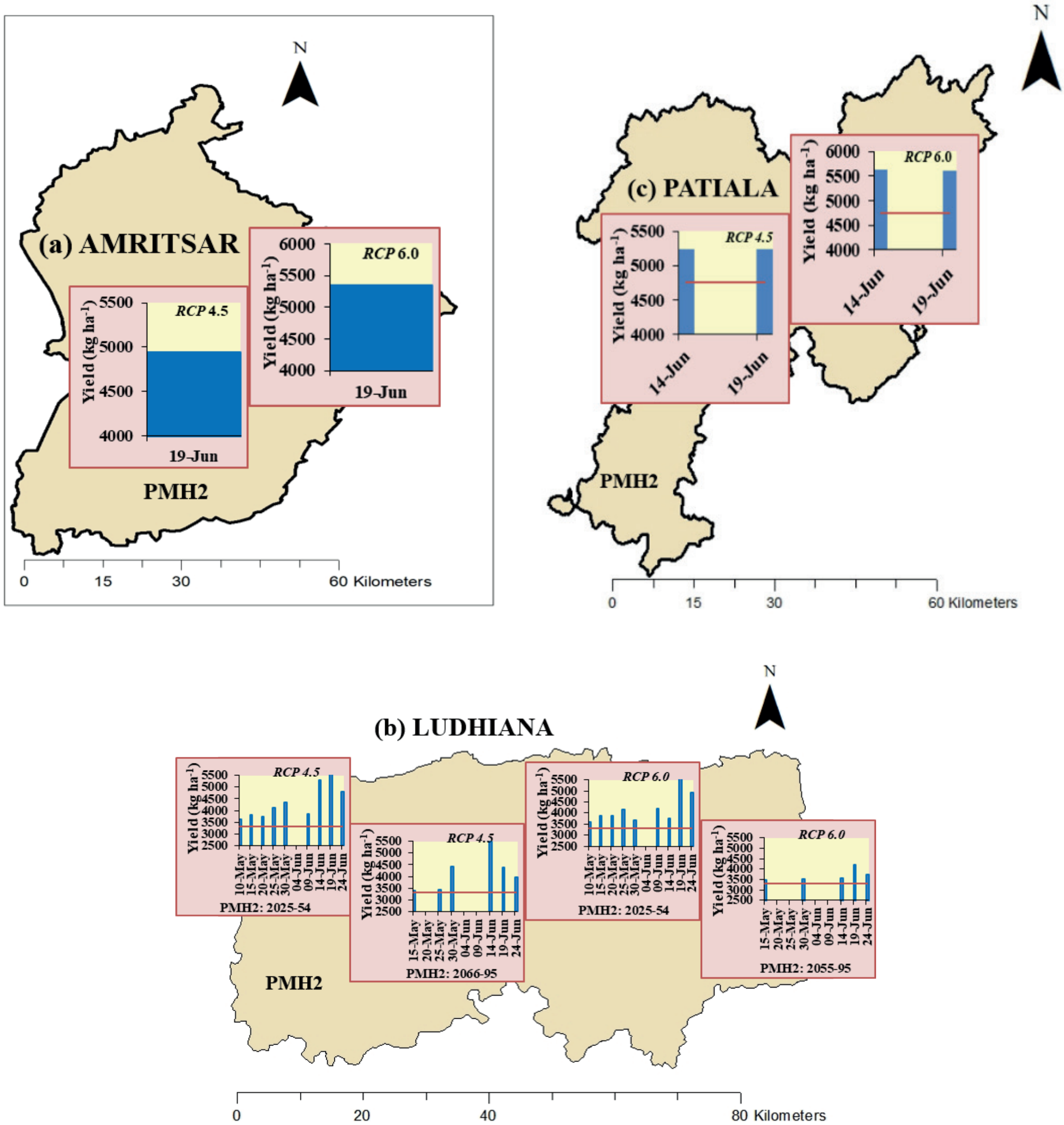

Fig. 3 (a-c): Adaptive sowing date option for maize cultivar PMH2 under the two scenarios in agroclimatic zone III: (a) Amritsar (b) Ludhiana and (c) Patiala

However, cv. PMH2 observed no significant yield increment during far future. Thus, cv. PMH1 may perform better in the region during mid May to end June for near future and during mid June for far future under future scenarios.

Agroclimatic zone III (Amritsar, Ludhiana and Patiala)

The cv. PMH1, under RCP 4.5 observed no yield improvement, yield improvement (4183 - 5830 kg ha^{-1}) for early May to end June (Fig. 2b) from baseline (3012 kg ha^{-1}) and yield improvement (5384 - 6156 kg ha^{-1}), for early to end June (Fig. 2c) from the baseline (5169 kg ha^{-1}), respectively at Amritsar, Ludhiana and Patiala during near future. Similarly, for far future, the observed yields were lower, higher (3302 - 5860 kg ha^{-1}) for early May to end June (Fig. 2b) from baseline (3012 kg ha^{-1}) and higher (4283 - 4483 kg ha^{-1}) for sowing window *i.e.* early to mid June (Fig. 3c) from the baseline (5169 kg ha^{-1}), respectively at Amritsar, Ludhiana and Patiala. The cv. PMH1, under RCP 6.0 observed yield improvement (5607 and 5563 kg ha^{-1}) for mid June (Fig. 2a)

Fig. 4: Adaptive sowing date option for maize cultivar PMH1 under the two scenarios in agroclimatic zone IV: Bathinda

from baseline (5250 kg ha^{-1}), yield improvement (3557-4461 kg ha^{-1}) for early May to end June (Fig. 2b) from baseline (3012 kg ha^{-1}) and yield improvement (5179-5857 kg ha^{-1}) for early to end June (Fig. 2c) from baseline (5169 kg ha^{-1}), respectively at Amritsar, Ludhiana and Patiala during near future. Similarly, for far future, the observed yields were lower, higher (3154 - 4316 kg ha^{-1}) for early May to end June (Fig. 2b) from baseline (3012 kg ha^{-1}) and higher (4283 - 4483 kg ha^{-1}) for early to mid June (Fig. 2c), respectively at Amritsar, Ludhiana and Patiala. The cv. PMH2, under RCP 4.5 observed yield improvement (4940 kg ha^{-1}) for mid June (Fig. 3a) from baseline (4861 kg ha^{-1}), yield improvement (3615 - 5751 kg ha^{-1}) for early May to end June (Fig. 3b) from baseline (3313 kg ha^{-1}) and yield improvement (5232 kg ha^{-1}), for mid June (Fig. 3c) from the baseline (4748 kg ha^{-1}), respectively at Amritsar, Ludhiana and Patiala during near future. Similarly, for far future, the observed yields were lower, higher (3385 - 5476 kg ha^{-1}) for mid May to end June (Fig. 3b) from baseline (3313 kg ha^{-1}) and lower, respectively at Amritsar, Ludhiana and Patiala. The cv. PMH2, under RCP 6.0 observed yield improvement (5348 kg ha^{-1}) for mid June (Fig. 3a) from baseline (4861 kg ha^{-1}), yield improvement (3593 - 5832 kg ha^{-1}) for early May to end June (Fig. 3b) from baseline (3313 kg ha^{-1}) and yield improvement (5605 - 5629 kg ha^{-1}) for mid June (Fig. 3c) from baseline (4748 kg ha^{-1}), respectively at Amritsar, Ludhiana and Patiala during near future. Similarly, for far future, the observed yields were lower, higher (3485 - 4227 kg ha^{-1}) for mid May to end June (Fig. 3b) from baseline (3313 kg ha^{-1}) and lower, respectively at Amritsar, Ludhiana and Patiala. The reported LAI changes from the baseline observed an increasing LAI deviation pattern of (- 0.5 to 0.5), (0 to 0.9) and (- 0.5 to 0.6) till end June, respectively in Amritsar (Fig. 6b), Ludhiana (Fig. 7c) and Patiala (Fig. 6d) for both maize cultivars and scenarios during near and far future.

A significant yield increment from baseline could be observed in Amritsar for mid June sowing date in cv. PMH1 during near future under RCP6.0 and under both the scenarios for PMH2. A significant yield increment from baseline could be observed in Ludhiana for early May to end June sowing date for both the cultivars and scenarios during near and future time period. Similarly, significant yield increment from baseline could be observed in Patiala during near and far future, respectively from early to end June and early to mid June for cv. PMH1 and respectively from mid June and mid May to end June for cv. PMH2 under both the scenarios.

Agroclimatic zone IV (Bathinda)

The cultivars PMH1 and PMH2 (Fig. 4) observed no yield improvement with significant decline in yields for all the sowing dates under both the scenarios during near as well as far future time periods. The reported LAI changes from the baseline observed an increasing LAI deviation (- 0.4 to 0.4) pattern till mid June (Fig. 6e) for both maize cultivars and scenarios during near and far future.

