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Irrigation and shifting planting date as climate change adaptation strategies for sorghum

Fikadu Getachew [a], Haimanote K. Bayabil [a,*], Gerrit Hoogenboom [b], Fitsum T. Teshome [a], Eshetu Zewdu [c]

[a] Department of Agricultural and Biological Engineering, Tropical Research and Education Center, IFAS, University of Florida, Homestead, FL, USA
[b] Department of Agricultural and Biological Engineering and Institute for Sustainable Food Systems, University of Florida, Gainesville, FL, USA
[c] Ethiopian Institute of Agricultural Research, Climate and Geospatial Research Department, Melkassa, Ethiopia

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ABSTRACT

Climate change is projected to have a global impact that affect food production and security. The objectives of this study were to determine the potential impact of climate change on sorghum yield for rainfed production systems and to evaluate the potential of irrigation and shifting planting dates as adaptation options for two major sorghum production regions in Ethiopia. The Decision Support System for Agrotechnology Transfer (DSSAT) Cropping System Model (CSM)-CERES-Sorghum model was used to simulate the impact of climate change on sorghum yield for two Representative Concentration Pathways (RCPs; RCP 4.5 and RCP 8.5) and for three future periods including the 2025s (2010–2039), 2055s (2040–2069), and 2085s (2070–2099). The Agricultural Model Improvement and Inter-comparison Project (AgMIP) framework was used to select five representative GCMs for hot/dry, cool/dry, middle, hot/wet, and cool/wet climate scenarios. Two climate change adaptation practices including supplemental irrigation at two levels (deficit and full) to the current rainfed production system and shifting planting dates were evaluated. The CSM-CERES-Sorghum model was calibrated and evaluated using eight years of experimental data from Meisso, eastern Ethiopia. The model was then run for Kobo and Meisso under different climate change and crop management scenarios. Based on model evaluation results, the model performed well for simulating sorghum yield (R^2 = 0.99), anthesis (R^2 = 0.86, RMSE = 1.3), and maturity (R^2 = 0.79, RMSE = 4.4). The results showed that the average temperature for Kobo and Meisso is expected to increase by up to 6 °C under RCP8.5 in 2085. For the rainfed production systems without adaptation practices, drought stress is projected to intensify during anthesis, which was reflected by projected yield reductions by up 2 t ha^{-1} for the two sites. Full irrigation was effective in reducing moisture stress and, thereby, increasing sorghum yield by up to 3 t ha^{-1} for Kobo and 2 t ha^{-1} for Meisso. On average, full irrigation resulted in a 1 t ha^{-1} yield increase compared with deficit irrigation. Early planting dates also resulted in an increase in yield compared to the baseline planting dates, especially when combined with supplemental irrigation, although late planting was consistently disadvantageous even with supplemental irrigation. This study highlighted that the CSM-CERES-Sorghum model can be effectively used to simulate climate change effects on sorghum yield and evaluate different climate change adaptation practices. The outcomes of this study can also help to implement management decisions towards climate change adaptation for the current subsistence and fragile rainfed crop production system in Ethiopia and similar ecoregions across the globe.

1. Introduction

Sorghum is the fifth most important cereal crop in the world, after wheat, maize, rice, and barley (Mejia and Lewis, 1999; Mundia et al., 2019). It is the second major crop after maize in Africa (Taylor, 2003), and it is considered to have been first domesticated in North Africa, possibly in Ethiopia around 1000 Before Christ (B.C.) (Doggett, 2009). Due to its unique nature of drought resistance compared to other cereals, sorghum is the most common food grain crop in sub-Saharan Africa (Obilana, 1994). As a result, it is widely grown in arid and semi-arid regions of Africa including in the East African highlands characterized by a monsoon rainfall season with a non-uniform rainfall distribution.

* Corresponding author.
E-mail address: hbayabil@ufl.edu (H.K. Bayabil).

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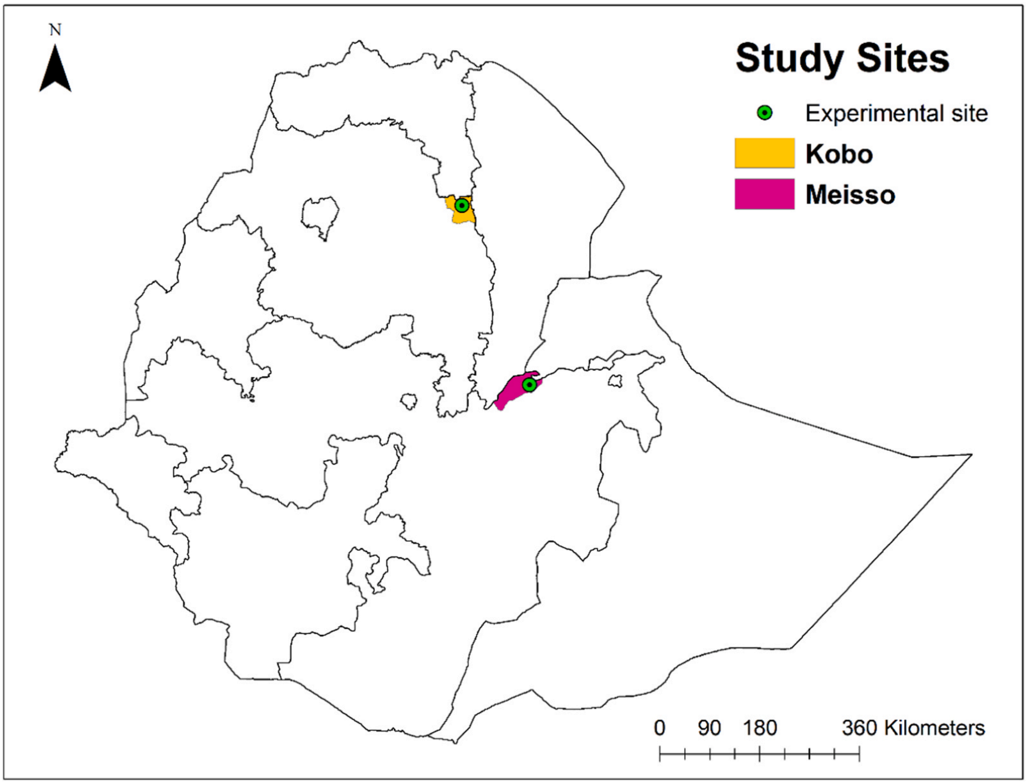

Fig. 1. Map of Ethiopia and locations of the two study sites.

The average production of sorghum in Africa has shown a steady increase from 11.6 in 1976 to 20.9 million tons in 2001 (Taylor, 2003). This increase in sorghum production is primarily attributed to increases in acreage in Africa in particular Ethiopia (Kinfe and Tesfaye, 2018; Taylor, 2003). However, only traditional cultivar varieties are commonly grown, and average sorghum yield remains below 1 t ha^{-1} because of insufficient inputs, such as fertilizers and pesticides, and subsistence farming practices (Ahmed et al., 2000). To meet increasing food demand due to population pressure, sorghum production is being expanded into environmentally sensitive areas (Matlon, 1990; Phalan et al., 2013). This practice is unsustainable, and efforts must be made to increase sorghum yield without expanding farmlands into vulnerable regions. In contrast, in places, where intensive agriculture is practiced with improved technologies and inputs such as hybrid seeds, fertilizer, and chemical inputs, sorghum yield is much higher and is comparable with other major cereals (Amelework et al., 2016; O'Sullivan, 2015; Potgieter et al., 2016; Schoof, 2015).

As the effect of climate change and variability intensifies, agricultural productivity is being significantly impacted and food security continues to be a daunting task (Alemu and Mengistu, 2019; O'Sullivan, 2015; Schoof, 2015). Multiple studies have shown that East Africa in general and especially Ethiopia are among the most vulnerable regions to climate change and variability (Alemu and Mengistu, 2019; Cooper and Coe, 2011; Rosell, 2011). Climate change is projected to result in extreme weather events such as severe droughts (Coe and Stern, 2011; Cooper and Coe, 2011; Haile et al., 2020; Rosell, 2011), and shifts in spatial and temporal rainfall distributions and intensities (Conway and Schipper, 2011; Dixit et al., 2011; Fotso-Nguemo et al., 2019).

Several studies have reported a strong linkage between climate change and variability and the overall performance of Ethiopia's economy, which mainly depends on a rainfed and subsistence agricultural sector that accounts for 41% of the Gross Domestic Product (GDP) and over 85% of employment (World Bank, 2006). Given such a heavy dependence of the agricultural system on rainfall, variations in the timing of the monsoon rainfall season and occurrence of extreme events such as drought and floods pose significant threats to the fragile agricultural sector and, thereby, the food security of the nation. A strong relationship has been reported between annual rainfall variability and the fluctuation of GDP (Coe and Stern, 2011; Suryabhagavan, 2017). Climate change also caused the greatest challenges to Ethiopian agriculture due to increased frequencies and intensities of droughts and extreme rainfall events (Haile et al., 2020; Suryabhagavan, 2017).

Although sorghum is well known for its drought tolerance, which can grow on marginalized lands, climate change and variability are expected to have a negative impact on sorghum production in Ethiopia. The arid and semiarid regions of Ethiopia, where sorghum is widely grown, are projected to experience unpredictable and highly variable rainfall, strong winds, high temperature, and high evapotranspiration (Fazzini et al., 2015), which in turn will impact sorghum production (Merga et al., 2014). In addition, there is limited information on adaptation practices that could be implemented to potentially reduce the impacts of climate change and variability on sorghum production.

The objectives of this study were to i) investigate the potential impact of climate change on sorghum yield under rainfed production systems and ii) evaluate the effectiveness of supplemental irrigation to the current rainfed production system and shifting planting dates as adaptation practices for two major sorghum producing regions in Ethiopia.

