Rising temperature coupled with reduced rainfall will adversely affect yield of *kharif* sorghum genotypes

Manjanagouda S. Sannagoudar[1,*], R. H. Patil[2], G. A. Rajanna[3], Avijit Ghosh[1], Amit K. Singh[1], Hanamant M. Halli[4], Vanitha Khandibagur[5], Sunil Kumar[1] and R. V. Kumar[1]

[1]ICAR-Indian Grassland and Fodder Research Institute, Jhansi 284 003, India
[2]Department of Agricultural Meteorology, University of Agricultural Sciences, Dharwad 580 005, India
[3]ICAR-Directorate of Groundnut Research, Regional Station, Rekalakunta, Ananthapur 515 001, India
[4]ICAR-National Institute of Abiotic Stress Management, Pune 413 115, India
[5]University of Horticultural Sciences, Bagalkot 587 102, India

The DSSAT-CERES-Sorghum model was used to test performance of four *kharif* sorghum genotypes to changes in rainfall and temperature over three sowing windows. Three rainfall scenarios (no change, –10%, –20%) and three temperature scenarios (no change, +1°C, +2°C) were incorporated to past 32 year (1985 to 2016) of recorded weather data, and average simulated outputs showed that, irrespective of cultivar and sowing time, reduction in rainfall had minimal effect on crop duration, but lowered grain yield by 3.34% and 12.85% respectively, at –10% and –20% rainfall scenarios. Rise in temperature from current levels to +1°C and +2°C reduced crop duration by 7 and 12 days, while final yield reduced by 9.4% and 20% respectively. Further, per cent reduction in yield increased with delay in sowing under both scenarios. This effect was more pronounced with combined effect of reduced rainfall and increased temperature. CSH-16 cultivar performed the best across scenarios, while the remaining cultivars followed the order: CSV-17 > CSV-23 > CSH-23. Early sowing (15 June) is suitable to attain higher yield compared to 30 June and 15 July sowing across scenarios.

Keywords: Grain yield, *kharif* season, rainfall, sensitivity analysis, sorghum genotypes, temperature.

SORGHUM (*Sorghum bicolor*) is one of the major cereal crops of India, grown mainly under rainfed conditions owing to its higher drought tolerance ability compared to other cereal crops. Hence it is extensively grown in the semi-arid tropics (SAT) under varied moisture regimes[1]. In India, around 2.31 million tonnes of sorghum grain is produced during *kharif* season from an area of 2.26 million hectares, but the average sorghum productivity (864 kg ha^{-1}) is much lower than the world average (1481 kg ha^{-1}) according to Department of Agriculture and Cooperation (DAC)[2]. Most sorghum cultivation is limited to rainfed conditions of arid and semi-arid regions coupled with uncertain moisture availability; its productivity is greatly constrained by climatic factors, particularly temperature and rainfall, compared to other crop management practices[3,4]. Karnataka, India, is predominantly semi-arid and situated in the tropics. Rainfall and temperature dominate all other climate parameters vis-à-vis crop growth and yield. The southwest monsoon (SWM; from June to September) accounts for a little more than 70% of the total annual rainfall of the Northern Interior Karnataka (NIK) region. Hence spatial and temporal variation in rainfall during this period greatly influences crop yield as NIK is much drier and warmer than the rest of the state. The long-term average rainfall variability (CV) during SWM season in NIK is much higher (21%) than that of entire Karnataka (15%) and India (11%) as a whole[5].

With climate change and associated variability in climatic factors, even under the most optimistic and efficient technology-driven scenario, the temperature will increase by at least 1°C and 2°C by 2050 and 2100 respectively. Some projections suggest that temperatures may even rise more than 3–4°C by the end of this century[4,6,7]. Correspondingly, rainfall patterns may change further, increasing both spatial and temporal variation in its occurrence. This would expose *kharif* sorghum not only to warmer climates, but also to moisture stress due to uneven or erratic distribution of monsoon rainfall. Hence there is a need to understand the response of the currently popular and/or recently released *kharif* sorghum cultivars and other crop cultivars to changes in both rainfall and temperature. This would help develop and/or optimize not only new agronomic practices as adaptation strategies, but also develop new cultivars which can better cope with future projected climates if the current cultivars fail to yield more. Likewise, researchers elsewhere in India used various adaptation strategies, viz. change in sowing date, optimizing irrigation and fertilizer schedule to minimize the yield reduction in wheat and maize. Similar strategies may also be required in sorghum, and detailed

*For correspondence. (e-mail: smanjanagouda928@gmail.com)