A significant yield decline was observed for both the maize cultivars in agroclimatic zone IV, thus Bathinda

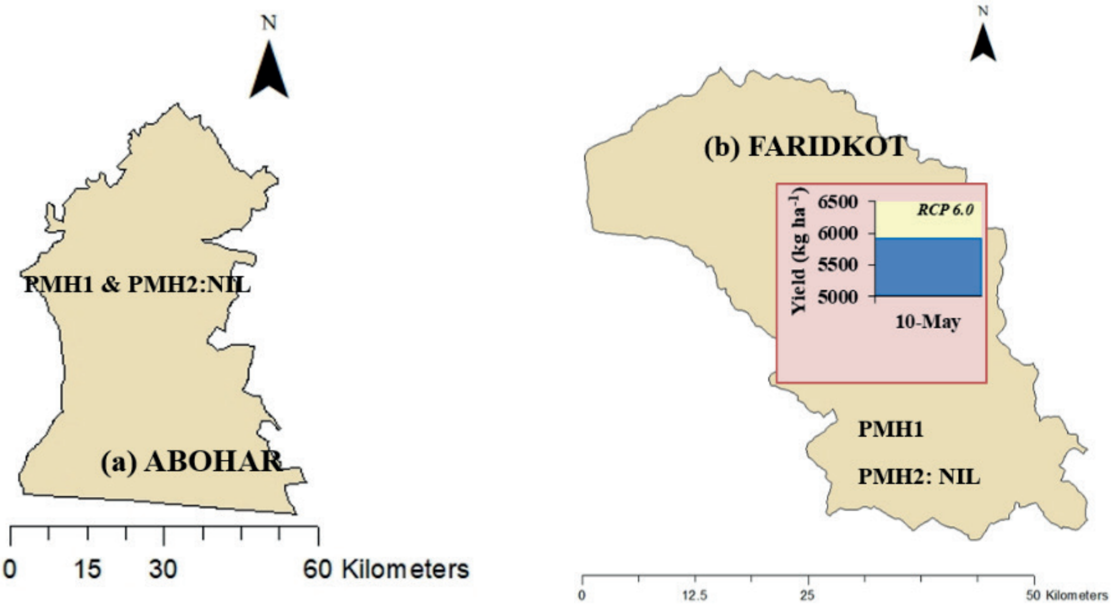

Fig. 5 (a-b): Adaptive sowing date option for maize cultivar PMH1 under the two scenarios in agroclimatic zone V: (a) Abohar and (b) Faridkot

might not be a suitable location for maize cultivation in Punjab

Agroclimatic zone IV (Abohar and Faridkot)

The cultivars PMH1 and PMH2 in Abohar (Fig. 5a) observed no yield improvement with significant decline in yields for all the sowing dates under both the scenarios during near as well as far future time periods. The reported LAI changes from the baseline observed an increasing LAI deviation (- 0.2 to 0.4) pattern till mid June (Fig. 6f) for both maize cultivars and scenarios during near and far future. At Faridkot, the cv. PMH1 observed yield increment (5920 kg ha^{-1}) from the baseline (5698 kg ha^{-1}) for early May sowing date under RCP6.0 (Fig. 5b) during near future period only. The cv. PMH2 observed no yield improvement and significant decline in yields for all the sowing dates under both the scenarios during near as well as far future time periods. The reported LAI changes from the baseline observed an increasing LAI deviation of -1.2 to 0.3 pattern for cv. PMH1 (Fig.6g) and -1.7 to 0.4 for cv. PMH2 (Fig.7g) till mid June under both the scenarios and time periods.

A significant yield decline was observed for both the maize cultivars in agroclimatic zone V with a slight increase for PMH1 under RCP6.0 for early May sowing date during near future. Thus, agroclimatic zone V

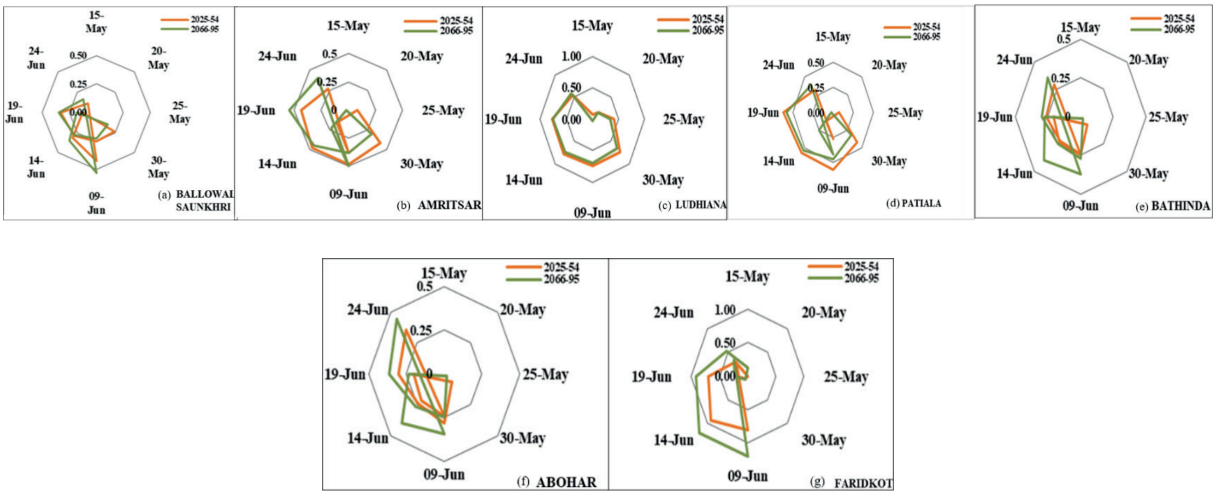

Fig. 6 (a-g): LAI relation under different adaptive sowing days for maize cultivars under the two Scenarios

comprising of Abohar and Faridkot might not be suitable for maize cultivation in Punjab.

Discussions

Role of models in climate change studies

Global Circulation Models (GCMs) are widely used models for the future predictions. GCMs have been continuously utilized in studying the climate change impact in various countries. The data for the four emission scenarios *i.e.* RCPs 2.6, 4.5, 6.0 and 8.5 are easily available on the MarkSim weather generator. The ensemble mean of the bias corrected temperature and rainfall data projected for the future time period was generated from the selected GCMs (CSIRO-Mk 3.6.0, FIO-ESM, GISS-E2R, IPSL-CM5A-MR). The weather data was downscaled and bias corrected (Kaur, 2020) for the selected GCMs and the ensemble mean of the four selected GCMs was used as an input weather file in the crop simulation models for studying the crop yield trends and quantification of the amount of impact caused due to the variable radiative forcings. Kaur *et al.* (2020) assessed the biasness in the weather data for seven districts of Punjab covering different agroclimatic zones using seventeen GCMs available on the website gisweb.ciat.cgiar.org/MarkSimGCM/. The assessed data showed overestimation of the annual average maximum temperature ranging between 1.76 - 2.73°C, the minimum temperature was underestimated/overestimated in the range 17.71 - 18.20°C/18.29 - 18.49°C, the annual average rainfall was overestimated within the range 635 - 997 mm and the annual average solar radiation was overestimated within the range 17.29 - 18.45 Wm^{-2}. After validation of the seventeen GCMs, satisfactory and significantly accurate results were obtained for five GCMs *i.e.* CSIRO - Mk3 - 6 - 0, FIO-ESM, GISS - E2R, IPSL - CM5A-MR and Ensemble of the seventeen GCMs. Due to errors and overestimation/underestimation of data, bias correction is very important before implementation of the GCM data in climate change studies. Kaur & Prabhjyot-Kaur (2022) used difference method to analyse the maximum temperature and rainfall at a monthly scale, on a daily time scale for solar radiation and no bias removal for minimum temperature. After bias removal on monthly time scale, the projected maximum temperature for the selected GCMs varied between 29.8°C - 30.3°C in comparison to the actual observed data (30.3°C); the projected rainfall data on the daily time scale varied between 468.1 - 557.9 mm in comparison to the actual rainfall (546 mm); the projected solar radiation varied between 15.1 - 15.2 Wm^{-2} from the actual solar radiation (15.3 $W\ m^{-2}$) and the minimum temperature varied between 17.8-18.0°C in comparison to the actual observed minimum temperature (18.3°C). (Kaur *et al.*, 2024) in another study reported the appropriateness of using the weather data obtained after bias correction from the GCMs in crop simulation model studies and their aptness in true future projections. The study compared the simulated weather data (temperature and rainfall) of four GCMs *i.e.* CSIRO - Mk3 - 6 - 0, FIO-ESM, GISS - E2-R and IPSL-CM5A - MR for a 70 - year time period with the observed data collected for a period of five years (2017 – 2021). The comparison was done for the two stabilization scenarios (RCP 4.5 and 6.0) at ACZI (Gurdaspur), ACZII (Ballowal Saunkhri), ACZIII (Ludhiana), ACZIV (Bathinda) and ACZV (Faridkot). Overestimation as well as underestimation was observed in the GCM simulated temperature and rainfall data on monthly, annual and seasonal time scale. Monthly variations in weather parameter dominated over the annual variations. Thus, GCMs have always been used as a prominent tool in climate change studies which requires to consider all minute uncertainties and variabilities to reduce the internal as well as inter model variability in the projected data values. Thus, the bias corrected data from the selected GCMs was used for the further analysis of maize yield projections and its optimization under future scenarios. Yaghoobzadeh (2022) assessed the climate change impact for sustainability of water resource management and national food security. The historical data available from the GCM for the Iranian stations was examined. The modeling of the historical period using models of the fifth climate change report showed that the longer annual time periods were most suitable for hydrological modeling. The rainfall estimates showed larger variations under RCP8.5 than the RCP4.5 scenario. On model comparison the GISS - E2-R model was found to lowly bias with application for rainfall estimation. Previously, the crop simulation studies under RCP scenarios were performed using the ensemble of the seventeen available GCMs in the MarkSim generator (Kothiyal *et al.*, 2023, Kothiyal *et al.*, 2023a, Kothiyal *et al.*, 2023b) while study on the ensemble mean of the selected GCMs (Kaur, 2020) remained untouched. The research highlights on the minute differences that might be noticed while studying the impact on crop yield from ensemble mean of different GCMs.