2. Materials and methods

2.1. Study sites

This study was conducted at Kobo (40°15′N, 9°24′E) and Meisso (39°39′N, 12°9′E), which are located in the northern and eastern regions of Ethiopia (Fig. 1). These lowland areas are characterized by a semi-arid climate with high rainfall variability and frequent droughts that affect crop productivity significantly. Nevertheless, the rainfed agricultural system remains the main livelihood of smallholder farmers. The average farm size in both locations is very small and thus subsistence

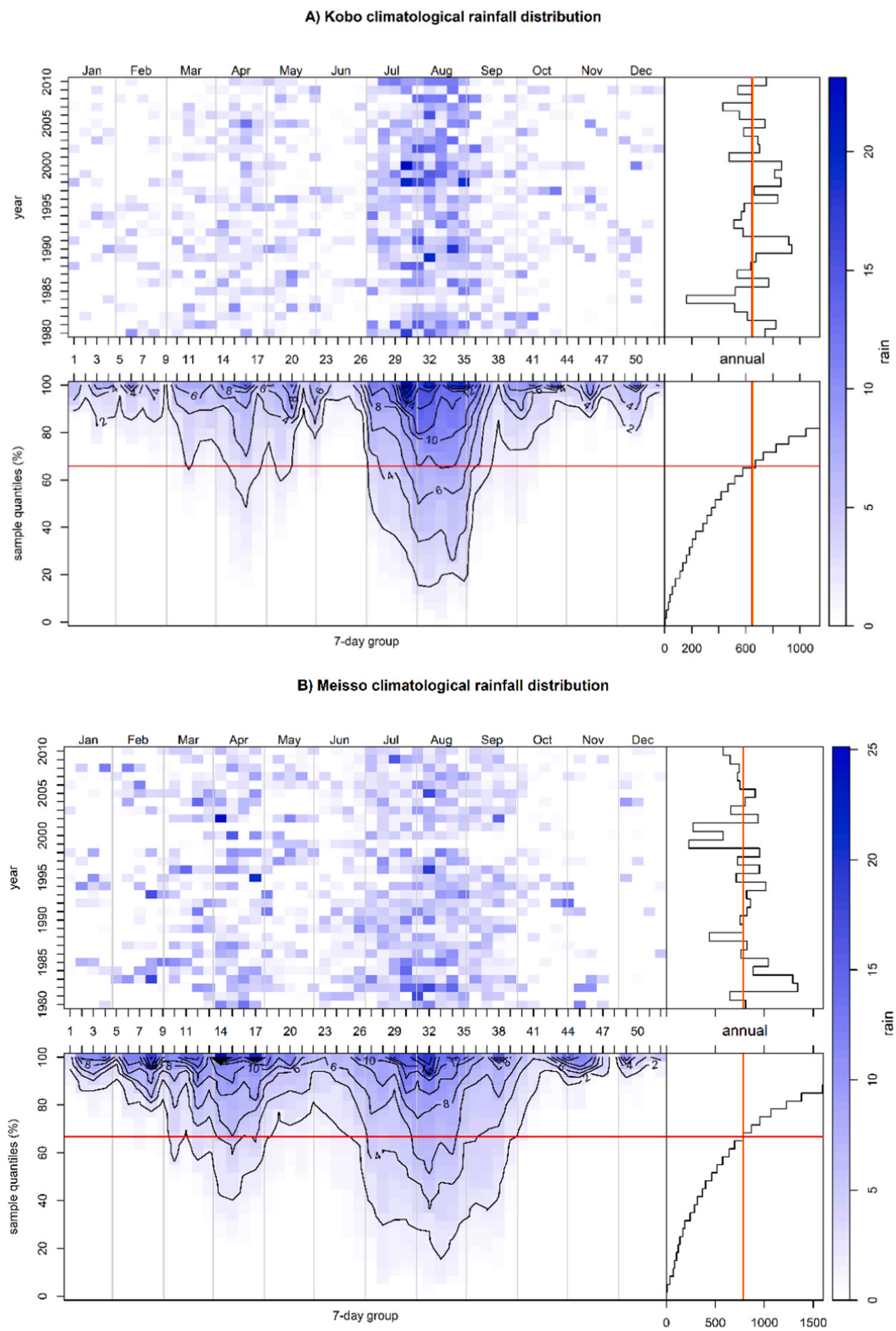

Fig. 2. Rainfall distribution for Kobo (a) and Meisso (b) study locations based on historical data (1980–2010).

Table 1
Summary of soil physical and chemical properties at Kobo and Meisso.

Site	Depth	Sand	Clay	Silt	LL	DUL	pH	TN	OM	CEC
	(cm)	(%)			(cm^3 / cm^3)			(%)		(meq/100 g)
Kobo	0–15	21	49	30	0.34	0.68	7.60	0.07	0.90	51.31
	15–30	31	59	10	0.35	0.69	7.76	0.09	1.03	53.45
	30–45	33	59	8	0.39	0.64	7.56	0.07	1.23	56.92
	45–60	27	65	8	0.37	0.65	7.61	0.09	1.10	50.08
	60–75	25	65	10	0.38	0.68	7.69	0.07	1.15	53.35
	75–90	23	57	20	0.42	0.63	7.80	0.12	1.65	56.00
	90–105	21	59	20	0.40	0.62	7.98	0.15	1.22	57.43
	105–200	21	59	20	0.40	0.62	7.98	0.15	1.22	57.43
Meisso	0–10	14	58	28	0.34	0.48	7.80	0.06	1.50	48.90
	10–30	16	60	24	0.35	0.49	8.00	0.08	1.04	41.80
	30–60	10	66	24	0.39	0.53	7.90	0.03	1.04	41.80
	60–90	12	62	26	0.37	0.51	7.90	0.01	1.04	41.80
	90–120	12	64	24	0.38	0.52	7.80	0.04	1.04	45.20
	120–150	8	70	22	0.42	0.55	7.80	0.03	1.04	40.50
	150–180	12	68	20	0.40	0.53	7.80	0.04	1.04	39.20

TN: Total nitrogen; OM: organic matter; CEC: cation exchange capacity. pH was based on 1:2.5 H_2O; LL: *soil drained* lower limit, UL: *soil drained* upper limit.

farming is dominant (Headey et al., 2014).

Smallholder farmers opt for low-risk cropping systems and rely heavily on drought-tolerant crops such as sorghum. Long-term average minimum and maximum temperatures are 14.8 and 29.8 °C for Kobo and 14.9 and 30.8 °C for Meisso. Both study sites have bimodal rainfall distributions with very short rainfall seasons between March and May, while the main rainy season occurs from June to September (JJAS) (Fig. 2). However, rainfall distributions are erratic and water scarcity is prevalent. On average, annual rainfall for Kobo is 653 and for Meisso is 825 mm.

2.2. Field experiment data

Field experimental data from 2005 to 2014 (except for 2008 and 2009) on sorghum phenology, yield, and biomass were obtained from the Melkassa Agricultural Research Center (MARC). This study was conducted as part of a national sorghum variety trial in Meisso (Fig. 1). A randomized complete block design was used with 3 replications. Each plot had an area of 15 m^2 (3 m width × 5 m length). The cultivar 'Teshale' that was used in this study is the most widely grown medium maturing cultivar in the lowland areas of Ethiopia. This cultivar was released by the Ethiopian Institute of Agricultural Research (EIAR) as part of its efforts for climate change adaptation options for arid and semi-arid regions of Ethiopia. Planting was done using a spacing of 75 cm between rows and 15 cm between plants. The planting depth was 5 cm, and the planting density was about 9 plants m^{-2}. During this experiment, planting was done after the onset of the rainy season once sufficient moisture is available in the soil to support germination. However, due to erratic rainfall distribution, short and extended dry spells are common in most places. A short dry spell even during the rainy season significantly affects yield, and thus irrigation is critical. Agronomic practices included a split application of fertilizer that consists of 100 kg ha^{-1} Diammonium phosphate (DAP) and 50 kg ha^{-1} of Urea at planting; and 50 kg ha^{-1} of urea thirty days after planting (approximately at five-leaf stage). The necessary management data for model calibration and evaluations were recorded.

2.3. Crop model simulation

The Cropping System Model (CSM)-CERES-Sorghum model (Jones et al., 2003; White et al., 2015) of the Decision Support System for Agrotechnology Transfer (DSSAT) (Hoogenboom et al., 2019) is one of the widely used crop simulation models. In this study, the CERES (Crop Estimation through Resource and Environment Synthesis)-Sorghum model within the DSSAT 4.7.6 was used. The CSM-CERES-Sorghum model simulates crop growth, development, and yield based on defined datasets of management, weather, soil parameters, and genetic coefficients of specific cultivars. The model also allows for the simulation of a dynamic plant and soil water, nitrogen, phosphorus, carbon balance, and the impact of best management practices on crop yield and yield components (Adam et al., 2018). Crop management practices such as cultivar type, planting date, fertilizer application time and rate, plant density, sowing depth, etc. were accurately represented during the model setup. Local farmers' fertilizer and tillage practices were followed and the 'Teshale' cultivar was sown at a density of 9 plants m^{-2} with 100 kg ha^{-1} DAP and 50 kg ha^{-1} of Urea during sowing and an additional 50 kg ha^{-1} Urea 30 days after sowing were applied. Initial soil conditions for nodule and root weight were set at 10 kg ha^{-1} each with 50% of the residue incorporated in the top 3 cm of soil. The model was calibrated and evaluated based on field experimental data before it was used to evaluate potential climate change impact on sorghum yield and evaluate the effectiveness of selected climate change adaptation practices for two sites selected in this study.

2.4. Weather and soil data

Daily minimum and maximum temperatures, rainfall, and radiation data for the two study sites were obtained from the national meteorology agency of Ethiopia (NMA). Soil profile data for Kobo and Meisso sites were obtained from MARC. Soil data have seven to eight different horizons with defined physical and chemical properties at each layer (Table 1). Soils at both sites have slightly basic pH (7.6–7.8) with relatively low organic matter contents (0.9–1.5%). A clay loam texture was dominant on the top 15 cm of soil at both sites (Table 1).

2.5. Climate change scenarios

Future climate change scenarios were created following the Agricultural Model Intercomparison and Improvement Project (AgMIP) protocol, which uses the delta statistics approach (Hudson and Ruane, 2015). Future climate scenarios were produced for three future periods 2025s (2010–2039), 2055s (2040–2069), and 2085s (2070–2099) based on Agricultural Model Intercomparison and Improvement Project (AgMIP) protocol (Rosenzweig et al., 2015) from the Coupled Model Inter-comparison Project Phase 5 (CMIP5) and two Representative Concentration Pathways (RCPs): RCP4.5 and RCP8.5. Five representative GCMs were selected out of the 20 GCMs that are available in the AgMIP climate scenario (Hudson and Ruane, 2015). Scatter plots of mean temperature and rainfall changes during the crop growing season with reference to the baseline period were used to select five representative GCMs for each site (Fig. 3). The five GCMs were chosen to represent the five quadrants in the scatter plot designated as 'cool/wet',