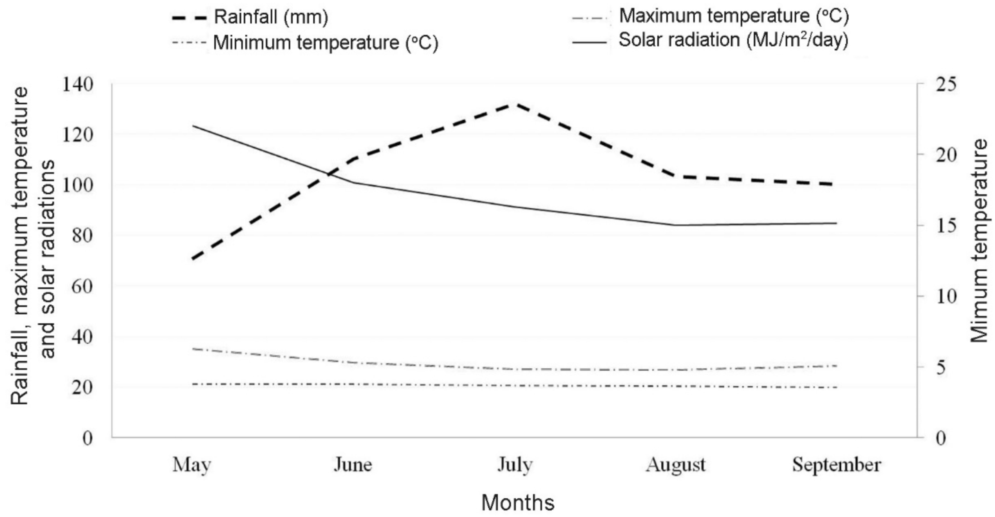

Figure 1. Mean monthly meteorological data from May to September for the past 32 years (1985–2016) in the experimental site.

studies are needed to quantify the impact of rising temperature on sorghum yield[8–11]. However, due to huge logistical requirements as well as time/resource constraints in undertaking field-based studies on climate change, crop simulation models (CSMs) are being used widely across the world to study the impact of climate change on the performance of crop(s), their different cultivars and overall system productivity. It is noteworthy that CSMs have proved to be handy and efficient tools to assess and quantify the impact of climate change on a long-term basis through seasonal analysis than a time-bound field experiment. For instance, researchers used InfoCrop and CERES models to study the impact of increased temperature and reduced rainfall in sorghum[12,13]. However, the effect on crop yield may vary from region to region and from season to season within a region for each crop and production system.

Therefore, climate studies to quantify the impact and device adaptation strategies are required in sorghum as well for the NIK region as a whole, which is more vulnerable to climate change than the rest of Karnataka and the Northern Transitional Zone (NTZ) in particular. In this background, a simulation study was undertaken to quantify the impact of changes in daily rainfall amount and mean temperature on rainfed *kharif* sorghum in NTZ grown on deep black soils using seasonal analysis tools in the DSSAT-CERES-Sorghum model.

Materials and methods

Experimental procedure

A field study was conducted at the University of Agricultural Sciences, Dharwad, Karnataka (15°26′N, 75°07′E at an altitude of 678 m amsl) under the AICRP on Sorghum project during *kharif* seasons of 2011 and 2012, which included four sorghum cultivars, namely CSV-17, CSV-23, CSH-16 and CSH-23, grown across three sowing windows, i.e. 15 June, 30 June and 15 July. The data from this set of experiments were used only to calibrate and validate the DSSAT-CERES-Sorghum model after optimizing the genetic coefficients for all four cultivars[14]. In the present study, we used these four optimized cultivars for further analysis using the DSSAT model. In order to simulate the impact of changes in temperature and rainfall on the performance of each of these four cultivars, the same four optimized and validated cultivars were used in this study to quantify both the independent and combined effects of increasing daily mean temperature and reduced rainfall on *kharif* sorghum genotypes using the DSSAT crop simulation model. For this historic weather data of 32 years (1985–2016) were collected from the same study location for seasonal analysis.

