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Impact of climate change on potato crop in India: Using multi-model ensemble climate projection

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सार – आलू भारत की एक महत्वपूर्ण खाद्य फसल है, इसलिए बदलते जलवायु परिदृश्यों के अंतर्गत खाद्य सुरक्षा सुनिश्चित करने के लिए आलू उत्पादन पर जलवायु परिवर्तन के प्रभाव का आकलन करना आवश्यक है। इस अध्ययन में सत्यापित SUBSTOR-Potato फसल मॉडल का उपयोग किया गया, जिसमें विभिन्न क्षेत्रीय जलवायु मॉडलों (RCMs) से प्राप्त डाउनस्केल्ड जलवायु आँकड़ों के आधार पर 2040-2069 (मध्य भविष्य) तथा 2070-2099 (दूर भविष्य) की अवधि के लिए आलू की उपज पर जलवायु परिवर्तन के प्रभावों का आकलन किया गया।परिणामों से यह स्पष्ट हुआ कि अध्ययन क्षेत्र में अधिकतम एवं न्यूनतम तापमान में वृद्धि की प्रवृत्ति है, जबकि दैनिक तापमान परास (डायर्नल टेम्परेचर रेंज, DTR) में कमी की प्रवृत्ति देखी गई। उन्नत (बढ़े हुए) CO_2 स्तर को शामिल न करने की स्थिति में, कंद (ट्यूबर) उपज में परिदृश्य एवं समयावधि के अनुसार 3.6% से 20.5% तक की कमी हो सकती है। इसके विपरीत, बढ़े हुए CO_2 स्तर को शामिल करने पर, आशावादी परिदृश्यों में उपज में 28.7% से 36.5% तक तथा निराशावादी परिदृश्यों में 34.4% से 35.9% तक की वृद्धि संभव है।तापमान वृद्धि की स्थिति में आलू की बढ़वार अवधि (फसल अवधि) में भी वृद्धि होने की संभावना है। कुल मिलाकर, भविष्य में बढ़ते तापमान के साथ बढ़े हुए CO_2 सांद्रण के अंतर्गत राज्यों में आलू उत्पादन पर सकारात्मक प्रभाव देखा गया, जिसमें मध्य प्रदेश में अधिकतम (+36.5%) वृद्धि दर्ज की गई। वहीं, बढ़े हुए CO_2 सांद्रण को शामिल न करने की स्थिति में, मध्य प्रदेश को छोड़कर अधिकांश राज्यों में नकारात्मक प्रभाव पाया गया, जबकि मध्य प्रदेश में उपज में +4.6% से +13.5% तक की वृद्धि देखी गई।हालाँकि, इस अध्ययन में विभिन्न RCMs के चयन के कारण कुछ अनिश्चितताएँ उत्पन्न हो सकती हैं, फिर भी ये परिणाम वैज्ञानिक समुदाय एवं नीति-निर्माताओं के लिए अत्यंत महत्वपूर्ण हैं, ताकि भारत में आलू उत्पादन को सुधारने हेतु उपयुक्त अनुकूलन रणनीतियाँ विकसित की जा सकें।

ABSTRACT. Potato is an important food crop in India, to quantifying the impacts of climate change on potato production is necessary to develop proper strategies to ensure food security under changing climatic conditions. This study employed validated SUBSTOR-Potato crop model using downscaled climate data from various Regional Climate Models (RCMs) to project the climate change impact on potato yields for 2040-2069 (mid-future) and 2070-2099 (far-future). Results indicated the increasing trend of maximum and minimum temperature while diurnal temperature range (DTR) shows decreasing trend over the study area. Without elevated CO_2, tuber yields could decrease by 3.6% to 20.5%, depending on the scenario and time period. However, with elevated CO_2, yields could increase by 28.7% to 36.5% under optimistic conditions and 34.4% to 35.9% under pessimistic conditions. The potato growing season would increase under a warming climate. Overall, the future warming with elevated CO_2 concentration across the states showed positive impact (maximum in Madhya Pradesh +36.5%), while without elevated CO_2 concentration, a negative effect has been observed over the states except in Madhya Pradesh where +4.6% to +13.5% increase in yield have been observed. However, uncertainties in this study might arise from the choice of different RCM selection but the results are important for the scientific community and policy makers to develop appropriate adaptation strategies to improve potato production in India.

Key words – SUBSTOR-Potato crop model, Climate change, Multi-model projection, Regional climate model.

1. Introduction

Climate change is a major concern as it is negatively affecting the natural as well as manmade ecosystem at a remarkable scale (IPCC, 2021; Ruane *et al.*, 2014). Agricultural productivity on a global scale is being affected by changing pattern of climate, a small change in climate parameters leads to decline in agricultural production significantly (Jaiswal *et al.*, 2023; Patel *et al.*, 2022; Naz *et al.*, 2022;Ortiz-Bobea *et al.*, 2021; Ren *et al.*, 2019; Vogel *et al.*, 2019; Ray *et al.*, 2019; Mall *et al.*, 2018; Wu *et al.*, 2016; Asseng., 2015; Kang *et al.*, 2009; Xu *et al.*, 2024). A detailed analysis from several studies from the last few decades suggests that the climate change and variability has undermined most of the agricultural sectors leading to challenges for food security in the future (IPCC 2021; FAOSTAT 2021., Singh *et al.*, 2013; Lobell & Gourdji, 2012; Mall *et al.*, 2006). Reduction in crop yields and shortening of phenological phases has been found due to increase in temperature (Eyshi Rezaei *et al.*, 2017; Hristine *et al.*, 2005). Furthermore, increase in CO_2 concentration had positive impact on accumulation of plant biomass and yield (Wang *et al.*, 2023; Frumhoff *et al.*, 2006; Finnan *et al.*, 2005; Trnka *et al.*, 2004; Pendall *et al.*, 2003; Donnelly *et al.*, 2001).

Potato is one of the important staple vegetable and cash crop with an annual production of 388 million tonnes, grown on 19.3 million hectares of land across the world (FAOSTAT 2021). Global potato production is predicted to decrease by 18%-32% in the 2050s (Hijmans, 2003) and in another study global potato yield is predicted to decline by 6% in 2055 and 26% in 2085 (Raymundo *et al.*, 2018). While other studies in Europe, China and USA suggest that potato tuber yield will increase or not change with climate change and elevated CO_2 in future but warming will offset the positive effect of CO_2 in projected scenarios (Tang *et al.*, 2022; Tooley *et al.*, 2021; Stockle *et al.*, 2010; Supit *et al.*, 2012). However, potato is a heat sensitive crop with optimum growing temperature range 14°C to 22°C and extreme temperature is the most significant factor reducing potato yield (Trapero-Mozos *et al.*, 2018; Raymundo *et al.*, 2017; Muthoni & Kabira, 2015; Singh *et al.*, 2015; Struik, 2007). Heat stress is directly or indirectly related to physiological processes, it affects the potato leaf area development and reduces the whole-canopy photosynthesis rate in heat sensitive potato varieties (Obiero *et al.*, 2020; Aien *et al.*, 2017; Fleisher & Timlin, 2006). Tuberization in potato mainly depends on the photoperiod, growth hormones and night temperature (Kolachevskaya *et al.*, 2019; Zhou *et al.*, 2019; Kolachevskaya *et al.*, 2018; Rykaczewska, 2017; Singh *et al.*, 2015; Sarkar, 2010). Tuber formation gets reduced above 22 ºC night temperatures and further tuberization may stress above 25 ºC, however potato plants can withstand up to 32 °C without significant loss in the total biomass (Trapero-Mozos *et al.*, 2018; Singh *et al.*, 2016).

India is a leading producer with an annual share of 13.6% (48.6 million tonnes) after China, covering a cultivated area of 2.06 million hectares (FAOSTAT 2021; DES 2021). India's GDP may reduce up to 1.5% due to climate change impact on agriculture (CPRI, 2021). In India, the share of potato crop in agricultural GDP is 0.4-0.43% (FAOSTAT 2021). The two major staple cereal crops i.e., rice and wheat, contribute 18.25% and 8.22% of agricultural GDP and cover 31.19% and 20.56% cultivable area, respectively. It can be noticed that from the unit area of cultivable land perspective, the contribution of potato in agricultural GDP is about 3.7 and 5.4 times higher than rice and wheat respectively (FAOSTAT, 2016).

Uttar Pradesh, West Bengal, Bihar, Gujarat and Madhya Pradesh are the major potato producing states in India (DES, 2021). Studies so far demonstrate that in Central and Eastern India potato yields are negatively impacted when seasonal temperature exceed optimum (Rana *et al.*, 2020; Pradel *et al.*, 2019; Haris *et al.*, 2015). Whereas, in North-Western parts of the country, potato yield is expected to increase as the temperature moves towards optimum levels from the present low temperatures (Pradel *et al.*, 2019; Singh *et al.*, 2009).