Crop simulation studies play a very important role when creating ideal conditions for the crop cultivated in the region. DSSAT and Agricultural Production Systems Simulator (APSIM) model are globally and widely applicable (Kogo *et al.*, 2019) for various crop and its management studies. However, DSSAT being an easy CSM tool has large applicability in climate change studies. Thus CERES-Maize model, a part of DSSAT was used to study the maize yield pattern of two cultivars under the current farming conditions and their adjustments under the future emission scenarios. Kothiyal *et al.*, (2022) sensitized CERES-Maize model using sensitivity index for maize hybrids PMH1 and PMH2. The calibrated and validated results proved the truthfulness and usefulness of the model with the required statistical indices. The statistical indices obtained for the anthesis, maturity, yield and LAI indicated the model to be suitable for its further applications. The normalized root mean square error was excellent for all the parameters except LAI where it was good. Thus, the results indicated that the model is suitable for further application in studying the climate change impact in the region. A study by Kothiyal *et al.* (2023a) concluded from the study that a linear decline in the crop yield was observed which requires proper farming adjustments for improved crop yield under the future scenarios. Thus, the individual analysis of different models showed that the second fortnight of June might be an adjusted sowing date for better yields but a single model does not provide reliable results. Thus, CERES-Maize model used an ensemble of the seventeen GCM data for its efficient employment in analysis of shift in sowing date under the extreme scenarios (RCP2.6 and RCP8.5). Nelson *et al.*, (2014) applied biophysical shocks using an end-century radiative forcing of 8.5 W/m^2 and this combined with negligent increase in carbon dioxide fertilization led to 17% global reduction by 2050 in comparison to a scenario under unchanging climatic conditions. The variable response to climate change is mostly observed due to increase in the agricultural production and its area, trade and prices with consumption having the lowest response to such changes. All these differences in the results depend on the type of model being used to study these characteristics. Thus, selection of model or models and structuring them with the appropriate data inputs is important for accurate and reliable climate change studies.

The uncertainties in the model results depend on the selection of the right crop simulation model and GCM. Scientists (Araya *et al.*, 2015) have reported that the climate change impact studies were strongly influenced by the selected GCM and crop weather models rather than the selection of an RCP. The study has been performed to analyse the maize yield trends and their optimization practices under different emission scenarios using the bias corrected GCMs found to be quite close and relative to the conditions of the state

Climate change in Punjab, India

Navin Singh Khakde (2021) reported India to be the largest carbon emitter after China and USA in the world and as this continues India would not be able to keep its Paris agreement where it pledged to reduce the carbon footprint since 2005 by 33-35% till 2030. As per the climate goal decided in Paris, the global average temperatures are required to be maintained below 2°C in order to avoid irreversible losses to climate system. A study by (Kaur & Prabhjyot-Kaur, 2016) on special report on emission scenarios (SRES) observed a linear increase in maximum-minimum temperature and rainfall under the A1B scenario during the mid century while during end century for B2 scenario, the maximum-minimum temperature would continue to increase at a slower rate than the A1B and A2 scenario and rainfall deficit by 78 and 30% would be experienced during the winter season under the A2 and B2 scenarios.

Kaur & Prabhjyot - Kaur (2022) reported the higher and lower limit for the different meteorological parameters as projected by the selected GCMs under the four emission scenarios at different locations. The highest and lowest limit, respectively for the projected weather data by the selected GCMs were 32.9°C (Bathinda) and 30.5°C (Ludhiana) for maximum temperature; at 20.8°C (Patiala) and 17.9°C (Amritsar) for minimum temperature; at 15.9 W/m^2(Bathinda) and 14.9 W/m^2 (Amritsar) for solar radiation and at 659 mm (Amritsar) and 346 mm (Abohar) for rainfall.

The future climate change can be easily quantified by the representative concentration pathway (RCP) defined by intergovernmental panel on climate change (IPCC) where they represent the radiative forcings which would impact the temperatures and precipitation patterns. A study by Kaur *et al.* (2022) analysed the past and future climate scenarios while considering the greenhouse gases and aerosols. They assessed the monthly temperature and rainfall patterns using the downscaled data from four selected GCMs *viz.* CSIRO -Mk3 - 6 – 0, FIO-ESM, GISS-E2-R, and IPSL-CM5A-MR under four RCPs (RCPs 2.6, 4.5, 6.0 and 8.5). The projected changes during spring and autumn season, respectively showed an increase by 2.1°C and 1.8°C for maximum temperature, by 3.2°C and 3.3°C for minimum temperature while the rainfall showed high variability pattern in Punjab. This projected rise during the February month would lead to terminal heat stress in wheat leading to reduced productivity. As per the study by Hari (2018) an increase has been predicted in the precipitation and temperature under the future scenarios due to which the summers would be warmer and drier with increased precipitation during winter months. Thus, the overall quantification of precipitation indicates normal rainfall but the distribution is focussed on few months or days. Such precipitation pattern may cause pressure on the water resources supplying irrigation during summer season and wetter situations during winter season for the crops. The temperature increase impacts the potential evapotranspiration demand which further impacts the physiological factors like soil moisture, thus affecting the water demands of the agricultural sector to overcome the yield losses. Due to these negative impacts, the groundwater recharge is heavily disrupted thus affecting the agricultural sector and population of the region.

Prabhjyot-Kaur *et al.* (2023) reported for the maize cultivation period in Punjab that the projected temperature and rainfall pattern under the stabilization scenarios would observe significant variations from the baseline. The maximum/minimum temperature would observe an increase from the baseline (35.2°C/25.7°C) under the stabilization scenario by 0.7 - 1.0°C/2.4 - 2.6°C; 1.2 - 1.5°C /3.0 - 3.2°C; 1.7 - 1.8°C/3.5 - 3.6°C during early, mid and late century, respectively while the rainfall was projected to decline from the baseline (524 mm) by 157 - 166 mm; 111 - 123 mm; 68 - 103 mm during respective periods. These projections for the maize cultivation period are expected to impact the maize yield and its growth parameters, thus, the study uses the information available under the stabilization scenarios for yield and maize growth analysis under current farming practices as well as under the optimized farming practices.

