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Projected Climate Change Impact on Sorghum (*Sorghum bicolor*) Yield in Fedis district Eastern Ethiopia

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Abstract

This study was conducted in Fedis district, to assess the impacts of climate change on sorghum (Sorghum bicolor L.) yield. The CERES-sorghum and APSIM-sorghum models were calibrated and validated using field experimental data of anthesis days, days to maturity and grain yield of two sorghum varieties, Melkam and Teshale. In the simulation, the initial climate data were modified by future climates under the medium (SSP2-4.5) and high (SSP5-8.5) emission scenarios. Historical climate data was sourced from the National Meteorological Institute of Ethiopia, alongside crop yield data and soil samples from the Oromia Agricultural Research Institute site in Fedis. For future projections, data from five GCMs using CMIP6 under SSP2-4.5 and SSP5-8.5 scenarios were used, and the Empirical Quantile Mapping approach for downscaling and bias correction. Different sowing windows and planting densities were evaluated for their effectiveness to increase sorghum yield under the future climate conditions of Fedis district. The results of models' calibration and validation showed high agreement between simulated and observed grain yields, with d-stat values >0.66 for CERES-sorghum and APSIM-sorghum, and the normalized RMSE less than 20%. However, all the models underestimated the yield. Statistical indices indicated that DSSAT-CERES and APSIM models accurately simulated sorghum yield in Fedis. The result of impact assessment showed that sorghum grain yield may increase at the range of 20.1 to 44.4% by 2030s and 2050s under both SSPs scenarios. Additionally, the result of adaptation options showed that sorghum yield may be increased through early planting date and increased plants density. In conclusion, future climate projections are expected to increase sorghum yield in Fedis and adaptations strategies including planting date and planting density can be used for better yields.

Key words: APSIM, Adaptive Strategies, Climate change Scenarios, CMIP6, DSSAT, Simulation.

1. Introduction

Recent studies demonstrated that greenhouse gas emissions constitute the major cause of climate change, which is expected to raise the average world temperature from 2.5℃ to 4.5℃ by the year 2100 (Farooq *et al*., 2023; Recha *et al*., 2017). At continental and regional levels, the consequences of these climate conditions are multidimensional and comprise agricultural yield reduction, food insecurity, water scarcity, biodiversity losses, increasing in pest and diseases outbreak, and soil degradation (Tarekegn *et al*., 2023). Africa has been identified as one of the parts of the world most vulnerable to the impacts of climate change. According to Serdeczyn *et al*. (2017) climate was projected to a warming trend in Sub-Saharan Africa (+4ºC the end of century), particularly in southern and East Africa; with frequent occurrence of extreme heat events, increasing aridity; and changes in rainfall patterns. In a context of population growth, climate change is expected to affect food security of many African countries since Africa is far from self-sufficient in agricultural production and this situation is projected to worsen in the future (Hall *et al*., 2017, Van and Zwart, 2018).

Ethiopia is one of the African countries highly affected by the changes in climate patterns (Bekuma *et al*., 2022). In Ethiopia, researches have proven that the temperature is increasing by 0.4 and 0.3ºC per decade in the lowland and midland areas of the country, respectively (Belay *et al*., 2021; Etana *et al*., 2020), with high rainfall variability in different regions due to rapid topography changes (Dubache *et al*., 2019; Gleixner *et al*., 2017; Shawul and Chakma, 2020). A study conducted in the Eastern part of the country, especially in East Hararghe zone, showed an irregular precipitation pattern in both *kiremt* (JJAS) and *belg* (MAM) seasons with a 29-48% precipitation concentration index (Girma, 2023). Additionally, East Hararghe zone is frequently impacted by extreme droughts and dry spell events. Serur and Kebira (2025) projected a significant increase in drought occurrences in this zone at the rate of -0.003 based on the standardized precipitation index at a 6-months timescale (SPI_6).

In Ethiopia, subsistence rain-fed crop production constitute the core of the economy on which livelihood is fully dependent (Mohammed and Misganaw, 2022). This agricultural system employs approximately 85% of the population and accounts for almost 45% of gross domestic product (GDP) and 60% of foreign exchange (Sime and Demissie, 2022; Teferi *et al*., 2025). Despite its significant contribution to the economy, the rainfall-based agriculture combined to traditional farming practices and climate change put at risk the country's food security (Gezie, 2019). Research demonstrated that the changing precipitation pattern and the warming trends could make rain-fed agriculture riskier and barrier for food production in Ethiopia (Tolossa *et al*., 2023; Asfew and Bedemo, 2022; Degife *et al*., (2021).