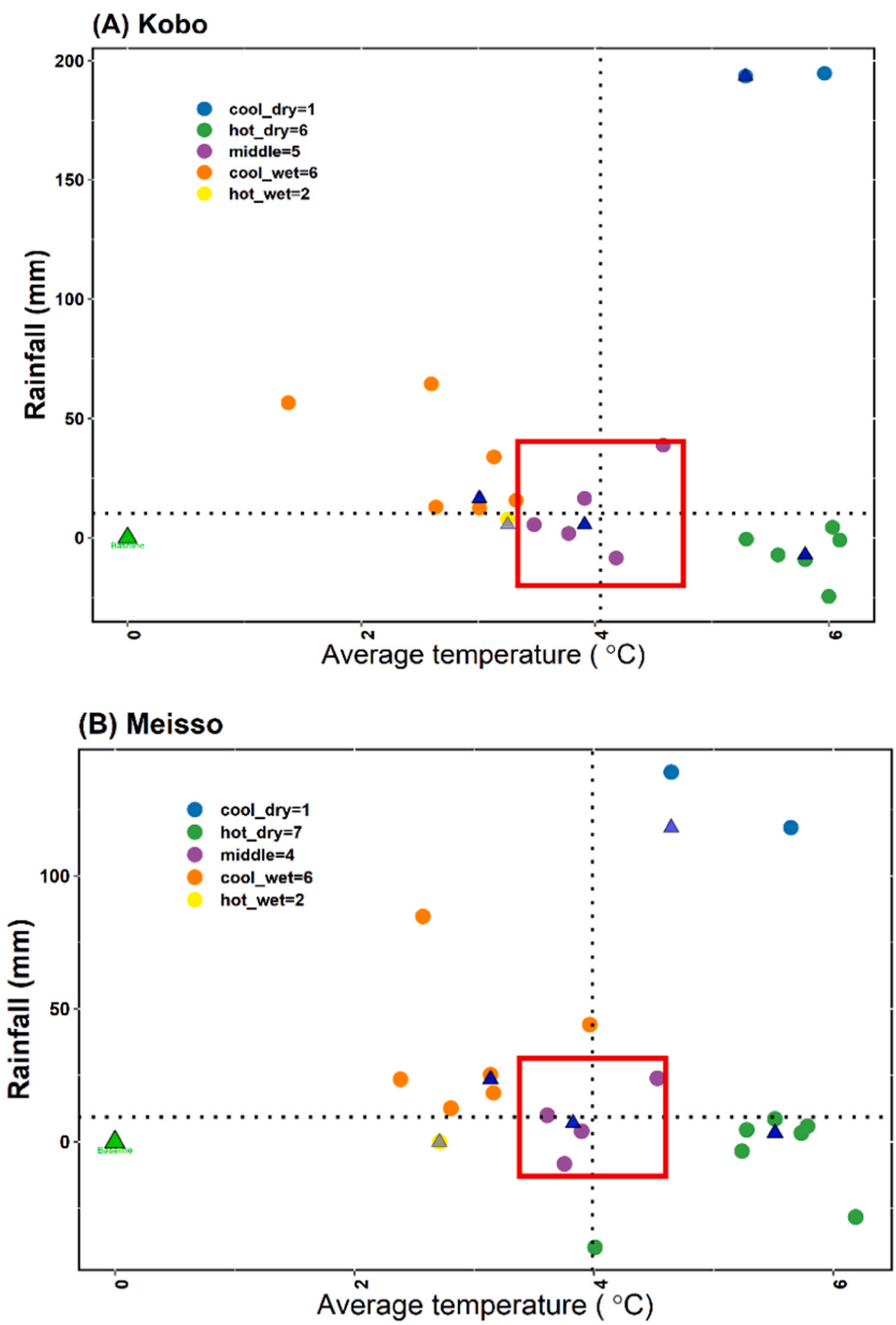

Fig. 3. Scatter plots of absolute change in temperature vs. percentage change in precipitation during the sorghum growing season from June to September for Kobo (a) and Meisso (b) under RCP8.5 of 2085s used to select five representative GCMs for each quadrant. Note: each quadrant was separated by the broken line and the middle red rectangle represents the middle quadrant. The blue triangles are the medians of the ensemble mean of GCMs at each quadrant and the green triangle is the reference baseline.

Table 2
Selected representative GCMs of the five quadrants for Kobo and Meisso sites based on RCP8.5 and the 2085s period.

Quadrant	Kobo	Meisso
cool/dry	CCSM4	NorESM1-M
cool/wet	CESM1-BGC	CESM1-BGC
hot/dry	ACCESS1–0	MPI-ESM-LR
hot/wet	IPSL-CM5A-LR	IPSL-CM5A-MR
middle	bcc-csm1–1	MIROC-ESM

'cool/dry', 'middle', 'hot/wet', and 'hot/dry' (Ruane and McDermid, 2017) (Tables 2 and 3). In addition, based on the AgMIP regional climate assessment protocol, CO_2 concentrations were set at 423 for 2025, 499 for 2055 and 532 ppm for 2085 for RCP4.5 and 532 ppm; and 432, 571, and 801 ppm for RCP8.5 in 2025s, 2055s, and 2085s periods, respectively (Rosenzweig et al., 2017).

2.6. Model calibration and evaluation

The model was calibrated using five years (2005–2007 and 2010–2011) and evaluated with three years (2011–2013) experimental data. Model calibration involved fine-tuning model parameters related to soil properties, climatic characteristics, and plant growth parameters so that simulated values compared (Buddhaboon et al., 2018; Hunt et al., 1993) reasonably well with observed data (Hoogenboom et al., 2012; Timsina and Humphreys, 2006). In addition to the species and eco-type parameters, seven genetic coefficients were used to define traits that differentiate cultivars within a crop species. The Genetic coefficient calculator (GENCALC) was used to estimate the genotype specific coefficient for DSSAT crop model (Román-Paoli et al., 2000). In GENCALC, the coefficients of a genotype are estimated iteratively by running the appropriate crop model (Anothai et al., 2008; Hunt et al., 1993; Jones et al., 2011). Genotype coefficients of the sorghum cultivar were estimated from a base cultivar coefficient that exists in the DSSAT database which resembles cultivar 'Teshale' with respect to maturity. The iteration continues until the model simulation fits well with the observed data set (Anothai et al., 2008). The genotype coefficients were determined in a specified sequence starting with those related to crop development followed by yield and yield components. Model performance evaluations were done during calibration and evaluation using the Coefficient of Determination (R^2, Eq. 1), Modified Modeling Efficiency (EF_1, Eq. 2), Index of Agreement (*d*, Eq. 3), Normalized Root Mean Square Error (nRMSE, Eq. 4), and Coefficient of Residual Mass (CRM, Eq. 5). R^2 and d values range between 0 and 1 while EF1 values range from $-\infty$ to 1. R2, d, and EF1 values 1 indicate perfect fits of model simulated with observed data. Smaller nRMSE values ($<$ 10%)

Table 3
Characteristics of the representative GCMs of the five quadrants for Kobo and Meisso sites based on RCP8.5 and the 2085s period (Source: Ruane and McDermid, 2017).

GCM	Institution	Horizontal resolution
ACCESS1-0	Commonwealth Scientific and Industrial Research Organization (CSIRO) and Bureau of Meteorology (BOM), Australia	1.25° × 1.875°
bcc-csm1-1	Beijing Climate Center, China Meteorological Administration	~ 2.8° × 2.8°
CCSM4	US National Center for Atmospheric Research (NCAR)	~ 0.9° × 1.25°
CESM1-BGC	US National Science Foundation (NSF), US Dep. of Energy	~ 0.9° × 1.25°
IPSL-CM5A-LR	Institute Pierre Simon Laplace (IPSL)	~ 1.9° × 3.75°
IPSL-CM5A-MR	Institute Pierre Simon Laplace (IPSL)	~ 1.3° × 2.5°
MIROC-ESM	University of Tokyo, Japanese National Institute for Environmental Studies	~ 2.8° × ~ 2.8°
MPI-ESM-LR	Max Planck Institute (MPI) for Meteorology (low resolution)	~ 1.9° × 1.875°
NorESM1-M	Norwegian Climate Centre	~ 1.9° × 2.5°

Table 4
Calibration and evaluation results of the CSM-CERES-Sorghum model. Values in parenthesis represent standard deviations.

Model setup	Variable	Observed	Simulated	R^2	EF_1	d	nRMSE	CRM
Calibration	Anthesis day	73 (± 2.1)	74 (± 3.5)	0.73	-0.19	0.81	2.98	-0.02
	Yield (kg/ha)	3814 (± 165.6)	4012 (± 137.5)	0.76	-0.33	0.70	5.11	-0.05
	Maturity day	124 (± 4.2)	123 (± 7.1)	0.59	-0.28	0.80	3.58	-0.01
Evaluation	Anthesis day	72 (± 2.2)	71 (± 2.2)	0.86	0.50	0.91	1.27	0.01
	Yield (kg/ha)	4137 (± 345.8)	4468 (± 520.2)	0.99	-0.09	0.83	6.45	-0.08
	Maturity day	115 (± 3.4)	118 (± 1.2)	0.79	-0.18	0.61	2.69	0.03

Table 5
Genetic Coefficients values for Sorghum cultivars 'Teshale' at Meisso (The source of Genetic parameters descriptions was from DSSAT V4.7.6 Genetic Coefficients parameter Descriptions (Hoogenboom et al., 2019)).

Genetic parameters	Description	Value
P1	Thermal time from seedling emergence to the end of the juvenile phase (expressed in degree days above TBASE during which the plant is not responsive to changes in photoperiod	334.6
P2	Thermal time from the end of the juvenile stage to tassel initiation under short days (degree days above TBASE)	102
P2O	Critical photoperiod or the longest day length (in hours) at which development occurs at a maximum rate. At values higher than P2O, the rate of development is reduced	13.31
P2R	Extent to which phasic development leading to panicle initiation (expressed in degree days) is delayed for each hour increase in photoperiod above P2O	277
PANTH	Thermal time from the end of tassel initiation to anthesis (degree days above TBASE)	617.5
P3	Thermal time from to end of flag leaf expansion to anthesis (degree days above TBASE)	362.7
P4	Thermal time from anthesis to beginning grain filling (degree days above TBASE)	90.8
P5	Thermal time from beginning of grain filling to physiological maturity (degree days above TBASE)	542.4
PHINT	Phylochron interval; the interval in thermal time between successive leaf tip appearances (degree days)	49
G1	Scaler for relative leaf size	1.9
G2	Scaler for partitioning of assimilates to the panicle (head).	4.5