An increase of 0.7 degree Celsius in the average surface temperature has already been witnessed in India during 2018-1901(Krishnan *et al.*, 2020). During recent years increasing trend of winter temperature and extreme temperature (heat stress), decrease in diurnal temperature range (DTR)& spatio-temporal changing pattern of mean & extreme rainfall has been observed & that are major concern for agriculture and health in India (Singh *et al.*, 2021a; Singh *et al.*, 2021b, Mall *et al.*, 2021, Chaubey *et al.*, 2022; Dubey *et al.*, 2023). It is projected that during mid and far future, rise in minimum temperature (T_{min})will be more than maximum temperature (T_{max}) causing DTR to decrease over different agro climatic zones of India (Singh *et al.*, 2023).

Dynamic crop simulation models (CSMs) along with global climate models (GCMs) or regional climate models (RCMs)output under different projected scenarios is an effective method to find out future climatic change impacts on agriculture production. CSMs around the world also work well at local level, which provides advantages to deal with interactions between climate factors, soil and management on crop growth and development (Rosenzweig *et al.*, 2014; Zhang *et al.*, 2017; Asseng *et al.*, 2015; Chen *et al.*, 2014; Jaiswal *et al.*, 2023; Patel *et al.*, 2022; Mall *et al.*, 2018). The inherent uncertainty in predictions and simulations can be minimized and assessed

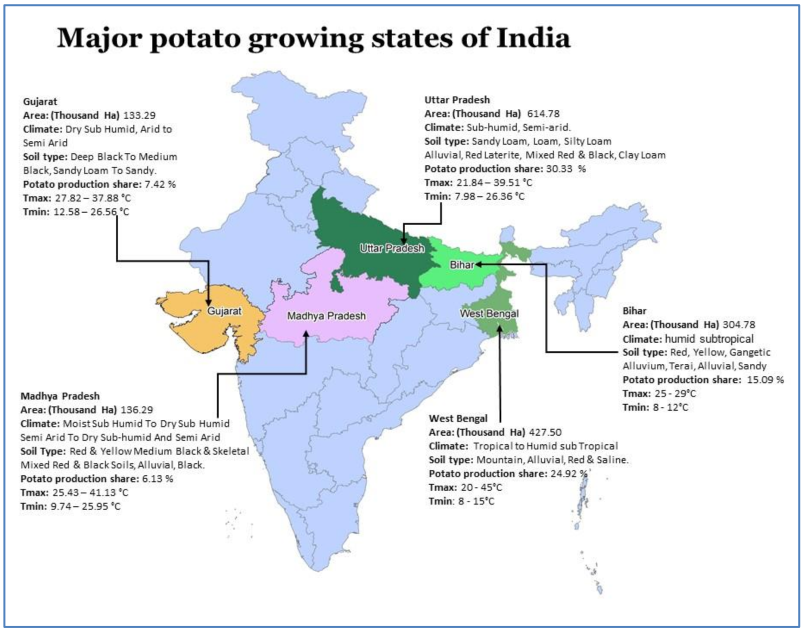

Fig. 1. Description of major potato growing states of India in detail with cultivated area, production, productivity, climate and soil types

at various climate change scenarios like different time periods and Representative Concentration Pathway (RCPs) by using multiple RCMs outputs (Jaiswal *et al.*, 2022; Singh *et al.*, 2021c). Globally, studies on the effect of climate change on potato's tuber yield, phenology, tuber quality, and nutrient management has been done; however, there are very limited studies for Indian context. To ensure future food security for growing population under changing climate conditions, it is imperative to assess the range of uncertainty as well as its impact on potato crop phenology and production (Cui *et al.*, 2018; Tilman *et al.*, 2011; Laux *et al.*, 2010). This ensures the adaptation for increasing the potato production under climate change scenarios at regional as well as national scale.

Therefore, this study has been undertaken to assess the impact of climate change on potato tuber yield and phenology of potato crop for major potato growing states of India using regional climate models projection in SUBSTOR-Potato model for two time periods *i.e*., mid-future (2040-2069) and far-future (2070-2099) under different CO_2 concentrations considering (AgMIP) protocol.

2. Data and methodology

2.1. *Study site*

The study was carried out for major potato growing states *i.e*. Uttar Pradesh, West Bengal, Bihar, Gujarat and Madhya Pradesh which contribute more than 80% of the potato grown area in India during short winter days from October to February/March (DES 2021; Pradel *et al.*, 2019). The study area is characterized by humid subtropical climate with wide temperature variations in different seasons ranging from mean temperature of 2–3°C during winter to 45°C during summer season, with an average annual rainfall of 900 to1200 mm. The novelty of this study lies in the assessment over major potato growing states of India using different regional climate models for understanding the regional dissimilarities in distribution of climatic variables and their impacts on potato crop. The details of the study area are illustrated in Fig. 1.

2.2. *Data and climate change scenarios*

Observed daily meteorological data *i.e*., T_{max}, T_{min} and rainfall during 1980-2009 (baseline period) for the five states of India provided from the Indian Meteorological Department (IMD). The daily surface solar radiation (srad) was estimated by the Hargreaves and Samani method (Hargreaves and Samani, 1985, 1982; Patel *et al.*, 2022). For future projection, five RCM outputs from two RCMs *viz*. Conformal-Cubic Atmospheric Model (CCAM) and Regional Climate Model (RegCM) were used. The CCAM ensemble data was obtained from portal managed by Indian Institute of Tropical Meteorology (CCCR-IITM), India. The spatial resolution of CCAM projected data was 0.50° x 0.50° which was driven from four different GCMs *i.e*., MPI-ESM-LR, CNRM-CM5, ACCESS1-0, NorESM1-M (Table 1).

TABLE 1

Description of the various RCMs selected for the study

RCM	RCM Description	Driving CMIP5 AOGCM	Name used	Contributing Modelling Center
RegCM4.6	Earth System Physics (ESP) ICTP- Italy (Giorgi *et al.*,2012)	MPI-ESM-MR (Giorgetta *et al.*, 2013)	RegCM	Max-Planck-Institute Earth System Model, Germany
CCAM (4 ensemble member)	Commonwealth Scientific and Industrial Research Organization (CSIRO), Conformal-Cubic Atmospheric Model (CCAM; McGregor andDix,2001)	ACCESS1-0 (Bi *et al.*,2013)	ACCESS1-0	CSIRO, Australia
		CNRM-CM5 (Voldoire *et al.*, 2013)	CNRM-CM5	Centre National de Recherches Me´te´ orologiques (CNRM), France
		MPI-ESM-LR (Giorgetta *et al.*, 2013)	MPI-ESM-LR	MPI-M, Germany
		NorESM1-M (Bentsen *et al.*, 2013)	NorESM1-M	Norwegian Climate Centre (NCC), Norway

The RegCM simulations were obtained by downscaling MPI-ESM-MR global climate model at DST-Mahamana Centre of Excellence in Climate Change Research (DST-MCECCR), Banaras Hindu University, India. Then data was re-gridded using bilinear interpolation method to 0.50° x 0.50° resolution to bring all the models at the same spatial resolution (Voropay *et al.*, 2021; Patel *et al.*, 2022). The projected data was divided into mid-future (2040-2069) and far-future (2070-2099) for both RCP 8.5 (pessimistic scenario) and RCP4.5 (optimistic scenario) corresponding to radiative forcing reaching 4.5W/m^2 and 8.5 W/m^2, respectively, in relation to the pre-industrial level by 2100 (Patel *et al.*, 2022).

The bias corrected climate data was used in the study (Jaiswal *et al.*, 2022; Laux *et al.*, 2021; Singh *et al.*, 2021c; Mall *et al.*, 2018; Teutschbein and Seibert; 2012). The monthly and seasonal mean of T_{max} and T_{min}, srad, and DTR were used to project the changes in climatic parameters in future with respect to the baseline period during potato growing season (October to February/ March). To investigate the inter-model variability, use of different downscaled GCMs data (using RCMs) will help in providing the range of uncertainty during the assessment of climate change impacts on agricultural crop for further improvements.

