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Assessment on vulnerability of sorghum to climate change in India

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ABSTRACT

It is important to analyse the impacts of climate change on target production system. However, it is more important to deduce possible adaptation strategies so that the research and developmental policies can be guided to meet the challenges of climate change. Impacts of climate change on the sorghum production system in India are analysed using InfoCrop-SORGHUM simulation model. In general, impact of climate change is projected to be more on winter crop in central (CZ) and south-central zones (SCZ), while in south-west zone (SWZ) the impacts are likely to be higher on monsoon crop. Climate change is projected to reduce monsoon sorghum grain yield to the tune of 14% in CZ and SWZ and by 2% in SCZ by 2020. Yields are likely to be affected even more in 2050 and 2080 scenarios. Climate change impacts on winter crop are projected to reduce yields up to 7% by 2020, up to 11% by 2050 and up to 32% by 2080. Impacts are projected to be more in SWZ region than in SCZ and CZ. But, the yield loss due to rise in temperature is likely to be offset by projected increase in rainfall. However, complete amelioration of yield loss beyond 2 °C rise may not be attained even after doubling of rainfall in south-central zone (SCZ) and in central zone (CZ). Results indicate that adaptation strategies like changing variety and sowing date can reduce the vulnerability of monsoon sorghum to about 10%, 2% and 3% in CZ, SCZ and SWZ regions in 2020 scenario. Adaptation strategies reduced the climate change impacts and vulnerability of winter crop to 1–2% in 2020, 3–8% in 2050 and 4–9% in 2080. This indicates that more low-cost adaptation strategies should be explored to further reduce the net vulnerability of sorghum production system in India.

1. Introduction

Sorghum ranks fifth among the world's most important crops. Its current world production stands at 64.58 million tonnes while in India current production is 7.4 million tonnes (FAO, 2008). It serves as a raw material for food, fodder and many industrial products. Sorghum, which has drought adaptation capability, is a preferred crop in tropical, warmer and semi-arid regions of the world with high temperature and water stress (Peacock and Heinrich, 1984). More than 70% of the world's total production of sorghum comes from the developing countries of Asia and Africa where the crop is grown with limited inputs of water and nutrients, it being a principal mainstay of resource and technology poor farmers. In India, sorghum is cultivated during both monsoon (rainy) and winter (post rainy) season, mainly as a rainfed crop (92% of the area) with about 85% of the production concentrated in Maharashtra, Karnataka and Andhra Pradesh (http://vasatwiki.icrisat.org/index.php/Area_and_distribution_of_sorghum), all falling under warm semi-arid region.

In India, national average productivity of sorghum is very low (880 kg/ha) as against high yield obtained in USA and China. Low productivity can be attributed to low and marginal management and rainfed cultivation. Since sorghum is grown as a rainfed crop, the climatic factors play a significant role in its productivity. With the threat of climate change looming large on the crop productivity, the most vulnerable regions of the world are the tropics, particularly the semi-arid regions where higher temperatures and increases in rainfall variability could have substantially negative impacts (Parry et al., 2004). According to IPCC (2007), the 21st century is projected to experience 1.8–4.0 °C rise in surface air temperature together with very likely occurrence of frequent warm spells, heat waves and heavy rainfall and a likely increase in the frequency of droughts.

Major climate change impacts on plants are through increase in the concentration of atmospheric CO_2, rise in temperature and change in rainfall. Earlier studies on the effect of carbon dioxide fertilization have reported no significant yield increase in sorghum, a C4 crop, as C4 photosynthesis is already CO_2 saturated (von Caemmerer and Furbank, 2003). However experiments (Ghannoum et al., 2000; Vu and Leon, 2009) have conclusively pointed out elevated CO_2 stimulation in carbon assimilation under drought conditions or in short-term water stress conditions. This is caused by an increase in water use efficiency via reduction in stomatal conductance.

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On the other hand, temperature influences yield mainly by controlling the rate of biomass accumulation and the duration of growth (Vu et al., 1997; Fuhrer, 2003) apart from pollen viability and seed setting (Schoper et al., 1986). Temperature influences the biomass accumulation mainly through photosynthesis. The activation state of Rubisco, the enzyme responsible for CO_2 assimilation in plants, reduces at temperatures above the optimum (Holiday et al., 1992); and its specificity for CO_2 and solubility of CO_2 relative to O_2 reduces with increase in temperature (Jordan and Ogren, 1984; Brooks and Farquhar, 1985), thus resulting in a net loss of carbon assimilation. But the optimum temperature for photosynthesis is higher in C4 plants as compared to C3 plants (Rosenberg et al., 1983; Taiz and Zeiger, 1991). The mean optimum temperature range for sorghum is 21–35 °C for seed germination, 26–34 °C for vegetative growth and development, and 25–28 °C for reproductive growth (Maiti, 1996). Secondly, temperature rise affects the duration of growth. Higher temperatures lead to a rapid accumulation of growing degree days; thus growth and development of the crop are faster, resulting in the reduction of phenophase duration, hence yield (Attri and Rathore, 2003). High temperatures decrease seed-filling duration (Fuhrer, 2003), resulting in smaller seed size and lower seed yields (Chowdhury and Wardlaw, 1978; Kiniry and Musser, 1988; Abrol and Ingran, 1996).

Apart from temperature, rainfall is another major factor which influences the crop yield, more so of rainfed crops. Since climate change is projected to affect food production in India (IPCC, 2007), it is important to quantify the impact of climate change on individual crops in order to derive specific adaptation strategies. Altering cultivars and planting times can allow low- and mid- to high-latitude cereal yields to be maintained at or above baseline yields for modest warming (IPCC, 2007) and yield can be increased if the crop growth period is increased (Cooper, 1992). Hence it is important to quantify the adaptation gains in order to assess the net vulnerability of target crop.