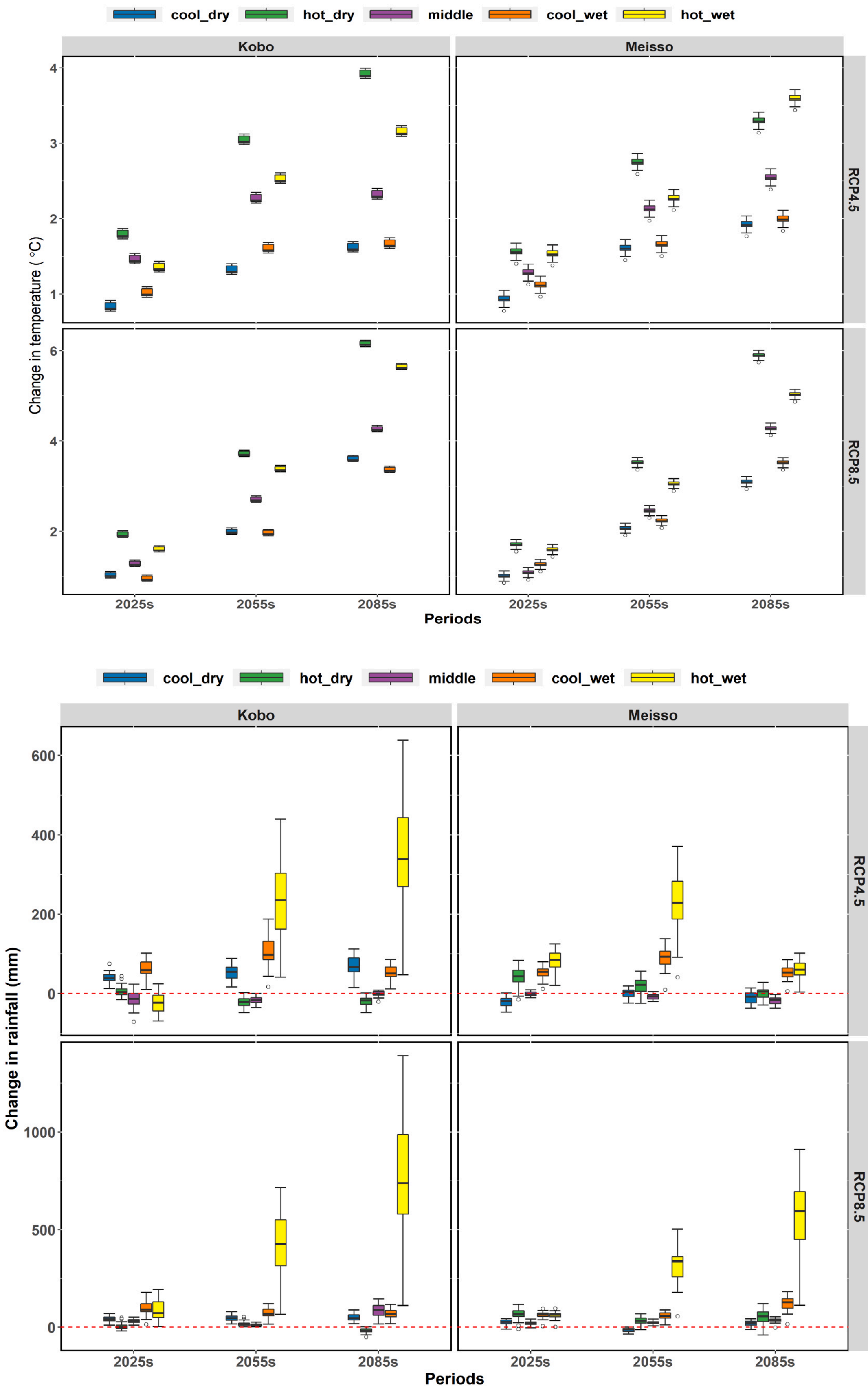

Fig. 4. Projected absolute changes in seasonal average temperature (a) and seasonal total precipitation (b) for Kobo and Meisso under two RCPs and for three future periods compared to the baseline.

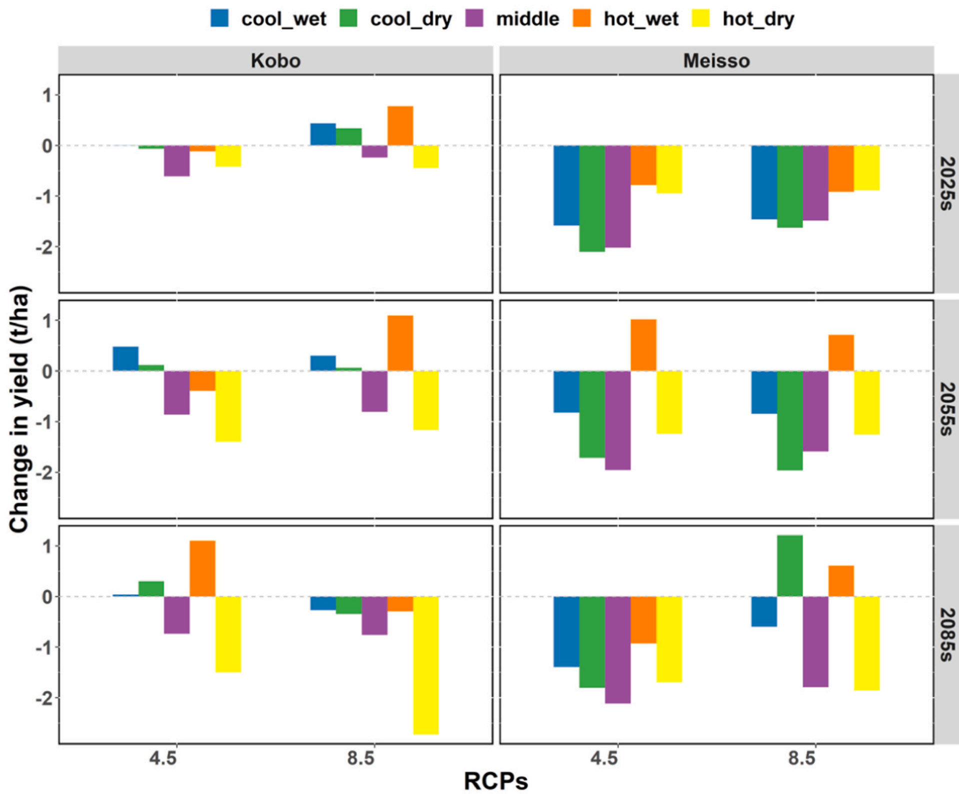

Fig. 5. Projected absolute changes in sorghum yield from rainfed production systems under different climate change scenarios and periods.

indicate excellent model performance (Jamieson et al., 1991). Positive and negative CRM values indicate overestimation and underestimation of observed data by the model, respectively.

$$R^2 = \frac{\sum_{i=1}^{n}(o_i - o)(s_i - \overline{s})}{\sqrt{\sum_{i=1}^{n}(o_i - \overline{o})^2}\sqrt{\sum_{i=1}^{n}(s_i - \overline{s})^2}} \quad (1)$$

$$EF_1 = 1 - \frac{\sum_{i=1}^{n}|s_i - o_i|}{\sum_{i=1}^{n}|o_i - \overline{o}|} \quad (2)$$

$$d = 1 - \frac{\sum_{i=1}^{n}(s_i - o_i)^2}{\sum_{i=1}^{n}(|s_i - \overline{o}| + |s_i - \overline{o}|)^2} \quad (3)$$

$$\mathbf{nRMSE} = \sqrt{\sum_{i=1}^{n}\frac{(s_i - o_i)^2}{n}}\,\mathbf{x}\,\frac{\mathbf{100}}{\mathbf{n}} \quad (4)$$

$$CRM = 1 - \frac{\sum_{i=1}^{n}s_i}{\sum_{i=1}^{n}o_i} \quad (5)$$

where s_i and o_i are simulated and observed values, $\overline{o}$ and $\overline{s}$ are mean observed and simulated values, and n is number of observations.

2.7. Climate change adaptation practices

The potentials of shifting planting date and supplemental irrigation with two levels (deficit and full irrigation) in alleviating the negative impacts of climate change on moisture stress and sorghum yield were evaluated. Sorghum planting date in the historical baseline periods was started on the onset of the main rainfall seasons (third week of June see Fig. 2). Kassie et al. (2013) has conducted survey about the farmers' management practices in kobo, and he indicated that the farmers usually started planting when the main rainy seasons started. We have also analyzed the historical rainfall conditions of both locations and it depicted that the main rainy seasons was started in June particularly Jun 21 for kobo and Jun 18 for Meisso (Fig. 2). In this paper the baseline planting date was also determined to be June 21 for kobo and June 18 for Meisso (Getachew et al., 2016; Kassie et al., 2013). Planting dates were selected by shifting the baseline plating dates by about 10 days forward and backward resulting in nine planting dates between early May to the end of July. In addition, deficit and full irrigation treatments were set based on daily root zone moisture balance. Deficit supplemental irrigation was set to trigger when percent available water content (PAWC) reaches 25% and irrigation will be applied only up to 75% of PAWC while the full irrigation refill point was 50% PAWC and was set to refill 100%. Optimal irrigation refill points are mostly recommended at 50% PAWC to avoid any moisture stress to the plant. Under limited moisture availability, actual evapotranspiration (ETa) will be reduced and smaller than the potential evapotranspiration (ETp).

The CSM-CERES-Sorghum model simulates drought stress as proportion of potential demand to the potential supply of water to the plant for photosynthesis, and the phenomenon is expressed as the moisture stress index for photosynthesis (WSPD) (Jones et al., 2003). The value of WSPD ranges from 0 to 1 where 0 is no stress and 1 is maximum stress.

3. Results and discussion

3.1. Performance of the CSM-CERES-Sorghum model

Results showed that the model was able to simulate anthesis, maturity and grain yield very well for both calibration and evaluation (Table 4). The model performed well in simulating days to anthesis (R^2 = 0.73, nRMSE = 2.98), days to maturity (R^2 = 0.59, nRMSE = 3.58) and grain yield (R^2 = 0.76, nRMSE = 5.11) during the calibration. Similarly, the model performance well during evaluation of anthesis (R^2 = 0.86, nRMSE = 1.27), maturity (R^2 = 0.79, nRMSE = 2.69) and grain yield (R^2 = 0.99, nRMSE = 6.45). Moreover d values were greater than 0.61, which indicate that good agreement between observed and simulated values. According to Jamieson et al. (1991)