Response of agricultural crops to climate change

As per a report by Down to Earth (2023), the increasing maximum and minimum temperature are expected to have a positive but weak effect on the maize and paddy yields but this non-significant impact is weakened due to the over exploitation of groundwater resources. Climate vulnerability add on to the many conventional problems occurring in a developing country like India where climate problems make the livelihood of the people more susceptible. Rama Rao *et al.* (2022) studied the yield impacts due to changing temperatures during the end-century and it was observed that these impacts were higher in maize crop where yields could be lower by 6% against the baseline *i.e.* 113 kg/ha while this yield reduction was lower for sorghum, chickpea and pearl millet *i.e.* 0.2 to 3.6% with respect to the baseline during mid-century. However, soybean and groundnut yield, respectively might increase by 11.2% and 14.8%. The yields have been predicted to decrease by 23.7%, 21.1%, 33.7%, 11.4% and 30.5%, respectively under steep increase in temperatures while groundnut and pigeon pea would observe an increase under climate change scenarios. The future yields would be higher than the current yields keeping in view the technological advancements. Now, future trends might remain the same depends on the technological development and transfer taking place under the climate change scenarios. Kumar *et al.* (2023) reported variable crop response to climate change across the *Kharif* and rabi season where amongst the *Kharif* crops, maize being the most responsive to temperature and rainfall changes would observe yield decline by 13% followed by cotton (11%) and rice (1%). With the increasing climatic changes these impacts would be large and the yield losses would increase by 24% for maize and cotton and 2% for rice crop. The wheat and potato crop would respond the same *i.e.* 5% each by the year 2050 which would further increase by 1% till 2080. Thus, with increasing temperatures and rainfall variations, the yield losses would observe a steeper yield decline.

In northern state (Punjab), Hundal and Kaur (2007) observed that deviation of maximum temperature on the higher side by 1 - 3°C from the normal would cause productivity decline by 10% and 3%, respectively for wheat and rice while in southern state (Tamil Nadu), Geethalakshmi *et al.* (2011) observed a decline upto 41% due to an increase in temperature by 4°C. A similar study on Jowar crop in Karnataka by Kaul and Ram (2009) reported that extreme variation in rain and temperature would impact its productivity adversely while in Kerala a 5°C increase in temperature would lead to continuous decline in rice yield upto 6% (Saseendran *et al*., 2000). A study by Naresh Kumar *et al.* (2011) in northeastern and coastal regions of India reported irrigated area decline for maize, wheat and mustard and for rice, sorghum and maize in western ghats under climate change. Kumar & Sidana, (2017) reported climate change fluctuations in Punjab where the rice and wheat yields are reducing since some decade, consequently leading to threaten our food security. During the rice-period an increase by 0.92°C and 0.06°C during wheat period was observed from the mean temperatures for the respective crop growing period indicating hot summer while rainfall shows a decreasing trend in all the agroclimatic zones of Punjab for 30 years of 208 mm during *Kharif* and 20 mm during rabi season. The simulated yield indicated a decrease in the rice yield by 1.20% with 1°C rise in minimum temperature and a decrease in wheat yield by 1.08% with a 1°C rise in maximum temperature. With significant climate change, the rice and wheat yield, respectively are expected to fall around 8.10% and 6.51%.

Yila *et al.* (2023) studied the variability in the meteorological data in Moyamba District, Southern Sierra Leone on the perception basis of farmers and Agricultural Extension Workers (AEWs). They perceived a decline in the annual rainfall amount, length of the rainy season, onset and withdrawal of the rainy season, increasing day and night temperatures and declining harmattan period since last 30 years. These observed rainfall and temperature variations as perceived by the farmers and AEWs agree with the scientifically analysed meteorological data. Majority farmers perceived negative impact on crop production and substantial losses in crops were caused due to extreme events like drought, high temperature, irregular rainfall pattern. The farmers and the AEWs may respond to the adverse weather events with the implementation of the climate-sensitive agricultural practices (CSA) as per their technical knowledge and financial status. Thus, there is a requirement to build the capacity of farmers and AEWs for adaptation and mitigation of negative climate change impacts. According to USGCRP report (2014), high nighttime temperatures negatively influenced the corn yields and warmer winters caused losses of 220 million dollars due to premature budding in Michigan cherries. The warmer temperatures and wet climate in combination with high carbon dioxide levels help thrive weeds, pests, diseases and fungi. U.S. farmers are spending heavy amounts on fighting weeds, competing with the crops for light, water and nutrients which are expected to increase in their range and distribution under climate change. The increasing range and distribution would expose farmers to new problems where they have to combat these new species. Rahman & Lateh (2017) reported an increase in the total annual rainfall during the monsoon season without any change during the dry winter season. In dry regions, the maximum and minimum temperature, respectively observed significant rise by 0.07 and 0.21°C in comparison to the other regions. The correlation between climate variation and rice productivity was studied using different indices where the Standard Precipitation Index (SPI) and Diurnal Temperature Range (DTR) was used to capture the ecosystem variability during the aman rice season with significant accuracy in coastal, terrace and dry regions at 49,45 and 41%, respectively. The SPI and DTR did not had a significant impact during the aus and boro rice season. Such local analysis would help as a tool in the interest of farming community when planning and training on the climate change adaptation strategies.

A review by (Dhillon & Sohu, 2024) reported that the unseasonal rainfall in combination with the temperature spikes during the rabi season of 2021-2022 in Punjab led to wheat yield and grain quality reductions by 651 kg/ha (Punjab) and 301 kg/ha (Haryana) when compared with the yield of 2020 - 2021. During the *Kharif* season of 2022, a new virus *i.e.* SRBSDV (Southern Rice Black-Streaked Dwarf Virus) was observed in the rice crop of Punjab and Haryana. Again, the adverse weather conditions occurring during 2022-2023 caused wheat yield reductions by 143 - 150 kg/ha in the above states. At national level too, during 2021-2022 (rabi season) and 2022 (*Kharif* season), wheat and rice observed losses of 3 mt each leading to food insecurity in the country. An article by Fateh Veer Singh Guram (2022) reported that with increase in temperatures, the food crop yields and cash crop yields would decline in South Asia causing food security issues in the region. The scientific researchers have projected decline in wheat and rice yield, respectively by 41 - 52% and 32 - 40% under the predicted temperature rise by 2.5-4.9°C. Mohapatra *et al.* (2024) used the Just-Pope approach to analyse the impact of weather variables on seasonal basis and extremes on average yield and variable crop yield for rice, chickpea, groundnut, bajra and sugarcane in India during 1990 - 2015. The results indicated that rainfall and evapotranspiration vary seasonally affecting the mean yields for most of the crops *i.e.* bajra, chickpea and groundnut while high summer rainfall with low evapotranspiration during monsoon causes a reduction in the variability of groundnut and chickpea yield. Thus, improvement in irrigation and water reallocation and management would help reduce the severe climate impacts on seasonal basis.

Climate Change impact on maize crop

Fateh Veer Singh Guram (2022) reported that Mr. Arun Joshi, a representative of Asia at International Maize and Wheat Improvement Center (CIMMYT) described the ultimate impact of climate change which is not only expected to push the temperatures on the higher side but also reduce the water availability due to lower rainfall amount and higher extreme rainfall events. These changes would impact the maize crop yield which is quite sensitive to the changing temperatures and rainfall thus may lead to yield decline in maize crop by 24%. Srivastava *et al.* (2021) evaluated the climate change impact on maize yield and its attributes using CERES-Maize model for the projected time period *i.e.* 2021-2050 and 2051 - 2080 using RCPs 2.6, 4.5, 6.0 and 8.5 W/m^2, for eastern part of India. The yield decline recorded under different RCPs, respectively when compared with the baseline values for the time period 1982-2012 recorded decline in yield by 10.58%, 14.80%, 21.02% and 23.39% for 2021-2050 and by 15.20%, 18.54%, 24.75% and 26.83% for 2051 - 2080 under irrigated conditions while under rainfed condition the recorded increase was higher, respectively by 10.55%, 9.20%, 8.13%, and 7.47% during 2021-2050 and by 10.63%, 6.65%, 7.47%, and 4.31% during 2051 - 2080. Thus, the results clearly indicate the rainfed conditions could help reduce the negative impact of temperatures on the maize yield.

Bias-corrected ensemble model data from the ensemble of seventeen GCMs was used by Kothiyal *et al.* (2023) to simulate the maize yield under RCP4.5 and RCP6.0 in different agroclimatic zones of Punjab for a period of 70 years (2025 - 2095) and it was observed that the maize yield reduced from the higher yield category (>5000 kg/ha) to lower yield category (<3000 kg/ha) under a temperature rise by 1°C in agroclimatic zones II, III and V (Faridkot). The PMH1 cultivar was able to compensate the high temperature impact and was able to perform well at the above zones. However, at agroclimatic zone IV and V (Abohar), an increase in temperature by 2°C led to declination in the yield categories from medium to low yield years. The rainfall amount in the region was insufficient in mitigating the temperature affect. The study helped in determining the suitable sowing window for maize crop in the region which could be further analysed using different GCMs for future periods under different scenarios. Kothiyal *et al.* (2022) reported using linear regression model, the decline in the maize yield under emission scenarios in Ludhiana district of Punjab and the projections indicated that large yield decline would be observed under high emission scenario (RCP8.5) and meagre yield decline under low emission scenario (RCP2.6). Though the results under the current sowing dates of maize showed that second fortnight of June could be estimated as a suitable sowing date under changing weather conditions but further analysis on suitable optimized sowing window is required in the region. Kothiyal *et al.* (2023c) used the current sowing window *i.e.* end May to end June in Punjab to simulate the temperature and rainfall impact on maize yield during near and far future under RCP2.6 and RCP8.5. Under all the scenarios during near and far future, respectively maize yield decline by 4 – 23% and 60 – 80% at AZ II, 5 – 60% and 60 – 90% at AZ III, 9 – 30% and 50 – 90% at AZ IV, 0 – 40% and 5 – 90% at AZ V at AZ V was observed. Thus, the declines in yield clearly show the requirement of suitable optimization practices for improved yields under future scenarios. A study by Kothiyal *et al.* (2023a) was performed on the yield trends under four GCM models *i.e.* (CSIRO - Mk-3-6-0, FIO-ESM, IPSL-CM5A-MR and Ensemble) and sowing date adjustments. The results showed that under RCP8.5, the projected high temperatures led to a linear decline ranging 5 - 90% and under RCP2.6 ranging 4 - 60% over the considered time period.