Cereal crops are negatively affected by the change in climate worldwide and yet they constitute the most source of dietary energy (Wang *et al.*, 2018). In Sub-Sahara region, cereals provide 50% of daily calorie intake (Alimagham *et al*., 2024). Ethiopia is among the countries where cereals are the primary source of food (Mann *et al*., 2019; Yen *et al*., 2023). In 2021, the Ethiopia Central Statistical Agency reported that from the total grain crops area, 81.19% of hectares of land were covered by cereals, with a production contribution of 88.36% of the total grain in the country, which is substantially higher than the proportion of other crops such as pulses (12.9%) and oilseeds (5.9%). Although cereal production accounts for more than 87% of total crop production in Ethiopia, the country is importing a large number of cereal crops to regulate the demand and supply in the domestic market (Asfew and Bedemo, 2022). Savary *et al*., (2025) revealed that corn yields decreased from 45.6 quintals per hectare in 2011 to 32 quintals in 2021, and wheat yields dropped from 33 quintals per hectare in 2011 to 29 quintals in 2021 due to climate change.

Sorghum (*Sorghum bicolor* L.) is among the major cereal crops that supply the bulk of the staples for the global population, in general and particularly the Ethiopian population (Gebresamuel *et al*., 2022). It is the second most important cereal crop after maize in Sub-Sahara, supporting almost 300 million people (Amelework *et al*., 2016), and the third most important cereal crop behind teff and maize in Ethiopia (Temesgen and Hailu, 2021). About 1.83 million hectares are used to grow sorghum in the country, which produce 4.34 million tons a year (Anega, 2024). In demanding conditions, sorghum may be able to withstand the consequences of a water shortage (Worede *et al*., 2020). The crop can also produce reasonable yield in poor soils owing to its nutrient uptake capacity (Tirfessa *et al*., 2023). Despite being a major food crop in many of Ethiopia's semi-arid regions, sorghum yield is still below the expected level because of abiotic and biotic factors. Climate change is constitute the major factor which reduces sorghum production in (Mohammed and Misganaw, 2022).

In East Hararghe, a semi-arid zone located in the Eastern part of Ethiopia, sorghum constitutes one of the most dependable food crops. Due to a climate categorized by inconsistent rainfall and drought, edaphic and biotic factors in this region ; sorghum productivity is less than 2.18 tons/hectare, which is below its genetic potential (4.54 tons/hectare) (FAOSTAT, 2017; Degebasa *et al*., 2022). Although the negative impact of climate change on sorghum production, its tolerance to environmental stress makes it highly suitable for semi-arid zones like East Hararghe (Deb *et al*., 2004 cited by Tolosa *et al*., 2023).

Research has been carried out to investigate the impact of climate change on sorghum production in the semi-arid zones of Ethiopia. For instance, Gardi *et al*., (2025) reported that sorghum presents high differential and location-specific yield responses across varieties under projected climate in the semi-arid environment of Ethiopia. A study conducted in the semi-arid areas of Amhara region by Mohammed and Misganaw (2022), using CERES-sorghum in the DSSAT model to assess the impact of climate change on sorghum yield, revealed that the grain yield may decrease by 2030s and 2050s under RCP4.5 and RCP8.5 scenarios. In Babile district, a district located in East Hararghe, Tolossa *et al*., (2024) realized an increasing in drought frequency and severity occurrences in both near, mid and end of the 21st century under RCP4.5 scenario and reported that this situation would have a negative impact on sorghum productivity in the district. However, there is limited information on the impacts of climate change on sorghum production and productivity in Fedis district, East Hararghe zone.

This study investigated how different climate change scenarios affect sorghum yield in Fedis district, filling critical gap in localized impact evaluations. By integrating site-specific climate and crop response data within the crop simulation models, the timing and magnitude of sorghum productivity in this semi-arid zone were assessed. Therefore, the overall objective of this research was to simulate the impact of climate change on sorghum yield in Fedis district, East Hararghe, Ethiopia. The more specific objective of the study was: 1) to calibrate and validate APSIM-sorghum and DSSAT CERES-sorghum for sorghum yield simulation in the climate conditions of Fedis. 2) to predict the impact of projected climate change on sorghum yield in the district. 3) to evaluate the effectiveness of change in sowing date and planting density as adaptation strategies for sustainable sorghum production in the study area.