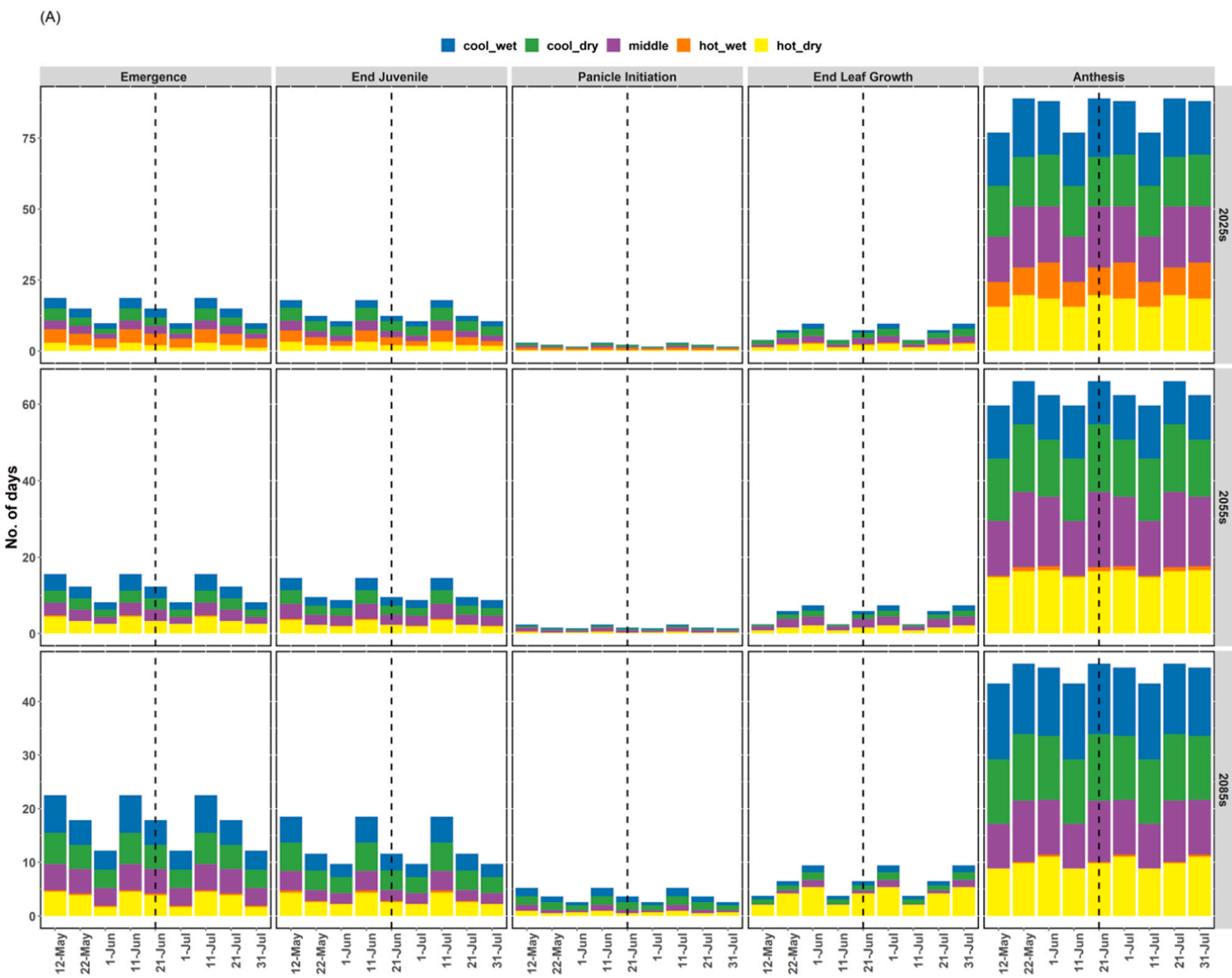

Fig. 6. Effects of shifting planting dates on moisture stress of rainfed sorghum production during selected crop growth stages for three future periods under five climate conditions and RCP8.5 for (A) Kobo and (B) Meisso. Planting dates shown using vertical dashed lines are the baseline.

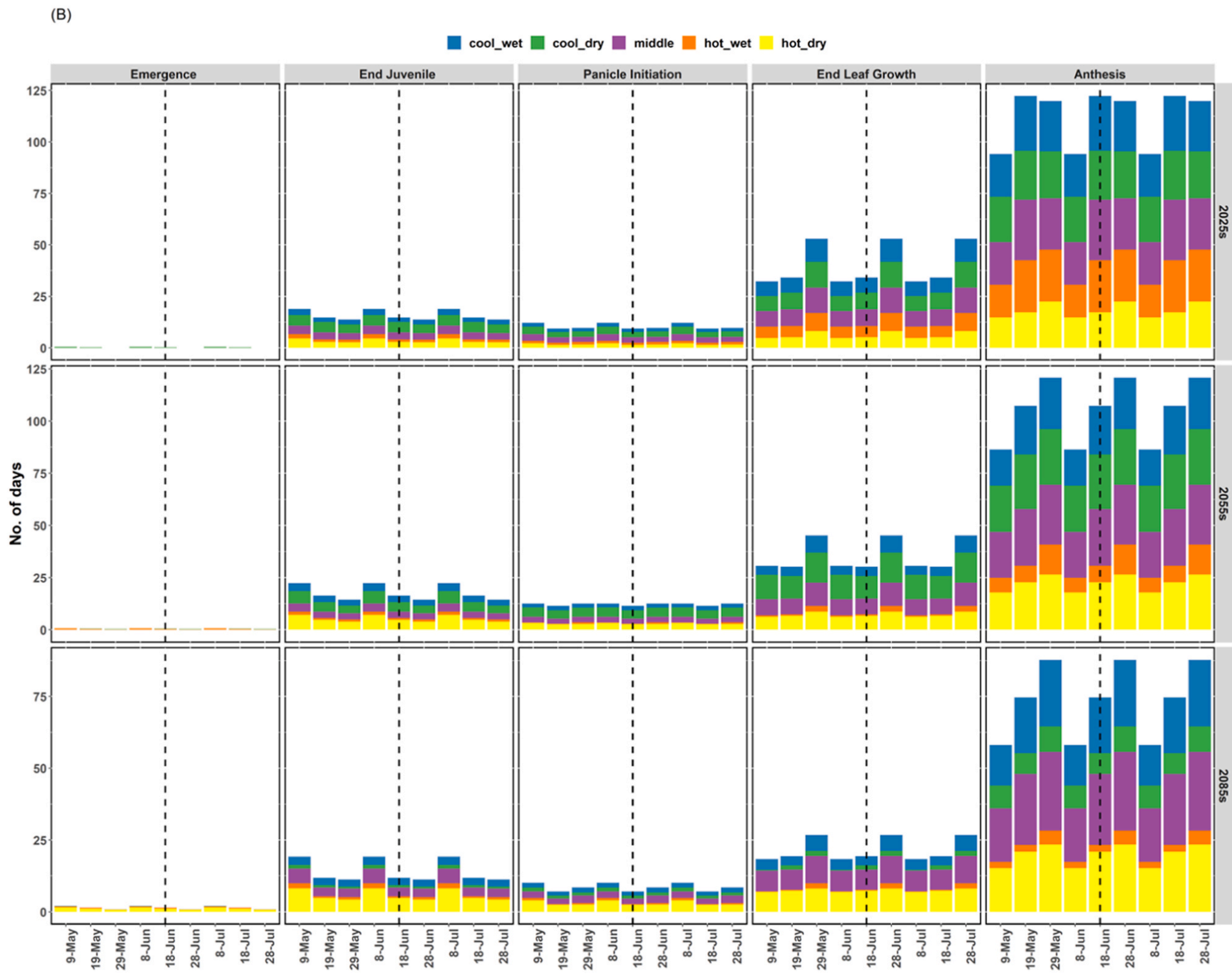

Fig. 6. (*continued*).

nRMSE values (< 10%) show that the overall performance of the model was excellent. Calibrated and evaluated genetic coefficients are summarized in Table 5.

3.2. Projected climate change

Projected climate change results showed that average temperature will increase for the three future periods (2025s, 2055s, and 2085s) as simulated by the five GCMs for the two RCPs (Fig. 4a). Average temperature is projected to consistently increase for all scenarios and periods for both locations and is expected to show a steady increase with the progression of the 21st century. The projected increase in average temperature during the crop growing season was estimated to reach up to 6 °C for RCP8.5 in the 2085s for both study sites (Fig. 4a). However, the projections for precipitation were mixed with an increase and decrease for the two sites in most hot/wet and cool/wet climate conditions under all RCPs and periods (Fig. 4b). The highest increases in total precipitation during the crop growing season were projected in 2085s and RCP 8.5 for hot/wet climate conditions. Overall, hot/wet climate conditions showed consistent increases in precipitation for both locations, but increases were higher for Kobo than Meisso (Fig. 4b). Consistent increases in projected precipitation was observed under hot/dry scenarios with the progression of the century. The hot/dry and cool/dry scenarios showed modest reductions in precipitation while the cool/wet and hot/wet scenarios showed increases compared to the baseline period (Fig. 4b).

Our results were in agreement with previous studies from Ethiopia, where findings have constantly shown that temperature would considerably increase while mixed projections were reported for rainfall (Conway and Schipper, 2011; NAPA, 2007). A study at Kobo by Kassie et al., 2014; Kassie, 2014 reported that projected annual rainfall would vary from − 40% to + 10% compared to the baseline, while the average annual temperature would increase by up to 4.1 °C by the 2080s (Fig. 4A). Kassie, 2014 also indicated that seasonal rainfall for Kobo will increase during November-December while during the main sorghum growing season rainfall will decrease by 12–35%. Similarly, a study in southern Tigray reported that minimum and maximum temperatures would both increase by up to 6 °C towards the end of this century (Hadgu et al., 2015). Arndt et al. (2011) found that in the 2080s rainfall in Ethiopia will decline by up to 20% during the main rainy season compared to the 1960–1990 period.

3.3. Sorghum yield projection

Yield projections for rainfed production systems showed a considerable decrease for all climate change scenarios, except for a few projected increases for the hot/wet, cool/wet, and cool/dry climate scenarios for two periods (Fig. 5). Overall, a larger reduction in yield was projected for Meisso compared to the baseline period (Fig. 5). Among the climate scenarios considered, the hot/dry scenario is projected to result in the largest reduction in yield across all locations, periods, and RCPs (Fig. 5). These results are in agreement with findings

