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Developing climate change agro-adaptation strategies through field experiments and simulation analyses for sustainable sorghum production in semi-arid tropics of India

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ABSTRACT

Change in rainfall pattern with longer dry period depletes soil water content (SWC) and incorrect sowing time adversely affects rainfed sorghum production in Semi-Arid Tropics (SATs). The present study was conducted to develop agricultural water management strategies for improving SWC and to evaluate sowing time as climate change agro-adaptations for sorghum production in SATs. The field experiments on two land-water management (flatbed, broad bed furrows (BBF)) and four nutrient management (application of macro-and micronutrients through combination of chemical and organic fertilizers) were conducted in 2014 and 2015 at International Crops Research Institute for the Semi-Arid Tropics, India. The average SWC in 'BBF' was higher over 'flatbed' by 0.90 cm and 1.06 cm in 0–30 cm soil depth, 0.67 cm and 1.02 cm in 30–60 cm depth, 0.51 cm and 0.84 cm in 60–90 cm depth and, 0.34 cm and 0.67 cm in 90–120 cm during 2014 and 2015, respectively. The SWC in BBF was higher over flatbed by 7.28% throughout 0–120 cm soil depth during longest dry period of 26 days in the year 2014. The simulation analyses using DSSAT Version 4.6 for Coupled Model Intercomparison Project Phase 5 with RCP 4.5 stated that postponing the normal sowing time (30 June) to 10 July resulted in lower grain yield reduction i.e. 14.75% in 2030 and 19.37% in 2050 as compared to base period (1988–2007) yield with normal sowing in Parbhani location of India. The BBF combined with macro-and micronutrients application through chemical fertilizer and postponing sowing time was found the effective climate change agro-adaptation strategies for improving sorghum production in SATs. This study indicates the need for desired policy orientation by the government to promote integrated land-water-nutrient management as the effective agro-adaptations to climate change in SATs.

1. Introduction

Rainfed agriculture accounts for 58% of global food grain production from 80% of the cultivable area (Kamdi et al., 2020; Raju et al., 2008) and sorghum [*Sorghum bicolor* (L.) Moench] is one of the major cereal crops grown mostly under rainfed conditions in Semi-Arid Tropics (SATs). Due to higher drought tolerance than other cereal crops, sorghum is a highly suitable crop for SATs (Ludlow and Muchow, 1990) and continues to be the main staple food for marginal farmers of developing countries in Asia and Africa (Murty et al., 2007). However, the agricultural water management in rainfed agriculture is facing implications of changes in rainfall pattern such as uncertainty in rainfall (Parry et al., 2004), increase in frequency and duration of droughts (Alexandratos and Bruinsma, 2012), and an increase in dryness and wetness (Rao et al., 2013). In the semi-arid and dry sub-humid zone (Klaij and Vachaud, 1992; Agarwal, 2000; Hatibu et al., 2003; Wani et al., 2009), crop production is not only limited by the extent of rainfall; but also by extreme variability like intense rainfall, few rainy events with poor spatial and temporal distribution of rainfall. The adverse meteorological conditions results in long dry spells, droughts, unseasonal rains and extended moisture stress periods, with no mechanisms for storing or conserving the surplus rain to use during the scarcity/deficit periods (Kanwar, 1999). The large scale adverse impact on food production and food security will be due to rising temperatures and changing rainfall

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patterns (Lesk et al., 2016). Fourth Assessment Report of the Intergovernmental Panel on Climate Change (Linden et al., 2015) stated that most of times the rainfall could occur for short-duration with high-intensity due to climate change.

These studies clearly indicate that the change in rainfall pattern and longer dry periods within rainy season are serious agricultural water management issues adversely affecting rainfed crop production through lower soil water content (SWC) in different soil layers and reduced rainwater use efficiency (RWUE) in SATs. In addition, the land-water management practices determine the yield of crop/cropping systems. Pathak et al. (2013) reported that soils in the SATs needs combination of new strategies and more appropriate soil and water management practices. This combination will effectively conserve and utilize the soil and water resources in production systems that increase productivity and assure harvest. Land-water management practices include broad bed furrows (BBF), flatbed, ridges and furrows, conservation furrow, tied ridges, open ridges, compartmental bunding, pit planting for in-situ water conservation. These land-water management practices conserved the moisture in soil and boosted yield contributing parameters and thereby yield of crops/cropping systems. The previous study conducted by the authors (Kamdi et al., 2020) on land-water management practice showed the efficiency of broad bed furrows on changes in SWC at the lowest and highest SWC up to 90 cm soil depth and increase in water productivity in different cropping systems. Several efforts have been made to address rainfall associated issues using land-water and agronomic management practices such as use of climate resilient cultivars, irrigation management and nutrient management practices. These management practices were used alone with an objective to increase grain yield in rainfed as well irrigated ecosystems, but lesser emphasis was placed on improvement of SWC in different soil layers and RWUE.

In addition to field experiments, crop modeling is a useful tool to assess the impact of climate change on crop yield and evaluate agro-adaptations options in limited time and expenses. The Decision Support System for Agrotechnology Transfer (DSSAT) is a Cropping System Model (CSM) used to simulate the growth, development, and yield of crops. CSM simulates the effect of climate, soil, and agronomic management practices on crop growth and yield which reduces the need for carrying out expensive field trials thus helping in the decision-making process in climate change adaptations (Lehmann et al., 2013; Choruma et al., 2019; Jones et al., 2003). The effect of climate change on diverse crops could be assessed by the use of simulation models (Challinor et al., 2014; Akinseye, 2020; Sannagoudar et al., 2020) to evaluate the effect of management options such as sowing dates, genotypes used, fertilization rates, water management etc., as the adaptation strategies. The studies (Kothari et al., 2020, 2020a) carried out in the SATs were also focused on the use of CSM to assess the climate change impacts on sorghum production.

There is a dearth of studies on the effect of land-water management on SWC in different soil layers throughout crop growing period and during longest dry periods, and RWUE in sorghum. There is limited or no information available on field-based land-water and nutrient management, and coupling of field experimental data with CSM for the decision-making process as an adaptation mechanism to rainfall variability in the SAT region. We hypothesized that the practicing broad bed furrows (BBF) as improved land-water management may store more water in the soil profile and increase the SWC, which can meet the water requirement of the crop in the dry spell period as compared to the conventional flatbed technique. In addition to land-water management, sowing of the sorghum at the optimum time may reduce the crop vulnerability by avoiding exposure of the critical growth stages to variation in rainfall and temperature in future periods.

The field experiment on integrated land-water and nutrient management combined with a simulation assessment of sorghum yield was the novelty of this comprehensive study to develop agricultural water management and an agro-adaptation strategy under future climate scenarios in SATs of India. In this comprehensive study, DSSAT Version 4.6 was used as a CSM to simulate the growth, development, and yield of sorghum. The CERES-Sorghum model was calibrated and validated using present field experimental data and minimum data sets like weather (daily maximum and minimum temperature, precipitation, and solar radiation), soil (soil surface and profile information), and experimental data (Field level input management and crop information). Several simulation studies (Rosenzweig et al., 1995; Mavromatis et al., 2002; Boomiraj et al., 2012; Singh et al., 2014) were conducted on evaluation of the model using field experimental data for one location and assessing the impact of climate change at a different location. Rosenzweig et al. (1995) clearly indicated performance of model using data from cropping systems currently used in respective countries could be used to assess the potential impacts of climate change on cropping systems across similar region. Mavromatis et al. (2002) used CROPGRO-Soybean model in DSSAT and estimated soybean cultivar coefficients for a number of cultivars in Georgia to predict the soybean yields in North Carolina. The simulation results clearly indicated the robustness and ability of the model to predict soybean yield predictions across region. Boomiraj et al. (2012) validated the InfoCrop-Sorghum model using data from several field experiments from All India Coordinated Research Trials conducted at various sorghum growing regions in India and future climate change adaptation strategy were developed for across India for similar regions. Similar crop modeling studies were conducted in chickpea (Singh et al., 2014).

In the present study, Parbhani location used as simulation study location is away from Hyderabad (field experiment site). As per Koppen-Geiger climate classification (Beck, H.E. et al., 2018), Parbhani location and Hyderabad (field experiment site) are classified in semi-arid zone. Hence, authors chose Parbhani location to simulate climate change scenario as an evaluation site, though Parbhani is away from Hyderabad. The present study was undertaken with specific objectives to 1) quantify grain yield and RWUE of sorghum, 2) analyse the effect of BBF against flatbed on changes in SWC in different soil layers during longest dry period, 3) calibrate and validate CERES-Sorghum model of DSSAT V4.6 using present field experiment data and 4) evaluate model for assessing the impact of climate change scenario (RCP 4.5) on sorghum grain yield with sowing date as an agro-adaptation strategy for Parbhani location of Maharashtra in India. The present study was unique and evaluated two different topics viz., field experiment to evaluate changes in SWC during longest dry period and simulation study to assess sowing time as an agro-adaptation strategy. These two different topics related to each other, wherein field experimental data on crop management was an input to the CERES-Sorghum model for calibration and evaluation.

2. Materials and methods

2.1. Field experiment

Field experiments were carried out to assess the effect of land-water and nutrient management practices on sorghum grain yield, changes in SWC, RWUE, and parameterization of Crop Environment Resource Synthesis (CERES) model of DSSAT. The experiments were carried out during the wet season (June-October) of the years 2014 and 2015.

2.1.1. Experimental site

The field experiments were conducted at the BW4 block of the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru in India. The local climate of the study area is semi-arid with an average annual rainfall of 895 mm with an incidence of 75–80% of the total rainfall in the wet season (June-October). The daily average maximum temperature during the wet season varied from 30° to 36°C in 2014 and from 31° to 34°C in 2015.

2.1.2. Soil properties of the experimental site

The soil at the experimental site was deep black (Vertisol) and clayey. Soil texture (sand, silt, and clay content) were analyzed using a hydrometer (Klute, 1986). Values of sand, silt, and clay content were averaged for 0–30 cm, 30–60 cm, 60–90 cm, and 90–120 cm soil depth for respective points. Hereafter, 0–30 cm soil depth is denoted as the top layer, 30–60 cm depth as the sub-layer, 60–90 cm depth as the middle, and 90–120 cm as the bottom layer.

Soil samples were collected from the top layer and analyzed for the initial physical and chemical properties of soil. Initial physical analysis of top soil sample showed 26.95% sand, 19.24% silt, 53.97% clay, and 1.23 g cm^{-3} bulk density. Initial chemical analysis of the top soil sample showed pH-7.60, EC-0.18 dS m^{-1}, organic carbon-0.32%, available nitrogen-194 kg ha^{-1}, phosphorous-7 kg ha^{-1}, potassium-411 kg ha^{-1}, sulphur-12 kg ha^{-1}, boron-0.9 kg ha^{-1} and zinc-0.6 kg ha^{-1}.

2.1.3. Field experimental details

The field experiments were conducted in the wet season during the years 2014 and 2015. The experiments were conducted to test the effect of two land-water management practices and four nutrient management in a factorial randomized block design with three replications. The individual plot size was 4.5 m by 20 m with a 1.5 m border on both sides. Two land-water management practices were flatbed (L1) and BBF (L2), and four nutrient management: (1) N1 = control, no fertilizer; (2) N2 = 100% recommended application of macronutrients through chemical fertilizer (CF); (3) N3 = N2 + 100% recommended application of S, Zn, and B through chemical fertilizer and (4) N4 = 50% of N2 + 50% of nitrogen through organic fertilizer as vermicompost.