2.3. *SUBSTOR-Potato model*

Simulations were performed using SUBSTOR-Potato model of DSSAT 4.7 (Hoogenboom *et al.*, 2019; Jones *et al.*, 2003; Griffin *et al.*, 1993). It has been used to estimate uncertainties and risks related to potato growth and yield for the baseline and future (Tubiello *et al.*, 2002). The SUBSTOR-Potato model simulates the growth and development of potato using variety, crop management, climate, soil and other farm information. The climate change impact assessments using this model has been widely used(Raymundo *et al.*, 2017; Daccache *et al.*, 2011; Holden *et al.*, 2005). In the study we used the calibrated and validated crop date in SUBSTOR-Potato model for impact assessment on potato crop over India (Yadav *et al.*, 2016;)

2.4. *Simulation experiment and analysis*

Potatoes are seemingly to be challenged by the increased temperature, atmospheric CO_2 and their interactions (Haverkort & Verhagen, 2008). The Potato crop model was used to simulate the phenology and yield of potato for baseline (1980-2009) with two different CO_2 concentration. The model was simulated at potential condition (*i.e.*, without any nutrient or water stress) at all states for baseline and future time periods (with and without elevated CO_2). A concentration of 380ppm was used in the base line as well as for future simulations without CO_2 effect, during mid-future and far-future under both RCP4.5 and RCP 8.5 scenario (Rosenzweig *et al.*, 2015; Patel *et al.*, 2022; Jaiswal *et al.*, 2023). Under RCP4.5, during 2050s corresponds to an elevated CO_2 of 499ppm and during 2080s corresponds to an elevated CO_2 of 532ppm. Under RCP 8.5, during 2050s correspond to an elevated CO_2 of 571ppm and 2080s correspond to an elevated CO_2 of 801 ppm has been considered. As a result, 40 climate change scenario experiments are obtained (5 models X 2 scenarios X 2 study periods X 2 CO_2 concentrations) for impact assessment (Patel *et al.*, 2022; Jaiswal *et al.*, 2023). The detailed information of different scenarios can also be accessed from a gmip.org (Rosenzweig *et al.*, 2015; Patel *et al.*, 2022).

Crop management practices were the same across the region along with sowing date (in the month of October) and harvesting date (in the last week of February) in next

TABLE 2

Ensemble mean of changes in maximum temperature and minimum temperature in mid-century (2040-2069) and end of the century (2070-2099) period as compared to baseline period (1980-2009) in 5 major potato growing states of India.

State	Parameter	RCP 4.5		RCP 8.5	
		2040-2069	2070-2099	2040-2069	2070-2099
Uttar Pradesh	T_{max} (℃)	1.34	1.38	2.16	3.3
	T_{min} (℃)	1.64	1.94	2.68	4.22
Bihar	T_{max} (℃)	1.4	1.68	2.34	3.26
	T_{min}(℃)	1.76	2.08	2.76	4.22
West Bengal	T_{max} (℃)	1.52	1.78	2.52	3.36
	T_{min}(℃)	1.4	1.74	2.38	3.88
Madhya Pradesh	T_{max} (℃)	1.38	1.24	2.1	3.18
	T_{min}(℃)	1.76	2.08	2.8	4.52
Gujarat	T_{max} (℃)	1.48	1.52	2.3	3.42
	T_{min}(℃)	1.72	2.1	2.78	4.48

year to minimize contacting. The initial field conditions were given as per the secondary data obtained for each state production (Jaiswal *et al.,* 2023; Dutt *et al.,* 2017; Thamburaj *et al.,* 2001). The model simulates potato crop growth based on validated crop genetic coefficients (Yadav *et al.,* 2016).

Climate variables have direct impact on crop growth, any deviation from the optimum range of temperature can lead to significant change in yield of potato (Patel *et al.,* 2022; Rana *et al.,* 2020; Pradel *et al.,* 2019). In the study, yield simulations were performed for the baseline climate as well as for the 20 scenarios and followed by obtaining an average of simulation for the respective time period (30 years) at each grid and then the percentage difference between average of simulated and baseline yields were calculated. In the final step, calculated yield for each grid of corresponding states has been aggregated into one column for state-wise analysis. Similarly, the change in phenology *i.e*., tuber initiation, leaf area index, and tuber dry weight of potato was also calculated for these 20 scenarios.

3. Results and discussion

3.1. *Changes in climate parameter in potato growth season*

Presently, the potato crop growing season's average T_{max} and T_{min} were 28.9 ℃ and 14.6 ℃ respectively, whereas mean seasonal temperature was 21.8 ℃. The results show that during potato growing season both T_{max} and T_{min} are going to increase in projected scenarios. Under RCP4.5 scenarios, T_{max} is expected to increase by 1.52 ℃ and 1.78 ℃ during the mid-future and far future respectively. Whereas in RCP8.5 scenarios, T_{max} is expected to increase by 2.52 ℃ in West Bengal during the mid-future and 3.42 ℃ during the far future over Gujarat. While T_{min} is expected to increase by 1.76 ℃ during the mid-future and 2.08 ℃ during far future under RCP4.5 in Bihar and Madhya Pradesh respectively. Whereas under RCP8.5 T_{min} is expected to increase by 2.78 ℃ in Gujarat during the mid-future and 4.52 ℃ in Madhya Pradesh during the far-future (Table 2).

Multi-model projections show a significant diversity in temperature changes in all the states with variable intensity under different scenarios. Under RCP4.5, the growth period average T_{max} is projected to rise by 0.7 ℃ (CNRM-CM5) in Uttar Pradesh to 2.0 ℃ (ACCESS1-0) in West Bengal, 0.7 ℃ (CNRM-CM5) in Madhya Pradesh to 2.2 ℃ (ACCESS1-0) in Bihar during mid-future (2040-2069) and far-future (2070-2099), respectively. While the seasonal average T_{min} rise will be comparatively high are ranging from 0.9 ℃ (CNRM-CM5) in West Bengal to 2.2 ℃ (ACCESS1-0) in Uttar Pradesh during mid-future (2040-2069) and far-future (2070-2099), respectively (Fig. S1). More increases were observed under RCP4.5, where the growth period average T_{max} will rise by 1.6 ℃ (NorESM-1M) in Uttar Pradesh to 3.4 ℃ (ACCESS1-0) in Gujarat and 2.1 ℃ (NORESM1-M) in Madhya Pradesh to 4.3 ℃ (ACCESS1-0) in Gujarat in mid-future (2040-2069) and far-future (2070-2099), respectively. Under RCP 8.5, rise in growth period average T_{min} will range from 1.8 ℃ (RegCM) in West Bengal to 4.0 ℃ (ACCESS1-0) in Gujarat, and highest increment of 3.4 ℃ (NorESM-1M) in West Bengal to 5.7 ℃ (ACCESS1-0) in