Seasonal analysis

For seasonal analysis study, the 32 years of observed historical weather data (1985–2016) from the Main Agricultural Research Station, Dharwad weather observatory were collected, and this period was considered as the 'current' scenario (Figure 1). Three temperature and rainfall scenarios were developed for this study. Temperature scenarios included current (observed during 1985–2016 with no changes) and +1.0°C and +2.0°C rise in daily average maximum and minimum temperatures over the current scenario. The three rainfall scenarios included no change in rainfall (observed during 1985–2016), and –10% and –20% reduction in daily rainfall over the first scenario (no change in rainfall). Each of these scenarios was developed for the 32-year period from 1985 to 2016. A total combination of nine scenarios were developed (Table 1). The DSSAT-CERES-Sorghum model was run for 32 years for each of

Table 1. Future climate scenarios considered for the seasonal analysis study

Sce* no.	Scenario	Remarks**
Sce-1	RF: NC +0°C	Rainfall and temperature no change, and is the current scenario
Sce-2	RF: –10% +0°C	Rainfall reduced by 10% and no change in daily average maximum and minimum temperatures
Sce-3	RF: –20% +0°C	Rainfall reduced by 20% and no change in daily average maximum and minimum temperatures
Sce-4	RF: NC +1°C	Rainfall no change and rise in daily average maximum and minimum temperatures by 1.0°C
Sce-5	RF: NC +2°C	Rainfall no change and rise in daily average maximum and minimum temperatures by 2.0°C
Sce-6	RF: –10% +1°C	Rainfall reduced by 10% and rise in daily average maximum and minimum temperatures by 1.0°C
Sce-7	RF: –10% +2°C	Rainfall reduced by 10% and rise in daily average maximum and minimum temperatures by 2.0°C
Sce-8	RF: –20% +1°C	Rainfall reduced by 20% and rise in daily average maximum and minimum temperatures by 1.0°C
Sce-9	RF: –20% +2°C	Rainfall reduced by 20% and rise in daily average maximum and minimum temperatures by 2.0°C

*Sce, Scenario. **Observed weather data for the period of 32 years (1985–2016).

four sorghum cultivars (CSV-17, CSV-23, CSH-16 and CSH-23) and over three dates of sowing (15 June, 30 June and 15 July). Totally 108 runs (four cultivars × three dates of sowing × nine climate scenarios), for each cultivar, 32 years were simulated, and only the average of 32 years of simulation output from each run is presented and discussed here.

The main rationale behind the use of historic weather (1985–2016) data was to simulate each cultivar exposed to different growing conditions (i.e. three sowing dates) over a period of 32 years that would expose the crops to naturally occurring weather variability that is, below average, above average and average weather (here rainfall and temperature) as well as extremes, if any.

Model description

DSSAT is a multi-process-oriented dynamic crop simulation model that operates on a daily time step and simulates crop growth and development of more than 25 different crops, including sorghum, in interaction with the weather, soil, management and crop cultivar-specific genetic coefficients. The DSSAT-CERES-Sorghum model, like most other models, requires four main types of input data: weather, soil, crop and management[15]. These input data were used for sorghum according to the recommendations of the University of Agricultural Sciences, Dharwad for the Northern Transitional Zone (NTZ No. 8).

Results and discussion

Crop growth and yield are largely determined by weather conditions during the growing season. Rainfall and temperature are two of the most important environmental factors that have a major role in determining crop growth, development and yield[16].

Effect of change in rainfall amount and temperature on physiological maturity

On average, under the current scenario (Sce-1, i.e. no change in rainfall and temperature), CSH-16 took 121 days for physiological maturity, followed by CSV-23 (116 days), CSH-23 (115 days) and CSV-17 (107 days), as shown by 32 years of simulation data. The DSSAT model captured the crop duration of each cultivar accurately. For instance, among the four tested cultivars, CSV-17 is a short-duration variety, and the model could simulate it as 107 days. With the increase in temperature, the duration for the physiological maturity is reduced by an average of 5–6 days for each 1°C increase in temperature (Table 2). In contrast, a reduction in rainfall by 10% and 20% did not impact crop duration. This suggests that mild moisture stress imposed by the reduction of daily rainfall during *kharif* season crop-growing cycle does not reduce crop duration. As hypothesized and expected, temperature alone affected phenology and total crop duration during *kharif* season in NTZ. However, the effect of sowing time on phenology was minimal. Averaged over all the scenarios and cultivars, delay in sowing by 15 days shortened the crop duration, on average, by only 1–2 days. This was expected in the *kharif* season (June–September) in the NTZ as the daily cardinal temperature ranges between 20°C and 30°C, and this period is mostly covered by the SWM clouds carrying cool winds. Similar observations on the decrease in the number of days taken for physiological maturity of sorghum genotypes, mainly due to high temperatures, have been made[17]. As high temperatures accelerate crop growth and development, it limits the solar radiation interception by the crops during the growing period. With less fuel for photosynthesis (i.e. conversion of CO_2 to organic compounds), the plant biomass tends to be lower, bringing mature plant biomass below potential levels[18–21]. Therefore, irrespective of other biotic and abiotic stresses, the highest crop yields are obtained when relatively mild temperatures increase the overall crop duration[22].

