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Multi-model projections of future climate and climate change impacts uncertainty assessment for cotton production in Pakistan

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ABSTRACT

Future climate projections and impact assessments are critical in evaluating the potential impacts of climate change and climate variability on crop production. Climate change impact assessment in combination with crop, climate models under different climate change scenarios is uncertain and it is challenging to select an appropriate climate scenario. This study quantifies the uncertainty associated with projected climate change impacts on cotton yield in Punjab, Pakistan using 29 general circulation models (GCMs) under high and moderate representative concentration pathway (RCP) scenarios (4.5 and 8.5) at near-term (2010–2039) and mid-century (2040–2069) time spans. Cropping System Model (CSM) CROPGRO-Cotton (DSSAT *v* 4.6) was calibrated and evaluated with field experiment data collected under arid/semi-arid climatic conditions. Enormous variation was observed in GCMs climatic variables, which were therefore classified into different categories. According to mean ensemble of 29 GCMs, there is a projected increase in seasonal average temperature 1.52 °C and 2.60 °C in RCP 4.5 and 1.57 °C and 3.37 °C in RCP 8.5 scenario as compared to the seasonal baseline (31.48 °C) in near-term (2010–2039) and mid-century (2040–2069), respectively. Maximum consensus by GCMs revealed the increase in temperature of 1.2–1.8 °C and 2.2 to 3.1 °C in RCP 4.5 scenario while 1.4–2.2 °C and 3.0–3.9 °C increase is expected under RCP 8.5 for near term and mid-century time periods, respectively. Similarly, rainfall changes are expected −8% to 15% and −5 to 17% in RCP 4.5 scenario while −8 to 22% and −2 to 20% change is expected under RCP 8.5 scenario in near term and mid-century time periods, respectively. Seed cotton yield (SCY) are projected to decrease by 8% on average by 2039 and 20% by 2069under the RCP 4.5 scenario relative to the baseline (1980–2010). Mean seed cotton yield is projected to decrease by 12% and 30% on average under the RCP 8.5 scenario. Uncertainties were observed in GCMs projections and RCPs due to variations in climatic variables projections. GCMs, GFDL-ESM2M (45% and 35%), GFDL-ESM2G (28% and 43%) and MIROC-ESM (39% and 70%) predicted the higher mean SCY reduction ensemble of cultivars than others under emission scenario of 4.5 in near term and mid-century, respectively. Lower SCY reduction was revealed in CCSM4, HADGEM2-CC, HADGEM2-ES, INMCM4 and CNRM-CM5 due to mild behavior of climatic variables especially temperature under RCP 4.5 in the near-term and mid-century. High reduction in mean SCY (16%–19%) is

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expected in CMCC-CMS, IPSL-CM5B-LR, GISS-E2-H, GFDL-ESM2M and GFDL-ESM2G under the RCP 8.5 scenario. However, under the same scenario, mean SCY increases by 1% in HADGEM2-ES and by 4% in HADGEM2-CC relative to the baseline yield (4147 kg ha^{-1}). GFDL-ESM2M and GFDL-ESM2G are hot and dry while HADGEM2-ES and HADGEM2-CC are hot but wet, resulting in less cotton yield loss. MIROC-ESM and GFDL-ESM2G projected a severe reduction in mean SCY (70% and 69%) due to a steep increase in maximum and minimum temperature (6.97 °C and 4.38 °C, 4.91 °C and 3.70 °C), respectively and sever reduction in rainfall by mid-century and may call worse case scenarios. Climate models like, CCSM4, HadGEM2-CC, HadGEM2-ES, INMCM4, CanESM2, CNRM-CM5, ACCESS1-0, BNU-ESM and MIROC5 are found less uncertain and showed stable behavior. Therefore, these models can be used for climate change impact assessment for other crops in the region. Adaptation management options like five weeks early sowing than current (10-May), increasing nitrogen fertilization (30%), higher planting density (18% for spreading and 30% for erect type cultivars) and 17% enhanced genetic potential of cultivars would compensate the negative impacts of climate change on cotton crop. This study provide valuable understandings and direction for cotton management options under climate change scenarios. This multi-model and multi-scenario analysis provides a first overview of projected changes in temperature and precipitation, cotton yield and potential management options under changing climate scenarios in arid to semi-arid climatic conditions of Punjab-Pakistan.