Crop growth simulation models are increasingly used for analyzing the impacts of climate change on various crops such as rice (Ohta and Kimura, 2007; Tao et al., 2008), wheat (Anwar et al., 2007; Hundal and Prabhjyot-Kaur, 2007; Chapman, 2008), maize (Yano et al., 2007; Xiong et al., 2007; Almaraz et al., 2008) and groundnut (Challinor et al., 2007; Challinor and Wheeler, 2008). Such analysis for sorghum was also carried out earlier for other countries (Easterling et al., 1992; Brown and Rosenberg, 1997; Zeng and Heilman, 1997; Tingem and Rivington, 2009). Even though, yield gap analysis was done for sorghum in India (Murty et al., 2007), countrywide studies on the analyses of climate change impacts are scarce. Earlier impact analyses, using the CERES-sorghum model, indicated a decrease in yield and biomass of rainy season sorghum but a marginal increase in yield of post rainy season sorghum grown on stored soil moisture (Ritchie and Alagarswamy, 1989; Rao et al., 1995; Chatterjee, 1998). However, no analysis was carried out quantify the gains due to potential adaptation strategies to deduce the net vulnerability of sorghum in India. Moreover, in these models, crop coefficients for temperature response are based on experiments conducted in temperate conditions. It is important to use the crop coefficients related to tropical areas as crop response to temperature can vary if tropical varietal coefficients are used. InfoCrop-SORGHUM is a dynamic crop growth simulation model which can simulate the effects of various environmental factors (Aggarwal et al., 2006a, 2006b) for tropical regions. Thus, the present study was undertaken with specific objectives to (i) calibrate and validate InfoCrop-SORGHUM model, (ii) use the validated model for quantifying the impact of climate change on sorghum yield and to (iii) assess the adaptation capacity of sorghum through change in sowing time and variety, and estimate net vulnerability of sorghum to climate change.

2. Materials and methods

2.1. Model description

InfoCrop-SORGHUM is a part of InfoCrop (Aggarwal et al., 2006a, 2006b), which is a Decision Support System (DSS) based on generic model. The models in this DSS are designed to simulate the effects of weather, soil, agronomic management (including sowing time, nitrogen, residues and irrigation) and major pests on crop growth and yield. The basic crop model has been written in Fortran Simulation Translator programming language (FST/FSE; Graduate school of Production Ecology, Wageningen, the Netherlands; Van Kraalingen, 1995). In this model, the total crop growth period is divided into three phases viz., sowing to seedling emergence, seedling emergence to anthesis and storage organ filling phase.

The model requires inputs on eight varietal coefficients which include radiation use efficiency, potential grain weight, etc. Crop management input data include time of planting, seed rate, depth of planting; amount, time and depth of placement of different organic matters and nitrogen; and amount, time and type of irrigation. Soil input data required are textural parameters, thickness, bulk density, saturated hydraulic conductivity, soil organic carbon, pH, slope, soil water holding capacity, permanent wilting point for each of the three soil layers. Model requires daily weather data of location for carrying out the simulations. Apart from these, model has a provision for changing the atmospheric CO_2 concentrations.

The influence of climate change parameters viz., rise of temperature and CO_2 and change in rainfall are simulated by influencing the source–sink aspects of the crop in the following ways.

1. The total development of a crop is calculated by integrating the temperature-driven developmental rates of the phases from sowing to seedling emergence, seedling emergence to anthesis and storage organ filling phases. The rate of development is linearly related to the daily mean temperature above base temperature up to the optimum temperature. Above this, the rate decreases.
2. Dry matter production is a function of radiation use efficiency (RUE), photosynthetically active radiation, total leaf area index (LAI), and a crop/cultivar specific light interception coefficient. RUE is further modified on the account of developmental stage, crop-specific response of photosynthesis to temperature, CO_2, water and nitrogen availability and other biotic factors. As far as influence of CO_2 is concerned, in InfoCrop-SORGHUM model concentration of CO_2 has very little influence on rate of photosynthesis as sorghum is a C4 crop. But under water stressed conditions, increase in CO_2 does indirectly increase C4 photosynthesis and yield by reducing water use and delaying drought stress via reduction in stomatal conductance and transpiration rate (Ghannoum et al., 2000). These effects are simulated in the model.
3. The net dry matter available each day for crop growth is partitioned into roots, leaves, stems, and storage organs as a crop-specific function of developmental stage, which as mentioned earlier is a temperature-driven state variable.
4. The net leaf area growth rate is a function of initial specific leaf area, initial leaf area index, dry matter partitioning to leaf, senescence and net loss in leaf area due to stresses. When the leaf area index is less than 0.75 during the initial stages of development, there is a greater control of temperature over the formation of leaf area. The photosynthetic characteristics of the non-lamina green areas are assumed to be the same as those of leaves. Non-lamina green area senescence rate is accelerated by temperature. Simulation of leaf senescence is based on several empirical constants relating to shading, ageing, nitrogen remobilization, temperature, water stress and death due to pests and diseases.

Table 1
Details of data base used for calibration and validation of InfoCrop-Sorghum.

Location	Lat. (°N)	Long. (°E)	Altitude (m amsl)	Crop season and year	Soil type	Experiment	Treatment	No. of treatments used for comparing with simulated values	Data source	Maximum temperature (°C) range	Minimum temperature (°C) range	Rainfall (mm)
Hyderabad	17	78	489	Oct–Feb 1988–1989	Red sandy	Irrigation and fertilizer trial	Irrigation (rainfed, irrigated) Six nitrogen levels (0, 30, 60, 90, 120 and 150 kg ha^{-1}) Variety: SPH-280	12	Rego et al. (1998)	20–32	9–24	9
Hyderabad	17	78	489	June–Sept 1976 to June–Sept 1984	Red sandy	Varietal performance	CHS-6	18	Huda (1988)	21–42	19–29	342–970
Hyderabad	17	78	489	July–Oct 1996–1999	Red sandy	Varietal performance	Rainfed CSH-6, CSH-9, CSH-14, CSH-16, CSH-17	20	NRC on Sorghum, Hyderabad	23.5–42	18–28	378–846
Hyderabad	17	78	489	Oct–Feb 1977–1978	Red sandy	Physiological	Irrigated and rainfed CSH-8	2	Sivakumar et al. (1979)	26–33	9.4–24	121
Indore	22.4	75.5	567	June–Oct 1998	Medium black	Varietal trail	CSH-9, CSH-14, CSH-16	3	Progress report, AICSIP (1998–1999)	25–45	21–31	886
Dharwad	15	75	700	Oct–Feb 1998–1999	Mixed red and black	Varietal performance	CSH-15R	1	Progress report, AICSIP (1998–1999)	25–34	12–22	193
Udaipur	24.6	73.78	273	July–Oct 1997, 1998	Sandy loam	Fertilizer trial	CSH-9	8	Patidar and Mali (2004)	29–39	14–28	607
Coimbatore	11	76	379	July–Oct 1998	Red and black deltaic alluvial	Varietal trial	CSH-9, CSH-14, CSH-16	3	Progress report, AICSIP (1998–1999)	26–34	20–26	274
Parbhani	30	77	700	July–Oct 1998	Medium to deep black clay loam	Varietal trial	CSH-9, CSH-14, CSH-16	3	Progress report, AICSIP (1998–1999)	29–33	19–24	97
Nagpur	21	79	301	July–Oct 1998	Medium to deep black clayey	Varietal trial	CSH-9, CSH-14, CSH-16	3	Progress report, AICSIP (1998–1999)	26–36	17–27	705
Akola	20.42	77.02	282	July–Oct 1998	Medium to deep black clay loam	Varietal trial	CSH-9, CSH-14, CSH-16	3	Progress report, AICSIP (1998–1999)	26–38	13–26.3	626