2. Materials and Methods

2.1. Description of the study area

Fedis district is located at 550 km East of Addis Ababa and about 24 km from Harar town in the southern direction, eastern Ethiopia. The district spans 8^0 30’ 0” and 9^0 14’ 0” N and 41^0 50’ 0” and 42^0 18’ 0” E (Figure 1). The altitude of the district varies from1200 m to 2118 m and the topographic feature is 70% plain area, 28% plateau and 2% mountain or hill. According to Asefa *et al*. (2021), the district’s mean annual maximum and minimum rainfall, mean annual maximum and minimum temperature are 673.44mm, 26.13°C, and 13.2°C, respectively. Fedis has a two-mode rainfall distribution pattern with first rainy season rains from March to May with erratic seasonal rainfall, while Jun to September is second rainfall season. The land use and land cover of the district is constituted by 21.02% of cropland, 2.80% covered by pasture, 11.2% of forest, 38.01% of grassland, 10.5% for communal land, and the remaining 14.04% covered by mountains, valley and otherwise unusable. Agriculture is the substantial source of livelihood of the community in Fedis district (Aweke *et al*., 2020). However, its productivity is law due to the rain-fed system. In addition, the farming system is subsistence type dominated by smallholder farmers (Zeleke *et al*., 2021).

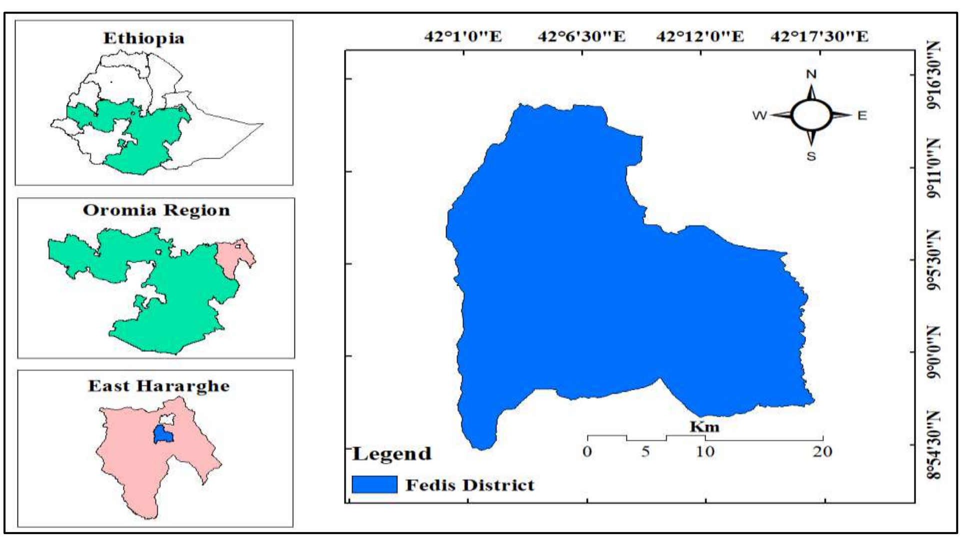

Figure 1. Map of the study area

2.2. Description of the crop models

APSIM crop model

The Agricultural Production System Simulator (APSIM) is a farming system model developed by the Agricultural Production Systems Research Unit (APSRU) to assess risk management in agricultural production (Feleke *et al*., 2021). It consists of modules categorized as crop, management, soil, and environment, and communicates via an APSIM engine. The model simulates over 20 crops including sorghum, soil characteristics, and management options, using input data like climate, soil, and crop data (Chisanga *et al*., 2021; Richetti *et al*., 2024). APSIM has been used to simulate cereal production, especially sorghum production in relation to climate variability and change across many areas. APSIM modelers mostly aimed to predict crop phenology, alteration in the photosynthesis process, biomass, yield gap and/or losses, grain filling and nutrients (Berghuijs et al., 2021; Chekole et al., 2024; Winn et al., 2023).