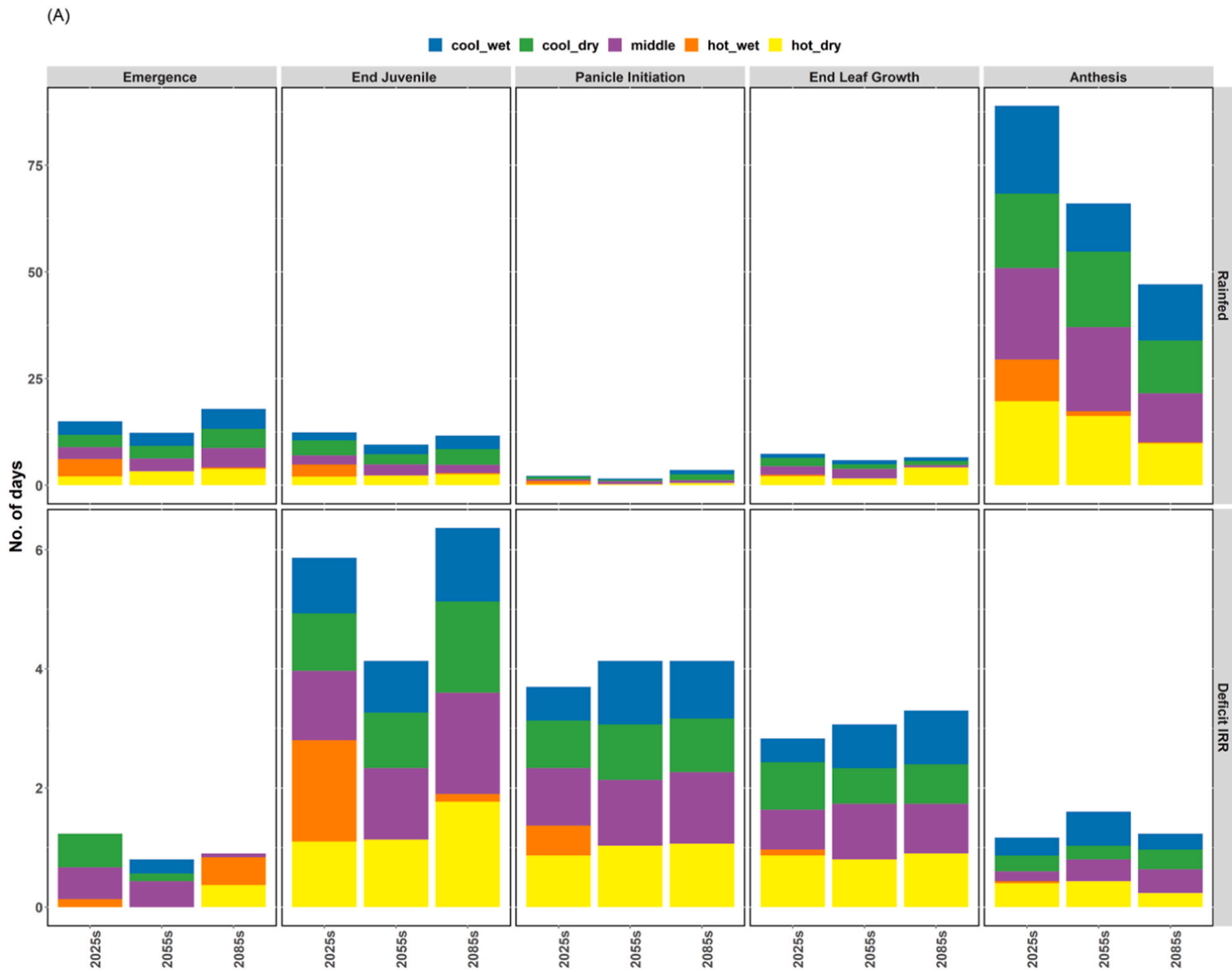

Fig. 7. Effects of *supplemental irrigation* on moisture stress *to the* rainfed sorghum production *during selected* crop growth stages for three future periods under five climate conditions and RCP8.5 for (A) Kobo and (B) Meisso. *Full irrigation showed no stress.*

from previous studies in the region. Multiple studies on crop production projected considerable yield reduction, particularly in sub-Saharan Africa including Ethiopia (Akinseye et al., 2020; Kassie et al., 2014). IPCC (2007) estimated that climate change would result in a 50% reduction in rainfed agricultural production in East Africa by 2020. The report by IPCC showed that an increase of temperature by 1–2 °C could likely have a negative impact on major cereal crops in lower latitude regions than higher latitude where the crops are already grown near their maximum temperature tolerance (e.g., > 35 °C for sorghum). The report suggested that agricultural productivity decreases due to less favorable weather conditions, reduced water availability for irrigation, increased heat stress, and prolonged droughts. Waithaka et al. (2013) also stated that temperature increase would lead to an increase in evapotranspiration, and, thereby, an increase in drought stress causing a reduction in yield. Their work showed that rainfed sorghum yield would decrease over a very large area in the western and northwestern parts of Ethiopia, with up to a 5–25% reduction in sorghum yield for the western parts of Tigray and Amhara region of Ethiopia. This reduction in yield in addition to an already sub-optimal farm productivity could have a significant impact on the food security and the fragile economy.

3.4. Effect of planting date on crop moisture stress

For the rainfed production system, severe moisture stress (0.75–1.0) was prevalent during most of the sorghum growth period starting at emergence to anthesis for both sites (Fig. 6). However, anthesis was the most affected stage by moisture stress across all RCPs and periods. Up to 80 days of severe moisture stress (0.75–1.0) per crop season were observed for Kobo (Fig. 6a) while for Meisso it could reach as high as 125 days per season (Fig. 6b). Moisture stress was relatively small during germination, end of panicle growth, and maturity. One notable observation was that moisture stress tends to decrease under RCP8.5 compared to RCP4.5 in 2055s and 2085s. This could be due to an increase projected rainfall and CO_2 concentration. The increase in CO_2 concentration could potentially result in reduced moisture stress due to a reduction in transpiration rates. Studies have shown that elevated CO_2 concentration reduces moisture stress (Leakey, 2009). Overall, the effect of planting date on moisture stress showed mixed results. Both early and late planting dates showed both an increase and decrease in moisture stress. Similarly, there was no difference between climate scenarios in moisture stress. Mastrorilli et al. (1995) reported that moisture stress during the sorghum flowering stage had the most significant effect on yield. Therefore, the stress that occurs around the flowering stages could be used as an indicator of yield reduction. However, it should be also noted that moisture stress during other sorghum physiological developmental stages can also have a negative effect on sorghum yield (Kothari et al., 2020). Other studies have reported that rainfed sorghum production would be negatively impacted by climate change due to high

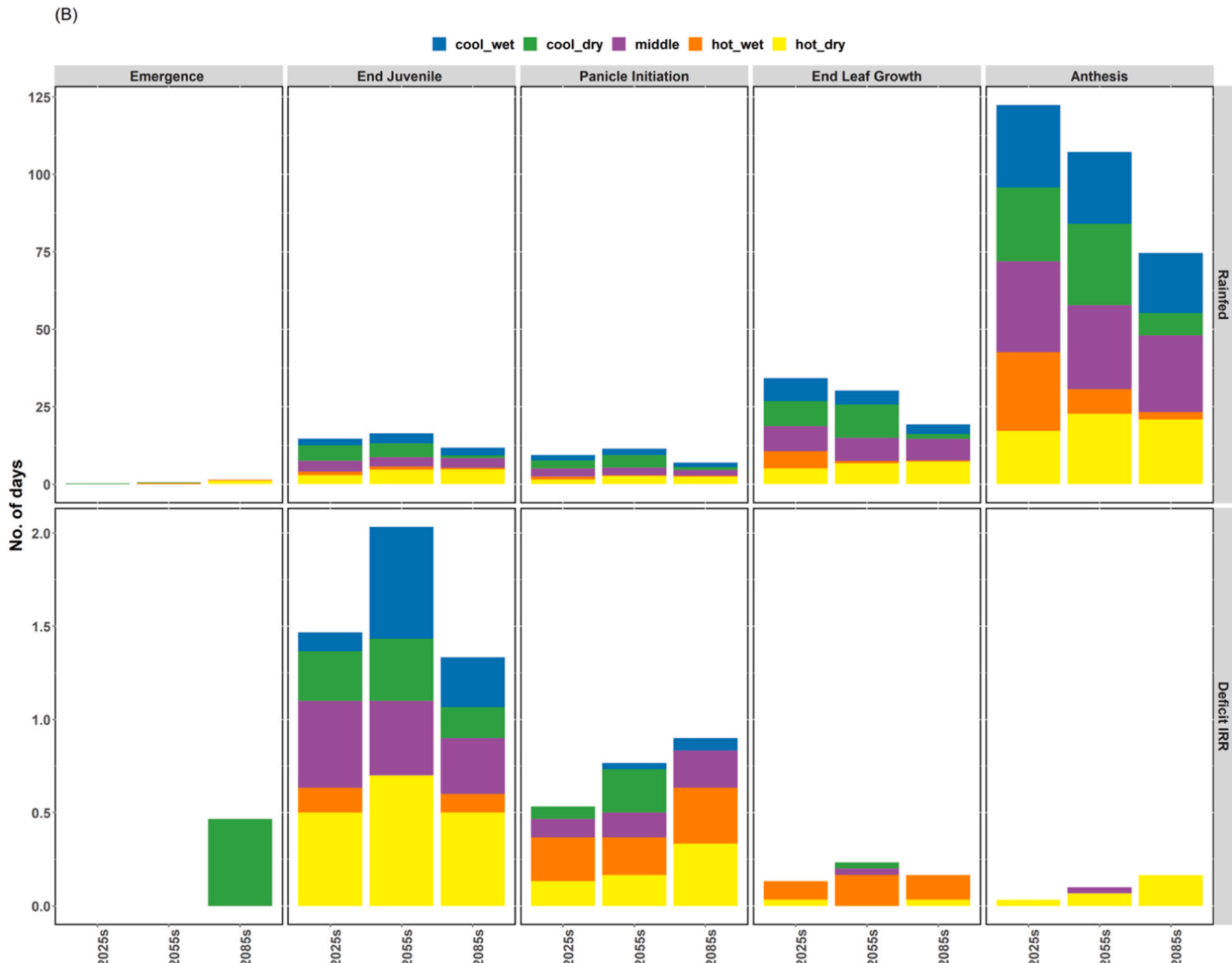

Fig. 7. (*continued*).

Table 6
Summary of rainfall and irrigation water application under rainfed and supplemental irrigation sorghum production.

Site	Period	Rainfall (mm)	No. of IRR events		Total IRR (mm)	
			Deficit IRR	Full IRR	Deficit IRR	Full IRR
Kobo	Baseline	379	14	17	203	304
	2025s	396	16	23	259	379
	2055s	381	16	23	245	369
	2085s	418	17	23	218	341
Average		394	16	22	231	348
Meisso	Baseline	337	14	19	225	344
	2025s	403	21	23	411	567
	2055s	404	17	21	383	540
	2085s	418	18	21	366	511
Average		391	18	21	346	491

moisture stress in these areas. Kassie et al. (2014) argued that rainfall and temperature projections in northern Ethiopia could be an indication that climate change could have a significant effect on rainfed sorghum production. They also reported that a decrease in rainfall during sorghum growth season coupled with a warming temperature trend will further exacerbate moisture stress. However, as discussed previously, early planting dates had a positive impact on sorghum yield for both locations, especially when combined with supplemental irrigation, which suggests its potential use as climate change adaptation practice. Shifting planting date has been tested as climate change adaptation practices for different crops such as rice (Dharmarathna et al., 2014), sorghum (Akinseye et al., 2020), wheat (Nouri et al., 2017), maize (Ahmad et al., 2020), and other crops.

3.5. Effect of supplemental irrigation on crop moisture stress

As expected, supplemental irrigation to the current rainfed production system resulted in considerable reductions in moisture stress for the two study sites (Fig. 7). Reduction in moisture stress from supplemental irrigation was proportional to irrigation level with full irrigation resulting in complete moisture stress-free days throughout the crop growing season. Deficit irrigation also resulted in a reduction of moisture stress by up to 50 days per season and most importantly the stress days were sparsely distributed across the crop growth period alleviating the stress during anthesis, which was the most affected growth stage (Fig. 7). The effectiveness of deficit irrigation in reducing moisture stress was slightly higher in Meisso (Fig. 7b) than Kobo (Fig. 7a). Reductions in moisture stress frequencies and severities from the deficit and full supplemental irrigation to the current rainfed production systems for both locations would result in an increase in sorghum yield.