Higher or lower temperatures than the optimum accelerate rate of senescence depending upon the crop sensitivity to temperature.

5. Temperature influences potential evapo-transpiration. Water stress is determined as the ratio of actual water uptake and potential transpiration. It accelerates phenological development, decreases gross photosynthesis, alters the allocation pattern of assimilates to different organs and accelerates rate of senescence.
6. Number of spikelets formed is determined shortly before anthesis. In InfoCrop, the net growth during this period and a crop-specific factor relating storage organ to growth are utilized to calculate the increase in the number of grain. A part of the grain formed could be lost due to pests' attack and due to adverse temperatures. Adverse temperatures during meiosis stage could significantly increase sterility. In InfoCrop, a part of the storage organ becomes sterile if either maximum or minimum temperatures of the day deviate from their respective threshold values during anthesis and a few days afterwards. This reduces the number of storage organs available subsequently for accumulating weight. The storage organ start filling up shortly after anthesis with a rate depending upon temperature, potential filling rate and the availability of dry matter for their growth. The growth of the storage organs is terminated on the attainment of potential weight, or due to non-availability of dry matter and on the fulfillment of the thermal time-dependent development stage.

2.2. Database for model calibration and validation

Performance of sorghum, being an important crop of rainfed area in India, is evaluated in a large number of experiments under different agro-climatic zones. However, datasets from 23 experiments were selected where information regarding model input requirements were available. These experiments were conducted in diverse agro-climatic conditions viz. Hyderabad, Indore, Coimbatore, Nagpur, Parbhani, Udaipur and Dharwad (Table 1). This database included physiological experiments, multi-location varietal trails, fertilizer and irrigation trails. The experiments were conducted in a period for 20 years from 1978 to 1999.

These experiments consisted of 76 treatments and are conducted in major sorghum growing in India (Table 1). Database consisted data on eight popular varieties, six nitrogen levels and irrigated and rainfed conditions. Physical properties of the typical soils of each location such as texture, bulk density, water content fraction at wilting point, field capacity, saturation and hydraulic conductivity were taken from literature. Soils in these locations varied from red sandy to deep black clay type. Daily weather data on minimum and maximum temperature, solar radiation, wind velocity, rainfall and vapour pressure for the experimental period were used for simulations. Among the locations, maximum temperature varied from 27 to 32 °C while the minimum temperature varied from 20 to 24 °C during monsoon crop growth season. On the other hand, the maximum temperature during winter crop growth season varied from 28.8 to 30 °C while the minimum temperature varied from 13 to 17 °C. The rainfall ranged from 460 to 830 mm during monsoon season and 72–196 mm during the winter season.

2.3. Model calibration

The InfoCrop-SORGHUM model was calibrated using the data set of a detailed experiment carried out at ICRISAT Centre, Patancheru (17.5°N, 78.5°E, 545 m altitude), India (Rego et al., 1998). In this experiment, sorghum crop was grown on vertisol with two rates of irrigation and six levels of nitrogen (Table 1) during October to February period. The model was calibrated for this experiment using the soil, management and climatic conditions of the experimental location. In this experiment, observations recorded on crop parameters included phenology (days to panicle initiation, 50% flowering, hard dough and physiological maturity); leaf area index (LAI); total dry matter (TDM); dry matter partitioning into stem, leaf, roots and panicle; and grain yield. Simulated values for the above parameters were compared with the observed values and iterations were done for some of the varietal coefficients to match the observed values on phenology, leaf area index (LAI), total dry matter and grain yield. In the experimental data set used for calibration, sorghum crop took 80 days from seedling emergence to 50% flowering and 36 days for grain filling period. Model simulated values were 82 and 41 for days to 50% anthesis and grain filling period, respectively.

Apart from this, model was calibrated for eight different varieties. The model requires eight genetic coefficients for simulating a crop variety. To generate such coefficients, detailed physiological experiments in controlled and field environments are needed to be conducted. As data on these aspects are not available, the genetic coefficients of various varieties were derived by repeated iterations so that the simulated phenology and grain yield matched the observed values for respective variety. These coefficients were further used while validating the model in different locations. Thus for calibrating the model, data on a total of 14 treatments were used.

2.4. Model validation

Using the calibrated model, validation was carried out for different locations viz., Hyderabad, Indore, Coimbatore, Nagpur, Parbhani, Udaipur and Dharwad, which represent major sorghum growing areas in India. The model was validated for monsoon (June–September) and winter (October–March) sorghum crop using the all other data sets (of 62 treatments) which were not used for calibration (Table 1). The observed values for parameters such as days to 50% flowering, total dry matter (TDM) and grain yield were used for comparing those from model simulations. In the above locations, validation was carried out for eight varieties viz., CSH 6, CSH 9, CSH 14, CSH 16, CSH 17, CSH 8, SPH-280 and CSH 15 R. The thermal time requirement for three phenological phases of different varieties ranged from 80 to 90 growing degree days (GDD) for seedling emergence, 970–1300 GDD for period from emergence to 50% flowering and 585–850 for grain filling period.

Model performance was assessed through various statistical parameters viz., model efficiency (ME), root mean square error (RMSE), index of agreement (IA) and model bias error (MBE), and calculated as per Nash and Sutcliffe (1970), Fox (1981), Willmott (1982) and Addiscott and Whitmore (1987), respectively.