Effect of reduced rainfall amount on grain yield

Among the four cultivars examined, under Sce-1 (i.e. no change in rainfall and temperature), CSH-16 recorded the highest grain yield (2041 kg ha^{-1}), followed by CSV-23 (1842 kg ha^{-1}), CSH-23 (1731 kg ha^{-1}) and CSV-17 (1059 kg ha^{-1}). The simulated findings of this study clearly

Table 2. Simulated physiological maturity (days) of *kharif* sorghum cultivars across dates of sowing as influenced by changes in mean temperature and rainfall amount (average of 32 years, 1985–2016)

Treatments/scenarios/ sorghum cultivars		RF: NC + 0°C	RF: –10% + 0°C	RF: –20% + 0°C	RF: NC + 1°C	RF: –10% + 1°C	RF: –20% +1°C	RF: NC +2°C	RF: –10% + 2°C	RF: –20% + 2°C
CSV-17	D_1	107	107	107	101	101	101	96	96	96
	D_2	108	106	106	100	101	101	95	95	95
	D_3	105	105	104	99	100	99	95	96	95
	Mean	107	106	106	100	101	100	95	96	95
CSV-23	D_1	117	117	117	111	111	111	106	106	105
	D_2	117	115	116	109	109	111	104	105	105
	D_3	114	114	114	108	108	108	102	104	103
	Mean	116	115	115	109	109	110	104	105	104
CSH-16	D_1	123	122	122	116	116	116	111	111	112
	D_2	121	120	121	114	114	116	109	110	110
	D_3	119	119	119	113	113	113	107	107	107
	Mean	121	120	121	114	114	115	109	109	110
CSH-23	D_1	117	116	116	110	110	111	105	105	105
	D_2	116	113	115	108	108	109	103	105	104
	D_3	112	112	112	107	107	106	101	103	102
	Mean	115	114	114	108	108	109	103	104	104
Mean within DOS across cultivars	D_1	116	115	116	110	109	110	104	105	105
	D_2	115	114	114	108	108	109	103	104	103
	D_3	113	112	112	107	107	107	101	102	102
Grand mean		115	114	114	108	108	108	103	104	103

DOS, Date of sowing; RF, Rainfall; NC, No change; D_1, 15 June; D_2, 30 June; D_3, 15 July.

show that the CSH-16 and CSV-17 cultivars being the longest and shortest duration types, have the highest and lowest grain yields respectively.

When rainfall was reduced by 10% and 20%, i.e. for Sce-2 and Sce-3, the simulated yield was reduced to 1955 and 1800, 1770 and 1627, 1653 and 1533, 1081 and 950 kg ha^{-1} respectively, for the cultivars CSH-16, CSV-23, CSH-23 and CSV-17. It was observed that a 10% drop in rainfall reduced the grain yield by 4.39%, 4.06%, 4.71% and 2.03% for CSH-16, CSV-23, CSH-23 and CSV-17 respectively, with an average of 3.80% across the cultivars. However, a 20% drop in rainfall reduced the grain yield much more, i.e. 13.38%, 13.21%, 12.91% and 11.47% respectively, with an average of 12.74% across the cultivars (Table 3). This shows that the effect of moisture stress on yield with an increased reduction in rainfall is not linear, i.e. not at a constant rate.

Effect of rising temperature on grain yield

Based on the simulation outputs of the four cultivars across sowing dates over 32 years, under Sce-1, CSH-16 recorded the highest grain yield (2041 kg ha^{-1}) followed by CSV-23 (1842 kg ha^{-1}), CSH-23 (1731 kg ha^{-1}) and CSV-17 (1059 kg ha^{-1}). Whereas with an increase in temperature by +1°C and +2°C, i.e. Sce-4 and Sce-5, the yield of all four cultivars was reduced (1880 and 1722, 1633 and 1565, 1615 and 1444, 972 and 829 kg ha^{-1} respectively). The simulated per cent reduction in yield was 8.56 and 18.52, 12.79 and 17.69, 7.18 and 19.87, 8.95 and 27.74 respectively, for Sce-4 and Sce-5 (Table 3).