The recommended dose of macronutrients (Directorate of Sorghum Research, 2007) for N2 as N-P_2O_5-K_2O was 80–40–30 kg ha^{-1}. For N3, in addition to these macronutrients, 30 kg ha^{-1} S, 10 kg ha^{-1} Zn and 0.5 kg ha^{-1} B were recommended as micronutrients. For the N4, the dose of vermicompost (1.0% nitrogen and 0.8% phosphorous) was based on the nitrogen requirement of sorghum. Vermicompost was applied to meet the 50% requirement of recommended nitrogen and the rest 50% of nitrogen was supplemented through chemical fertilizer. The fertilizers as per treatments were applied before sowing except for N, where 50% of N was added as basal and the remaining 50% at 30 days after sowing. The fertilizers sources for nutrients were Urea for nitrogen, DAP (Di ammonium phosphate) for phosphorous and nitrogen, Single Super Phosphate for phosphorous, Muriate of Potash for potassium, Gypsum for sulphur, Zinc sulphate for zinc, and Agribor for boron.

The BBF system, a 120-cm wide bed with 30-cm wide and 15-cm deep furrows on both sides, was made with the help of bullock-drawn Tropicultor implement. During both the years of experimentation, the seeding rates were 7.5 kg ha^{-1} for sorghum cultivar CSH16 with a row spacing of 45 cm. The experimental field was kept free from weeds throughout the crop growth period and necessary plant protection measures were taken to control insect attack and diseases.

2.2. Field data collection

2.2.1. Above ground biomass sampling and soil moisture monitoring

Sorghum plant samples for recording above ground biomass were collected at 15, 30, 45, 60, 75 days after sowing (DAS) and at maturity during both years. From each plot, representative plants were considered as sample (Wani et al., 1999). The sampled plants were uprooted keeping roots intact, cleaned, and washed in water to remove surface contamination, and separated into roots, stems, leaves, and heads, if any. Thereafter, the plant parts were kept in paper packets which in turn were placed in an oven for drying at 80 °C till constant weights were obtained. Dry biomass of leaves, stems, and roots were noted. The sum of the weights of leaf and stem of these plants was used as the total above ground dry biomass production estimation.

The sorghum crop was grown as rainfed. The field experiment with six access tubes were installed up to 120 cm soil depth in each land-water management for the nutrient management 'N3′ treatment only to maintain uniformity. A calibrated neutron probe (503DR Hydroprobe, CPN International, Concord, CA) was used to monitor SWC (Wani et al., 1999) at selected intervals up to 120 cm depth. The source of the neutron probe was lowered down to 120 cm soil depth at 15 cm intervals and SWC was recorded from eight depths at regular interval. The SWC values at each 15 cm soil depth were computed into volumetric water content and averaged for the top, sub, middle, and bottom soil layer.

Standard deviation (σ) and standard error were calculated by the following equations:

$$\sigma = \sqrt{\frac{\sum (X - \overline{X})^2}{n - 1}} \tag{1}$$

$$Standarrd \quad error = \frac{\sigma}{\sqrt{Number \quad of \quad values \quad in \quad the \quad data \quad set}} \tag{2}$$

Where $\sum$= add up.
σ = standard deviation.
X = Individual observations.
$\overline{X}$ = average.
n = number of observations.

2.2.2. Grain yield and rainwater use efficiency of sorghum

For grain yield estimation, the sorghum crop was harvested from an area of 9.0 m^2 in each plot, where plant sampling was not done earlier. Sorghum heads were dried in an oven. Seeds from individual plots were cleaned and weight of seed was recorded. In the present study, total rainfall (mm) during sorghum growing period was recorded and RWUE was determined in treatment plots. RWUE of sorghum was calculated by the following equation:

$$\text{Rainwater use efficiency}(kgha^{-1} \quad mm^{-1}) = \frac{\text{Grain yield}, kgha^{-1}}{\text{Total rainfall, mm}} \tag{3}$$

2.3. Simulation

The CERES-Sorghum of DSSAT V4.6 was calibrated and validated using present field experimental data. This model was used to simulate the grain yield under climate change scenarios in the Parbhani location of Maharashtra in India, which has a semi-arid tropical climate. The N3 treatment (application of macro-and micronutrient through chemical fertilizer) recommended in this study was evaluated as an adaptation strategy.

2.3.1. Location characterization, climate change scenarios and trend analysis

Parbhani location of Maharashtra in India was selected for simulation of sorghum grain yield (Fig. 1). It is situated at 19.25° N latitude and 76.50° E longitude with 891 mm annual rainfall and the average maximum and minimum temperature are 31 °C and 18 °C, respectively. The layer-wise physical properties of soil in Parbhani location consisted of 14.5% sand, 35.5% silt, and 50% clay in 0–15 cm soil depth; 13% sand, 35% silt, and 52% clay in 15–22 cm soil depth; 15% sand, 34.1% silt, and 50.9% clay in 22–30 cm soil depth; and 31% sand, 38.5% silt, and 30.5% clay in 30–32 cm soil depth (Soil resource inventory of Marathwada, 2002). Sorghum has fibrous root system with 86–87% root biomass and 77–78% root length found in 0–40 cm soil depth (Myers, R. J.K, 1980). Hence, 0–30 cm soil depth was considered in this simulation study. The soils at ICRISAT and simulation site (Parbhani) are vertisols with similar properties and soil data included in the DSSAT model for evaluation. Authors used climate data of Coupled Model Intercomparison Project Phase 5 (CMIP5) for 5 no. of Global Circulation Models (GCMs) and multi-model mean approach was adopted. The future climate data was computed for the study area and climate change scenarios were created for the periods 2021–2040 and 2041–2060 with a representative concentration pathway (RCP) as RCP 4.5 (Van Vuuren et al., 2011). The RCP 4.5 climate scenario was selected for evaluation of agro-adaptation, because RCP 4.5 is a stabilized scenario of long-term, in

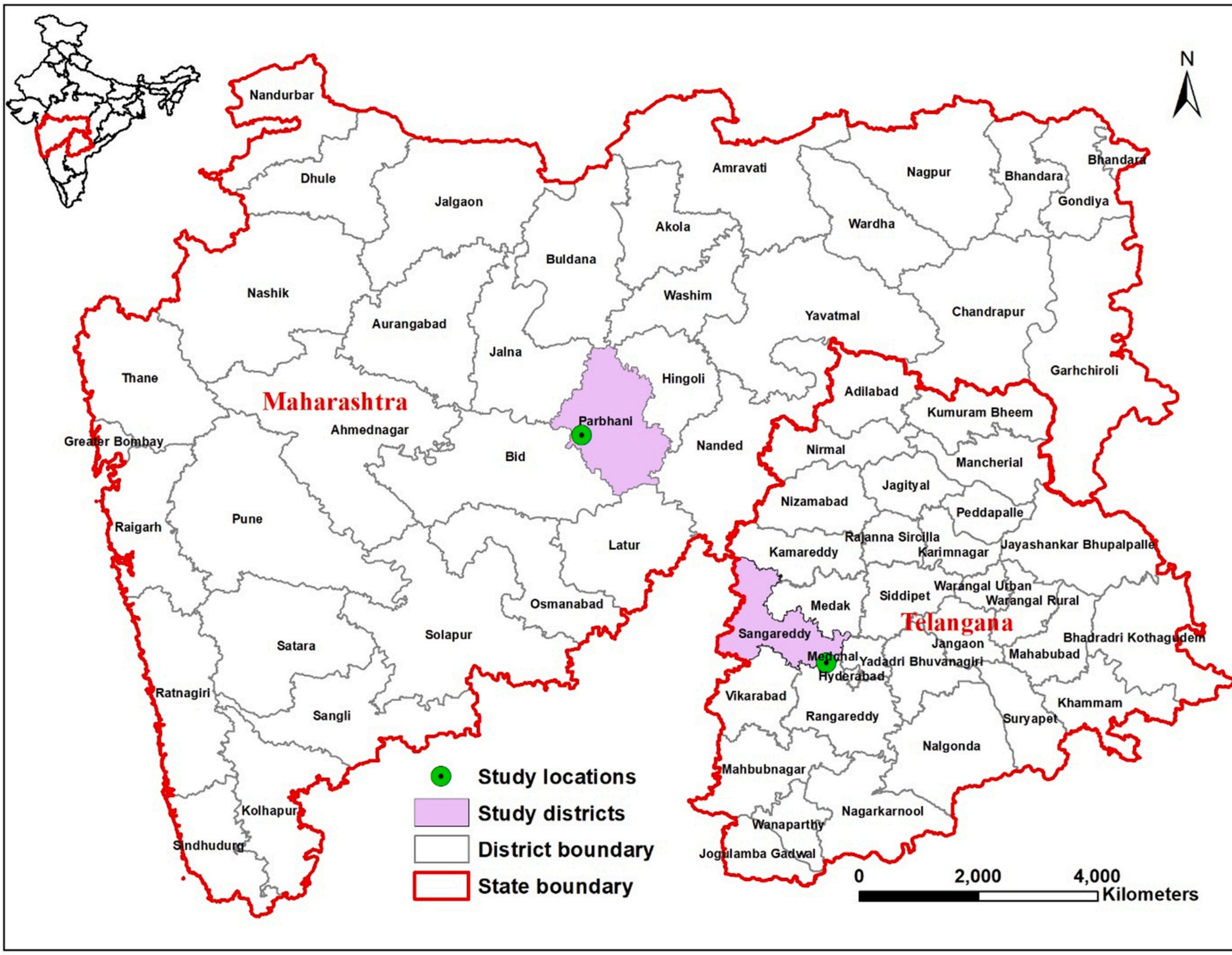

Fig. 1. Field experiment location at ICRISAT, Hyderabad in 'Telangana state' and simulation assessment of sorghum yield for Parbhani location in 'Maharashtra state' in semi-arid tropics of India.

which total radiative forcing is stabilized at 4.5 W m^{-2} without overshoot and to be stabilized by the year 2100 owing to improved technologies and reduced greenhouse gas emissions.

The trend analysis of time series data of the hydrologic variables such as precipitation and temperature consist of determining the magnitude of the trend and its statistical significance (Dash et al., 2009; Kumar and Jain, 2010; Subash and Sikka, 2014). Sen's slope estimator determines the magnitude of the trend and the Mann-Kendall test determines the significance of the trend. In present study, these tests were carried out on time series data of maximum temperature, minimum temperature, rainfall, and solar radiation for the base period (1988–2007) and future periods (2020–2040 and 2041–2060) for RCP 4.5 scenarios on annual basis.

Sen's slope estimator.

Sen's slope estimator (Sen, 1968) determines the magnitude of the trend (true slope) per year. To determine the magnitude of the slope of data, the slope (β) of all the data pairs was calculated.

$$\beta_i = \frac{x_j - j_k}{j - k}, i = 1, 2, \ldots n \quad j > k \tag{4}$$

Where, x_j and x_k are the values of data points at time j and k, respectively provided $j > k$. The median of these β values give Sen's slope estimator 'm' as;

$$m = \begin{cases} \beta_{\frac{n+1}{2}} & if \quad n \quad is \quad odd \\ \frac{1}{2}\left(\beta_{\frac{n}{2}} + \beta_{\frac{n+2}{2}}\right) & if \quad n \quad is \quad even \end{cases} \tag{5}$$

The positive value of 'm' indicates an increasing trend whereas negative value indicates decreasing trend.

Mann-Kendall test.