2.5. Simulation of baseline yields

Using the validated InfoCrop-SORGHUM model, grain yields were simulated for three regions viz., central zone (CZ-represented by Indore), south-central zone (represented by Hyderabad) and south-west zone (represented by Dharwad) for baseline period of past 25 years (1970–1995). These regions are the major sorghum growing areas and varied for climatic and soil conditions (Table 2). In simulations, crop was sown in the middle of general sowing window recommended for respective area, thus the monsoon crop was sown in the last week of June at Indore and Hyderabad and in the first week of June at Dharwad. The winter crop was sown in the middle of September at Indore and Hyderabad; while at Dharwad it was sown in the third week of September. Yields obtained from these simulations were averaged to get 'baseline yields' for respective locations in each season. At Indore, normally a winter crop is not cultivated. But in this study, a winter crop was also simulated with

Table 2
Agro-climatic characteristic of study locations during monsoon and winter cropping season (values represent mean of baseline 1970–1995).

Mean weather parameters	Indore (22.4°N; 75.5°E; 567 m amsl)		Dharwad (15°N; 75°E; 700 m amsl)		Hyderabad (17°N; 78°E; 489 m amsl)	
	M	W	M	W	M	W
Daily solar radiation (MJ m^{-2})	16.72	16.57	16.9	17.0	14.4	19.7
Maximum temperature (°C)	31.23	29.7	31.3	28.8	27.5	29.2
Minimum temperature (°C)	23.3	13.7	22.9	16.4	20.3	15.9
Total rainfall (mm)	831.4	72.6	617.3	208.1	461.2	163.9
Soil type	Medium black soil		Red Sandy Soils		Mixed red and black soils	

M: monsoon season; W: winter season; amsl: above mean sea level.

minimal irrigation to test sorghum's viability at this location. At all three locations, rain fed crop was simulated during the monsoon season. Considering the farmers' practice, winter season crop was simulated with minimal supplemental irrigation. Fertilizer inputs were also provided as per farmers' general practice for sorghum cultivation in India.

2.6. Impact assessment

Impact of climate change on grain yield of maize was studied using two approaches. In the first approach, impact of fixed rise in temperature, CO_2 concentration and change in daily rainfall was analysed using a 3-factorial matrix combination of these three parameters. For this, temperature (minimum and maximum) was raised at fixed levels of 1, 2, 3, 4 and 5 °C. The CO_2 concentrations used were at 369, 450 and 550 ppm. Further, change in daily rainfall amounts starting from a complete deficit, i.e. −100% to a 100% increase were used at 10% steps of increment. Yields were simulated after coupling the changes in above parameters to the observed weather data of the baseline years (25 years). Since the projections on rainfall, which indicate a positive shift in Indian subcontinent, are highly uncertain, the climatic variability (including rain fall distribution and variability) that existed in baseline years is assumed to occur in changed scenarios as well. The impact of climate change on sorghum was studied at three locations – Indore (Madhya Pradesh), Hyderabad (Andhra Pradesh) and Dharwad (Karnataka) during both monsoon and winter seasons.

In an alternative approach, HadCM3 global climate model outputs on temperature (minimum and maximum) and rainfall for 2020, 2050 and 2080 A2a scenarios were coupled to the baseline weather data. The projected carbon dioxide levels as per Bern CC model for these scenarios (414, 522 and 682 ppmV CO_2 for 2020, 2050 and 2080, respectively) were also included in the InfoCrop model for simulations. All other simulation conditions were maintained as explained earlier. To express the impacts on yield, the simulation results on grain yield for climate change scenarios were compiled and relative yield deviations from baseline yields were calculated.

2.7. Adaptation and vulnerability analysis

Once impact of climate change on sorghum production system is analysed, it is imperative that the adaptation capacity, which helps in assessing the vulnerability of the system, is also worked out. Two low-cost options, independently and in combination were tested as adaptation strategies to minimize the adverse impacts of climate change on sorghum production. They are (a) change in a variety which has similar vegetative duration in future scenarios as that of the current variety under present environment, (b) change in sowing time which includes advancement and late sowing from current sowing time and (c) interactions of both. For changing the variety, vegetative phase was restored to the current variety level taking in to consideration of reduction in vegetative period (i.e., seedling emergence to 50% flowering) under increased temperature and changed rainfall conditions at normal sowing time. In addition to this, shifting of sowing dates viz., early, normal and late sowing from the current date of sowing was done in combination with change in variety to get the best possible adaptations for changed temperature, CO_2 and rainfall scenarios and also for HadCM3 A2a climate change scenarios. The combinations which gave the highest yield in each scenario were taken as the best suitable adaptation option. In all, about 5,67,000 simulation runs were made for the entire analysis.

Yields at all these best adaptation options were compiled to calculate the adaptation gains. For this, net yield gain due to best possible adaptation strategy at each scenario was calculated and then expressed as the relative change from the mean baseline yield. Thereafter, net vulnerability in respective scenario was derived by subtracting the adaptation gains from the baseline. In instances where impacts are positive, simulations were run for similar adaptation strategies for quantifying the additional benefits and thus in these situations net positive impacts included adaptation gains.

3. Results and discussion

3.1. Model validation

The InfoCrop-SORGHUM model could satisfactorily simulate the phenology and grain yield of sorghum cultivars in different locations. Simulated days to anthesis, days to physiological maturity and grain yield matched with their observed values with R^2 values of 0.93, 0.71 and 0.81, respectively (Fig. 1). Data indicate that in spite of slight over estimation of grain filling period, the simulation values grain yields closely matched observed values. The statistical parameters for days to 50% anthesis indicate a low but positive MBE with RMSE indicating that the model slightly prolonged the days for 50% anthesis. However, the these variations are well within acceptable error level as indicated by a very high value of AI and ME where values close to 1 are regarded as better simulations (Table 3). Statistical results indicated high MBE and RMSE for grain filling period and consequently for days to maturity. Model simulated grain filling period is determined by growing degree days and source–sink balance. Leaf area index also has closely matched with that of observed one (Fig. 1) at different stages of crop growth. The grain yield has low values of MBE and RMSE and high IA and ME. Results indicate that the model has a tendency to slightly over esti-

Table 3
Statistical indicators of model performance.