1. Introduction

Climate change is expected to increase the vulnerability of agricultural systems (Rosenzweig et al., 2014) by increasing temperature, changes in rainfall patterns, and increased frequency of extreme weatehr events in most parts of the world (IPCC, 2014) and especially in Pakistan (Ahmad et al., 2015; Nasim et al., 2016). Projected changes are expected to have a negative impact on crops in Paksitan, especially in arid to semi-arid regions (IPCC, 2013; Ahmad et al., 2015; Rasul et al., 2016; Abbas et al., 2017). Cotton is the most important cash crop in Pakistan, providing feed, fiber and oil. It holds a lion's share in the foreign exchange (55%) and production accounts for 1.5% in GDP and 7.1% in value added agriculture (GOP, 2015). Increases in temperature and changes in precipation may have negative impact on cotton growth and productivity (Bange and Milroy, 2004; Gwimbi and Mundoga, 2010; Iqbal et al., 2016). Elevated CO_2 concentration (eCO_2) positively relates to crop growth, biomass and cotton yield by promoting photosynthesis and decreasing transpiration and stomatal conductance and overall it enhances water use efficiency (Williams et al., 2015; Luo et al., 2016; Fahad et al., 2016a,b,c,d). However, more recent studies have shown that interactive effects of $CO_{2,}$ projected increase in temperature and variability in precipitation in future climate scenarios could potentially offset the positive effect of CO_2 induced by doubling its concentration (Paz et al., 2012; Hatfield and Prueger, 2015; Nasim et al., 2016c). Physiological and metabolic processes occurring in cotton have thermal range spanning 23–32 °C, which is considered as the optimal range for growth and development (Cottee et al., 2010; Nasim et al., 2011). Optimum temperature for efficient growth is reported to be 33 °C while significant reduction in flower and boll retention has been recorded above 36 °C (Singh et al., 2007; Luo, 2011; Nasim et al., 2016b). Cotton growth and seed cotton yield are dramatically affected by temperature variations (Nasim et al., 2011; Luo et al., 2014; Nasim et al., 2016a; Rahman et al., 2017). The boll growth period shortens with high temperature, resulting in smaller boll, and ultimately a lower cotton yield (Reddy and Zhao, 2005; Nasim et al., 2012; Fahad and Bano, 2012; Fahad et al., 2013, 2014a,b, 2015a,b). Environmental stresses, mainly temperature is the main cause of yield variability over time; high temperature during the day followed by high night temperature may exacerbate these harmful effects. Unforeseen periodic incidents of heat stress are projected to happen more frequently in the region. These changes in climatic conditions could affect cotton phenology, growth and yield, and threaten sustainable cotton production in the future.

Uncertainty in climate change impact projections are related to multiple factors including climate model and greenhouse gas emission scenario selection, complexities in atmosphere modeling, downscaling methods, incomplete understanding of the processes included in climate models and uncertainties in crop models (Wilby et al., 2009; Asseng, 2013; Challinor et al., 2013; Osborne et al., 2013; Uusitalo et al., 2015; Mason-D'Croz et al., 2016; Amin et al., 2017a). Most studies rely on only a few climate models and a single greenhouse gas (GHG) emission scenario those were unable to characterize uncertainties in climate risk assessment (Meehl et al., 2007; Bassu et al., 2014; Tao et al., 2009; Rötter et al., 2011; Amin et al., 2017b). More robust climate change impact assessment are based on multi-climate model (GCMs) projections as well as multiple scenarios (Tebaldi and Knutti, 2007; Kassie et al., 2015; Araya et al., 2015). Process-based dynamic crop models can be used for climate risk assessment (Ewert et al., 2015), but must be rigorously calibrated with growth and yield attribute data (Challinor et al., 2013; Adhikari et al., 2015; Bassu et al., 2014; Uusitalo et al., 2015; Kersebaum et al., 2015; Awais et al., 2017). As a result, models predict the expected impacts of, and uncertainties associated with climate change scenarios on the growth and yield of agricultural crops (Thorp et al., 2014; Rosenzweig et al., 2013, 2014; Ruane et al., 2013). Climate change impact assessment studies offer a means of quantifying uncertainties related to climate risks, and provide decision-support for more sustainable crop production. Crop model-derived yield predictions based on multiple GCMs and emission scenarios (RCPs) provide more reliable climate change impact assessments (Asseng, 2013; Rosenzweig et al., 2013; Ruane et al., 2013). These studies can also be used to discover and assess the uncertainty in yield predictions and as well as to evaluate model performance (White et al., 2011; Challinor et al., 2013; Wajid et al., 2013; Mason-D'Croz et al., 2016). This study aims to quantify uncertainty in climate change impact assessment on cotton production by using all available climate models (GCMs), under both harsh and mild emission scenarios from 2010 to 2069, which has not yet been done in the study region. Existing studies are limited to old emission GHGs scenarios of IPCC (A2, B2, A1B, B1) and very few GCMs and are based in parts of the world (Voloudakis et al., 2015; Gwimbi and Mundoga, 2010; Adhikari et al., 2015; Yang et al., 2014; Hebbar et al., 2013; Luo et al., 2016) where climatic conditions are very different. Specifically, our goals are to 1) assess the potential impacts of future climate change and variability on cotton production derived from CSM-CROPGRO-Cotton, and 2) quantify the uncertainty in climate change impacts projections using 29 GCMs across the world under high and moderate RCPs scenarios (4.5 and 8.5) for early (2010–2039) and mid-century (2040–2069) time spans.

2. Materials and methods

2.1. Environmental conditions of site and experimental details

The study was conducted in Punjab (31°30 N, 73°26 E), which is characterized by arid/semi-arid environmental conditions. The study area experiences important diurnal fluctuations where mean daily air