On average deficit and full irrigation for Kobo resulted in 16 and 22 irrigation events, which were equivalent to 231 and 348 mm of total irrigation during the crop growth season, respectively. Similarly, for Meisso, deficit and full irrigation on average required 346 and 491 mm which were applied over 18 and 21 irrigation events, respectively (Table 6).

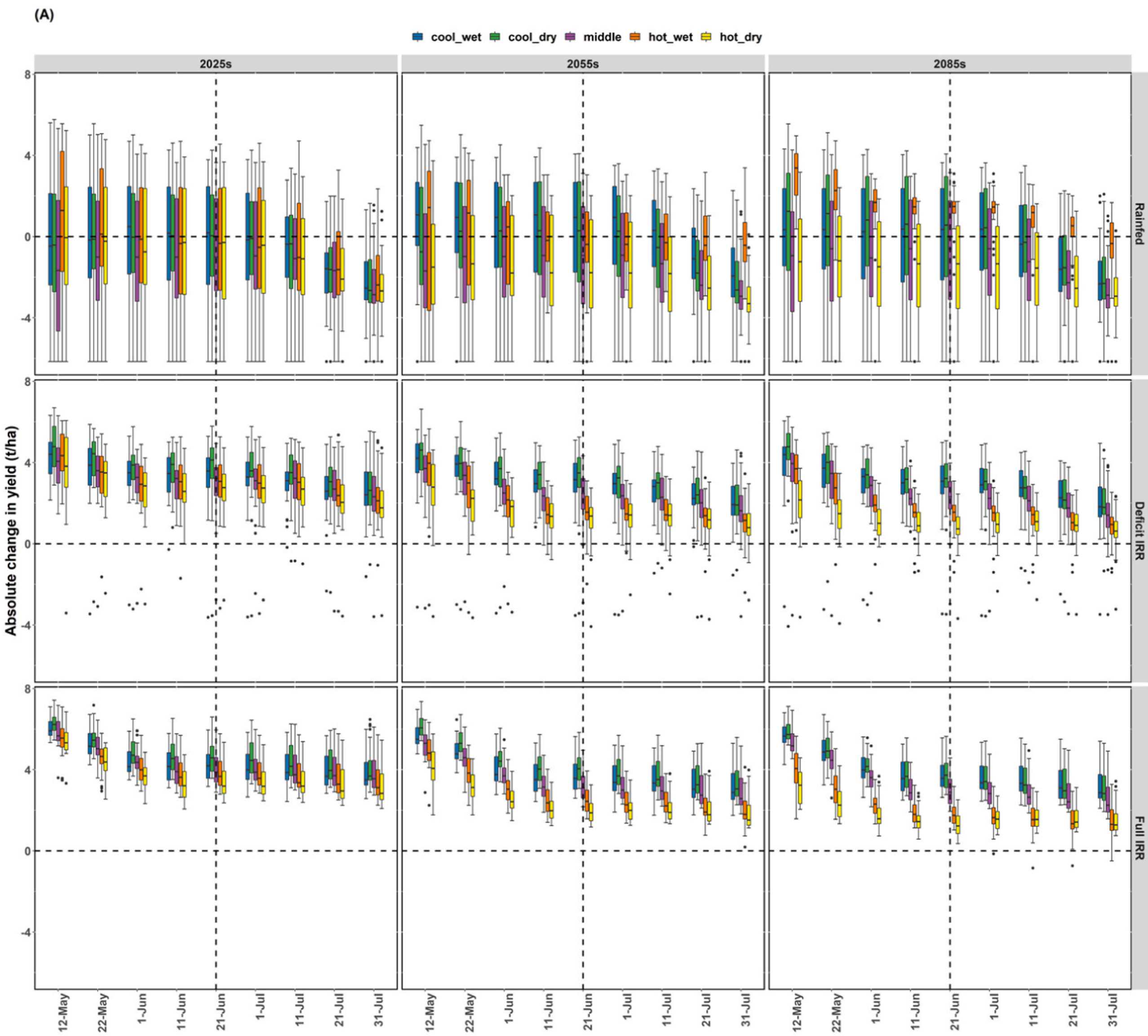

Fig. 8. Effects of shifting planting dates and supplemental irrigation on projected sorghum yield for three periods under five climate scenarios and two RCPs (A) RCP 4.5 and (B) RCP 8.5 for Kobo.

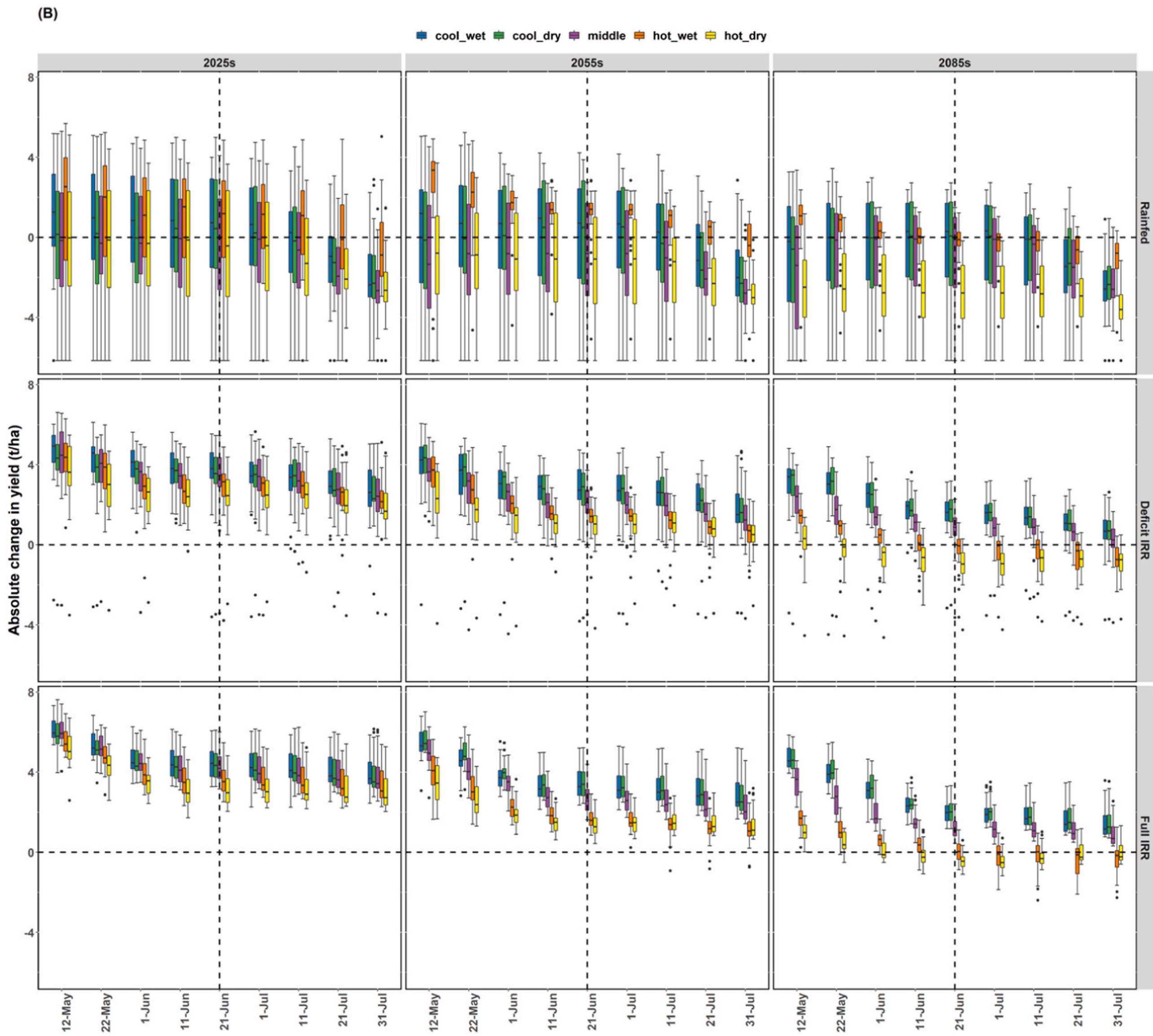

Fig. 8. (*continued*).

3.6. *Effect of supplemental irrigation and planting date on sorghum yield*

The reduction in the frequency of moisture stress and severity due to implementation of deficit and full supplemental irrigation practices to the current rainfed production systems were also reflected by projected increase in sorghum yield for both sites (Figs. 8 and 9). The increase was sufficiently high to offset the projected reduction in yield of up 2 t ha^{-1} and resulted in a net yield increase for all climate change scenarios and periods (Figs. 8 and 9). Full irrigation was effective in reducing moisture stress and, thereby, increasing sorghum yield by up to 3 t ha^{-1} for Kobo and 2 t ha^{-1} for Meisso. On average, the yield difference between deficit and full irrigation was about 1 t ha^{-1}. Our findings were in agreement with several studies that showed the effectiveness of irrigation as climate change adaptation practice (Finger et al., 2011; Kassie et al., 2015; Muluneh et al., 2017).

For the rainfed production system, sorghum yield percentage change was estimated to be − 4, − 7,− 3% in the 2025s, 2055s, 2085s respectively at Kobo under RCP4.5, meanwhile it would be − 28,− 18,− 30% in the 2025s, 2055s, 2085s respectively at Meisso under RCP4.5 compared to the baseline. As we applied deficit irrigation the sorghum production would projected to increase by 50,36,33% in the 2025s, 2055s, 2085s respectively at Kobo under RCP4.5, while it would increase 39, 33, 24% in the 2025s, 2055s, 2085s respectively at Meisso under RCP4.5 compared to the baseline. The sorghum production even goes higher as we applied full irrigation in both locations.

Among the five climate conditions, cool/wet and cool/dry conditions resulted in higher yield while hot/dry conditions resulted in the lowest yield even with supplemental irrigation. Between the two locations, the yield was higher and more variable for Kobo than for Meisso. Similarly, yield differences among climate scenarios were higher in Kobo than Meisso (Fig. 8). Overall, the average yield for the two locations was consistently higher under RCP4.5 than RCP8.5 (Figs. 8 and 9). This could be due to increased CO_2 concentration, which favors high biomass production that may not necessarily lead to an increase in grain yield. Ottman et al. (2001) reported that elevation of CO_2 concentration increases sorghum biomass production in drier areas (Ottman et al., 2001). Increases in CO_2 concentration have shown both positive and negative effects on sorghum (Kothari et al., 2020). For example, results from the Free Air CO_2 Enrichment (FACE) experiments at Maricopa, Arizona (Ottman et al., 2001) and open-top field chamber studies at Auburn, Alabama (Prior et al., 2003) reported both increases and reductions of grain sorghum yield from elevation of CO_2 concentrations.