Combined effect of reduction in rainfall and rise in temperature on grain yield

The ranking of cultivars with respect to yield remained the same, under Sce-6 and Sce-7, i.e. 10% and 20% reduction in rainfall, and each scenario coupled with +1°C rise in temperature, compared to Sce-1, but the reduction in yield of all the cultivars was greater than the individual effects of either reduced rainfall or rise in temperature. The simulated yield of cultivars in the same order as above, compared to Sce-1, reduced to 1747 and 1618, 1538 and 1448, 1444 and 1361, 890 and 846 kg ha^{-1} respectively, for Sce-6 and Sce-7. The reduction was to the extent of 16.82 and 33.22, 19.76 and 29.80, 19.87 and 27.93, 18.98 and 38.61% respectively, for Sce-6 and Sce-7 (Table 3). Similarly, under Sce-8 and Sce-9, i.e. 10% and 20% reduction in rainfall, and each coupled with a +2°C rise in temperature, the simulated yield of cultivars in the same order, compared to Sce-1, reduced further to 1618 and 1369, 1448 and 1239, 1361 and 1186, 846 and 687 kg ha^{-1} respectively. The simulated per cent reduction in grain yield was 26.14 and 49.08, 27.20 and 48.66, 27.18 and 45.95, 25.17 and 54.14 respectively, for Sce-8 and Sce-9. Among the four cultivars tested, CSH-16 performed better under all the temperature and rainfall scenarios, followed by CSV-17, CSH-23 and CSV-23. The short-duration variety CSV-17 performed better than CSH-23 and CSV-23 when the crops were exposed to reduced rainfall and rise in temperature, which may be due to an early harvest and escaping from stress at the critical period of growth.

The extent of the reduction in grain yield was directly linked to increased temperature and reduced rainfall. Exposure to higher temperatures led to faster accumulation

Table 3. Simulated grain yield (kg ha^{-1}) of *kharif* sorghum cultivar across dates of sowing as influenced by changes in mean temperature and rainfall amount (average of 32 years, 1985–2016)

Treatments/scenarios/ sorghum cultivars		RF: NC + 0°C	RF: –10% + 0°C	RF: –20% + 0°C	RF: NC + 1°C	RF: –10% + 1°C	RF: –20% + 1°C	RF: NC + 2°C	RF: –10% + 2°C	RF: –20% + 2°C
CSV-17	D_1	1164	1190	1075	1082	1001	961	924	805	755
	D_2	1126	1056	973	1036	921	862	868	856	682
	D_3	952	931	802	797	747	714	695	630	623
	Mean	1081	1059	950	972	890	846	829	764	687
CSV-23	D_1	2026	1926	1822	1864	1749	1657	1705	1516	1387
	D_2	1789	1694	1628	1656	1456	1392	1649	1472	1238
	D_3	1710	1689	1431	1380	1408	1296	1341	1270	1093
	Mean	1842	1770	1627	1633	1538	1448	1565	1419	1239
CSH-16	D_1	2256	2163	1974	2035	1940	1840	1974	1696	1604
	D_2	1969	1866	1813	1831	1697	1546	1673	1456	1301
	D_3	1897	1835	1614	1774	1603	1468	1519	1445	1203
	Mean	2041	1955	1800	1880	1747	1618	1722	1532	1369
CSH-23	D_1	1928	1836	1777	1899	1660	1586	1694	1434	1358
	D_2	1654	1571	1503	1537	1363	1304	1373	1393	1150
	D_3	1612	1551	1318	1409	1308	1192	1266	1231	1049
	Mean	1731	1653	1533	1615	1444	1361	1444	1353	1186
Mean within DOS across cultivars	D_1	1850	1772	1662	1720	1588	1511	1574	1363	1276
	D_2	1617	1564	1479	1515	1359	1276	1391	1294	1093
	D_3	1538	1507	1291	1340	1267	1168	1205	1144	992
Grand mean		1668	1614	1478	1525	1404	1318	1390	1267	1120

of thermal units/heat units, which indicates fulfilment of thermal requirements without producing sufficient biomass or economic yield[23,24]. Lower yield under reduced rainfall could be mainly attributed to moisture stress. Soil moisture plays a crucial role in crop growth, uptake of nutrients and yield. Moreover, inadequate moisture dramatically affects seed germination, cell division, tillering and plant nutrient uptake. The nutrients enter the root surface from the soil by mass flow and diffusion mechanisms. These mechanisms are highly correlated to soil moisture content. Due to water deficit, stomatal conductivity, transpiration, photosynthesis and various physiological processes are affected and harm crop growth and yield[25].