The Mann-Kendall test (Mann, 1945; Kendall, 1975) is a non-parametric test, which is carried out to assess the significance of the trend of variable over time. The test evaluates the null hypothesis which states there is no trend in data against the alternative hypothesis which states existence of an upward (positive) or downward (negative) trend. The statistic (S) has been defined as;

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \text{sgn}(x_j - x_i) \tag{6}$$

Where n is the number of data (years) points. Further, considering $(x_j - x_i) = X$, the value of sgn(X)

$$\text{sgn}(X) = \begin{matrix} +1 if & x > 0; \\ 0 if & x = 0 \\ -1 if & x < 0 \end{matrix} \quad (7)$$

For large samples (n > 10), the test is carried out using normal distribution with mean E [S] = 0 and variance given by;

$$\text{var}(S) = \frac{n(n-1)(2n+5) - \sum_{k=1}^{m} t_k(t_k - 1)(2t_k + 5)}{18} \quad (8)$$

Where 'm' is the number of tied groups in the dataset and t_k is the number of data points in j^{th} tied group. For the normally distributed data, the standard normal variate Z is given by;

$$Z = \begin{cases} \frac{S-1}{\sqrt{\text{var}(S)}} & if \quad S > 0 \\ 0 & if \quad S = 0 \\ \frac{S+1}{\sqrt{\text{var}(S)}} & if \quad S < 0 \end{cases} \quad (9)$$

The null hypothesis is rejected at α level of significance in two-sided test if $|Z_{calculated}| > Z_{\alpha/2}$. In the present analysis, the null hypothesis was tested at 95% confidence level (i.e. α = 0.05).

2.3.2. Calibration and validation of CERES-Sorghum

The data on phenological events such as sowing date, panicle initiation day, anthesis day, physiological maturity day, time series above ground biomass, yield components, and grain yield were used for the model calibration and validation. Genotype parameters of the CERES-Sorghum model were estimated through calibration and evaluation process. The genotype coefficients for the 'CSH16′ cultivar of sorghum were calibrated for the recommended macro and micro-nutrient management using respective first year experimental data on phenology, time series biomass, yield components, and grain yield. The second year experimental data were used for evaluation of the model. Model performance indicators such as Root Mean Square Error normalized (RMSEn) and D-index were used for calibration and validation of model performance (Willmott et al., 1985).

$$RMSE_n = \frac{\left(\frac{\sum_{i=1}^{n}(S_i - Ob_i)^2}{n}\right)^{0.5}}{\overline{Ob_{avg}}} \quad (10)$$

$$D - index = 1 - \frac{\sum_{i=1}^{n}(S_i - Ob_i)^2}{\sum_{i=1}^{n}(|S_i - \overline{Ob_{avg}}| + |Ob_i - \overline{Ob_{avg}}|)^2} \quad (11)$$

Where S_i and Ob_i are the model simulated and experimental measured values, respectively.

$\overline{Ob_{avg}}$ is the average of observed values and n is the number of observations. In the present study, the values of RMSE were 0.18 and 0.23, and D-index were 0.99 and 0.97 during model calibration and evaluation, respectively.

2.3.3. Sorghum grain yield simulation for climate change scenario

Sorghum grain yield under climate change scenarios was simulated for Parbhani location in semi-arid tropics of India using calibrated genotype parameters of the cultivar, and existing crop management practices. The effect of different sowing dates on sorghum grain yield was simulated for the Parbhani location in semi-arid tropical India. The sowing dates were three weeks before and after the normal sowing date (June 30 in sorghum) during the rainy season. Accordingly, sowing dates were 10 June, 20 June, 30 June, 10 July, and 20 July in sorghum. A smaller interval of 5 days may not bring the variation in the temperature. Hence, to capture the effect of varying temperature and to get the response of changing climate on crop yield, sowing dates with 10 days interval as an adaptation strategy was evaluated. Moreover, several researchers (Ameta and Sumeria, 2004; Singh et al., 2017; Sannagoudar et al., 2023) clearly indicated that, incidence of shoot fly, stem borer and midge increase in sorghum sown in July than sorghum sown in June and per cent reduction in yield increased with delay in sowing after 20 July. Hence, in the simulation study, 10 June, 20 June, 30 June, 10 July and 20 July as sowing dates were considered and more late planting dates after 20 July were not considered in the present simulation study. It is important to note that, sowing time is very crucial operation from farmers point view and further management practices viz., inter-cultivation, weeding, nutrient management and irrigation application depends on optimum sowing time. Therefore, only sowing dates were evaluated as an agro-adaptation strategy and additional adaptation strategies viz., nutrient management and SWC were not evaluated, though measured SWC data was available. The climate scenarios were employed for simulation of sorghum grain yield at different sowing dates with recommended macro and micro-nutrient management and the best date of sowing with the highest grain yield in the base period was identified for sorghum for the Parbhani location. The best date of sowing in the base period (1988–2007) was identified and grain yield was simulated for future periods (2021–2040 and 2041–2060) in the RCP 4.5 scenario.

Variable sowing dates with recommended macro and micro-nutrient management in sorghum were evaluated as agro-adaptations to climate change in the semi-arid tropics of India. The change in simulated grain yield of sorghum for the future climate change scenarios (RCP 4.5) in varying sowing dates was compared with the normal sowing date in the base year for evaluation of the adaptation strategy at Parbhani location in the semi-arid tropics of India. The percentage change in the yield was calculated under varying sowing dates with respect to normal sowing date in base period to find out the suitable sowing date for the future scenarios in RCP 4.5 to minimize the adverse impact of climate change on sorghum.

$$Change \quad in \quad yield \quad (\%) = \frac{Y_c - Y_b}{Y_b} \times 100 \quad (12)$$

Y_c = Average yield of sorghum with changed climate scenario under varying sowing dates.

Y_b = Average yield of sorghum in base period with normal sowing date.

2.4. Statistical analysis

The data collected on grain yield and RWUE were statistically analyzed with analysis of variance test (Gomez and Gomez, 1984) and the least significant difference (LSD) of the treatment means were calculated at the $p < 0.05\%$ level. The LSD values were calculated whenever the *F*-test was found to be significant. In the case of non-significant effects, the standard error of means (SEm) alone was considered.

3. Results and discussions

3.1. Grain yield and rainwater use efficiency of sorghum

The data pertaining to grain yield and RWUE of sorghum were statistically analyzed for both years (2014 and 2015). The grain yield of sorghum in both years was significantly higher in BBF than in flatbed (Fig. 2a). In BBF, the grain yields of sorghum were 2449 and 2873 kg ha^{-1} in 2014 and 2015, respectively. The BBF increased the sorghum grain yield by 22.20% in 2014 and 33.56% in 2015 over flatbed. The RWUE was significantly influenced by land-water management during the first year (2014) only. The RWUE recorded in BBF (12.03 and 6.26 kg ha^{-1} mm^{-1} of rainwater) was higher compared to flatbed (9.94 and 5.29 kg ha^{-1} mm^{-1} of rainwater) in the years 2014

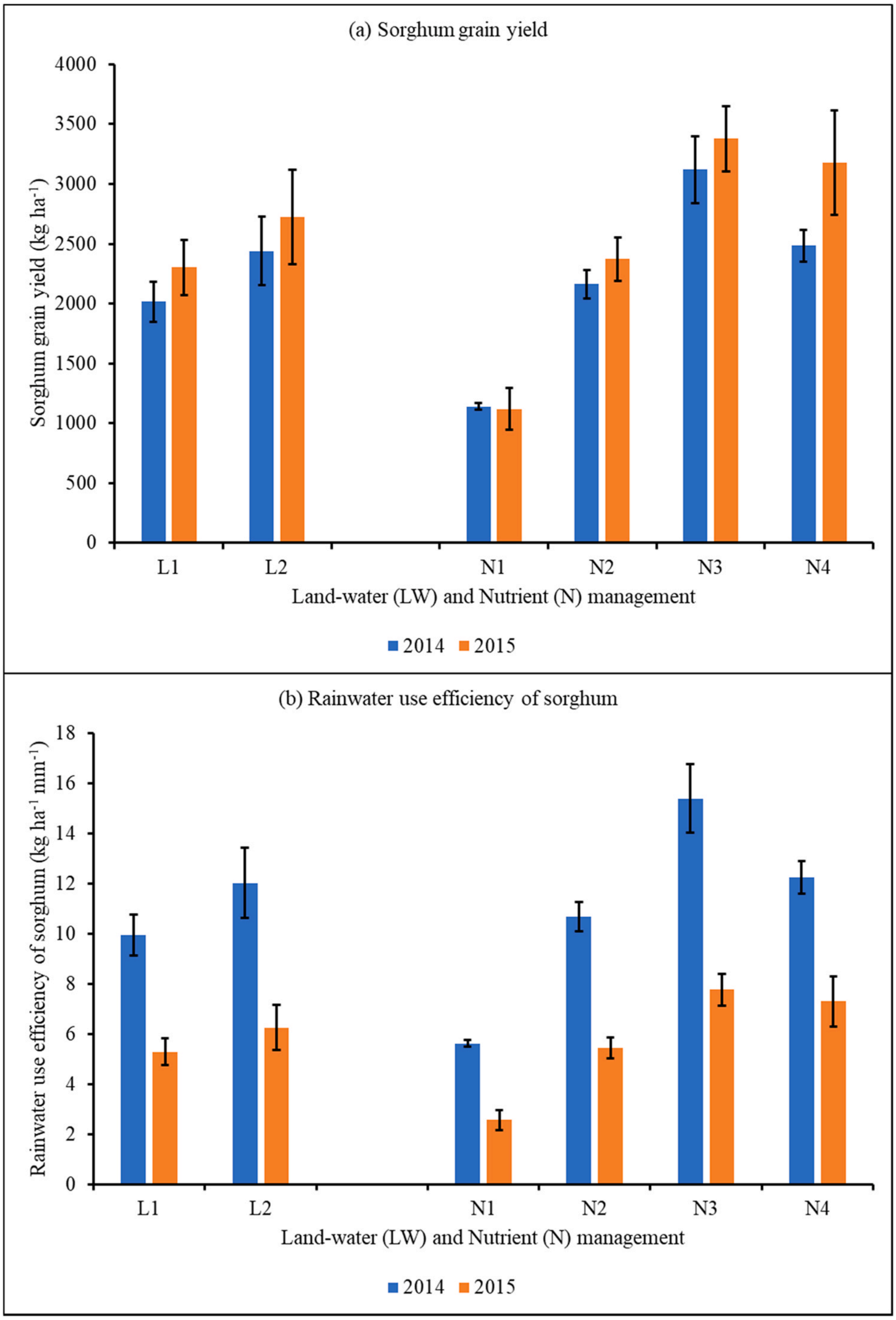

Fig. 2. Grain yield (a) and rainwater use efficiency (b) of sorghum as influenced by two land-water management (L1 =Flatbed and L2 =Broad bed furrows) and four nutrient management (N1 = control, no fertilizer; N2 = 100% recommended application of macronutrient through chemical fertilizer; N3 = N2 + 100% recommended application of S, Zn, and B through chemical fertilizer and N4 = 50% of N2 + 50% of nitrogen through organic fertilizer as vermicompost) during the year 2014 and 2015. The error bar indicates standard error.

and 2015, respectively (Fig. 2b). The grain yield of sorghum responded markedly to nutrient management treatments and a significantly higher grain yield was recorded in N3 (3120 kg ha^{-1}) compared to N1 (1140 kg ha^{-1}), N2 (2163 kg ha^{-1}), and N4 (2484 kg ha^{-1}) in 2014. However, the sorghum grain yield in N3 (3379 kg ha^{-1}) was statistically comparable with N4 (3177 kg ha^{-1}), and both the treatments were significantly superior to N1 and N2, in the year 2015 (Fig. 2a).