The outcomes of the simulations were enhanced by APSIM's modifications and adaptations to the current environment (Gavasso-Rita *et al*., 2024). Researchers discovered an underestimation in the APSIM results in 2012. According to Lobell *et al*., (2012) this is due to the model's triangular approach to the thermal period, which took 26°C as the peak value and showed values above 34°C for a significant portion of the season. However, they asserted that APSIM was unique due to its particular technique for estimating senescence speed in extremely hot environments.

DSSAT and CERES-sorghum model

The Decision Support System for Agrotechnology Transfer (DSSAT) is a crop simulation platform that uses inputs and outputs to run various models (Liu *et al*., 2011). It includes crop-soil-weather models, uncertainty and economic models, and support software. DSSAT allows users to adapt and evaluate models for their conditions, provide insights into production, profitability, and stability, and understand field interactions (Shawon *et al*., 2025; Wajid *et al*., 2021). The DSSAT model, which contains the submodule CERES for cereal crops, requires detailed input data, including field data, soil characteristics, and management data. It is widely used to assess climate change effects on crop production and evaluate best management options under changing climate scenarios (Cao *et al*., 2012; Chisanga *et al*., 2021).

DSSAT is a mainly used crop model for assessing long-term cultivation yield and soil nitrogen dynamics, contributing to studies on rainfed crop productivity, nitrogen input effects, climate change impacts on yield and water demand, drought-tolerant variety performance, and semi-arid crop response (Gunawat *et al*., 2022; Jiang *et al*., 2021). Initially, it overestimated grain yields and nitrogen content, but recent updates have improved its predictive accuracy, particularly in soil moisture during the growing season (Hoogenboom *et al*., 2019).

This model can be integrated with hydrological, socio-economic, and parameter estimation models to evaluate water supply, food security impacts, and crop genetics, respectively (Chisanga *et al*., 2021; Kloss *et al*., 2012; Wajid *et al*., 2021). Notably, DSSAT helps to assess the effects of climate change on crop yield, nitrogen use, and water efficiency by considering key factors such as water availability and greenhouse gas concentrations (G. Nelson et al., 2018), while some studies have shown overestimation of yields and nitrogen, calibration remains crucial for accuracy. Ultimately, DSSAT serves as a dependable tool for developing mitigation strategies in agriculture (Gavasso-Rita *et al*., 2024).

2.3. Climate data

The needed historical climate data, maximum and minimum temperature (Tmax and Tmin), and rainfall were gathered from the National Meteorological Institute of Ethiopia for the period 1992-2022 years of Fedis district; and the solar radiation (Rs) data downloaded data from Climate Engine website (https://app.climateengine.org/climateEngine). The NetCDF data format of future Tmax, Tmin and rainfall of five GCM model of CMIP6 climate data including ACCESS-CM2, EC-Earth3, MIROC6, MPI-ESM1-2-LR, and NorESM2-MM were downloaded from Copernicus website (https://cds.climate.copernicus.eu/datasets/projections-cmip6?tab=download).

To develop climate change projections at the station level, the statistical downscaling and bias correction via Empirical Quantile Mapping (EQM) approach was applied. Data from the five global climate models (Table 1), each evaluated under the medium-forcing middle-of-the-road pathway (SSP2-4.5) and the high-end forcing pathway (SSP5-8.5) scenarios were downscaled, focusing on the periods 2040-2069 (mid-century) and 2070-2100 (end of the 21st century).

Table 1. Descriptions of the GCMs used for climate future projections.

	CMIP6 models	Institute	Country	Lon. x Lat.
1	ACCESS-CM2	Commonwealth Scientific and Industrial Research Organization	Australia	1.9 x 1.3
2	EC-Earth3	EC- Earth consortium	Europe	0.7 x 0.7
3	MIROC6	Model for Interdisciplinary Research on Climate	Japan	1.4 x 1.4
4	MPI-ESM1-2-LR	Max Planck Institute for Meteorology	Germany	1.9 x 1.9
5	NorESM2-MM	Norwegian Climate Centre	Norway	1.25 x 0.94