Keeping in view the above results obtained in the study area, an ensemble mean of four selected GCMs (Table 1) for the region predicted a yield decline by 12 - 40%, 9 - 43%, 7 - 57%, 1 - 95%, respectively at ACZII, ACZIII, ACZIV and ACZV during near and far future time period. However, the study also reported that mid and end June observed slight yield increase under the current farming practices for the future time period. This expected slight increase in the yield during a particular sowing date may be used for a further detailed study of the optimized sowing dates under the stabilization scenarios.

Shiferaw *et al.* (2024) assessed the climate change impacts under RCPs 4.5 and 8.5 during 2050s in comparison to the baseline period of 1971 - 2005 and the results showed that the annual mean minimum temperature would observe an increase by 1.9-2.3°C and maximum temperature by 1.4 - 3.0°C while the projected rainfall would observe an annual increase during the autumn and summer season for 2050s as 3.7-16.8% and 8.7-12.2%, respectively under RCP4.5 and RCP8.5 in Woybo catchment of Ethiopia. Thus, these increasing temperatures and reduced rainfall would increase the annual mean potential evapotranspiration (PET) by 0.1-6.8%, Crop Water Requirement (CWR) by 6.2 - 17.2% and Irrigation Water Requirements (IWR) by 4.6 - 16.4%. The future projections clearly depict and increase in the PET and IWR of maize crops when compared with the baseline period.

The future climate studies are very important for an agricultural state like India, thus such studies can further be explored for adjustment in the farming practices and studying the climate change impact on the other growth parameters of the crops. Maize crop is a major cereal crop of India and known to be a sensitive crop towards climate change. The current study reported slight significant deviations in the LAI pattern from the baseline varying 0 to 1 with the larger variations in ACZV of -1 to 1. LAI variations have been reported by very few studies particularly for crops.

Adaptation strategies in mitigating climate change impact

Simulation studies that have been performed worldwide show that climate change causes adverse impact on the crop yields under no adaptation measures causing threat to national food security (Aggarwal *et al*. 2022). The yields have been projected to decline by 4%, 3 - 18% and 3 - 38%, respectively in rice, maize and pigeon pea which depends on the location, variety and emission scenario considered while evaluating the yield losses. However, some model studies show significant results under optimized farming practices which could help in protecting or sometimes increasing the crop yields. Crop models have been regularly used to study the possible climate change impacts caused under increasing temperatures, reducing rainfall and rising carbon dioxide levels, etc. Application of crop models help in resource optimization and opting for robust and sustainable farming practices to maintain sustainable agricultural productivity. Though models consist of limitations and uncertainties but a multi-model approach and high quality data supports in model improvement at an acceptable level. Srivastava *et al.* (2022) studied the adverse impact of climate change on crop production and adoption of appropriate practices which could help reduce the losses. Taking appropriate fertilization levels along with the sowing dates are economic and effective strategies which can be used to avoid climate change impact in different climatic regions. Varying sowing dates were used as a strategic adaptation method to cope with the climate change impact on maize yield in eastern India under rainfed and irrigated conditions. CERES-Maize model was used to evaluate the maize yield under different sowing dates for projected time periods 2050s and 2080s under RCPs 2.6, 4.5, 6.0 and 8.5 W/m^2 and the projected results were studied in comparison to the baseline (1982-2012). The results indicated that under rainfed conditions, the late sowing (30 June and 10 July) was found effective under RCPs 6.0 and 8.5 for 2050s and 2080s during tasseling stage in maize with a decline in the solar radiation intensity while higher temperature stress caused reduced grain yield for the recommended (20 June) and early sowing data (30 May and 10 June). The recommended sowing date (15 January) was appropriate for the 2050s under all the RCPs while the early sowing date (25 December) was suitable for the 2080s under RCP8.5. Under irrigated conditions, the recommended sowing date (15 January) was suitable for time slice 2050s in all the RCP scenarios, while the earlier sowing date (25 December) was found to be suitable in the time period of 2080s with RCP 8.5. Thus, optimizing sowing dates would prove to be an effective strategy for less wastage and efficient resource usage.

A review by Dhillon and Sohu (2024) reported global warming to be a large contributor in climate change where extreme events like increasing heatwave frequency, droughts, erratic rainfall, landslides, floods, etc. are occurring almost everywhere. The climate change events are continuously affecting the ecosystems and in spite of efforts involved in greenhouse gas mitigation, global temperatures have risen by 1.1°C above the pre-industrial period. The projections for the country clearly indicate that the adverse effects in the climate variable and developing country like India would intensify. Wide rainfall variability has been recorded in various parts of the country and an overall negative trend has been reported since the mid of 20th century. Rahman & Lateh (2017) reported an increase in the total annual rainfall during the monsoon season without any change during the dry winter season. In dry regions, the maximum and minimum temperature, respectively observed significant rise by 0.07 and 0.21°C in comparison to the other regions. The correlation between climate variation and rice productivity was studied using different indices where the Standard Precipitation Index (SPI) and Diurnal Temperature Range (DTR) was used to capture the ecosystem variability during the aman rice season with significant accuracy in coastal, terrace and dry regions at 49, 45 and 41%, respectively. The SPI and DTR did not had a significant impact during the aus and boro rice season. Such local analysis would help as a tool in the interest of farming community when planning and training on the climate change adaptation strategies. In rainfed rice production alleviation of climate change risk could be possible with the adjusted sowing/transplanting period. Cultivar selection and other mitigation strategies pertained to the type of crop, their regions and problems in order to effectively cope up with the impacts of climate change. Stress-tolerant rice varieties would be a boon for rainfed rice cultivation which is suffering due to the shifts in the monsoonal rainfall and increasing DTR. These varieties can bear high temperatures and has low water demand. A study by Bannayan *et al.* (2016) reported in Northeast Iran a decline in maize yield by 2.6 to 82% during 21st century at most of the study locations when compared with the baseline. A vulnerability index was used to determine climate change impact and what adaptation strategies would be an efficient tool in different considered areas. Different sowing dates were used as an adaptation method and these were experimented to indicate that delayed sowing would be advantageous in obtaining higher yield at all locations during the future period.

(Kothiyal *et al.* (2023a) studied the yield trends under four GCM models *i.e.* (CSIRO-Mk-3 - 6-0, FIO-ESM, IPSL-CM5A-MR and Ensemble of seventeen GCMs) and sowing date adjustments. The results showed that under RCP8.5, the projected high temperatures led to a linear decline ranging 5 - 90% and under RCP2.6 ranging 4 - 60% over the considered time period. Adoption of viable practice of shifting the sowing dates was able to nullify the impact of temperature and rainfall where the yield was predicted to increase during early June, mid to end June and early to end May at ACZII, ACZIII and ACZV (Faridkot) for PMH1and PMH2. Simulations for optimized sowing dates indicated ACZIV and ACZV (Abohar) unsuitable for maize cultivation. A similar study by (Kothiyal *et al.* (2023b) in Punjab with adjusted sowing dates integrated with the changes in the applied nitrogen concentration showed that the shifted sowing dates when combined with the nitrogen concentration of 145, 165 and 185 kg ha^{-1} gave improved yields during three time slices *i.e.* early century (2030-2050), mid century (2050-2070) and end century. The PMH1 cv. observed an increase in yield at ACZII, ACZIII and ACZIV (Faridkot), respectively by 11 - 38%, 7 - 35% and 32% under RCP 2.6; by 14 - 43%, 18 - 97% and 8 - 23% under stabilization scenarios (RCPs 4.5 and 6.0) and no increment under RCP8.5. The study indicated that maize sowing during second week of June in all the ACZs except Ludhiana (third week of June) and Faridkot (second week of May) coupled with nitrogen amount of 165 or 185 kg ha^{-1} was appropriative adaptive strategy for maize crop cultivation in Punjab. Thus, the studies were found useful in reducing the impact of climate change by altering the agricultural practices as per the climate change issue.