The RWUE of 15.39 kg ha^{-1} mm^{-1} was significantly higher in N3 (100% recommended application of macro and micro-nutrients) over the N1, N2, and N4 nutrient management treatments in the first year (2014). However, the nutrient management treatment N3 (7.77 kg ha^{-1} mm^{-1} of rainwater) and N4 (7.30 kg ha^{-1} mm^{-1} of rainwater) were comparable but significantly higher than N1 and N2 during the second year (2015) (Fig. 2b). The interaction effect between land water management and nutrient management treatments on grain yield and RWUE of sorghum was significant in first year (2014–15) only.

The land-water management 'BBF' with 100% recommended application of macro-and micronutrients through chemical fertilizer (N3) significantly influenced the sorghum grain yield. This combined effect of land-water and nutrient management resulted from the timely availability of nutrients in the required quantity, which further enhanced nutrient uptake and its accumulation in different plant parts. This is reflected in higher grain yield in BBF with the recommended application of macro- and micro-nutrients through chemical fertilizer. Moreover, the combined and interlinked various components like increased availability of soil moisture, enhanced availability, and better transportation of macro (N, P, and K) and micronutrient (S, Zn, and B) in BBF with N3 (CF for macro- and micro-nutrients) possibly resulted in effective functioning of plant's physiological process like maintaining membrane integrity which enhanced the ability of membranes to transport vital nutrients (Cakmak et al., 1995; Sadeghzadeh and Rengel, 2011), which lead to increased sorghum grain yield.

In this study, integrated nutrients management (N4) through CF and vermicompost resulted in higher grain yield as compared to the application of macronutrients only through CF (N2) in sorghum. Vermicompost is an enriched source of nutrients (Chander et al., 2013) and its application could improve nutrient availability, crop growth, and yield components. Compared to CF, nutrients from vermicompost were slowly released and were available slowly for longer period for crop uptake. The slow-release pattern of nutrients in the integrated nutrient management treatment (N4) (Densilin et al., 2011; Kumar et al., 2011) possibly did not fulfill the nutrient requirement of crops at specific growth stages, hence could not attend the yield as in N3 (recommended macro- and micronutrients through CF). Results of the long-term experiments at the heritage watershed site at ICRISAT, Patancheru, India have shown that integrated watershed interventions, which focused on balanced nutrient management along with crop, and land-water management practices can sustainably increase rainfed crop yield by five folds as compared to that under traditional farmers practice (Wani et al., 2012; Wani and Rockström, 2011).

The sorghum grain yield was lowest in no fertilizer application (Control), which was due to the inability of the soil to fulfill the nutrient requirement of plant for proper growth and development. The consistent uptake of nutrients by plants declined the macro and micro-nutrient reserves from native soil fertility (Bell et al., 2010) and nutrients were inappropriately available to plants, which further resulted in lower grain yield in no fertilizer application.

The RWUE depends on grain yield and a higher yield of sorghum resulted in higher RWUE. Higher RWUE in BBF and N3 treatments could be due to the combined effect of higher SWC and the 100% recommended application of N, P, K, S, Zn, and B which enhanced grain production. This combined effect of land-water management and nutrient provided a sufficient amount of water and nutrients, which not only increased aboveground crop biomass but also root biomass which effectively utilized water and nutrients. The growth of aboveground crop biomass contributed to efficient conversion of unproductive evaporation loss in productive transpiration, which resulted in increased crop yield and RWUE.

3.2. Soil water content in sorghum

Soil water content plays a crucial role in determining crop

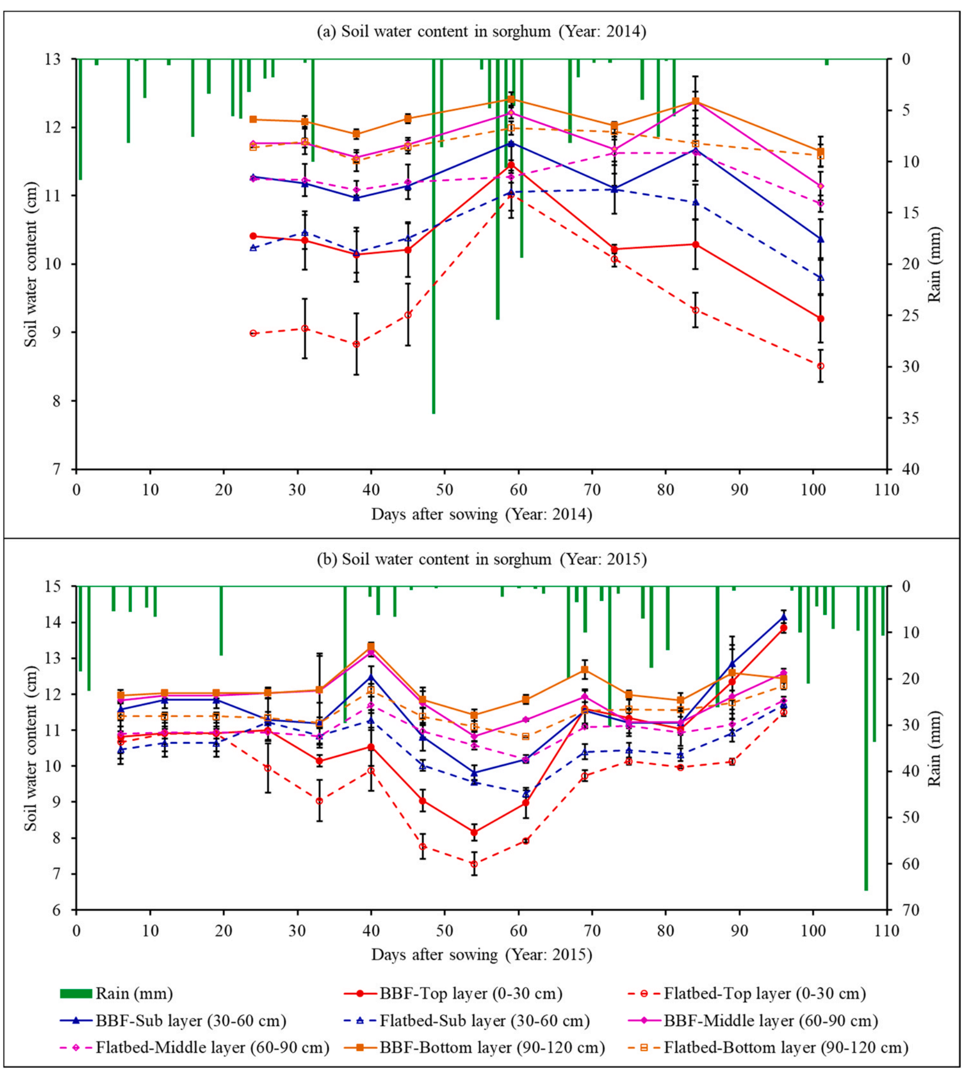

Fig. 3. Soil water content (cm) in the top layer (0–30 cm), sub layer (30–60 cm), middle layer (60–90 cm) and bottom layer (90–120 cm) of BBF and flatbed in sorghum during 2014 (a) and 2015 (b). The error bars indicate standard error.

productivity in SATs (Patil and Sheelavantar, 2004; Pathak et al., 2011; Hati et al., 2013) and SWC were monitored for a short duration and commonly focused only on the top soil layer. In this study, SWC was evaluated in four soil layers (top, sub, middle and bottom) under the two land-water management practices in rainfed sorghum. Compared to flatbed, the average SWC in BBF was higher by 0.90 cm and 1.06 cm in the top layer, 0.67 cm and 1.02 cm in the sub-layer, 0.51 cm and 0.84 cm in the middle layer and, 0.34 cm and 0.67 cm in the bottom layer of soil during 2014 and 2015, respectively (Fig. 3a and b).

Land-water management practices have a direct effect on SWC (Fig. 3a and b). The formation of raised beds due to BBF restricted the velocity of runoff generated from rainwater and allowed more opportunity time for soil water to retain in the furrows as compared to the flatbed. Moreover, raised bed increased the soil surface area and improved the horizontal movement of water from furrow to the inner layer of BBF. Also, BBF decreased runoff, and the infiltration rate was increased due to more time for water to infiltrate into deeper soil layers and increased SWC in different soil layers throughout 0–120 soil profile. The Vertisol has typical characteristics i.e. the dry period before rainy season resulted in the formation of large cracks in furrows and micro-cracks on raised beds appear during the dry period within the rainy season. This distinctive nature of Vertisols significantly reduced runoff generated from rainwater and increased SWC in BBF compared to the flatbed. While high runoff towards the slope without any obstruction decreased infiltration rate and contributed to lower SWC in the flatbed. Moreover, compaction of soil reduces internal drainage leading to decreased soil water conservation and thereby lower SWC in flatbed (Patil and Sheelavantar, 2004; Pathak et al., 2011; Hati et al., 2013).

3.3. Soil water content during longest dry period in sorghum

The SWC varies with the occurrence of rainfall and dry period between two rainy events. The SWC reached to highest when heavily rained and lowest in the dry period during the crop growing period. In SATs, dry period during the crop growing season is common and variation in SWC during such dry period would be the researchable area for the Authors to understand the effect of BBF over flatbed. Thus, the longest dry period during the cropping period was considered to study the variation in SWC between dry periods. The longest dry period of 26 days occurred between 76 and 101 DAS during the first year (2014).