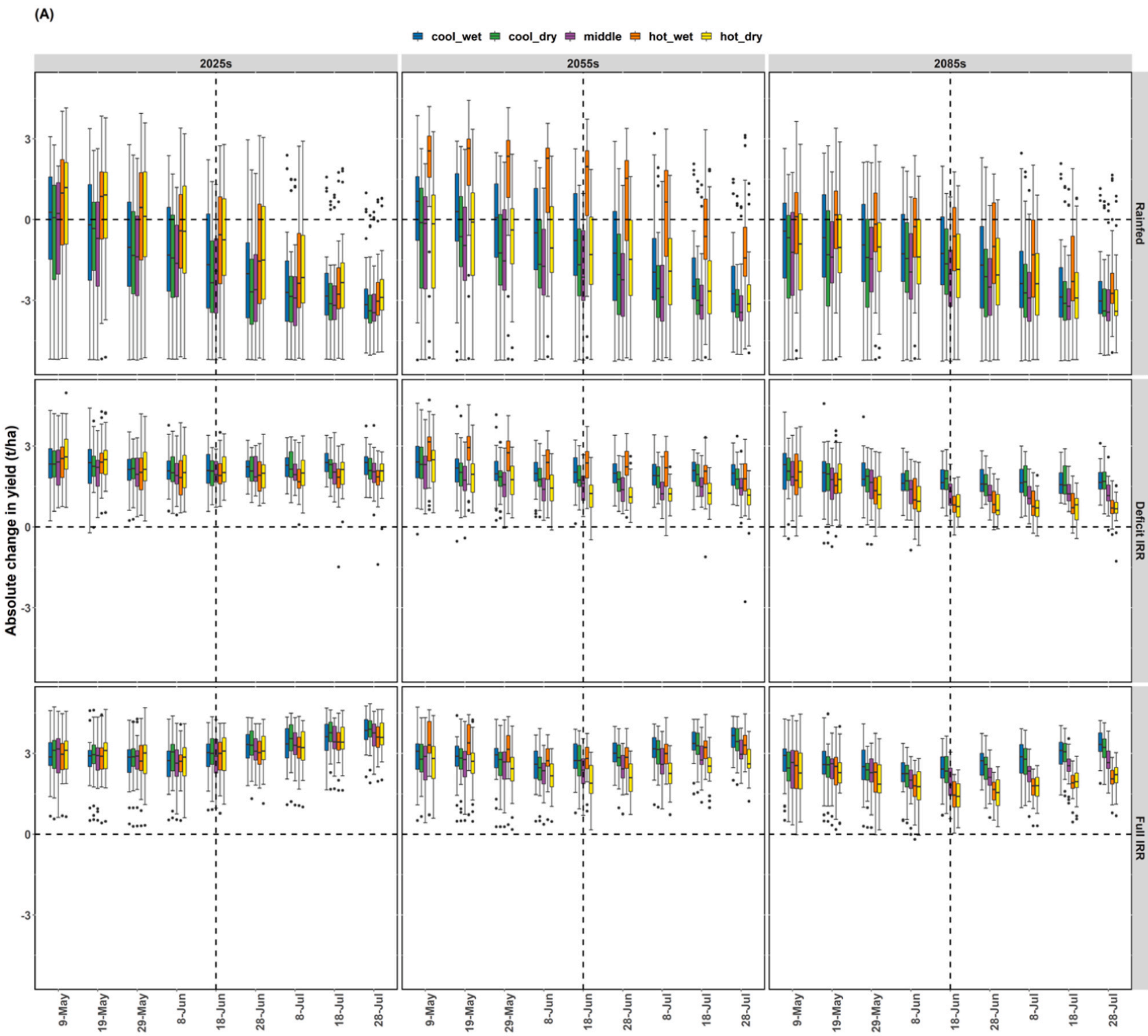

Fig. 9. Effects of shifting planting dates and supplemental irrigation on projected sorghum yield for three periods under five climate scenarios and two RCPs (A) RCP 4.5 and (B) RCP 8.5 for Meisso.

Early planting dates tend to increase crop yield compared to the baseline planting dates (June 21 for Kobo and June 18 for Meisso) and late planting dates under rainfed or with supplemental irrigation production systems (Figs. 8 and 9). However, the effects of early planting were higher when implemented with irrigation than under rainfed. Similar studies have also reported that early planting dates were beneficial in increasing early maturing sorghum cultivars (Akinseye et al., 2020). It is also worth noting that results varied between the five climate scenarios where cool/wet and hot/wet scenarios resulting in higher yield increases. Affordability of adaptation practices is equally important as their effectiveness for wider implementation by smallholder farmers. These findings would have significant practical implications as farmers could easily implement such adaptation practices for climate change. In northern Ethiopia, a study by Gebrekiros et al. (2016) estimated that under current panting dates, future sorghum yield would decrease between 5% and 24% compared to the baseline period (Gebrekiros et al., 2016).

4. Conclusion

Our results showed that average temperature will increase by up to 6 °C for both study sites. Meanwhile, rainfall projections showed mixed results where reductions and increases were estimated compared to the baseline period for both locations. Under the current rainfed production system, crop moisture stress is also projected to intensify especially during crop anthesis, which in turn negatively affects sorghum yield. Overall, the sorghum yield under the rainfed production system was very low (< 6.2 t ha^{-1}). Average yield projections also show reductions for both sites, which highlights the need for climate change adaptation practices that could help increase sorghum yield. These identified impacts of climate change on moisture stress status by crop growth stages will allow farmers to apply a targeted irrigation and still possibly achieve optimal yield irrespective of the projected climate. Moreover, it will also provide critical information to breeders to develop improved cultivars that can adapt the impacts of climate change. Results from this study show that irrigation could play a significant role in tackling moisture stress frequency and severity and thereby increase sorghum

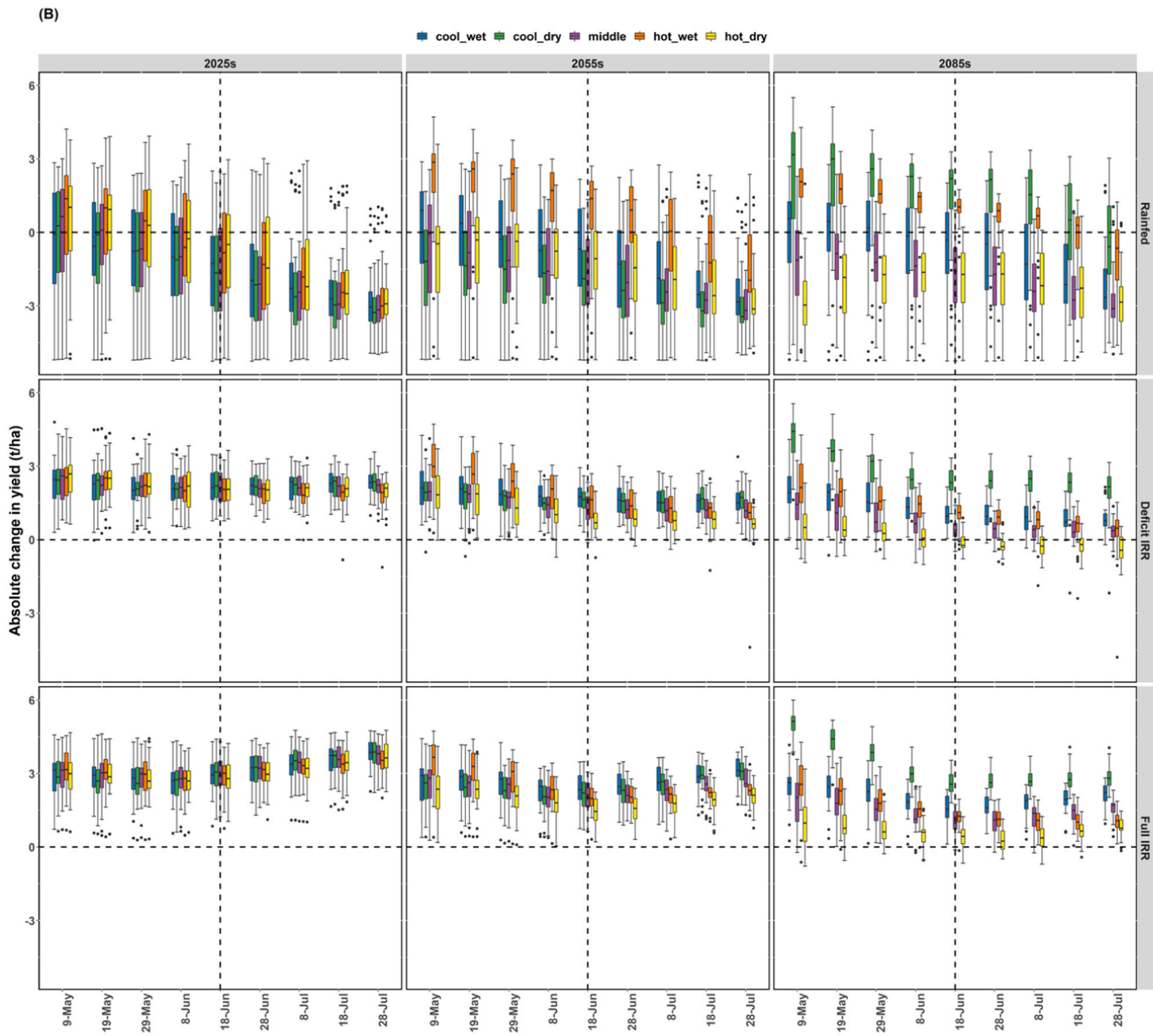

Fig. 9. (*continued*).

yield. The yield increase was positively correlated with increases in supplemental irrigation from, rainfed to the deficit, and full irrigation. Full irrigation was effective in increasing sorghum yield by up to 3 t ha^{-1} for Kobo and 2 t ha^{-1} for Meisso. On average, yield difference between deficit and full irrigation was about 1 t ha^{-1}. Similarly, early planting dates tend to increase crop yield, especially when implemented with supplemental irrigation. Overall, results from this study would help to inform policy and management decisions towards climate change adaptation efforts. As such, these findings would have significant practical implications as smallholder farmers need adaptation practices that could be implemented easily with small or no capital investment. In this regard, shifting planting dates should be investigated further as potential climate change adaptation practices not only for sorghum but also for other staple crops. In addition, future studies should investigate irrigation water availability for supplemental irrigation, cost-benefit analysis, the feasibility of small-scale irrigation schemes that can be implemented at smallholder farm levels.

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.

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