The current study reports that the ensemble mean of the selected four models was simulated to quantify the yield declines of maize cultivars under stabilization scenarios, thus modification of the sowing dates was used to indicate the yield and LAI performance under these scenarios. Both the maize cultivars performed well during near future in some agroclimatic zones while during far future PMH1 was found to be more sustainable under future scenarios. The cultivars performed well with higher yields during mid May to end June at ACZII, early May to end June at ACZIII and early May under RCP6.0 alone at ACZV (Faridkot). ACZIV and ACZV (Abohar) were found unsuitable for maize cultivation with non-significant yield increment. The current results when compared with previous reported studies clearly show similar results (Table 1) where mid June was observed to be the most preferred sowing date for ACZII and ACZIII while Early May for ACZV cultivation. However, the sowing dates vary or the results vary with the GCMs used in the study. Abohar and Faridkot lie in the same agroclimatic zone (ACZV) but the difference lies in the soils of the two locations as well as the rainfall amount. Abohar lies more towards the Rajasthan state of India due to which it experiences arid type of climate and the projected rainfall is in the range of 220 - 340 mm which is towards lower side. However, in case of Faridkot the projected rainfall is in the range of 250-500 mm. Thus, this might be the reason for the variable response of the locations to maize cultivation.

LAI under Climate Change

A sensitivity analysis of the CERES-Maize model was performed by Kothiyal *et al.*, (2022) for PMH1 and PMH2 in Punjab and as the statistical analysis gave reliable results, the model was used to simulate the optimum sowing window and LAI response for maize crop. The results showed that the cv. PMH1 grown between 20 May to 7 June simulated grain yield of 5200-6000 kg ha^{-1} with LAI lying between 2.9 - 3.2 while cv. PMH2 grown between the same sowing window simulated a varied yield between 4200 - 5400 kg ha^{-1} with LAI lying between 2.8 - 3.0. Similarly, when the simulated results of delayed sowing were observed, the grain yield reduced at the expense of profuse vegetative growth. Lazauskas *et al.* (2012) performed a simulation study for LAI using DSSAT model at the Institute of Agriculture, Lithuanian Research Centre for Agriculture and Forestry in Dotnuva, Kėdainiai, Lithuania and it showed that as per the previous climate change scenarios, major climate change impact could be observed on the LAI development in winter wheat when compared with increase in the air temperatures which would result in the shifting of the maximum LAI to earlier dates during spring season and leaf senescence during summer season. If on the daily basis, the weather is higher by 2°C than a shift was observed in the maximum LAI by 21 - 23 days with an equivalent precipitation amount and distribution. Ramezani *et al*. (2020) obtained monthly projections for different climate variables from an average of the 9 AOGCMs - AR5 during the future time period (2020-2039) and annual projections from 2004 - 2039 under the two extreme emission scenarios (RCP 2.6 and RCP8.5). These were utilized to understand the climate change impact on LAI. The results revealed an increase in the LAI with an increase in temperatures, precipitation and carbon dioxide levels which was observed to be higher under RCP 8.5 than RCP 2.6. Thus, the average LAI increase for the Kasilian catchment area was 3.1% and 2.2%, respectively under RCP 2.6 and RCP 8.5 during the future period with respect to the baseline (2004-2013). Thus, the results show a positive impact of projected rise in the temperature and rainfall.

Kim *et al.* (2017) and Krishnaswamy *et al.* (2014) reported that the LAI response is expected to vary with the atmospheric and climatic changes. A study in the Montana region of USA reported that in a forested region, an increase in the atmospheric parameters like the temperature, precipitation and carbon dioxide would lead to an increase in the LAI. However, a study in southeastern Australia by Tesemma *et al.* (2014) reported a decline in LAI of the crop, pasture and tree in future when the precipitation is expected to decline and temperatures would rise in the region. This clearly represents the varying nature of LAI from region to region and it is prominently influenced by the climatic factors as well. Therefore, studies on LAI response to changing climate in variable region is required to understand the vegetation growth response. Also, the study showed that the vegetative feedback was primarily sensitive to the temperature changes than the LAI so it was observed to be higher under RCP 8.5 than RCP 2.6. Tesemma *et al.* (2014) independently calibrated and validated the model in good agreement with the MODIS LAI data and the results for the application of the developed model showed that under future climate change scenarios, a consistent decrease in the mean annual LAI values would be seen in the crop by 10 - 38%, pasture by 5 - 24% and tree lands by 2 - 11% from the historical average values under all the scenarios (RCPs 2.6, 4.5, 6.0 and 8.5). The mean monthly LAI observed a decline from its historical mean monthly values by 5 - 14%, 3 - 9% and 1 - 4% in crop, pasture and tree, respectively for the lowest emission scenario (RCP2.6). The respective vegetation observed a decline by 12 - 45%, 5 - 32% and 2 - 16% under the highest emission scenario (RCP 8.5). In semiarid and arid regions the dynamic interaction of the climate and vegetation helps in water management. The study reported the crop LAI to be most sensitive, followed by tree LAI, followed by pasture LAI. Deng *et al.* (2024) observed LAI decrement by 0.4-16.9% and soil organic carbon (SOC) decline by 5.9-11.6% depending on the future period, land cover and the emission scenario. Bannayan *et al.* (2016) reported changing climate impact on maize production under future scenarios in north-eastern part of Iran where the phenological stages, maximum LAI and grain yield would decline under the future emission scenarios. A study on the maximum LAI variation from the baseline (3.46) under A2 and B1 scenario for medium nitrogen levels in southern Québec, Canada observed slight increasing pattern by 0.6 and 2.3, respectively (Joshi *et al.*, 2014).

The simulations for the LAI under current sowing time showed slight deviations varying between -1 to 1 from the baseline under the stabilization scenarios with maximum deviation for the far future while the LAI trend under optimized sowing dates showed an increasing trend. The increase in the LAI was very minor by -0.1 to 0.3, -0.5 to 0.9, -0.4 to 0.4 and -1.2 to 0.4, respectively at ACZII, ACZIII, ACZIV and ACZV. Though, few crop studies show the impact of future emission scenarios on LAI of the crop but as the impact varies from region to region and even vegetation to vegetation, it is difficult to fix on a particular LAI pattern under climate change impact. In maize crop too, not much studies have focussed on the simulated LAI pattern under changing climatic conditions. As the area remains unexplored such studies might add on and be used for derivation of further interpretations.

Varying rainfall and temperature patterns have been reported in different agroclimatic zones of Punjab which is commonly known as the granary of India. The projections reveal their adverse impact on the crop yields that may lead to food insecurity in the country. Thus, implementation of optimized farm management practices for crop production and adoption of mitigation practices can help manage the food losses in the country. These alternative management methods may include selection of suitable cultivar, crop diversification, suitable sowing dates, appropriate fertilizer and irrigation levels and other various climate-smart practices, amongst which cultivar selection and selection of suitable sowing date is the easiest and the most low-cost measure in combating climate change impacts. The climate change stress on the water resources has led to focus on the improvement of crop water use efficiency (WUE) for efficient resource utilization. For such improvement various potential methods have gained importance like sensor-based micro-irrigation/fertigation system, IoT based approaches to manage the amount of water application and other smart technologies like sensor-based application of pesticides, biofertilizers and bio-pesticides, etc. India with diversity has wide application and unexplored area in this field which can be achieved with stronger manpower, more resource efficient methods, infrastructure, expansion of international and national ties by linking the basic and applied researches, institutional and departmental collaborations can also help in developing and diffusing innovative technologies. Thus, all the efforts should focus on climate-resilient and resource efficient technologies and methods.

Limitations

Climate change studies using crop models and GCM data use ideal conditions so biasness and uncertainty remains a challenge. GCM evaluation has shown that bias correction and its accuracy needs to be determined before its further usage as input file in the crop simulation models. Without bias correction, the data results may not be accurate and reliable. In case of crop simulation models, nutrient, pests, weed stress and intercropping are not considered in their ideal conditions so it may result into less reliable results.