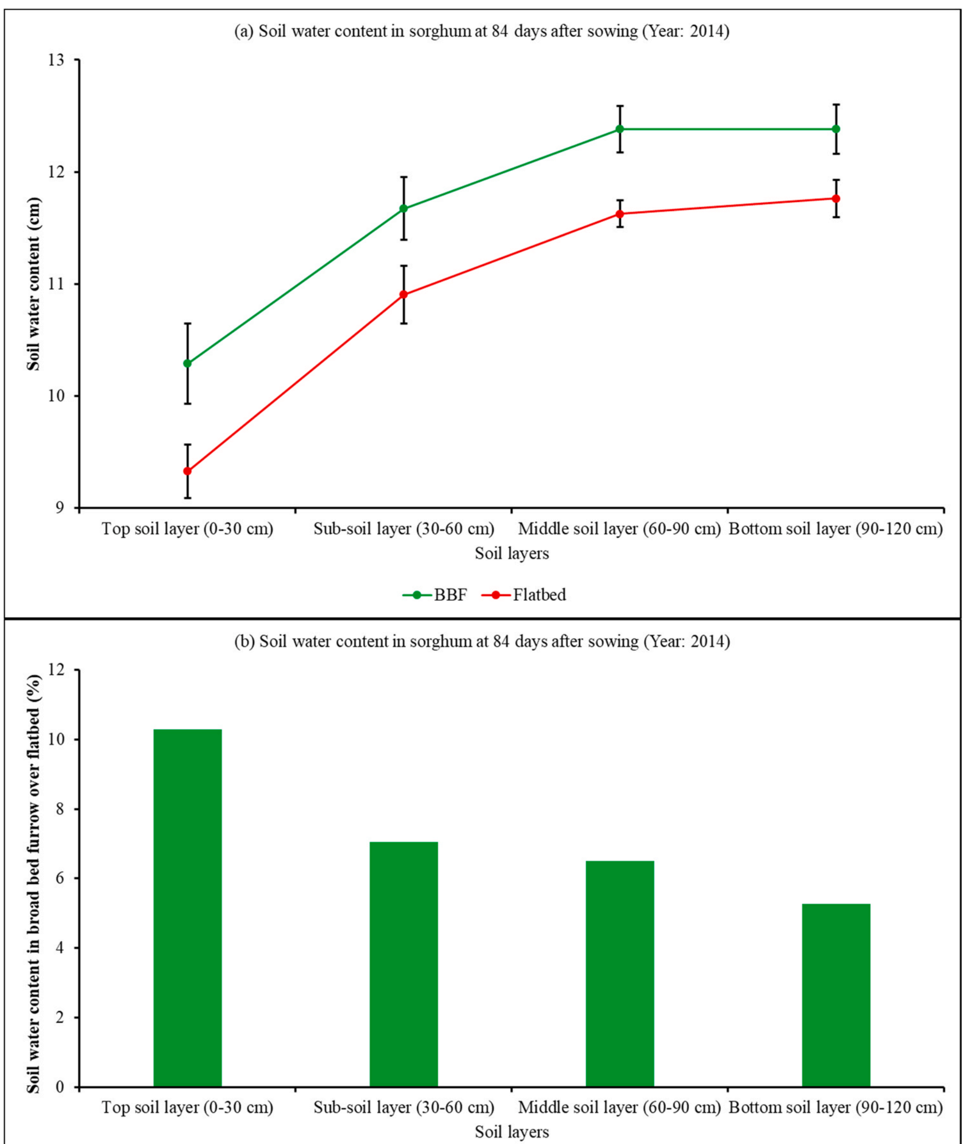

Fig. 4. Soil water content in BBF and flatbed during longest dry period in the top, sub, middle, and bottom soil layers in sorghum at 84 days after sowing during 2014. The error bars indicates standard error.

Therefore, the SWC data point at 84 DAS in 2014 was evaluated to test the effect of BBF over flatbed (Fig. 4a and b).

The analysis of data revealed that the SWC in BBF was higher over flatbed in different soil layers during the longest dry period of 26 days in sorghum (Fig. 4). The SWC during the longest dry period at 84 DAS was 10.29 cm and 9.33 cm in the top layer, 11.67 cm and 10.91 cm in sub-layer, 12.38 cm and 11.63 cm in the middle layer, and 12.38 cm and 11.76 cm in bottom soil layer in BBF and flatbed, respectively (Fig. 4a). Layer wise assessment of SWC data during the longest dry period indicated that percent increase of SWC in BBF over flatbed showed decreasing trend as the soil depth increased i.e. bottom < middle < sub < top soil layer. The SWC in BBF increased over flatbed by 10.30% in the top layer, 7.05% in the sub-layer, 6.50% in the middle layer, and 5.27% in the bottom layer during the longest dry period in sorghum at 84 DAS (Fig. 4b).

The poor internal drainage in Vertisols resulted in reduced water infiltration from the top to bottom soil layer. Compared to the middle and bottom layer of soil, the formation of micro-cracks during the dry period within the rainy season contributed to infiltrate and recharge soil water up to the top layer. This indicates that lesser soil water recharge happened in the middle and bottom layers of soil. Hence, SWC in BBF over flatbed during the longest dry period showed a decreasing trend with increased soil depth under sorghum (Fig. 4). Similar results were noted in the long-term study from 1976 to 2010 (Pathak et al., 2013) at ICRISAT, Hyderabad in the semi-arid zone, which showed mean annual deep drainage was 3% in lower rainfall regions (< 750 mm annual rainfall) and 13% in medium rainfall regions (750–900 mm annual rainfall) of the mean annual rainfall. In the same study (Pathak et al., 2013), poor soil water recharge i.e. reduced infiltration was noted in Vertisols with low rainfall areas in SAT regions and thereby lower SWC in middle and bottom soil layers compared to the top soil layer. Another reason for decreasing SWC trend as the soil depth increased could be

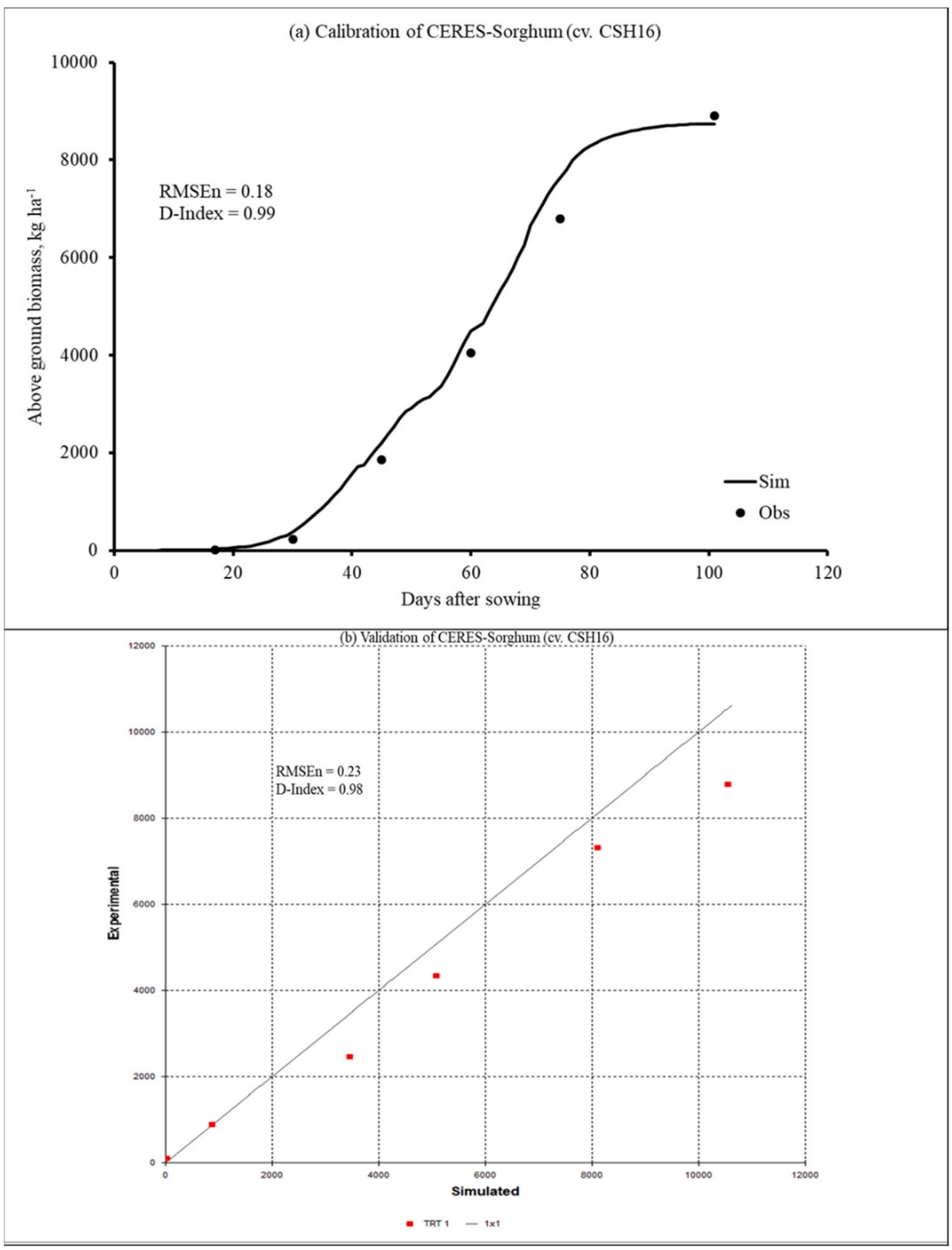

Fig. 5. Observed (Obs) and simulated (Sim) time series above ground biomass of sorghum (cv. CSH16) grown with recommended macro-and micronutrients management at ICRISAT, Hyderabad (a) Calibration of CERES-Sorghum (cv. CSH16) during rainy season of the year 2014 and (b) Validation of CERES-Sorghum (cv. CSH16) during rainy season of the year 2015. The RMSEn indicate Root Mean Square Error normalized (RMSEn).

more crop foliage coverage around sorghum maturity stage, which reduced the soil temperature owing to lesser solar radiation on the surface soil resulting in decreased evaporative losses and thereby soil moisture conservation.

In the field study, longest dry period occurred at 84 days after sowing, which was grain filling stage in sorghum. The grain filling stage is critical crop growth stage, when crop's water and nutrient requirement is more. However, sufficient SWC in BBF during longest dry period might have contributed to appropriate availability of water and nutrients during grain filling stage, thereby higher water and nutrient uptake, and leading to higher grain yield of sorghum in BBF. Several studies reported that moisture conservation measures such as BBF increased sorghum yield by 13.16% (Patil et al., 1991) and pearl millet by 17% in ridge and furrows (Singh and Verma, 1996) over flatbed planting due to higher SWC (Ramesh and Devasenapathy, 2007; Thakur et al., 2011) and better availability of water, which also transported nutrients (Chander et al., 2013).

3.4. Sorghum yield simulation for the climate change scenarios

3.4.1. Model calibration and validation

The genotype coefficients of CERES-Sorghum model were calibrated using the crop experimental data of recommended macro- and micronutrient management through CF. During the calibration process, a close match between observed and simulated values of time series above ground biomass of sorghum (RMSEn=0.18 and D-index=0.99) was noted when grown with recommended macro and micronutrients management through CF (Fig. 5). Compared to the observed value (Table 1), the simulated days for anthesis were within ± 2 days and physiological maturity was within ± 1 day and the grain yield variation was marginal (3%). The calibrated genotype coefficients for sorghum are given in Table 2. The calibrated coefficients were validated for above ground biomass and grain yield using experimental data of the second year (2015) for macro-and micronutrient management treatments conducted in the field experiment. During validation, the above ground biomass of experimental and simulated values were in a close match (Fig. 5) up to maturity. Between the simulated and observed values of biomass, the lowest variation (RMSEn= 0.23 and D-index=0.98) was noted with recommended macro and micronutrient management treatment (N3).

3.4.2. Climate trend analysis and crop yield simulation

The trend analysis of maximum temperature (Tmax), minimum temperature (Tmin), rainfall, and solar radiation (SRAD) was carried out for the base period (1988–2007) and future periods (2021–2040 and 2041–2060) for RCP 4.5 climate scenario at the Parbhani location in SAT of India. The analysis was carried out with the Mann-Kendall test and Sen's slope estimator and the results are presented in Table 3. For the Tmax and Tmin, an increasing trend was observed for the base period (1988–2007) as well as future periods (2021–2040 and 2041–2060) in RCP 4.5. The increasing trend was significant ($p < 0.05$) for Tmax, which stated an increase in temperature at 0.065 °C year^{-1} in 2021–2040 and 0.046 °C year^{-1} in 2041–2060. For rainfall, a negative trend was noted for the base period (1988–2007) as well as the future period (2021–2060), however, they were non-significant. For the solar radiation, significantly negative trend ($p < 0.01$) was observed for the base period (1988–2007) and future periods (2021–2060), which is expected to decrease in the range 0.081–0.082 MJ m^{-2} day^{-1} year^{-1}.

Table 1
Simulated and observed phenology and grain yield of sorghum grown under Broad bed furrow with recommended macro and micro-nutrients management during rainy season of the year 2014 at ICRISAT, Hyderabad (Calibration of CERES-Sorghum).