Drought-like situations are induced by moisture stress, which can be caused by increased temperatures and/or lack of water[26,27]. Further, it can occur at seedling, flowering, and ripening stages of growth and adversely affect the yields[27,28]. Most morphological and physiological characteristics at the seedling stage are disturbed by moisture stress[29]. Likewise, many studies have reported that moisture stress predominantly inhibits shoot growth more than root growth[30–32]. Reduction in the growth of seedlings is also the result of restricted cell multiplication and elongation, as drought stress directly inhibits development by reducing cell division and elongation[33]; hence rise in temperature and moisture stress both affect the plant biophysiological processes.

Effect of changes in rainfall across dates of sowing on crop performance

The simulated effect of change in temperature and rainfall during the crop growing period sown on different dates (15 June, 30 June and 15 July) revealed that the grain yield decreased with an increase in temperature under all three dates of sowing. Simulation outputs also revealed that the extent of reduction in grain yield varied with the date of sowing. Among the three dates of sowing, irrespective of cultivars, under Sce-1, 15 June-sown crops recorded the highest grain yield (1850 kg ha^{-1}) followed by 30 June (1617 kg ha^{-1}) and 15 July (1538 kg ha^{-1}). Whereas the reduction in rainfall alone by 10% and 20%, i.e. for Sce-2 and Sce-3, the simulated yield was reduced to 1772 and 1662, 1564 and 1479, 1507 and 1291 kg ha^{-1} respectively. This shows that a 10% reduction in rainfall reduces grain yield by 4.40%, 3.38% and 2.05% respectively, for 15 June, 30 June and 15 July sowing (average of 3.27%). However, a 20% reduction in rainfall alone lowers the yield much more, i.e. 11.31%, 9.33% and 19.13% respectively, which across the dates of sowing averaged at 13.25%.

Effect of rising temperature across dates of sowing

Irrespective of the cultivars, under Sce-1, 15 June-sown crops recorded the highest grain yield (1850 kg ha^{-1}), followed by 30 June (1617 kg ha^{-1}) and 15 July (1538 kg ha^{-1}). However, when temperature alone was increased by 1°C and 2°C, i.e. Sce-4 and Sce-5, the simulated yield was reduced to 1720 and 1574, 1515 and 1391, 1340 and 1205 kg ha^{-1} respectively. This showed that a 1°C increase in temperature alone lowers the grain yield by 7.55%, 6.73% and 14.77% respectively, for 15 June, 30 June and 15 July. However, a 2°C increase in temperature lowers the yield much more, i.e. 17.53%, 16.24% and 27.63% respectively, which across the dates of sowing averaged at 20.46% (Table 3). Further, with the rise in temperature from the current levels to +2.0°C, the reduction in yield was simulated to be higher in late-sown crops, i.e. 15 July (9.52%) in comparison with early sowing, i.e. 15 June (5.23%) and 30 June (8.80%).

Combined effect of reduction in rainfall and rise in temperature across dates of sowing on grain yield

The reduction in rainfall by 10% and each coupled with +1°C and +2°C rise in temperature reduced the yield of all the cultivars. The effect was much more than that of either reduced rainfall or a ++rise in temperature alone. The reduction was to an extent of 16.49% and 35.73%, 18.98% and 24.96%, 21.38% and 34.44% respectively, for Sce-6 and Sce-7 under 15 June, 30 June and 15 July sowing. Similarly, under Sce-8 and Sce-9, i.e. 20% reduction in rainfall, and each coupled with +1°C and +2°C rise in temperature, the yield of cultivars in the same order reduced to 1511 and 1276, 1276 and 1093, 1168 and 992 kg ha^{-1} respectively. The simulated reduction in grain yield was 22.43% and 44.98%, 26.72% and 47.94%, 31.67% and 55.04% respectively, for Sce-8 and Sce-9.

In all the scenarios, higher grain yields were simulated in early-sown crops (15 June), which might be attributed to relatively longer crop duration and improved access to soil moisture. This helps enhance metabolite synthesis, which will increase total dry matter production during grain-filling and maturity, thereby improving the yield. As a result, early sowing with the commencement of SWM often benefits the crop due to higher soil moisture availability, thus preventing the moisture stress likely to occur with late sowing, even during the *kharif* season.

Among the four cultivars tested, CSH-16 performed better under all the temperature and rainfall scenarios, followed by CSV-17, CSH-23 and CSV-23. Several studies also reported the simulated outputs on sorghum genotypes in India, e.g. the grain yield of CSH-16 would increase substantially (0.1%) at Gwalior, Madhya Pradesh, up to 2020 and then decline, whereas both CSH-16 and CSV-17 would produce higher yields (3.3% and 1.7% respectively) at Kota, Rajasthan up to 2020. No variation was simulated thereafter until 2050, but yields again declined beyond 2050 up to 2080 in both cultivars. The changes in grain yield reduction with the projected climate change scenarios at different locations across India have been primarily attributed to current variations in the temperature range and rainfall[12].