Conclusions

Punjab is known to be granary of India where major cereals stand at risk to the changing climatic conditions. The variations in the temperature and rainfall pattern along with the depleting water resources continue to remain a challenge for an important agricultural state. Amongst most of the cereal crops, maize remains a vulnerable crop to climate change. The present study has been conducted to understand the maize yield trends and its growth under the current and future sowing dates with constant farming practices. Punjab has diverse climatology so to cover the state its different agroclimatic zones have been selected covering seven major locations of the state. The variations have been evaluated under the stabilization scenarios (RCPs 4.5 and 6.0) during near (2025 - 2055) and far future (2066 - 2095). The study has also tried to report the inherent biasness and uncertainty in the GCM data. It has been able to distinguish between the previous and current study under different sowing conditions and usage of different GCM ensemble. An ensemble mean of temperature and rainfall data obtained from the four selected GCMs, downscaled and bias corrected for the seven locations was used as an input file to run the calibrated and validated CERES-Maize model to simulate yield and LAI pattern for near and far future under RCPs 4.5 and 6.0. The reported deviations in the meteorological parameters during the maize cultivation period under stabilization scenarios varied by an increase from the respective baseline (35.2, 25.7 and 524 mm) by 1 - 2°C for maximum, 2 - 4°C for minimum and 68 - 166 mm for the rainfall. These projected temperature and rainfall variations caused yield declines varying between 10 - 90% with maximum decline in the ACZIV and ACZV where the expected temperature rise is more than the decrease in rainfall. Maize is a sturdy crop with comparatively less water demand but high sensitivity to fluctuating temperatures. At ACZV, the temperatures are expected to increase by 2 - 3°C which could lead to yield losses in the considered locations with slight LAI deviations from the baseline between -1 to 1. Keeping in view the results, the current sowing dates were modified to adjust them with the changing temperatures and rainfall patterns and it was found that the cv. PMH1 performed well in both near and far future period. The cultivars showed yield increase during mid May to end June at ACZII, early May to end June at ACZIII and early May under RCP6.0 at ACZV (Faridkot) with increasing trend in the LAI at different agroclimatic zones. Thus, the climate change impact study holds importance for Punjab state and for policy making. These optimized practices can be used for recommendation purpose in the state and further it can be used for application purpose in further climate change studies.

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Conflict of Interest

The authors declare no conflict of interest.

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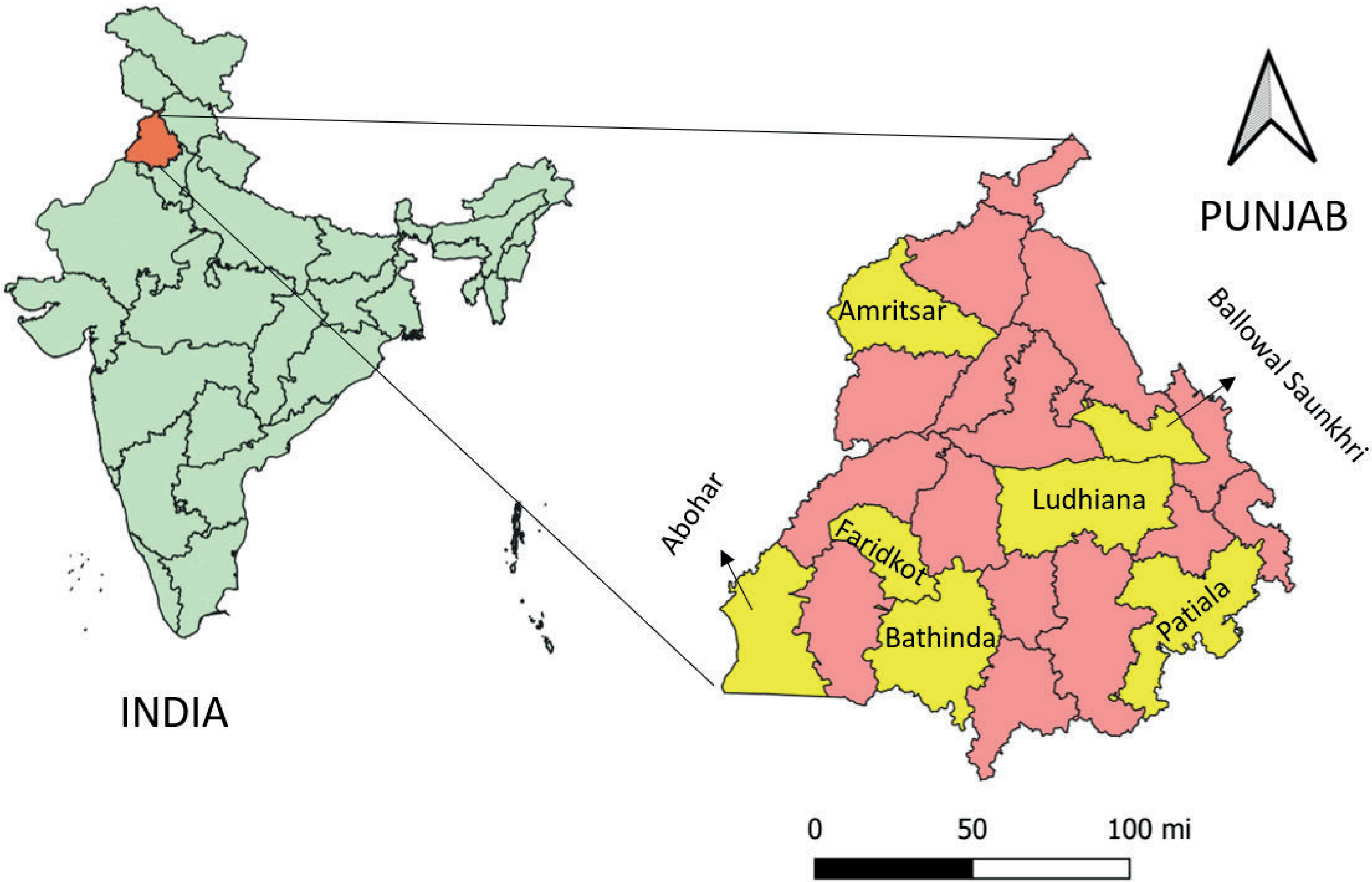

Fig. 1 - The selected locations under different agroclimatic zones of Punjab, India

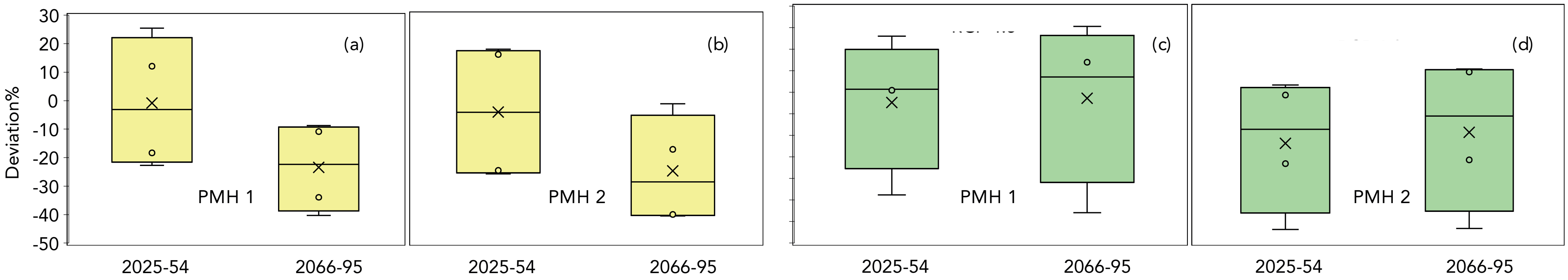

Fig. 2 - Yield (a & b) and LAI (c & d) deviation under RCPs 4.5 and 6.0 during mid and end century for maize cultivars at agroclimatic zone II (Ballowal Saunkhri)

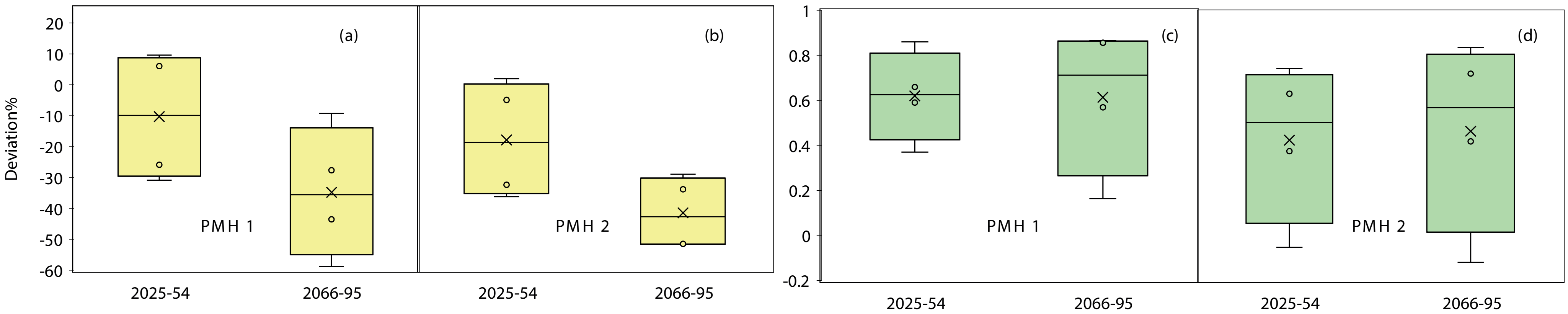

Fig. 3 - Yield (a & b) and LAI (c & d) deviation under RCPs 4.5 and 6.0 during mid and end century for maize cultivars at agroclimatic zone III (Amritsar)