Crop parameters	Simulated	Observed	Change
Anthesis day (DAP)	64	62	+ 2 days
Physiological maturity (DAP)	101	102	-1 day
Grain yield at maturity (kg ha^{-1})	3837	3733 (± 74)	+ 3%

DAP: Days After Planting, Value in bracket is standard deviation.

Table 2
Calibrated genotype coefficients of sorghum (cv. CSH16).

Coefficients	Value
P1, °C-days	350.5
P2, °C-days	102.0
P2O, h	13.5
P2R, °C-days	35.0
PANTH, °C-days	617.5
P3, °C-days	152.5
P4, °C-days	81.5
P5, °C-days	600.0
PHINT, °C-days	49.0
G1	12.0
G2	6.8

P1: Thermal time from seedling emergence to the end of the juvenile phase, P2: Thermal time from the end of the juvenile stage to tassel initiation under short days, P2O: Critical photoperiod, P2R: Extent to which phasic development leading to panicle initiation is delayed for each hour increase in photoperiod above P2O, PANTH: Thermal time from the end of tassel initiation to anthesis, P3: Thermal time from to end of flag leaf expansion to anthesis, P4: Thermal time from anthesis to beginning grain filling, P5: Thermal time from beginning of grain filling to physiological maturity, PHINT: Phylochron interval; the interval in thermal time between successive leaf tip appearance, G1: Scaler for relative leaf size, G2: Scaler for partitioning of assimilates to the head

The maximum sorghum grain yield (5240 kg ha^{-1}) was simulated for 30 June sowing (normal sowing date) with recommended macro and micronutrient management for the base period (1988–2007), while the grain yield declined in future periods during 2030 and 2050 (Fig. 6). The decrease in the sorghum grain yield was 16.39% in 2030 and 19.98% in 2050 for the RCP 4.5 scenario as compared to the base period yield (Fig. 7). Sannagoudar et al. (2023) reported that maximum reduction of sorghum grain yield was 32.85% due to the combined effect of reduced rainfall (20%) and rise in temperature (+2 °C) in the Karnataka, India situated in semi-arid region. The simulated output of this study also showed that early sowing of sorghum in June is suitable to attain higher yield compared to late sowing in July. Kothari et al. (2020) simulated the climate change impacts on grain sorghum production under full and deficit irrigation strategies and indicated that grain sorghum yield under full irrigation was expected to be reduced by 5% by mid-century (2036–2065) and by 15% by late-century (2066–2095) under RCP 8.5 compared to the baseline period (1976–2005). Another study conducted by Kothari et al. (2020a) assess the impacts of climate change on yield and water use of grain sorghum and reported that the irrigated grain sorghum yield is expected to decrease by 5–13% and 16–27% by mid-century (2036–2065) and late-century (2066–2095), respectively under RCP 8.5 compared to the baseline (1976–2005).

3.4.3. Evaluation of agro-adaptation

The sorghum grain yield was simulated for different sowing dates as an agro-adaptation option to find suitable sowing time to minimize the adverse impact of climate change on the grain yield in the future periods of 2030 and 2050 for the RCP 4.5 climate scenario. The grain yield of sorghum was simulated for the future periods (2030 and 2050) with the five sowing dates (10 June, 20 June, 30 June, 10 July, and 20 July) for the Parbhani location. The normal sowing date for sorghum in Parbhani location is around last week of June (30 June). At Parbhani, the

Table 3
Trend Analysis of Weather Data for Base Period (1988–2007) and Future Periods (2021–2040 and 2041–2060) Under the Climate Change Scenario (RCP 4.5) for Parbhani Location in SAT of India.

Maximum temperature		Minimum temperature		Rainfall		Solar Radiation	
Z value	Sen's slope, °C $year^{-1}$	Z value	Sen's slope, °C $year^{-1}$	Z value	Sen's slope, mm $year^{-1}$	Z value	Sen's slope, MJ m^{-2} day^{-1} $year^{-1}$
Base period (1988–2007)							
0.52	0.009	1.56	0.037	-0.19	-0.009	-3.05 * *	-0.081
RCP 4.5 (2021–2040)							
1.98*	0.065	0.94	0.031	-0.62	-0.031	-3.08 * *	-0.081
RCP 4.5 (2041–2060)							
2.56*	0.046	1.62	0.036	-0.32	-0.015	-3.15 * *	-0.082

* : significance level at α = 0.05; * *: significance level α = 0.01

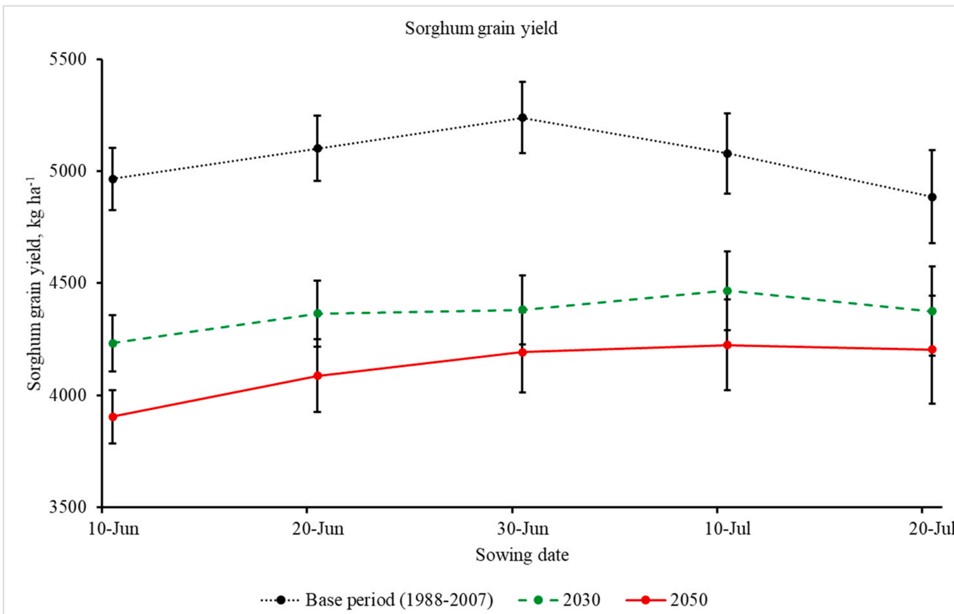

Fig. 6. Effect of varying sowing dates on simulated grain yield of sorghum (cv. CSH16) in base period (1988–2007) and future periods (2030 and 2050) for the climate change scenario (RCP 4.5) at Parbhani location in semi-arid tropics of India. The error bar indicates standard error.

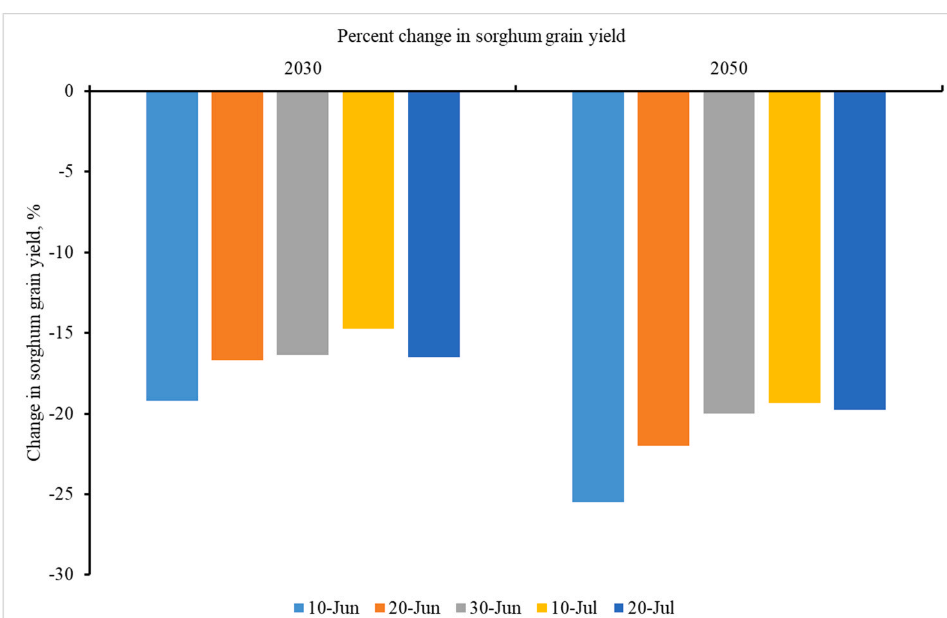

Fig. 7. Percentage change in the simulated sorghum grain yield under different sowing dates for the future periods (2030 and 2050) as compared to sowing date (30 June) in base period (1988–2007).

simulated grain yield of sorghum during 2030 and 2050 decreased with advanced sowing time (before 30 June), but increased with the later sowing date i.e. 10 July (Fig. 7). As compared to the base period yield (1988–2007) on normal sowing (30 June), the yield of sorghum decreased by 19.22% and 25.48% during 2030 and 2050, respectively for the early sowing on 10 June. In contrast, postponing of sowing (10 July) resulted in lower grain yield reduction i.e. 14.75% in 2030 and 19.37% in 2050 as compared to base period yield with the normal sowing (30 June). The grain yield reduction in 2050 was higher than in 2030 with all the five sowing dates (Fig. 7).

During the base period, variability in sorghum grain yield might be due to the sensitivity of grain crops to high temperatures during the reproductive stage than the vegetative stage (Farooq et al., 2011). The SATs are the most vulnerable regions and crop productivity could be substantially affected due to higher temperature and increase in rainfall variability, which was predicted in future climate change scenarios (Gray, 2007). However, the negative impact of higher temperature on tropical crop yields in future periods could be ameliorated by adjustment in sowing time, which could be one of the effective adaptation strategy to minimize the grain yield losses. The adjustment in sowing dates might not expose the crop to high temperature and heat stress during the reproductive stage.

This present simulation study for the Parbhani location stated that sorghum grain yield is reduced by 19.22% and 25.48% in 2030 s and 2050 s, respectively for RCP 4.5 scenario on 10 June sowing (early sowing dates) compared to the base period sorghum grain yield (5240 kg ha^{-1}) with normal sowing date (30 June). The yield reduction in future climate on 10 June sowing was higher than 30 June sowing. This higher yield reduction with early sowing is likely due to rise in temperature by 1.40 °C in 2021–2040 and 1.97 °C in 2041–2060 during crop growing period compared to base period (1988–2007) temperature (Fig. 8). This rise in temperature during future periods (2021–2040 and 2041–2060) might have increased evaporation losses of soil water. However, compared to early sowing, sorghum grain yield losses were relatively lower for postpone of sowing (10 July and 20 July). When the sowing is postponed to 10 July, the average temperature during sorghum reproductive growth period were 26.78 and 27.32 °C in 2021–2040 and 2041–2060, respectively. In future periods, the adverse impact of rising temperature on sorghum yield could reduce because temperatures were lower by 3.04 °C during 2021–2040 and 3.4 °C during 2041–2060. The optimum range for average daily temperature during the reproductive period is reported to be 25–28 °C for the sorghum crop (Prasad et al., 2006; Prasad et al., 2008).