Crop parameters	MBE	RMSE	IA	ME
Days to 50% anthesis	0.16	2.01	0.98	0.93
Days to maturity	0.83	4.92	0. 90	0.51
Days to grain filling	0.56	3.05	0.84	0.40
Grain yield	8.86	576.4	0.94	0.81

MBE: mean bias error; RMSE: root mean square error; IA: index of agreement; ME: model efficiency.

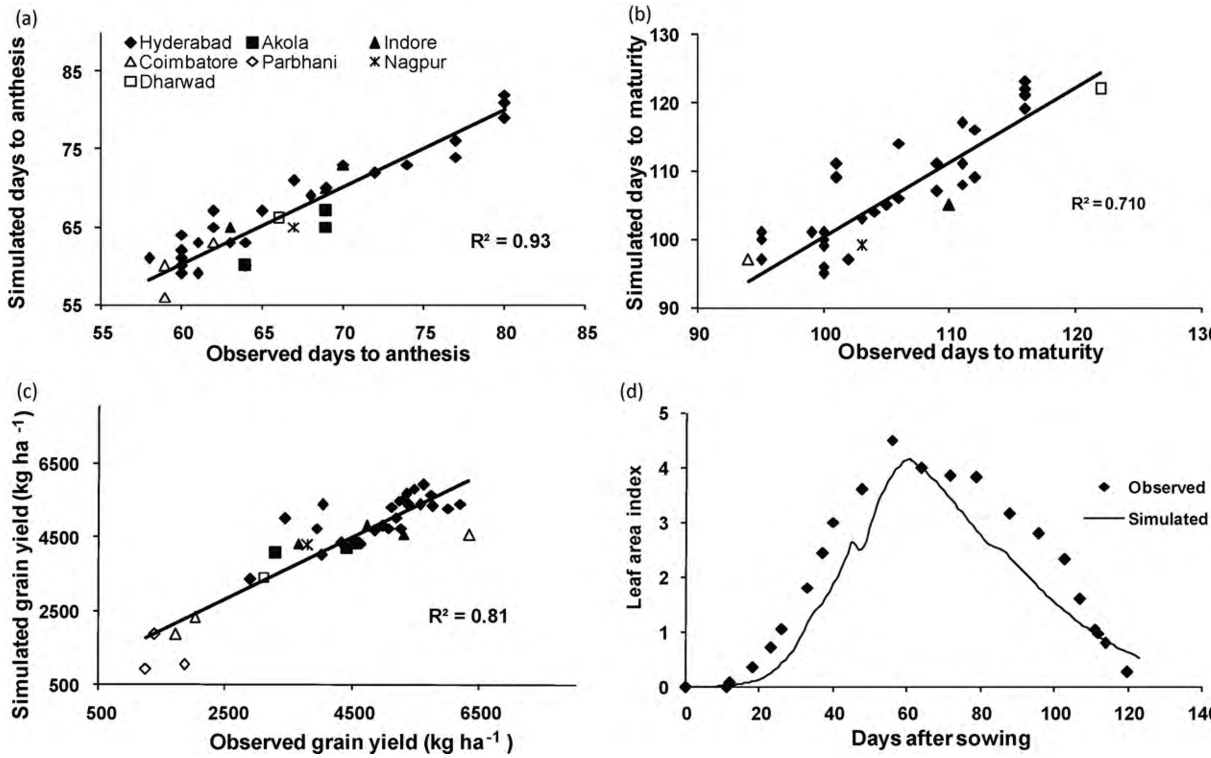

Fig. 1. Simulated and observed (a) days to 50% flowering, (b) physiological maturity, (c) grain yield and (d) time course leaf area index in different agro-climatic zones.

mate the phenology and grain yield. However, all these are within the error of 12% which is acceptable for study of this nature where similar positive biases will be inherent of all simulations and the results are largely drawn from relative changes in different scenarios. Thus these minor deviations in model will not influence the final trends obtained as far as climate change impact, adaptation and vulnerability assessment studies are concerned.

3.2. Impact of rise in temperature and CO_2, and change in rainfall on sorghum yield at current levels of management

The impact of rise in temperature and CO_2, and change in rainfall on yield of sorghum crop was quantified under rainfed conditions during the monsoon season and with minimal irrigation during winter season. Analysis indicated that rise in temperature may reduce monsoon sorghum yields in all three zones (Fig. 2). Loss in yield is projected to be ~6–37% with rise in temperature up to 5 °C. With 1 °C increase in temperature, the loss in yield from current yields likely to be to the tune of 7.6% in SWZ, 4.2% in SCZ and 5.2% in CZ. Further increase in temperature is projected to accelerate the loss in grain yield with greater impact in SWZ followed by in CZ and SCZ. Results indicated that sorghum crop in SWZ is sensitive to climate change induced warming in rain fed condition than in CZ and SCZ. However, the yield loss due to rise in temperature by 1 °C is projected to be offset by a 10% increase in rainfall in SWZ, by 40% increase in rainfall in SCZ and by 20% increase in CZ. Increase in rainfall by 20% and 40% can offset the yield loss at 2 °C rise in SWZ and CZ, respectively. The yield loss projected for SWZ at a 5 °C rise in temperature can be completely offset by a 40% increase in rainfall. But complete amelioration of yield loss beyond 2 °C rise may not be attained even after doubling of rainfall in CZ and SCZ. Rise in atmospheric CO_2 concentration to 550 ppmV is projected to improve the yields by about 8% comparative to baseline yields mainly in deficit rainfall scenarios. This improvement can be attributed to improvement in water use efficiency in water stress conditions.

During the winter season, even though about 6% loss in sorghum yield is projected with rise in temperature by 1 °C, magnitude of yield loss is projected to vary with region if temperature rises beyond 1 °C. If temperature rise by 2 °C, projected yield loss is ~8% in SCZ; 12% in SWZ and 15% in CZ. Further rise in temperature projected to cause more yield loss in SWZ and CZ than in SCZ (Fig. 3). In CZ region, currently, farmers do not grow winter sorghum. However, simulations of about 25 years showed economic yield could be obtained during winter season if irrigation is provided at the panicle initiation, anthesis and grain filling stages of crop at this location. Winter sorghum also is projected to be benefitted due to rise in atmospheric CO_2 to 550 ppm with about 8% increase in yields, particularly in stress conditions.