2.4. Soil data

The Oromia Agricultural Research Institute authorized soil samples collection at his site in Fedis and these samples were taken to Haramaya university laboratory for analysis. Soil samples were analyzed to determine the soil type, slope and drainage characteristics, and physico-chemical parameters. The soil parameters analyzed include the soil bulk density, soil texture, drained upper limit (DUL), saturated volumetric water content (SAT), lower limit, available phosphorus, soil organic carbon content, total nitrogen or in soil NO_3^- and NH_4^+ concentrations amount in kg/ha; soil pH; effective cation exchange capacity (CEC); and exchangeable bases (Table 2). The texture of the soil was determined using the Bouyoucos hydrometer method based on Day (1965), while the core sampling method was used to determine the soil bulk density (Al-Shammary *et al*., 2018). Furthermore, a glass electrode attached to a digital pH meter helped to make a suspension of a 1:5 soil/water ratio in order to measure the pH of the soil (Baker *et al*., 1983). The proportion of organic matter was computed by multiplying the organic carbon percentage by 1.724, and the organic carbon content was ascertained using the procedure described by Nelson and Sommers (1996).

The extraction of HNO_3 and HNO_4 acids was done using the EPA method 3051 based on Xing and Veneman (1998). This method allows the extraction of the acid-soluble portion of any given element.

The Kjeldahl method, as outlined in Jackson (1973), was used to calculate total nitrogen. Kjeldahl N, titration by Spectro colorimetry determines the NH_4^+ concentration, while the modification of this method allows the titration of NO_3^- before Kjeldahl mineralization based on Pansu and Gautheyrou (2006). The available amounts of P and K was extracted from the soil with a calcium-acetate-lactate buffer based on Schüller (1969). Phosphorus was measured photometrically according to Watanabe and Olsen (1965) with a Unicam 8700 UV/VIS spectrometer and potassium with an AAS (Varian Spectra AA-10). The soluble Na, Ca and Mg was evaluated using the inductively coupled plasma-atomic emission spectroscopy (ICP-AES) method (Hendershot *et al*., 1993). Soil CEC was determined by saturating with ammonium acetate based on Summer *et al*. (1996). The drained upper limit (DUL), saturated volumetric water content (SAT), and lower limit were calculated automatically by DSSAT model after filling the others soil parameters.

Table 2. Soil physical and chemical properties of Fedis District.

Parameters	**Soil Depth (cm)**					
	0-15	**15-30**	**30-60**	**60-90**	**90-120**	**120-150**
Clay (%)	22	35	34	36	32	34
Silt (%)	25	12	12	10	13	29
Sand (%)	53	53	54	54	55	37
Organic carbon (%)	1.5	1.4	1	0.8	0.7	0.5
Total Nitrogen (%)	0.32	0.20	0.08	0.04	0.08	0.08
CEC (meq/100g)	39.4	35.8	33.4	30.4	30.1	29
Bulk density, g/cm^3	1.59	1.61	1.56	1.58	1.56	1.82
DUL (cm^3/cm^3)	0.308	0.35	0.324	0.32	0.299	0.332
DLL (cm^3/cm^3)	0.177	0.239	0.223	0.228	0.205	0.21
pH	8.4	8.4	8.5	8.3	7.8	7.8
PWP (g/g%)	16.2	13.5	25.2	15	27.3	22.8
Ava. P(mg/kg)	17.26	9.70	10.30	7.51	7.5	5.45
Ava.K (mg/kg)	0.79	0.78	0.8	0.72	0.58	0.46
FC (%)	25.49	28.26	33.82	34.59	32.1	28.6
Ca (cmol (+)/kg)	29.64	26.46	27.12	24.15	17.57	16.66
Mg (cmol (+)/kg)	10.37	9.83	9.52	8.51	7.61	7.61
Na (cmol (+)/kg)	0.83	0.61	0.95	0.57	0.52	0.55

2.5. Crop management and yield data

Crop data included management and yield data. Four years crop data of sorghum varieties, Melkam and Teshale, were provided by the Oromia Agricultural Research Institute. 2021/2022 crop data were used for models' calibration, while 2023/2024 crop data served for models' validation. Melkam and Teshale sorghum varieties were considered for data collection due to data availability, their high yield and drought tolerance (Mengesha *et al*., 2021; Tsehaye *et al*., 2025). Regarding crop management data, precise planting dates, depths, row spacing, plant population, and cultivar details; fertilizer applications (dates, types, nutrient rates, methods, and placement); and residue management were collected. For yield data, harvest dates, yields (grain yields), and yield components (days to flowering and maturity) were necessary for precise calibration and validation of DSSAT and APSIM crop models (Feleke *et al*., 2021; Richetti *et al*., 2024; Winn *et al*., 2023). The table 3 below presents the characteristics of Melkam and Teshale sorghum varieties.