Besides temperature, negative trend was noted for rainfall during the base period (1988–2007) and future periods (2021–2060). On the 10 July sowing date, flowering to grain filling stage i.e. reproductive period is expected to appear in September. The grain filling stage in sorghum occurs between 70 and 80 DAS, which can be seen during last week of September for the 10 July sowing date. Similarly, the grain filling stage for early sowing (10 June) will appear in August, but for later sowing date (after 10 July), it may appear in October. From Fig. 9, this can be understood that the reduction in rainfall in future period is lower in September as compared to August and October. Thus, during the grain filling stage, the crop will be less affected by drought if sown around 10 July. Therefore, sowing of sorghum around 10 July in future period is recommended to mitigate the adverse impact of rising temperature and variability in rainfall due to climate change.

4. Conclusions

Climate change has a severe adverse effect on rainfed crop production systems in semi-arid tropics (SATs). The present study was conducted with specific objectives to evaluate the effect of broad bed furrow over flatbed for improving rainwater use efficiency and soil water content in different soil layers during longest dry period and recommend sowing time as an agro-adaptation strategy for sorghum production in SATs in India. The results of the study revealed that compared to flatbed, broad bed furrow had significantly higher rainwater use efficiency (21% in 2014 and 18% in 2015) of sorghum. The broad bed furrow conserved higher soil water compared to 'flatbed' throughout the sorghum growing period in all the four soil layers (0–30 cm, 30–60 cm, 60–90 cm, and 90–120 cm), maximum being in the top layer (0–30 cm) with an increase up to 11% over flatbed. Layer-wise soil water content data during the longest dry period of 26 days in the year 2014 indicated that the percent increase of soil water content in broad bed furrow over flatbed showed decreasing trend as the soil depth increased i.e. bottom < middle < sub < top soil layer. The adverse effect of climate change on sorghum production in semi-arid regions can be minimized to a certain

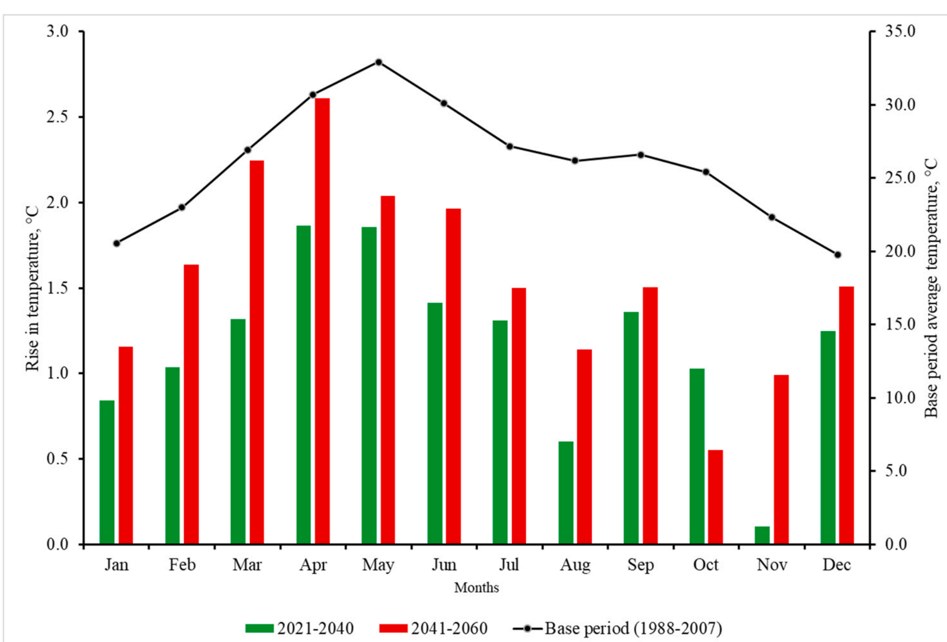

Fig. 8. Rise in daily average temperature for different months in future climate change scenario (RCP 4.5) for the periods (2021–2040 and 2041–2060) as compared to base period (1988–2007) average temperature at Parbhani location in semi-arid tropics of India.

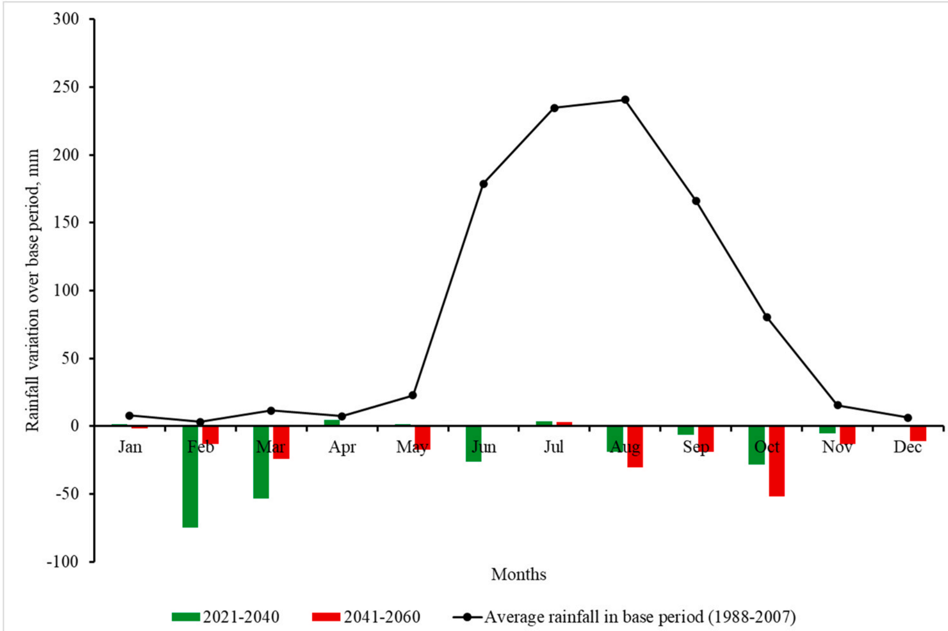

Fig. 9. Variation in rainfall for different months in future climate change scenario (RCP 4.5) for the periods (2021–2040 and 2041–2060) as compared to base period (1988–2007) average rainfall at Parbhani location in semi-arid tropics of India.

extent by postponing the sowing operation from 30 June to 10 July in the future period (2021–2040 and 2041–2060) in Parbhani, India. However, further later planting of sorghum after 10 July is more prone to incidence of shootfly, hence may not be recommended for normal cultivars. Results of the present study could be recommended to similar agro-climatic regions in SATs of Asia and Africa, where sorghum production is low due to climate change. Based on the findings of this study, it would be concluded that integrated land-water-nutrient management and postponing the sowing time (to 10 July) of sorghum are likely to be the promising agricultural water management and agro-adaptation strategies to minimize the adverse effects of climate change and sustainable production of sorghum for future climate scenarios in SATs.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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References

Agarwal, A., 2000. Drought? Try capturing the rain. Cent. Sci. Environ. 1–16. Retrieved from. http://eprints.icrisat.ac.in/.

Akinseye, F.M., 2020. Improving sorghum productivity under changing climatic conditions: A modelling approach. Field Crops Res. 246 (November 2019), 107685 https://doi.org/10.1016/j.fcr.2019.107685.

Alexandratos, N. and Bruinsma, J., 2012, World Agriculture towards 2030/2050: the 2012 revision. WORLD AGRICULTURE. Retrieved from www.fao.org/economic/esa.

Ameta, O.P., Sumeria, H.K., 2004. Effect of sowing dates on the incidence of insect pests and productivity of sorghum {Sorghum bicolor (L.) Moench}. Indian J. Agric. Res. 38 (4), 278–282.

Beck, H.E., Zimmermann, N.E., McVicar, T.R., Vergopolan, N., Berg, A., & Wood, E.F. (2018). Present and future Köppen-Geiger climate classification maps at 1-km resolution. Scientific data, 5(1), 1–12.

Bell, M., Moody, P., Klepper, K. and Dave, L., 2010, The challenge to sustainability of broadacre grain cropping systems on clay soils in northern Australia. World, (August), 302–305. Retrieved from http://nrmlibrary.com.au/files/challengetosustainabilityofbroadacregraincropping.pdf https://www.iuss.org/19th%20WCSS/Symposium/pdf/2300.pdf.

Boomiraj, K., Marimuthu, S., Wani, S.P., Ravikumar, S., Tani, S., 2012. Vulnerability assessment of kharif rainfed sorghum to climate change in SAT regions of India. J. Agrometeorol. 14 (1), 2–8.

Cakmak, I., Kurz, H., Marschner, H., 1995. Short-term effects of boron, germanium and high light intensity on membrane permeability in boron deficient leaves of sunflower. Physiol. Plant. 95 (1), 11–18. https://doi.org/10.1111/j.1399-3054.1995.tb00801.x.

Challinor, A.J., Watson, J., Lobell, D.B., Howden, S.M., Smith, D.R., Chhetri, N., 2014. A meta-analysis of crop yield under climate change and adaptation. Nat. Clim. Change 4 (4), 287–291. https://doi.org/10.1038/nclimate2153.

Chander, G., Wani, S.P., Sahrawat, K.L., Kamdi, P.J., Pal, C.K., Pal, D.K., Mathur, T.P., 2013. Balanced and integrated nutrient management for enhanced and economic food production: Case study from rainfed semi-arid tropics in India. Arch. Agron. Soil Sci. 59 (12) https://doi.org/10.1080/03650340.2012.761336.

Choruma, D.J., Juraj, B., Oghenekaro, N.O., 2019. "Calibration and Validation of the EPIC Model for Maize Production in the Eastern Cape, South Africa". *Agronomy* 9 9 (no), 494. https://doi.org/10.3390/agronomy9090494.

Dash, S.K., Kulkarni, M.A., Mohanty, U.C. and Prasad, K. (2009). Changes in the characteristics of rain events in India. https://doi.org/10.1029/2008JD010572.

Densilin, D.M., Srinivasan, S., Manju, P., Sudha, S., 2011. Effect of individual and combined application of biofertilizers, inorganic fertilizer and vermicompost on the biochemical constituents of chilli (Ns-1701). J. Biofertil. Biopestici 2 (106), 2. https://doi.org/10.4172/2155-6202.1000106.

Directorate of Sorghum Research, (2007): www.sorghum.res.in.

Farooq, M., Bramley, H., Palta, J.A., Siddique, K.H.M., 2011. Heat stress in wheat during reproductive and grain-filling phases. Crit. Rev. Plant Sci. Taylor Fr. Group. https://doi.org/10.1080/07352689.2011.615687.

Gomez, K.A., Gomez, A.A., 1984. Statistical Procedures for Agricultural Research. John Wiley & Sons,. 〈https://pdf.usaid.gov/pdf_docs/PNAAR208.pdf〉.

Gray, V., 2007. Climate change 2007: The physical science basis summary for policymakers. Energy Environ. 18 (3–4), 433–440. https://doi.org/10.1260/095830507781076194.

Hati, K.M., Chaudhary, R.S., Mandal, K.G., Misra, A.K., Singh, R.K., Wani, S.P., … and Pathak, P. (2013). Effect of land management and cropping systems on runoff, soil loss, soil water dynamics and crop yield in a Vertisol of central India. J. of the Indian Society of Soil Sci., 61(2), 79–88.

Hatibu, N., Young, M.D.B., Gowing, J.W., Mahoo, H.F., Mzirai, O.B., 2003. Developing improved dryland cropping systems for maize in semi-arid Tanzania. Part 1: Experimental evidence for the benefits of rainwater harvesting. Exp. Agric. 39 (3), 279–292. https://doi.org/10.1017/S0014479703001285.

Jones, J.W., Hoogenboom, G., Porter, C.H., Boote, K.J., Batchelor, W.D., Hunt, L.A., Wilkens, P.W., Singh, U., Gijsman, A.J., Ritchie, J.T., 2003. The DSSAT cropping system model. *European J. of agronomy.* 2003 Jan 1;18(3-4) (235–65).