Temperature rise driven decrease in vegetative phase, grain filling period and crop duration can be attributed as the main reason for decrease in yield. Warmer air temperatures hasten the life cycle of a crop (Vu et al., 1997; Fuhrer, 2003), grain growth rate is increased reducing the duration of grain filling, finally reducing the total grain weight (Chowdhury and Wardlaw, 1978; Kiniry and Musser, 1988; Abrol and Ingran, 1996). Apart for high temperature induced pollen sterility (Schoper et al., 1986), reduction in the phenology of crop due to temperature rise lead to reduction in the number of grains formed, which also contributed in reduction of yield. Significant reduction in leaf photosynthetic rates was noted with season long growth temperatures in the range of 36/26 to 44/34 °C. High temperature (≥36/26 °C) significantly decreased seed set, seed number, seed size, seed-filling duration, and seed yields when compared with optimum temperature (32/22 °C). Growth temperature of 40/30 °C delayed panicle exertion by about 30 days, while panicle exertion was completely inhibited at growth temperatures of 44/34 °C (Prasad et al., 2006). Even though, such high temperatures during crop growth season in India generally do not occur; crop in areas with low rainfall face high day/night temperatures, particularly during dry-spells, causing reduction in yield. Apart from this, temperature rise create greater water stress conditions due to increase in evapo-transpiration loss leading to

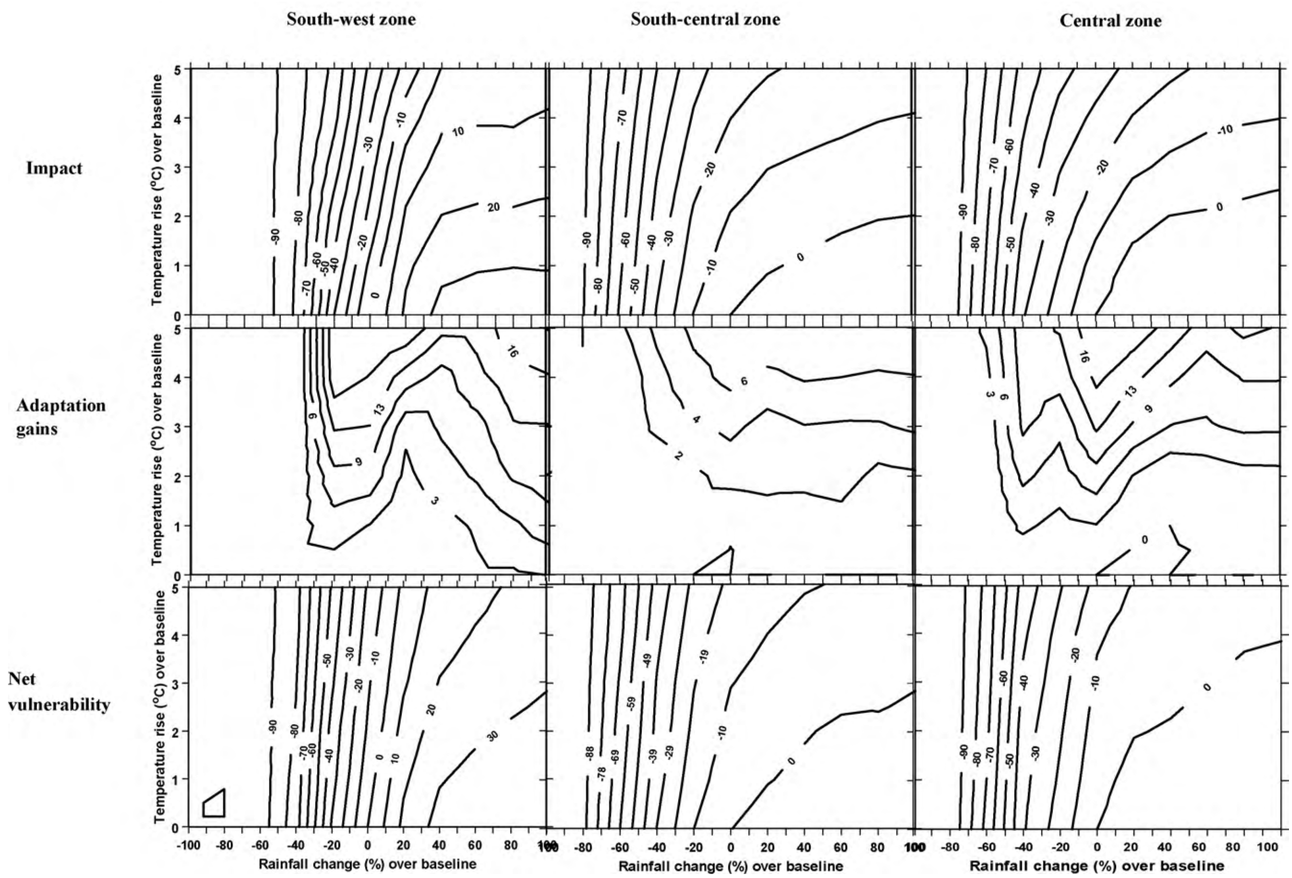

Fig. 2. Impact, adaptation gains and net vulnerability of monsoon sorghum crop in distinct agro-climatic zones in India.