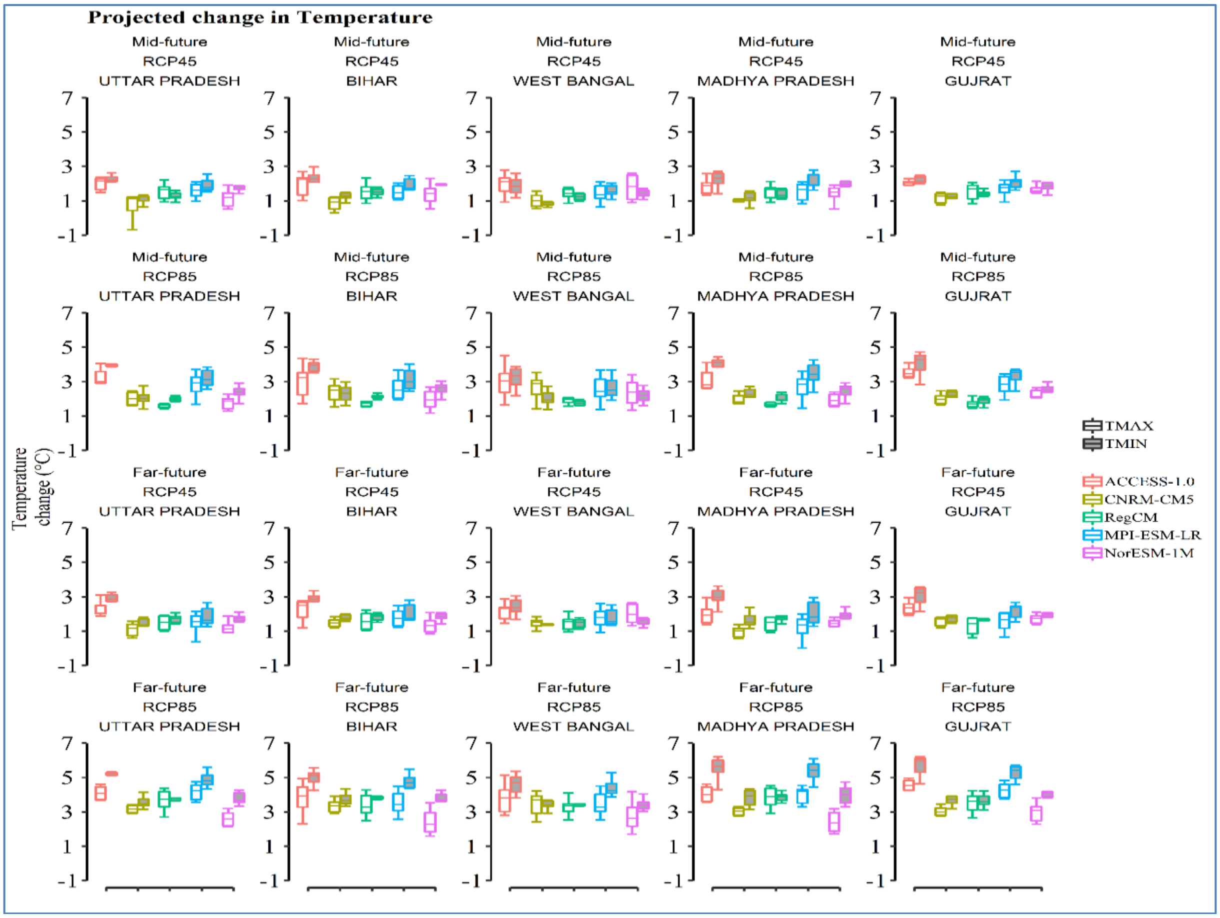

Fig. 2. Change in mean seasonal temperature as projected by climate models relative to baseline period (1980-2009) under different representative path ways during mid-century (2040-2069) and end-of-century (2070-2099) in 5 major potato growing states of India

Gujarat during mid-future (2040-2069) and far-future (2070-2099) respectively. Uncertainty due to different climate models shows that ACCESS1-0 is projecting the higher increment in temperature while RegCM, NorESM-1M and CNRM-CM5 are projecting the lower temperature rise as compared to baseline (Fig. 2).

During the mid-future and the far-future scenarios under RCP 4.5 and RCP 8.5, the range of srad for all 5 states were found to be decreasing as well as increasing in the magnitude of -0.5 to 0.1 MJ/M^2/day for the mid-future and from -0.8to 0.1 MJ/M^2/day during the far-future under RCP 4.5. At RCP 8.5, decreasing as well as increasing srad in the magnitude of -0.6 to 0.2 MJ/M^2/day during the mid-future and -0.9 to 0.0 MJ/M^2/day during far-future is expected. The long-term mean during growth period is shown in Fig. S2.

Model uncertainty showed that RegCM showed an increment during mid-future at RCP 4.5 in Uttar Pradesh, Madhya Pradesh and Gujarat. CNRM-CM5 showed an increment during mid future at RCP 8.5 in West Bengal. NorESM -1M showed an increment during far-future at RCP 4.5 in West Bengal (Fig.3).

It has been noticed that the T_{min} is increasing faster than the T_{max} during both mid-future and far-future leading to decrease in DTR over the study area. The DTR varies during growing season from 8.5 °C to 14 °C in West Bengal, 10.2 °C to 17 °C in Madhya Pradesh, 10 °C to 16 °C in Gujarat, 8.2 °C to 15.2 °C in Bihar and 9.2 °C to 15.6 °C in Uttar Pradesh. Fig. S3 shows that, during December to February across the study area under RCP 8.5 scenario, DTR will increase between 14.5 °C to 16 °C during mid future, whereas under RCP 4.5, DTR is expected to increase by 14.0 °C to15.2 °C.

3.2. *Projected change in potato phenology*

The result indicates that plantation to tuber initiation period would be larger in most of the climatic scenarios across the states. During the mid-future under RCP4.5, planting to tuber initiation period will increase from +0.9 days (Bihar) to +3.2 days (Gujarat), whereas under RCP

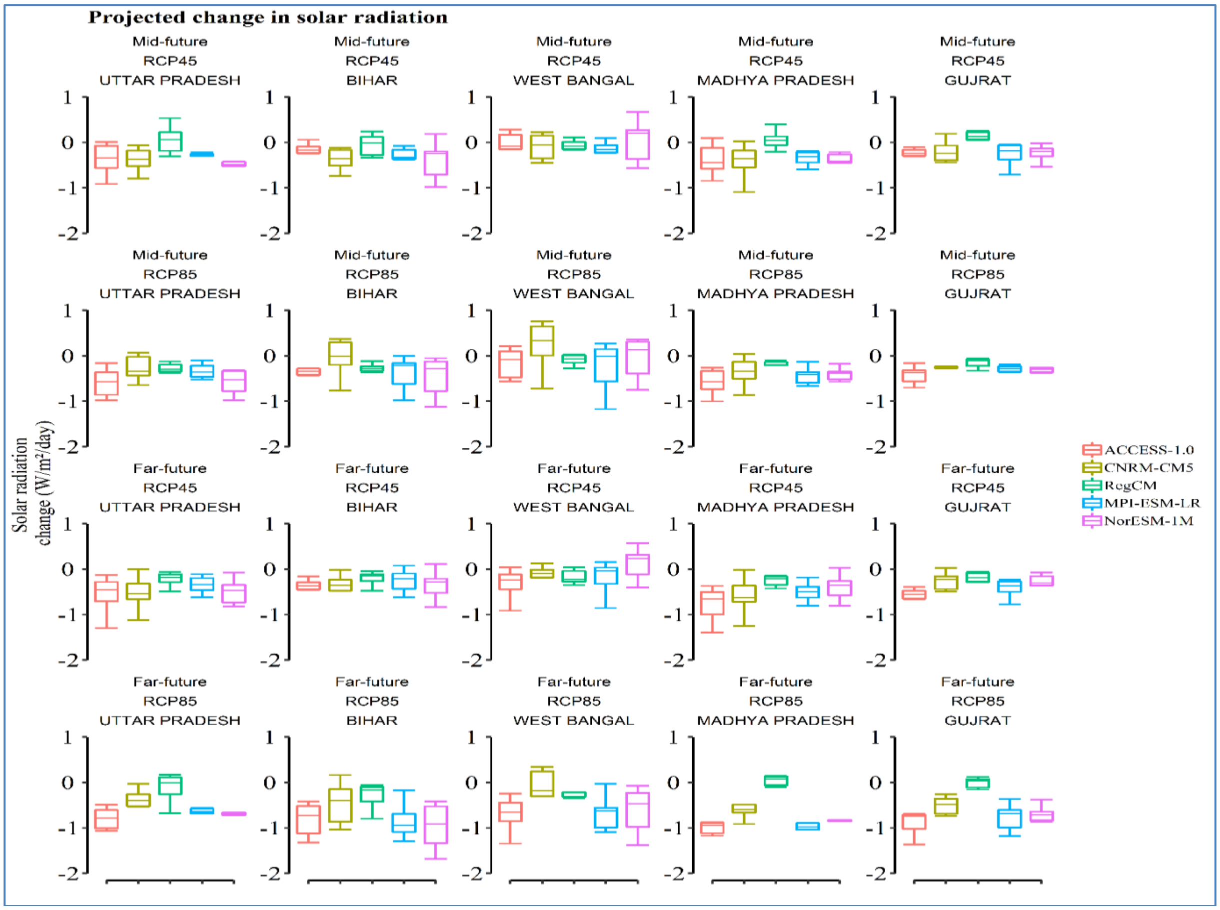

Fig. 3. Change in mean seasonal solar radiation as projected by climate models relative to baseline period (1980-2009) under different representative path ways during mid-century (2040-2069) and end-of-century (2070-2099) in 5 major potato growing states of India

8.5, this period will increase from +1.0 days (Uttar Pradesh) to +3.7 days (Gujarat). While during the far-future under RCP 4.5, planting to tuber initiation will increase from +0.9 days (Uttar Pradesh) to +3.5 days (Gujarat), whereas under RCP 8.5 this will increase from +1.0 (Uttar Pradesh) to+3.8 days (Gujarat). (Figs. 4 & 5), (Table 3).

Increase in leaf area index and tuber dry weight has a positive impact on potato yield. In this study the result indicates that leaf area index varies across the states. During mid-future under RCP 4.5 and 8.5, the leaf area index would be higher to the maximum extent in Gujarat *i.e.*, +3.4% and +3.6% respectively. The leaf area index again would be higher to the maximum extent in Gujarat by +3.8% under RCP 4.5 and in West Bengal by +3.4% under RCP 8.5 for the far-future scenario (Figs. S4 & S5) (Table4).

Tuber dry weight will be higher to the maximum extent in Madhya Pradesh *i.e.*, +7.7% and +9.3% during the mid-future under RCP 4.5 and 8.5 respectively. While, during the far-future under RCP 4.5 and RCP 8.5 the tuber dry weight would be higher to the maximum extent in Madhya Pradesh i.e., +9.1% and +8.9% respectively (Fig. S6 & S7), (Table 5).