Conclusion

This DSSAT model-based study shows that at 10% and 20% reduced rainfall, the per cent reduction in grain yield would be 3.23 and 11.39 respectively, whereas an increase in temperature alone would decrease grain yield to the tune of 8.57% and 16.67% at +1°C and +2°C respectively. The combined effect of reduced rainfall (–20%) and rise in temperature (+2°C) results in the maximum reduction of grain yield by 32.85%. This indicates that rainfall and temperature are pivotal in deciding the crop duration and grain yield of *kharif* sorghum under future climatic conditions of the NTZ, which is considered a safe environment for *kharif* sorghum. The present study shows that even the *kharif* sorghum crop requires supplemental irrigation during long, dry spells or if the crop experiences moisture stress due to deficit rainfall for better yield. Thus, this study recommends early sowing with the normal commencement of monsoon or wherever possible with one irrigation crop must be sowed early to obtain maximum yield.

Conflict of interest: None.

1. Sandeep, V. M. *et al.*, Projected future change in water requirement of grain sorghum in India. *J. Agrometeorol.*, 2017, **19**, 217–225.
2. DAC, *Agriculture Statistics at a Glance*, Directorate of Economics and Statistics, Department of Agriculture and Cooperation, Government of India, 2016; http://eands.dacnet.nic.in/PDF/5-Year_foodgrain2010-15.xls
3. Assefa, Y., Staggenborg, S. A. and Prasad, P. V. V., Grain sorghum water requirement and response to drought stress. *Crop Manage.*, 2010; doi:10.1094/CM-2010-1109-01-RV.
4. Neil, C. and Rao, K. P. C., Simulation analysis of factors affecting sorghum yield at selected sites in eastern and southern Africa, with emphasis on increasing temperatures. *Agric. Syst.*, 2013, **121**, 53–62.
5. Venkatesh, H., Shivaramu, H. S., Rajegowda, M. B. and Rao, V. U. M., *Agro-Climatic Atlas of Karnataka*, All India Co-ordinated Research Project on Agrometeorology, Vijayapura and Bengaluru Centres, 2016, p. 211.
6. Jukanti, A. K., Manga, V. K., Bhatt, R. K. and Pathak, R., Differential response of pearl millet genotypes to high temperature stress at flowering. *J. Environ. Biol.*, 2017, **38**(5), 791.
7. Attri, S. D. and Rathore, L. S., Simulation of impact of projected climate change on wheat in India. *Int. J. Climatol.*, 2003, **23**, 693–695.
8. Pramod, V. P. *et al.*, Impact of projected climate on wheat yield in India and its adaptation strategies. *J. Agrometeorol.*, 2017, **19**, 207–216.
9. Rajanna, G. A. and Dhindwal, A. S., Water dynamics, productivity and heat use efficiency responses in wheat (*Triticum aestivum*) to land configuration techniques and irrigation schedules. *Indian J. Agric. Sci.*, 2019, **89**, 912–919.
10. Halli, H. M. and Angadi, S. S., Influence of land configuration and deficit irrigation on nutrient uptake and grain yield of maize (*Zea mays* L.). *J. Farm Sci.*, 2019, **32**(4), 397–402.
11. Naik, B. S. S. S., Murthy, K. R. and Rupesh, T., Comparative response of sorghum genotypes to varied levels of nitrogen in rice-fallows of North Coastal Region of Andhra Pradesh. *J. Environ. Biol.*, 2020, **41**, 1710–1718.
12. Boomiraj, K., Marimuthu, S., Wani, S. P., Ravikumar, S., Manikandan, N. and Tani, S., Vulnerability assessment of *kharif* rainfed sorghum to climate change in SAT regions of India. *J. Agrometeorol.*, 2012, **14**, 2–8.
13. Marine, C. G., Flavio, J., Rafeel, D. A. R. and Camilo, L. T. O., Sensitivity of the sorghum yield to individual changes in climate parameters: modelling based approach. *Bragantia*, 2015, **74**, 341–349.
14. Sannagoudar, M. S., Patil, R. H. and Rajanna, G. A., Calibration and evaluation of DSSAT-CERES model for *kharif* sorghum genotypes. *J. Exp. Agric. Int.*, 2019, **30**(3), 1–8.