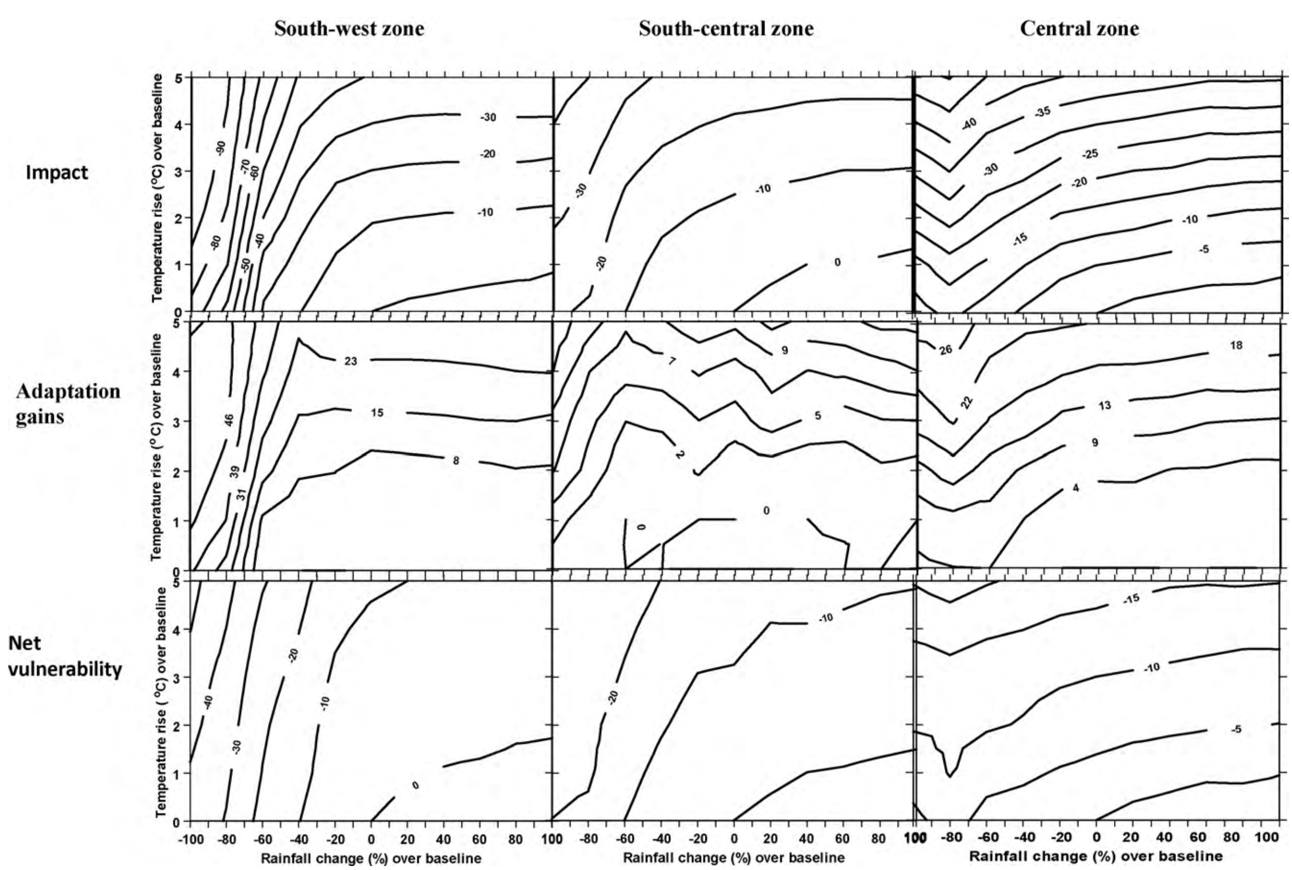

Fig. 3. Impact, adaptation gains and net vulnerability of winter sorghum crop in distinct agro-climatic zones in India.

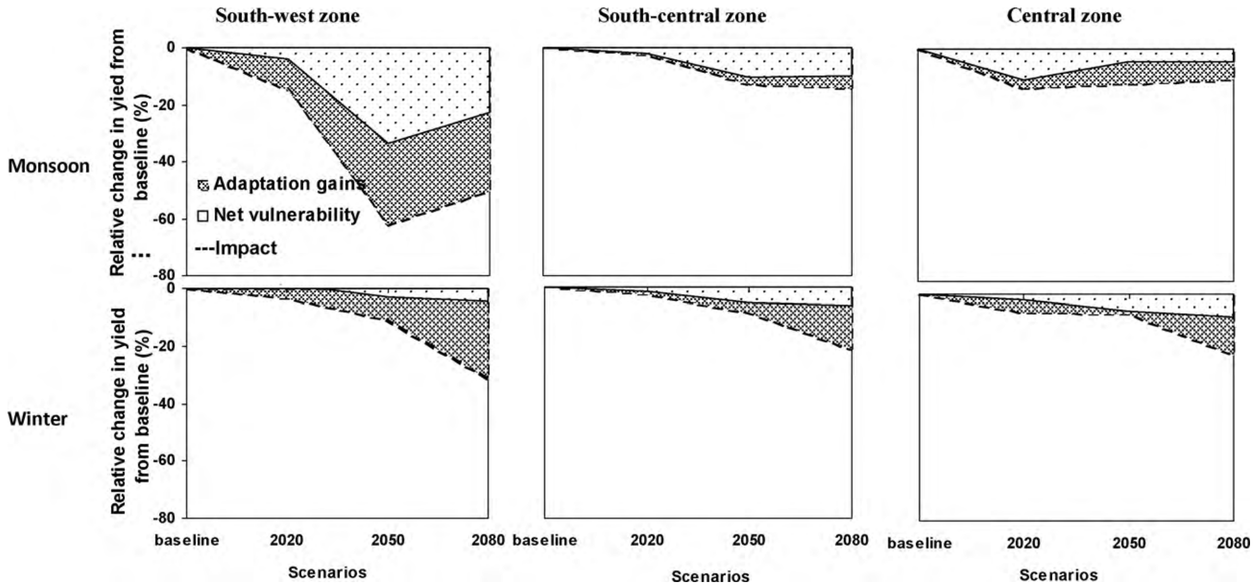

Fig. 4. Impact of climate change on grain yields of sorghum and adaptation gains and net vulnerability during monsoon and winter in different agro-climatic zones. The bottom dash-line indicates impacts.

reduction in number of grains formed and finally the yield. These cumulative effects cause yield reduction in climate change scenarios.

3.3. Impact of climate change on sorghum yields

To capture the impact of projected climate change scenarios, simulations were carried out using the HadCM3 model A2a scenario projection on temperature and rainfall along with the Bern CC model projections on atmospheric CO_2 concentrations in 2020 (414 ppmV), 2050 (522 ppmV) and 2080 (682 ppmV) scenarios. In these, spatio-temporal variations exist in projected rise in temperatures and also in projected changes in rainfall with higher rise in temperature in SCZ and SWZ. An increase in monsoon rainfall and a reduction in winter rainfall is projected. Average seasonal rainfall in SWZ region is least among the regions considered. These outputs of global climate model were input along with projected CO_2 levels into InfoCrop-SORGHUM to simulate the impacts of climate change on grain yield with current management practices. Climate change is projected to reduce monsoon sorghum grain yield to the tune of 16% in CZ and SWZ and by 3% in SCZ by 2020 (Fig. 4). Yields are likely to be affected to the tune of 17% in CZ and SCZ to 76% in SWZ during 2050 and 2080 scenarios. Climate change impacts on winter crop likely to reduce yields up to 7% by 2020, up to 11% by 2050 and up to 32% by 2080. Impacts are projected to be more in SWZ region followed by SCZ and CZ. Decline in yields is projected to be more rapid post 2020 scenario.