3.3. *Potato yield response with future climate*

Result showed that, without considering CO_2 effect during the mid-future under RCP 4.5 and RCP 8.5, the potato yields would be reduced between -3.6 to -17.5% and -2.4 to -20.5% respectively. During the far-future under RCP 4.5 and RCP 8.5, the potato yield reduction was observed in between -0.1 to -15.2% and 0.3 to 20.5% across the states respectively except Madhya Pradesh which showed increasing yield by +1.1% to +3.5%. Without considering CO_2, the reduction in potato yield was observed with a significant amount of variation in each state by using different climate model projections during mid-future and far-future. During mid-future in West Bengal under RCP 4.5 and RCP 8.5 scenario the climate models reveal highest reduction of -17.5% and -20.5% respectively by ACCESS -1.0, while during the

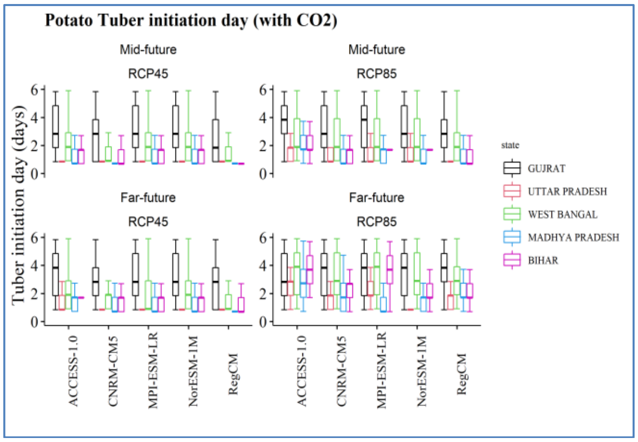

Fig. 4. Simulated change in tuber initiation days (compared with baseline1980-2009) with CO_2 in mid-century (2040-2069) and end-of-century (2070-2099) under RCP 4.5 and RCP 8.5 using different climate models in 5 major potato growing states of India

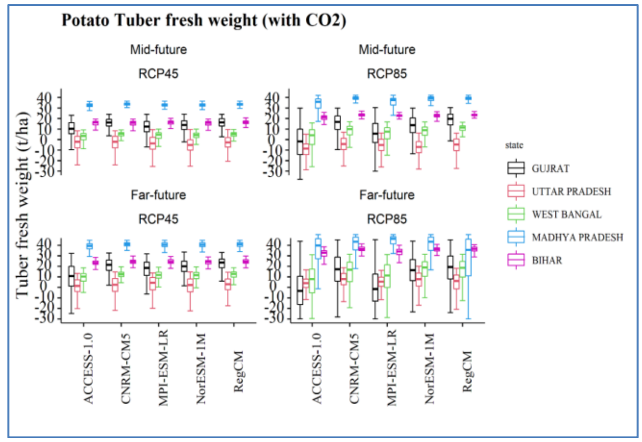

Fig. 7. Simulated potato tuber fresh weight yield change with CO_2 in mid-century (2040-2069) and end-of-century (2070-2099) under RCP4.5 and RCP 8.5 compared with baseline (1980-2009) using different climate models in 5 major potato growing states of India

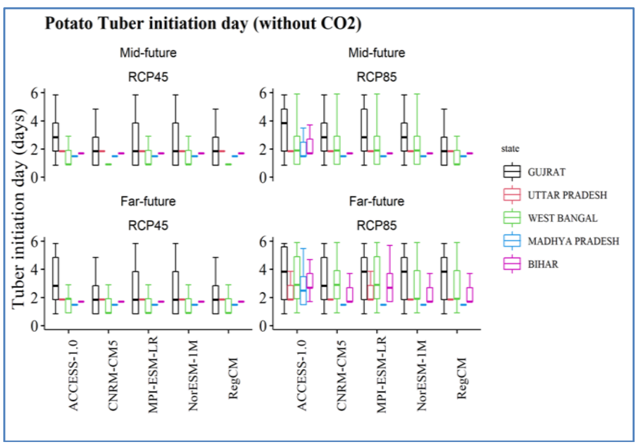

Fig. 5. Simulated change in tuber initiation days (compared with baseline1980-2009) without CO_2 in mid-century (2040-2069) and end-of-century (2070-2099) under RCP 4.5 and RCP 8.5 using different climate models in 5 major potato growing states of India

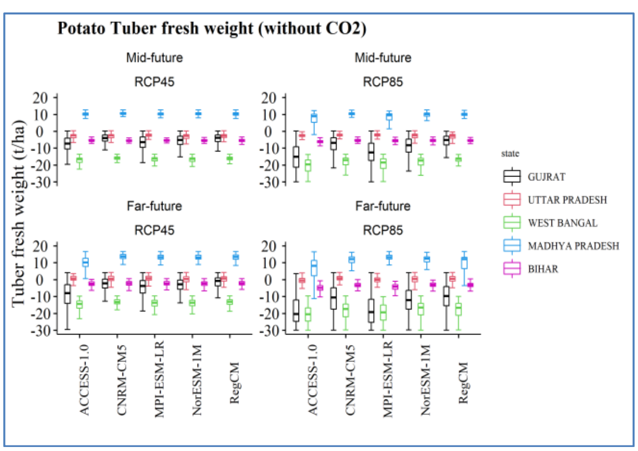

Fig. 6. Simulated potato tuber fresh weight yield change without CO_2 in mid-century (2040-2069) and end-of-century (2070-2099) under RCP4.5and RCP 8.5 compared with baseline (1980-2009) using different climate models in 5 major potato growing states of India

far-future, reduction of-15.2% and -20.5% observed again by ACCESS-1.0 for the same. Similarly, in Gujarat-17.7% reduction in yield was found by ACCESS-1.0. In Bihar, during mid-future under RCP 4.5 & RCP 8.5 the reduction of -5.6% and -6.3%were noticed as projected by CNRM-CM5 and ACCESS-1.0 respectively. During the far-future under RCP 4.5 and RCP 8.5, the reduction of -2.5% and -5.2% were noticed as projected by NorESM-1M and ACCESS-1.0 respectively. In Uttar Pradesh, during the mid-future under RCP 4.5 and RCP 8.5 the reduction of -3.6% and -3.4% were noticed as projected by NorESM-1M and RegCM respectively. During far-future under RCP 4.5 and RCP 8.5 the lowest reduction of -0.1% and -0.3% were noticed as projected by CNRM-CM5 and MPI-ESM-LR respectively for the same (Fig. 6).

However, an increase in yield has been observed when CO_2 effect is considered. The increase in yield with CO_2 is found all across the states ranging from +0.8 in Gujarat to +36.5% in Madhya Pradesh. During mid- future at RCP4.5 and RCP8.5, the maximum increase was noticed in Madhya Pradesh by +28.7% and +36.5% respectively. While during the far-future at RCP 4.5 and RCP 8.5, the maximum increase was noticed by +35.9% and 34.4% in Madhya Pradesh respectively. While on the other hand marginal reduction of -1.5% were noticed in Gujrat during the far-future at RCP 8.5 (Fig. 7), (Table6).

3.4. *Discussion*

3.4.1. *Change in phenology under future climate change*

Potato crop is sensitive to heat stress (Dutt *et al.*, 2017; Kumar, 2007). Based on the results obtained,

TABLE 3

Ensemble mean of tuber initiation day deviation in 5 major potato growing states of India Under different CO_2 concentrations and RCPs.

State	Scenario	2040-2069		2070-2099	
		Tuber initiation days'change (days) without CO_2	Tuber initiation dayschange (days) with CO_2	Tuber initiation dayschange (days) without CO_2	Tuber initiation dayschange (days) with CO_2
Uttar Pradesh	RCP 4.5	1.82	1.0	1.82	1.02
	RCP 8.5	1.86	1.3	2.08	1.86
Bihar	RCP 4.5	1.72	1.28	1.72	1.4
	RCP 8.5	1.62	1.74	2.7	2.88
West Bengal	RCP 4.5	1.44	1.88	1.54	2.02
	RCP 8.5	1.9	2.46	2.92	3.38
Madhya Pradesh	RCP 4.5	1.56	1.18	1.56	1.18
	RCP 8.5	1.68	1.56	1.92	1.98
Gujarat	RCP 4.5	2.3	2.92	2.42	3.04
	RCP 8.5	2.8	3.34	3.52	3.5

TABLE 4

Ensemble mean of leaf area index deviation in 5 major potato growing states of India under different CO_2concentrations and RCPs

State	Scenario	2040-2069		2070-2099	
		LAI change (%) without CO_2	LAI change (%) with CO_2	LAI change (%) without CO_2	LAI change (%) with CO_2
Uttar Pradesh	RCP 4.5	0.46	-2.1	0.66	-1.76
	RCP 8.5	0.44	-2.14	0.42	-1.9
Bihar	RCP 4.5	-0.26	-1.46	-0.08	-0.34
	RCP 8.5	-0.24	0.0	-0.34	-0.28
West Bengal	RCP 4.5	2.34	2.1	2.4	2.86
	RCP 8.5	2.3	3.16	2.06	3.22
Madhya Pradesh	RCP 4.5	1.0	1.86	0.94	2.06
	RCP 8.5	0.76	2.08	0.46	1.9
Gujarat	RCP 4.5	2.2	3.32	2.16	3.6
	RCP 8.5	1.24	3.06	0.54	2.98

TABLE 5

Ensemble mean of tuber dry weight deviation in 5 major potato growing states of India under different CO_2concentrations and RCPs.