Table 3. Characteristics of Sorghum Varieties (Melkam and Teshale) used for the study.

No.	**Agronomic information**	**Melkam**	**Teshale**
1	Altitude (masl)	1200-1600	1200-1600
2	Rainfall (mm)	500-800	500-800
3	Seed rate (kg ha-1)	8	8
4	Days to anthesis	76-82	76-82
5	Days to maturity	118	118
6	Plant height (cm)	112-139	167
7	Spacing (cm)	75 /20	75/20
8	Temperature	15-34	15-34
9	Planting density (plants m^{-2})	7	7
10	Fertilizer rate (kg ha-1)	DAP = 100, Urea = 50	DAP = 100, Urea = 50
11	Potential yield (t ha^{-1})	4-8	3.3-7

2.6. Models' calibration and validation

The calibration of APSIM-sorghum and CERES-sorghum models was done integrating soil data at different vertical layers, climate data, crop management data and sorghum yield of 2021/1022 cropping season. Three crop parameters, including the days to flowering (DTF), days to maturity (DTM), and grain yield were considered for the impact assessment. The cultivar-specific parameters were estimated by iteration against the data measured under potential conditions.

The crop models were validated using 2023/2024 crop data provided by the Oromia Agricultural Research Institute. For the two models, the goodness or weakness of fit between the simulated and observed-values were evaluated by using different statistical indices, such as root mean square error (RMSE), normalized root mean square error (nRMSE), the index of agreement (d-index) and coefficient of determination (R^2) based on Cao *et al*. (2012); Janová, (2012).

The root mean square error (RMSE) measures the average magnitude of the estimated errors between the model and the station data (Equation 1). A lower RMSE value means greater central tendencies and smaller extreme errors. An RMSE value of zero shows the perfect score.

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(Pi - Oi)^2} \tag{1}$$

where n is the number of observations, P_i the predicted value for the i^{th} measurement and O_i the observed value for the i^{th} measurement.

The normalized root mean square error (nRMSE) is a better indication for evaluating model performance, since normalizing the RMSE can help to make it scale-free. The nRMSE is a percentage that connects the RMSE to the observed range of the variable. This gives a number between 0 and 1, with values closer to 0 indicating better-fitting models. The normalized nRMSE is expressed in percent, calculated based on Loague and Green, (1991); and Magaia *et al*. (2017) by Equation 2:

$$\mathrm{nRMSE} = \frac{\mathrm{RMSE}*100}{\overline{\mathrm{O}}} \quad (2)$$

Here nRMSE is normalized root mean square error and O is the mean value of observed crop data.

Additionally, for comparison, the R^2 regression statistic (coefficient of determination) was also used for model fitness. It represents the proportion of the variation in simulated and observed (Equation 3).

$$R^2 = 1 - \frac{\text{sum of square of error}}{\text{Sum of square of total}} \quad (3)$$

The index of agreement, calculated using the equation 4 below, varies from 0 to 1, with higher values indicating better agreement between the model and observations, similar to the coefficient of determination R^2 (Legates and McCabe, 1999).

$$d = 1 - \left[\frac{\sum_{i=1}^{n}(Q_i - R_i)^2}{\sum_{i=1}^{n}\left(|Q'_i| + |R'_i|\right)^2}\right],\ 0 < d < 1 \quad (4)$$

where Qi and Ri refer to observed and predicted-values respectively for all studied variables and n is the number of observations.

2.7. Future impacts assessment on sorghum yield simulation

The future yield of sorghum in the research region was analyzed through the simulation procedure. The baseline yield served as a reference for simulating the yields of different varieties under the study area's historical (1992-2022) and projected (2050s and 2080s) climatic conditions. Lastly, the following formula was used to calculate the yield percentage change for sorghum from the baseline yield by the 2050s (2040-2069), and 2080s (2070-2100) under SSP2-4.5 and SSP5-8.5 scenarios.

$$\Delta Y = \frac{\mathrm{Ysim} - \mathrm{Yobs}}{\mathrm{Yobs}} * 100 \quad (5)$$

where, Yobs is the baseline yield (kgha^{-1}), Ysim is the simulated value, and ΔY is the change in yield.