3.4. Assessment of adaptation options and net vulnerability

Since climate change is projected to affect the sorghum production in India, it is imperative that low-cost and implementable adaptation strategies are derived for reducing the impacts. Two such adaptations options viz., change in variety and change in sowing date, were tested for their effectiveness in reducing the climate change impacts on sorghum production system.

Analysis on adaptation of sorghum to rise temperature and CO_2 and change in rainfall indicated that the adaptation gains in monsoon (Fig. 2) and winter (Fig. 3) crops, calculated as the relative yield change over base line yields, are projected to be higher in CZ and SWZ of India than in SCZ region, where the impacts are projected to be relatively less.

3.5. Monsoon crop

Sowing sorghum by first week of June in SWZ and in last week of June in CZ and SCZ can reduce the impact of temperature rise (Fig. 2). These shifts in sowing date ensure, in rainfed situation, availability of soil moisture to the crop and also conducive temperatures during grain filling period. Adaptation gains can be up to 14% in SWZ and CZ while it is likely to be about 7% in SCZ with 1–5 °C rise in temperature, thus bringing down the vulnerability of sorghum production in India to about 3–5% with 1 °C rise, 6–8% with 2 °C rise, 10–11% with 3 °C rise, 13–16% with 4 °C rise and 18–20% with 5 °C rise in temperature. Delayed sowing in CZ and SCZ regions can help crop to avoid water stress period during initial crop growth. Adaptation gains due to change in variety and sowing date are likely to be better with a 20–30% increase in rainfall in SWZ. Adaptation gains are projected to be more at increased temperature coinciding with increase in rainfall. On the other hand, rainfall deficit of 50% and beyond can cause crop failure.

In HadCM3 model scenarios, adaptation measures are projected to reduce the climate change impact by about 25% in SWZ region in 2050 (Fig. 4). On the other hand adaptation gains in monsoon crop in SCZ and CZ are projected to be around 2–4% in 2020, 4–10% in 2050 and 2080 scenarios. Thus adaptation strategies can reduce vulnerability of monsoon sorghum to about 10%, 2% and 3% in CZ, SCZ and SWZ regions in 2020 scenario. Better adaptation gains post-2020 scenario can reduce vulnerability to only 4% in CZ, whereas vulnerability is projected to be about 11% in SCZ and 40% in SWZ.

3.6. Winter crop

Adaptation strategies are projected to reduce the climate change impacts by up to 25% in winter sorghum (Fig. 3). Study indicates that sorghum production system in CZ is the most vulnerable to temperature rise even after accommodating adaptation gains. A temperature rise beyond 3 °C is likely to result in more than 11% vulnerability of sorghum in this region. However, sorghum in SCZ and SWZ regions is less vulnerable even at 4 and 5 °C rise of temperature (Fig. 3). The analysis indicated a net vulnerability of 2–3% with rise in temperature by 1 °C; 5–8% by 2 °C; 7–11% by 3 °C; 8–14% by 4 °C; and 12–17% by 5 °C. However, increase in rainfall can reduce the vulnerability by about 3–5%. The impact of temperature rise on winter crop can be reduced by sowing in third week of September in SWZ and by last week of September to early October in SCZ and CZ. In CZ, delayed sowing (by 2nd week of October) can reduce the impacts if temperature rise is 3 °C and above.

Since climate change scenarios projected an increase in winter rainfall and temperature, winter sorghum crop is less vulnerable to climate change The adaptation gains projected are around 2–4% in 2020, 1–11% in 2050 and 12–26% in 2080 scenarios, thus nullifying the vulnerability in SWZ region. However, the vulnerability of winter crop in SCZ and CZ regions stands at 1–2% in 2020, 3–8% in 2050 and 4–9% in 2080, while that of SWZ remains at 3–4% post-2020 scenarios.

The adaptation gains in yield are projected for all regions. However, since net vulnerability still exists, more low-cost, eco-friendly adaptation strategies need to be explored. Since this simulation study was aimed at finding out impact of climate change on sorghum grown under current input levels, better management may decrease the vulnerability of the crop to climate change but this would entail more economic investment in future. Breeding varieties where the crop phenology could be restored to current level even as temperature rises would be more beneficial for reducing the climate change impacts and help majority of resource poor farmers. Since sorghum is a drought hardy crop, it may gain more importance in future temperature rise scenarios in comparison to other staple crops. In this perspective, current assessment on impact of climate change on sorghum production, adaptation capacity and vulnerability estimates provide vital inputs for future crop production strategies.

4. Conclusions

Calibrated and validated InfoCrop-SORGHUM could be used to simulate the impacts of climate change on sorghum crop in India. The analysis indicated that climate change impacts are projected to reduce the grain yield of sorghum more during winter than in monsoon except for SWZ region, where monsoon crop yield loss is projected to be higher in A2a scenario. The yield loss may be huge for locations where current temperatures are already high and rainfall is low. At places where current temperatures are relatively low with moderate rainfall, yield loss likely to be less. Adaptation through breeding of cultivars with similar duration of vegetative phase as that of current cultivars even in temperature rise scenarios along with changed planting time can help in realizing significant adaptation gains. An advancement of sowing of monsoon sorghum variety, which has a phenology of current variety, by 1 week in south-west region, is proposed as a combination of adaptation strategy. On the other hand delaying in sowing to last week of June is proposed for south-central region. In central India, change in variety alone can reduce the climate change impacts. In case of winter sorghum, a delay in sowing by a fortnight is proposed for reducing the impacts of climate change in central and south-central region while continuation of current date of sowing can be followed in south-west zone. However, if yield levels have to be maintained other options such as high temperature tolerant varieties, soil moisture conservation need to be considered as adaptation strategies for climate change. An integrated approach to reduce the impact of climate change is more likely to give desirable results for sustain the sorghum yields in India.

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