State	Scenario	2040-2069		2070-2099	
		Tuber dry weight change (%) without CO_2	Tuber dry weight change (%) with CO_2	Tuber dry weight change (%) without CO_2	Tuber dry weight change (%) with CO_2
Uttar Pradesh	RCP 4.5	-0.64	0.32	0.02	1.42
	RCP 8.5	-0.58	0.24	-0.08	1.02
Bihar	RCP 4.5	-1.1	4.14	-0.48	5.84
	RCP 8.5	-1.14	6.04	-0.78	6.86
West Bengal	RCP 4.5	-3.36	1.78	-2.8	3.26
	RCP 8.5	-3.82	2.84	-4.18	2.4
Madhya Pradesh	RCP 4.5	1.98	7.52	2.44	8.98
	RCP 8.5	1.62	8.78	1.74	7.22
Gujarat	RCP 4.5	-1.24	3.64	-0.94	4.64
	RCP 8.5	-2.38	3.5	-3.84	1.4

TABLE 6

Ensemble mean of yield deviation in 5 major potato growing states of India under different CO_2 concentrations and RCPs.

State	Scenario	2040-2069		2070-2099	
		Yield change (%) without CO_2	Yield change (%) with CO_2	Yield change (%) without CO_2	Yield change (%) with CO_2
Uttar Pradesh	RCP 4.5	-3.22	1.58	0.12	7.08
	RCP 8.5	-2.86	1.3	-0.34	5.18
Bihar	RCP 4.5	-5.5	20.66	-2.34	29.22
	RCP 8.5	-5.74	30.32	-4.02	34.32
West Bengal	RCP 4.5	-17.42	8.82	-14.12	16.32
	RCP 8.5	-18.76	14.36	-18.84	12.22
Madhya Pradesh	RCP 4.5	9.9	28.7	12.18	36.50
	RCP 8.5	8.32	35.90	9.14	34.40
Gujarat	RCP 4.5	-5.96	18.36	-4.36	23.22
	RCP 8.5	-10.26	17.72	13.84	9.92

there will be rise in T_{max} and T_{min} during the potato growth season. The increase in optimum temperature at critical stages of crop growth *i.e.*, tuber initiation and tuber formation can negatively impact the potato production (Das *et al.*, 2021; Dutt *et al.*, 2017; Thamburaj *et al.*, 2001). Rise in T_{max} and T_{min} will lead to speedy accumulation of growing degree days reducig the duration of phenological duration (Jennings *et al.*, 2020; Dutt *et al.*, 2017; Singh *et al.*, 2013).Similarly, a study by Daccache *et al.* (2011) projected a future potential yield increase of 13–16% with rising temperature and elevated atmospheric CO_2 concentrations. Overall, in this study we found that, due to increase in temperature, there will be shortening of the plant crop growth period across all 5 major potato growing states of India.

3.4.2. *Change in potato tuber yield*

Potato crop requires a mean temperature of 24 °C during emergence, 20 °C during tuber formation and at threshold of 18 °C during bulking period under optimum conditions (Dutt *et al.*, 2017). A seasonal mean temperature of more than 32 ℃ stops the growth and reduces the yield (Thamburaj *et al.*, 2001). The optimum maximum and minimum temperature during sprouting, tuber initiation, tuber formation, bulking of tuber is 25 ℃ and 12 ℃ respectively while in our finding the maximum and minimum temperature were found to be 28.9 ℃ and 14.6 ℃ respectively for the same phenological stages which ultimately affect the yield. It is reported that there will be an increase of 6-20% in yield by the climate models with adaptation with every unit rise in temperature (Singh *et al.*, 2013; Jennings *et al.*, 2020). Some of the studies show mix result of decreasing as well as increasing trend in potato yield in major potato growing states under increased CO_2 concentrations (Rana *et al.*, 2020; Jennings *et al.*, 2020; Pradel *et al.*, 2019). Other crop simulation models such as WOFOST reported a mixed trend of increase as well as decrease in potato yield in India during mid future and far future depending on climatic variability and CO_2 concentration (Rana *et al.*, 2020). The yield profits were also reported in the study by Raymundo *et al.*, 2018 and Hijmans, 2003. Our findings are also supported by other studies that shows the reduction in potato yield due to rise in temperature when CO_2 effects are not considered but the increased CO_2 concentration shave more positive effect on potato due to enhanced photosynthesis rate and no water/nutrient stress (Jennings *et al.*, 2020; Singh *et al.*, 2013). From the above results without considering elevate CO_2 concentration it is found that India may emerge as the vulnerable country for the region where the potato yield was found to be decreasing. The decrease in yield will not only affect the potato production but also affect the income of the small/marginal farmers and stakeholders.

3.4.3. *Changes in phenology and yield due to change in DTR*

The yield of potato tubers is vulnerable to high temperatures and is affected by asymmetric increases in day and night temperatures (Kim and Lee, 2019). The increase in T_{min} has been higher than the increase in T_{max}, reducing global DTR (Easterling *et al.*, 1997; Harris *et al.*, 2014; Mall *et al.*, 2021; Singh *et al.*, 2023). Changes in diurnal temperatures have an interactive effect on the way the potato plant grows and night temperatures have been thought to have a profound effect on potato growth and yield compared to daytime temperatures (Gregory, 1956; Levy, 2007). It has been reported that high night temperatures have a negative impact on crop growth and yield of potato (Prasad and Djanaguiraman, 2011; Garcia *et al.*, 2015). Earlier studies have shown that high temperatures, especially high night temperatures, delay tuber induction, enhance tuber setting, and delay the onset of rapid tuber development (Slater, 1968; Sale, 1979; Struik, 2007). Leaf photosynthesis is thought to be less sensitive at higher temperatures than tuber growth as suggested by (Ku *et al.*, 1977; Leach *et al.*, 1982; Timlin *et al.*, 2006).

3.4.4. *Uncertainty and limitations of the study*

Robust input data with multi-model projections could be a solution to minimize the uncertainty for future crop simulation. There is unexplained variation in predictions made on the impact of future climate on crop yield uncertainty, it varies depending on the use of crop models (Wang *et al.*, 2017; Lobell & Gourdji, 2012). The current study has shown that the uncertainty is deeply aggregated with the climate model used and climates scenario considered. There is a clear proof of potato yield reductions in the study when CO_2 concentrations were not considered. Different climate projections without CO_2 concentration revealed a wide variation in the impact and behaviour of climate variables in each potato growing state of India. When CO_2 effects were considered, all climate models for all 5 states showed an increase in yield during both time period and scenarios except model NorESM-1M during mid future under RCP 4.5 in Uttar Pradesh and ACCESS-1.0 during far future under RCP 8.5 in Gujarat, where a decrease in yield was observed. Our results are consistent with other studies where the model uncertainty has been observed (Rahman *et al.*, 2018). There are some limitations of assessing the response of potato to climate change, which are that the study has considered only a single dominant variety of the crop in the country simulated on a single crop model, while other new varieties and crop models may produce different results (Patel *et al.*, 2022). The study was carried out with no water and nutrient stress, along with no other extreme weather events like heat waves, cold waves, Diurnal temperature Range (DTR), pests and diseases *etc*. Whereas, it is found that DTR and heatwaves have negative impact on crop yield (Mall *et al.*, 2021; Singh *et al.*, 2021a; Singh *et al.*, 2013). This study relies on climate and crop model for the assessment to f potato yield in future climate(Jennings *et al.*, 2020; Pradel *et al.*, 2019; Dutt *et al.*, 2017), hence optimizing different model parameters, improving model structure and selecting the well validated crop model best suited for regional impact study should be helpful (Patel *et al.*, 2022).