Kamdi, P.J., Swain, D.K. and Wani, S.P. (2020). Efficient land water management practice and cropping system for increasing water and crop productivity in semi-arid tropics. Agron. J. 112 (4), 2552–2568.https://doi.org/10.1002/agj2.20207.

Kanwar, J.S., 1999. Need for a future outlook and mandate for dryland agriculture in India. In: Singh, H.P., Ramakrishna, Y.S., Sharma, K.L., Venkateswarlu, B. (Eds.), Fifty Years of Dryland Agricultural Research in India. CRIDA, Hyderabad, India, pp. 11–20.

Kendall, M. (1975). Multivariate analysis (No. BOOK). Charles Griffin.

Klaij, M.C., Vachaud, G., 1992. Seasonal water balance of a sandy soil in Niger cropped with pearl millet, based on profile moisture measurements. Agric. Water Manag. 21 (4), 313–330. https://doi.org/10.1016/0378-3774(92)90053-Y.

Klute, A., Page, A.L., 1986. Methods of soil analysis. Part 1. Physical and mineralogical methods; Part 2. Chemical and microbiological properties (No. BOOK). American Society of Agronomy, Inc,. https://doi.org/10.1002/gea.3340050110.

Kothari, K., Ale, S., Bordovsky, J.P., Munster, C.L., 2020. Assessing the climate change impacts on grain sorghum yield and irrigation water use under full and deficit irrigation strategies. Trans. ASABE 63 (1), 81–94.

Kothari, K., Ale, S., Bordovsky, J.P., Porter, D.O., Munster, C.L., Hoogenboom, G., 2020a. Potential benefits of genotype-based adaptation strategies for grain sorghum production in the Texas High Plains under climate change. Eur. J. Agron. 117, 126037.

Kumar, C.G., Bhunia, G. and Kumar, C.S.. The effect of vermicompost and other fertilizers on cultivation of tomato plants. J. of hortic. and Forestry, 3 (2), 42–45. Retrieved from http://www.academicjournals.org/jhf https://d2011oi.org/ 10.5897/JHF.9000110.

Kumar, V., Jain, S.K., 2010. Trends in seasonal and annual rainfall and rainy days in Kashmir Valley in the last century. Quat. Int. 212 (1), 64–69. https://doi.org/10.1016/j.quaint.2009.08.006.

Lehmann, N., Finger, R., Klein, T., Calanca, P., Walter, A., 2013. Adapting crop management practices to climate change: modeling optimal solutions at the field scale. Agric. Syst. 117, 55–65. https://doi.org/10.1016/j.agsy.2012.12.011.

Lesk, C., Rowhani, P., Ramankutty, N., 2016. Influence of extreme weather disasters on global crop production. Nature 529 (7584), 84–87. https://doi.org/10.1038/nature16467.

Linden, P. Van Der , & Office, M., 2015, Climate Change 2007: Impacts, Adaptation and Vulnerability Intergovernmental Panel On Climate Change Climate Change 2007: Impacts, Adaptation and Vulnerability Working Group II Contribution to the Intergovernmental Panel on Climate Change Summary for. Environmental Research Letters, (March).

Ludlow, M.M., Muchow, R.C., 1990. A critical evaluation of traits for improving crop yields in water-limited environments. Adv. Agron. 43, 107–153. https://doi.org/10.1016/S0065-2113(08)60477-0.

Mann, H.B. (1945). Non-Parametric Test Against Trend. Econometrica, 13(3), 245–259. Retrieved from http://www.economist.com/node/18330371?story%7B_%7Did=18330371.

Mavromatis, T., Boote, K.J., Jones, J.W., Wilkerson, G.G., Hoogenboom, G., 2002, Repeatability of model genetic coefficients derived from soybean performance trials cross different states. Crop Sci. 42, 76_/89.

Murty, M.V.R., P., Singh, Wani, S.P., Khairwal, I.S. and Srinivas, K.. (2007). Yield Gap Analysis of Sorghum and Pearl Millet in India Using Simulation Modeling. Global Theme on Agroecosystems Report no. 37. Patancheru 502 324, Andhra Pradesh, India: International Crops Research Institute for the Semi-Arid Tropics. 82 pp.

Myers, R.J.K., 1980. The root system of a grain sorghum crop. Field Crops Res. 3, 53–64.

Parry, M.L., Rosenzweig, C., Iglesias, A., Livermore, M., Fischer, G., 2004. Effects of climate change on global food production under SRES emissions and socio-economic scenarios. Glob. Environ. Change 14 (1), 53–67. https://doi.org/10.1016/j.gloenvcha.2003.10.008.

Pathak, P., Wani, S.P., Sudi, R.R., 2011. Long-term effects of management systems on crop yield and soil physical properties of semi-arid tropics of Vertisols. Agric. Sci. 02 (04), 435–442. https://doi.org/10.4236/as.2011.24056.

Pathak, P., Sudi, R., Wani, S.P., Sahrawat, K.L., 2013. Hydrological behavior of Alfisols and Vertisols in the semi-arid zone: Implications for soil and water management. Agric. Water Manag. 118, 12–21. https://doi.org/10.1016/j.agwat.2012.11.012.

Patil, S.L., Sheelavantar, M.N., 2004. Effect of cultural practices on soil properties, moisture conservation and grain yield of winter sorghum (Sorghum bicolar L. Moench) in semi-arid tropics of India. Agric. Water Manag. 64 (1), 49–67. https://doi.org/10.1016/S0378-3774(03)00178-1.

Patil, S.N., Muzumdar, G.K., Pore, D.B., 1991. Effect of moisture conservation measures on growth and yield of sorghum-pigeonpea intercropping in watershed area. Indian J. Soil Conserv. 19 (1&2), 6–11.

Prasad, P.V.V., Boote, K.J., Allen, L.H., 2006. Adverse high temperature effects on pollen viability, seed-set, seed yield and harvest index of grain-sorghum [Sorghum bicolor (L.) Moench] are more severe at elevated carbon dioxide due to higher tissue temperatures. Agric. . Meteorol. 139 (3–4), 237–251. https://doi.org/10.1016/j.agrformet.2006.07.003.

Prasad, P.V.V., Pisipati, S.R., Mutava, R.N., Tuinstra, M.R., 2008. Sensitivity of grain sorghum to high temperature stress during reproductive development. Crop. Sci. 48 (5), 1911–1917. https://doi.org/10.2135/cropsci2008.01.0036.

Raju, K.V., Aziz, A., Sundaram, S.,M., Sekher, M., Wani, S.P., Sreedevi, T.K., 2008. Guidelines for Planning and Implementation of Watershed Development Program in India: A Review. Glob. Theme Agroecosyst. Rep. no. 48.

Ramesh, T., Devasenapathy, P., 2007. Natural resources management on sustainable productivity of rainfed pigeonpea (Cajanus cajan L.). Res. J. Agric. Biol. Sci. 3 (3), 124–128.

Rao, A.K., Wani, S.P., Singh, K.K., Ahmed, M.I., Srinivas, K., Bairagi, S.D. and Ramadevi, O. (2013). Increased arid and semi-arid areas in India with associated shifts during 1971–2004. J. of Agrometeorology. 2013;15(1):11–8.

Rosenzweig, C., Allen, L.H., Jr., Jones, J.W.., Tsuji, G.Y., Hildebrand, P.. (Eds.), Climate Change and Agriculture: Analysis of Potential International impacts (ASA Special Publication No. 59). Amer. Soc. Agron., Madison, WI 1995, p. 382.

Sadeghzadeh, B., Rengel, Z., 2011. Zinc in Soils and Crop Nutrition. Mol. Physiol. Basis Nutr. Use Effic. Crops 335–375. https://doi.org/10.1002/9780470960707.ch16.

Sannagoudar, M.S., Patil, R.H., Kumar, R.V., Singh, A.K., Ghosh, A., Halli, H.M., 2020. Simulated impacts of rise in temperature on kharif sorghum genotypes in Northern Transitional Zone of Karnataka, India. Cereal Res. Commun. 48 (1), 113–120. https://doi.org/10.1007/s42976-020-00011-6.

Sannagoudar, M.S., Patil, R.H., Rajanna, G.A., Ghosh, A., Singh, A.K., Halli, H.M.,. & Kumar, R.V. (2023). Rising temperature coupled with reduced rainfall will adversely affect yield of kharif sorghum genotypes. Current Science (00113891), 124(8).

Sen, P.K., 1968. Estimates of the Regression Coefficient Based on Kendall's *Tau*. J. Am. Stat. Assoc. 63 (324), 1379–1389. https://doi.org/10.1080/01621459.1968.10480934.

Singh, B., Kumar, N., Kumar, H., 2017. Seasonal incidence and management of sorghum shoot fly, Atherigona soccata Rondani-A Review. Forage. Research 42, 218–224.

Singh, P., Verma, R.S., 1996. Nitrogen uptake and quality of pearl millet as influenced by moisture conservation practices and N fertilization. Indian J. Soil Conserv. 24 (1), 85–89.

Singh, P., Nedumaran, S., Boote, K.J., Gaur, P.M., Srinivas, K., Bantilan, M.C.S., 2014. Climate change impacts and potential benefits of drought and heat tolerance in chickpea in South Asia and East Africa. Eur. J. Agron. 52, 123–137.

Soil resource inventory of Marathwada, 2002. Department of Agricultural chemistry and soil science, Marathwada Agricultural University. Parbhani 431 (402), 6.

Subash, N., Sikka, A.K., 2014. Trend analysis of rainfall and temperature and its relationship over India. Theor. Appl. Climatol. 117 (3–4), 449–462. https://doi.org/10.1007/s00704-013-1015-9.

Thakur, N.S., Kushwaha, B.B., Sinha, N.K., 2011. Productivity and water use in kharif sorghum (Sorghum bicolor) under different land configuration and mulching. Indian J. Agron. 56 (1), 47–51.

van, Vuuren, D.P., Edmonds, J., Kainuma, M., et al., 2011. The representative concentration pathways: An overview. Clim. Change 109 (1), 5–31. https://doi.org/10.1007/s10584-011-0148-z.

Wani, S.P., Rockström, J., 2011. Watershed development as a growth engine for sustainable development of rainfed areas. Integr. Watershed Manag. Rainfed Agric. 35–52. https://doi.org/10.1201/b11424-3.

Wani, S.P., Singh, P., Pathak, P., 1999. Methods Manag. data Watershed Res.: Tech. Man. Train. Workshop (5)).

Wani, S.P., Pathak, P., Sreedevi, T.K., Singh, H.P., Singh, P., 2009. Efficient management of rainwater for increased crop productivity and groundwater recharge in Asia. Water Product. Agric.: Limits Oppor. Improv. 199–215. https://doi.org/10.1079/9780851996691.0199.

Wani, S.P., Dixin, Y., Li, Z., Dar, W.D., Chander, G., 2012. Enhancing agricultural productivity and rural incomes through sustainable use of natural resources in the Semi Arid Tropics. J. Sci. Food Agric. 92 (5), 1054–1063. https://doi.org/10.1002/jsfa.4721.

Willmott, C.J., Ackleson, S.G., Davis, R.E., Feddema, J.J., Klink, K.M., Legates, D.R., et al., 1985. Statistics for the evaluation and comparison of models. J. Geophys. Res 90 (C5), 8995. https://doi.org/10.1029/jc090ic05p08995.