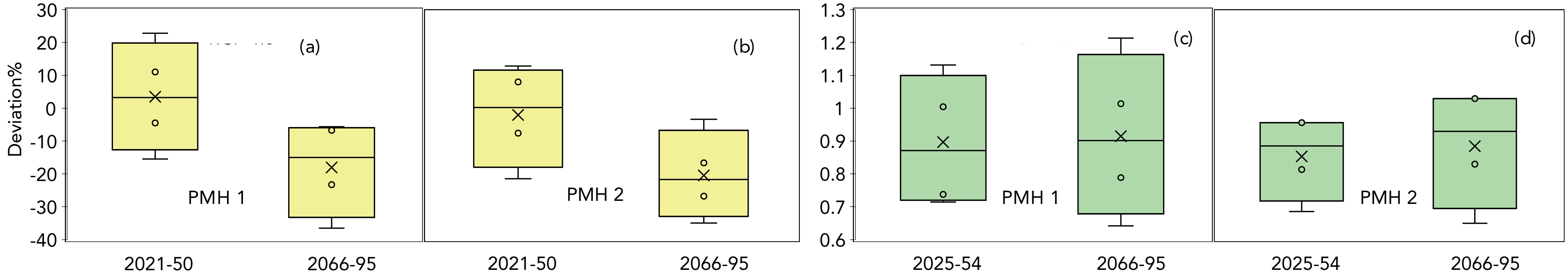

Fig. 4: Yield (a & b) and LAI (c & d) deviation under RCPs 4.5 and 6.0 during mid and end century for maize cultivars at agroclimatic zone III (Ludhiana)

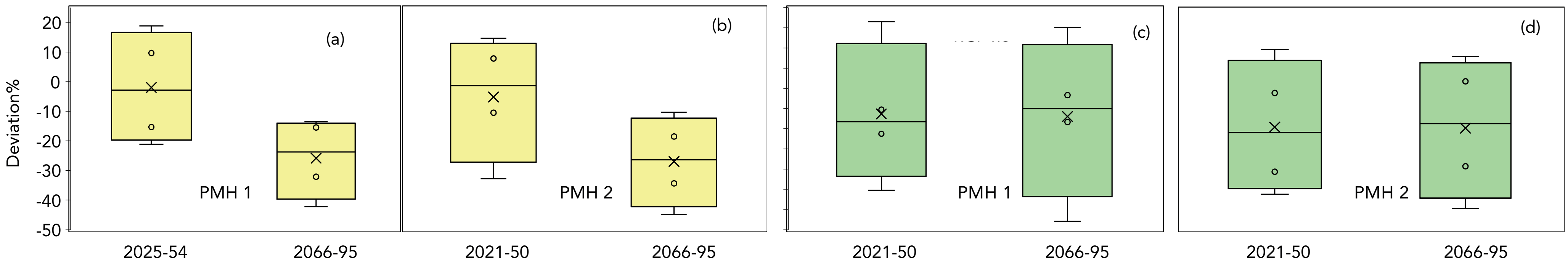

Fig. 5: Yield (a & b) and LAI (c & d) deviation under RCPs 4.5 and 6.0 during mid and end century for maize cultivars at agroclimatic zone III (Patiala)

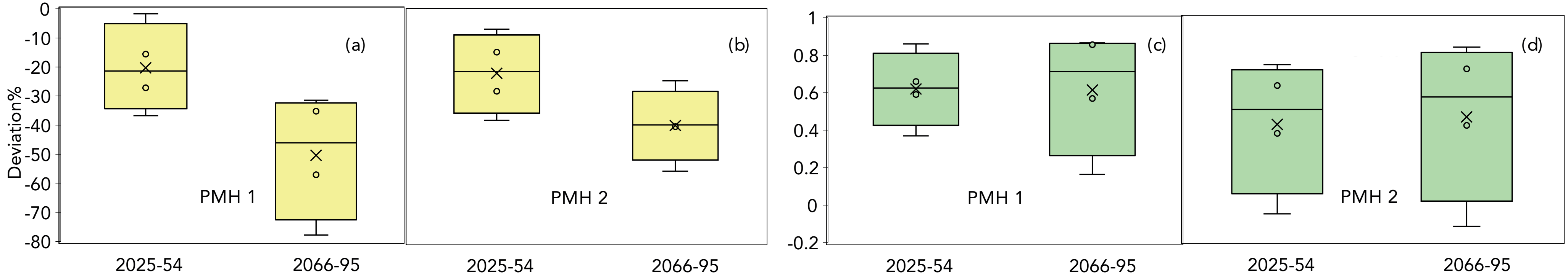

Fig. 6: Yield (a & b) and LAI (c & d) deviation under RCPs 4.5 and 6.0 during mid and end century for maize cultivars at agroclimatic zone IV (Bathinda)

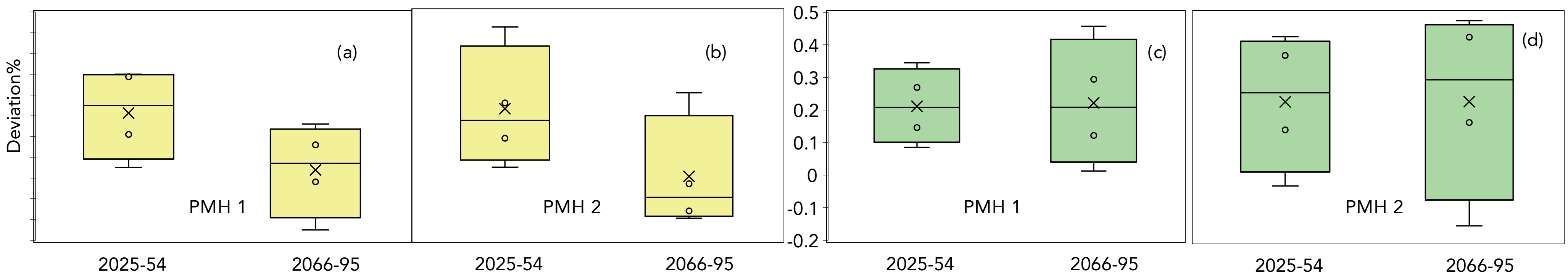

Fig. 7: Yield (a & b) and LAI (c & d) deviation under RCPs 4.5 and 6.0 during mid and end century for maize cultivars at agroclimatic zone V (Abohar)

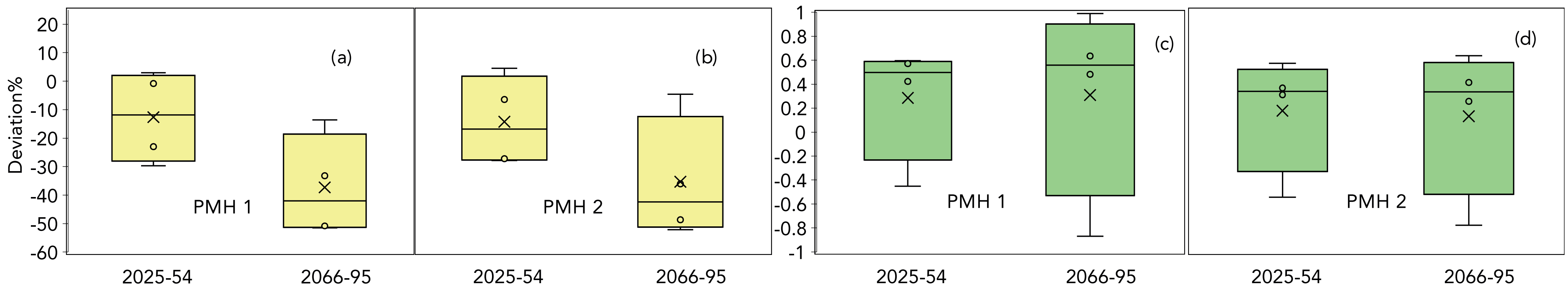

Fig. 8: Yield (a & b) and LAI (c & d) deviation under RCPs 4.5 and 6.0 during mid and end century for maize cultivars at agroclimatic zone V (Faridkot)