4. Conclusions

The study has shown that there is a significant increase in temperature based on all climate change scenarios and increase in T_{min} would be higher than T_{max} The impact assessment revealed that the days to tuber initiation from planting of potato will increase across all the states by +0.9 to +3.8 days showing a positive impact on potato phenology. This will lead to an increase in potato yield all over the major potato growing states of India ranging from + 0.4 to 36.5% with a consideration of higher CO_2 concentration whereas when the higher CO_2 concentration effect was not considered, a decrease in potato yield in the range of -0.1 to -20.5% reported under both the scenarios. Associated climate models uncertainty revealed that CNRM-CM5, RegCM and ACCESS1-0 have projected a higher increase across all the states and scenarios while NorESM-1M has shown lower increase in yield as compared to the remaining climate models. It is concluded that India emerged as the vulnerable country for potato production during late 21st century. The study recommends framing of suitable adaptation strategies for increasing potato yields such as investment in climate resilient crop varieties, boosting production, benefits and support to farmers in the vulnerable region which may lead to both meeting the demand for potatoes as well as increasing farmers' income and their livelihood and so, boosting the economy of the country.

Data Availability Statement

The authors thank the Earth System Grid Federation (ESGF) infrastructure and the Climate Data Portal hosted at the Centre for Climate Change Research (CCCR), Indian Institute of Tropical Meteorology (IITM) for providing CORDEX South Asia data (http://cccr.tropmet.res.in/home/ftp_data.jsp, http://cccr.tropmet.res.in/home/workshop/sept2014/index.html). The authors wish to thank the India Meteorology Department (IMD) for making available the observation dataset (https://www.imdpune.gov.in/cmpg/Griddata/Min_1_Bin.htmlhttps://www.imdpune.gov.in/cmpg/Griddata/Max_1_Bin.html).

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Supplementary: -

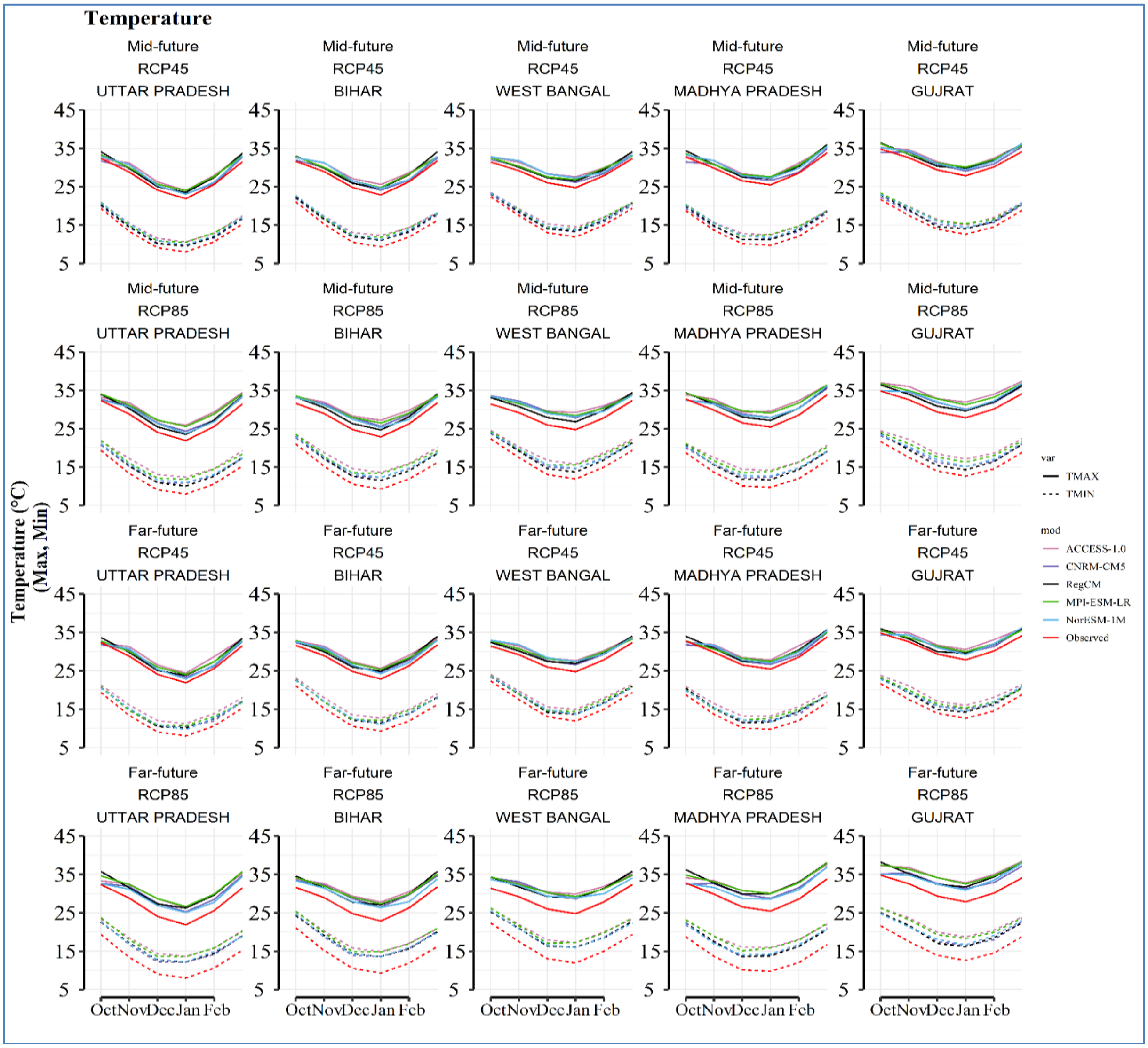

Fig. S1. Average monthly (potato growing season) maximum temperature (T_{max}) and minimum temperature (T_{min}) during baseline period (1980-2009), mid-century (2040-2069) and end of the century (2070-2099) under RCP 4.5 and RCP 8.5 as projected by different climate models in 5 major potato growing states of India. Here the solid lines represent the T_{max} and dashed lines represent the T_{min}.

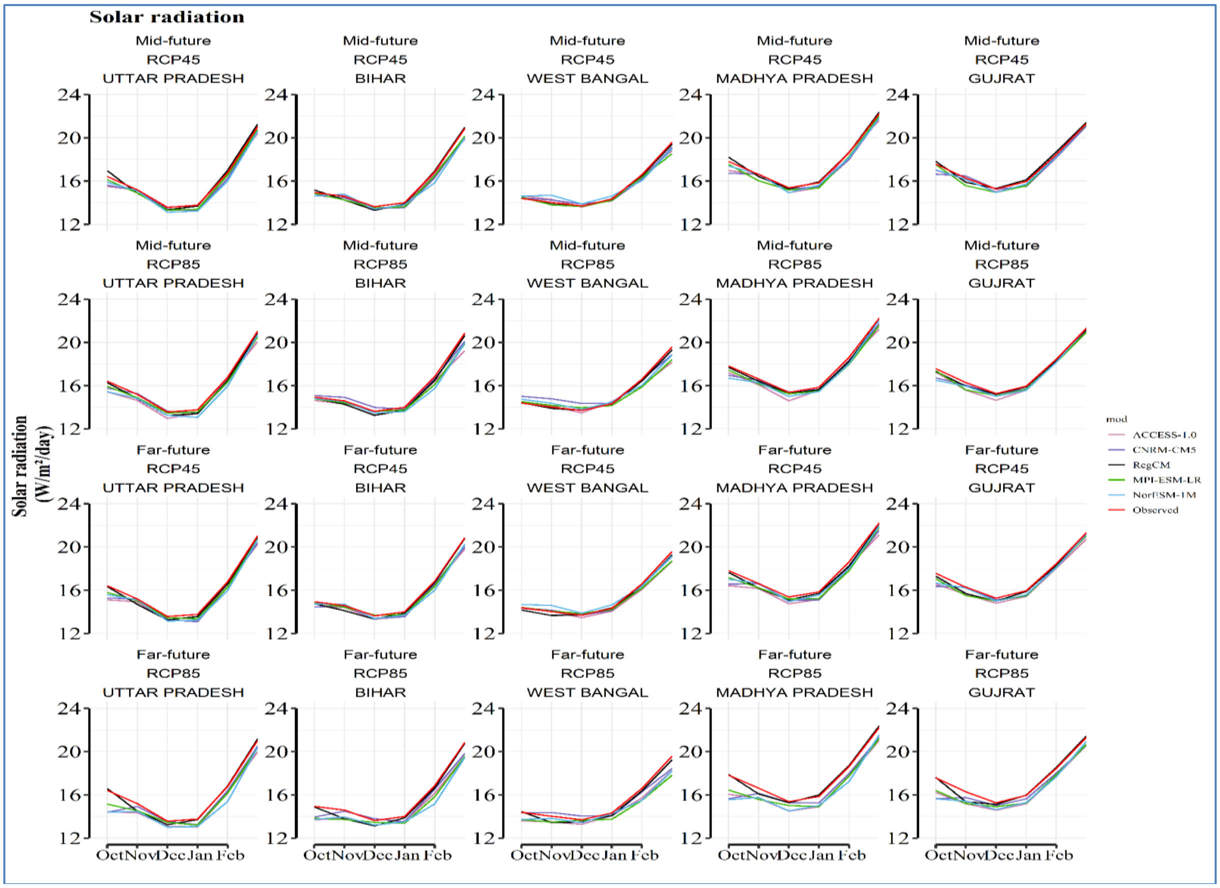

Fig. S2: Average monthly (potato growing season) solar radiation during baseline period (1980-2009), mid-century (2040-2069) & end of the century (2070-2099) under RCP 4.5 and RCP 8.5 as projected by different climate models in 5 major potato growing states of India.