15. Jones, J. W. *et al.*, The DSSAT cropping system model. *Eur. J. Agron*., 2003, **18**, 235–265.
16. Prasad, P. V. V. and Staggenborg, S. A., Impacts of drought and/or heat stress on physiological, developmental, growth, and yield processes of crop plants. In *Response of Crops to Limited Water: Understanding and Modeling Water Stress Effects on Plant Growth Processes* (eds Ajuha, L. R. *et al.*), American Society of Agronomy/Crop Science Society of America/Soil Science Society of America, Madison, WI, USA, 2008, pp. 301–356.
17. Sannagoudar, M. S., Patil, R. H., Kumar, R. V., Singh, A. K., Ghosh, A. and Halli, H. M., Simulated impacts of rise in temperature on *kharif* sorghum genotypes in Northern Transitional Zone of Karnataka, India. *Cereal Res. Commun.*, 2020, **48**, 113–120.
18. Sibma, L., Relation between total radiation and yield of some field crops in the Netherlands. *Netherl. J. Agric. Sci.*, 1970, **18**, 125–131.
19. Duncan, W. G., Shaver, D. L. and Williams, W. A., Insulation and temperature effects on maize growth and yield. *Crop Sci*., 1973, **13**, 187–191.
20. Stone, P., The effects of heat stress on cereal yield and quality. In *Crop Responses and Adaptations to Temperature Stress* (ed. Basra, A. S.), Food Products Press, Binghamton, NY, USA, 2001, pp. 243–291.
21. Scott, R. K., English, S. D., Wood, D. W. and Unsworth, M. H., The yield of sugar beet in relation to weather and length of growing season. *J. Agric. Sci.*, 2009, **81**, 339–347.
22. Muchow, R. C. and Bellamy, J. A. (eds), In Proceedings of the International Symposium on Climatic Risk in Crop Production: Models and Management for the Semiarid Tropics and Subtropics, Brisbane, Australia, 2–6 July 1990.
23. Kumar, G., Adak, T., Chakravarty, N. V. K., Chamola, R., Katiyar, R. K. and Singh, H. B., Effect of ambient thermal regime on growth and yield of *Brassica* cultivars. *J. Oilseed Brassica*, 2007, **9**, 47–52.
24. Adak, T. and Chakravarty, N. V. K., Quantifying the thermal heat requirement of *Brassica* in assessing biophysical parameters under semi-arid micro-environments. *Int. J. Biometeorol.*, 2010, **54**, 365–377.
25. Khaton, M. A., Sagar, A., Tajkia, J. E., Islam, M. S., Mahmud, M. S. and Hossain, A. K. M. Z., Effect of moisture stress on morphological and yield attributes of four sorghum varieties. *Prog. Agric*., 2016, **27**(3), 265–271.
26. Campos, H., Cooper, M., Habben, J. E., Edmeades, G. O. and Schussler, J. R., Improving drought tolerance in maize: a view from industry. *Field Crops Res*., 2004, **90**, 19–34.
27. Tuinstra, M. R., Grote, E. M., Goldbrough, P. M. and Ejeta, G., Genetic analysis of post-flowering drought tolerance and components of grain development in *Sorghum bicolor* L. Moench. *Mol. Breed.*, 1997, **3**, 439–448.
28. Kebede, H., Subudhi, P. K., Rosenow, D. T. and Nguyen, H. T., Quantitative trait loci influencing drought tolerance in grain sorghum (*Sorghum bicolor* L. Moench). *Theor. Appl. Genet.*, 2001, **103**, 266–276.
29. Bibi, A., Sadaqat, H. A., Akram, H. M. and Mohammed, M. I., Physiological markers for screening sorghum (*Sorghum bicolor*) germplasm under water stress condition. *Int. J. Agric. Biol. Sci*., 2010, **12**, 451–455.
30. Salih, A. A., Ali, I. A., Lux, A., Luxova, M., Cohen, Y., Sugimoto, Y. and Inanaga, S., Rooting, water uptake, and xylem structure adaptation to drought of two sorghum cultivars. *Crop Sci*., 1999, **39**, 168–173.
31. Younis, M. E., El-Shahaby, O. A., Abo-Hamed, S. A. and Ibrahim, A. H., Effects of water stress on growth, pigments and assimilation in three sorghum cultivars. *J. Agron. Crop Sci.*, 2000, **185**, 73–82.
32. Okcu, G., Kaya, M. D. and Atak, M., Effects of salt and drought stresses on germination and seedling growth of pea (*Pisum sativum* L.). *Turk. J. Agric. For.*., 2005, **29**, 237–242.
33. Kramer, P. J., *Water Relations of Plants*, Academic Press, New York, USA, 1983, pp. 155–106.

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