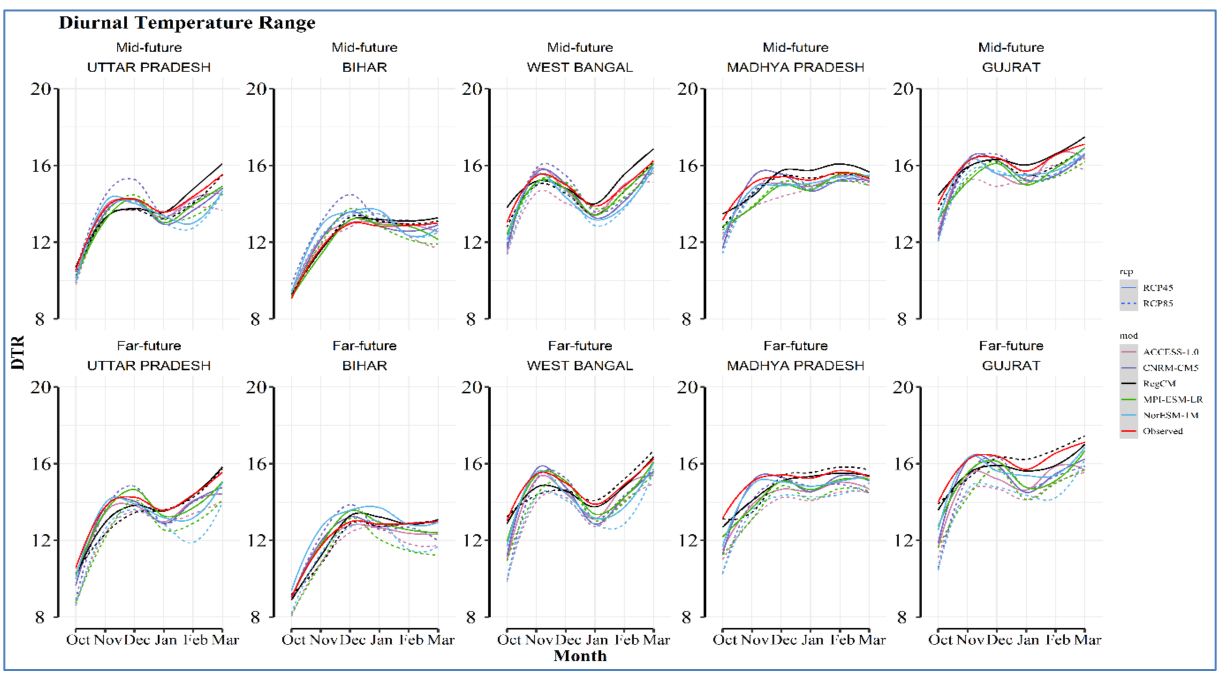

Fig. S3: Average monthly (potato growing season) diurnal temperature range (DTR) baseline period (1980-2009), mid-century (2040-2069) and end of the century (2070-2099) under RCP 4.5 and RCP 8.5 as projected by different climate models in 5 major potato growing states of India

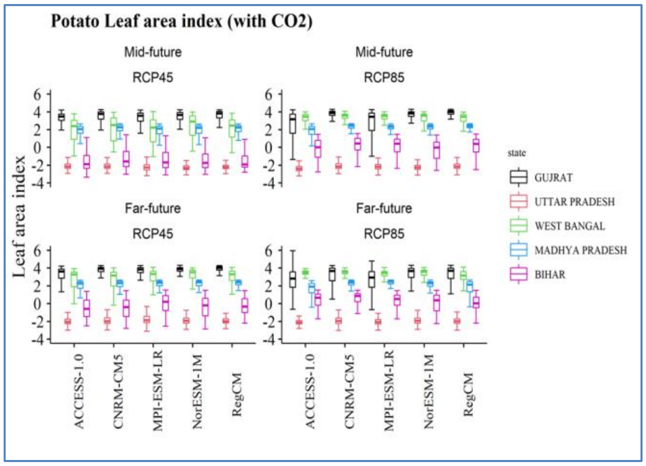

Fig. S4. Simulated change in leaf area index (compared with baseline 1980-2009) with CO_2 in mid-century (2040-2069) and end-of-century (2070-2099) under RCP 4.5 and RCP 8.5 using different climate models in 5 major potato growing states of India

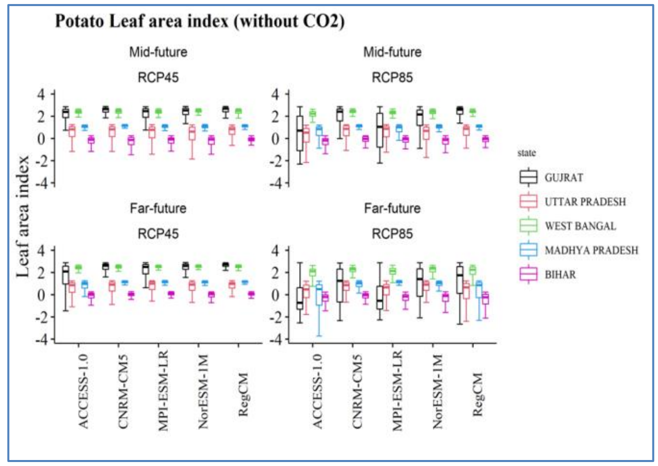

Fig. S5. Simulated change in leaf area index (compared with baseline 1980-2009) without CO2 in mid-century (2040-2069) and end-of-century (2070-2099) under RCP 4.5 and RCP 8.5 using different climate models in 5 major potato growing states of India

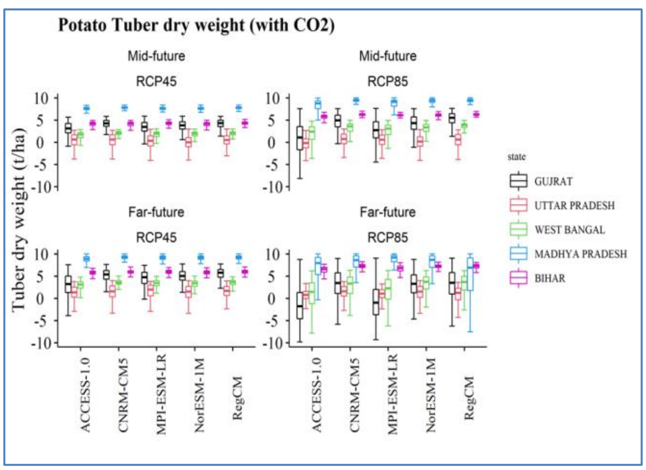

Fig. S6: Simulated potato tuber dry weight yield change with CO2 in mid-century (2040-2069) and end-of-century (2070-2099) under RCP 4.5 and RCP 8.5 compared with baseline (1980-2009) using different climate models in 5 major potato growing states of India.

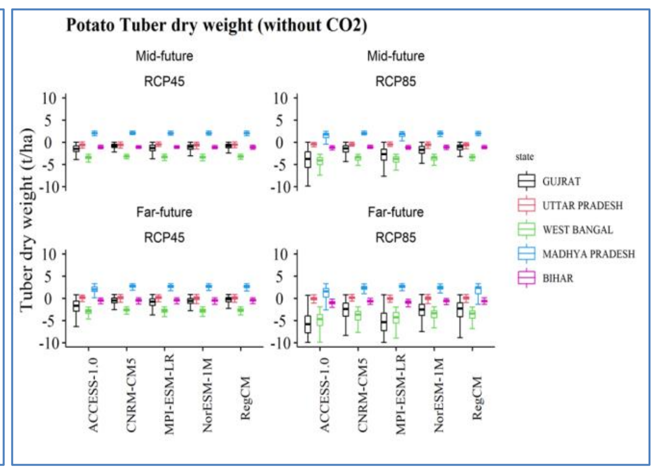

Fig. S7: Simulated potato tuber dry weight yield change without CO2 in mid-century (2040-2069) and end-of-century (2070-2099) under RCP 4.5 and RCP 8.5 compared with baseline (1980-2009) using different climate models in 5 major potato growing states of India