2.8. Adaptation options

Various adaptation strategies were tested to reduce the impact of climate change on sorghum production. These agronomic adaptation options include the planting date adjustment and plant density. According to Muluken and Alemayehu (2024), sorghum has two sowing dates in the semi-arid zones of Ethiopia: the dry/early sowing in late June and the wet/late sowing in early July. Therefore, to test the impact of planting dates on sorghum productivity, we applied four planting date: 10^{th} June, 20^{th} June, 2^{and} Jully and 12^{th} Jully categorized as early, normal, late and very late planting dates, respectively. Three planting densities were considered for the impact assessment based on Hailu and Geremu (2021): very dense [11 plants per m^2], dense [9 plants per m^2], and normal [7 plants per m^2].

3. Results

3.1. Result of crop models' calibration and validation

The CERES-sorghum model was calibrated using experimental date of anthesis, days to maturity, and grain yield collected during the 2021-2022 main cropping seasons. The findings of this calibration demonstrated a good adjustment of crop genetic coefficients for all the crop parameters (Table 4). High coefficients of agreement between observed and simulated crop data were observed for both Melkam and Teshale varieties, with d-stat >0.78 for the three crop parameters. A high fitness of the model was also shown in simulating both the days to anthesis, physiological maturity and grain yield, with better coefficient of determination (R^2) values. Melkam variety presented R^2 values equal to 0.82, 0.65 and 0.78 for the date of anthesis, days to maturity and grain yield, respectively (Table 4). For Teshale, the coefficients of determination were 0.8 for date of anthesis, 0.67 for days to maturity, and 0.68 for grain yield, respectively. The RMSE for anthesis, maturity day and grain yield for Melkam variety were 2 days, 1 day, and 174.3 kg/ha, respectively. For Teshale, the RMSE values for the respective parameters were 2 days, 2 days, and 203.4 kg/ha. The nRMSE (%) was less than 10% for all the crop parameters and for both Melkam and Teshale varieties, meaning the model is performing well for considered sorghum varieties in Fedis.

The APSIM-sorghum was calibrated using the same data. Result from Table 5 revealed high coefficients of agreement between observed and simulated crop data for both Melkam and Teshale varieties (d-stat >0.65), but Melkam variety performed well as compared to Teshale variety. The correlation between observed and simulated crop data provided values almost similar to the coefficients of agreement regarding variety. The anthesis day and grain yield of Melkam variety presented high R^2 values (0.76 and 0.85), while 0.83 and 0.57 were recorded for anthesis day and grain yield of Teshale variety, respectively. Regarding the maturity day, the fitness of model was law for both Melkam ($R^2 = 0.57$) and Teshale ($R^2 = 0.53$) varieties. The findings also showed an excellent performance of the model calibration for the two varieties and on all the crop parameters (nRMSE <10%), expect on the grain yield of Teshale variety (nRMSE = 15.9%) (Table 5).

Table 4. CERES-sorghum calibration for Melkam and Teshale varieties.

Varieties	Parameters	Obs	Sim	R^2	RMSE	nRMSE (%)	d-stat
Melkam	Anthesis day	78	81	0.82	1.72	1.21	0.85
	Maturity day	119	123	0.65	1.43	1.09	0.9
	Yield (kg/ha)	3073.5	2986.3	0.78	174.3	5.42	0.87
Teshale	Anthesis day	81	86	0.8	2.2	2.38	0.82
	Maturity day	121	127	0.67	1.93	1.64	0.88
	Yield (kg/ha)	2956	2832.7	0.68	203.4	4.34	0.79

Notes: Obs: observed; Sim: simulated; RMSE: root mean squared error; nRMSE: normalize RMSE; d-stat: Wilmot index of agreement.

Table 5. APSIM-sorghum calibration for Melkam and Teshale varieties.

Varieties	Parameters	Obs	Sim	R^2	RMSE	nRMSE (%)	d-stat
Melkam	Anthesis day	78	80	0.76	2.109	1.37	0.89
	Maturity day	119	126	0.57	10.5	5.8	0.71
	Yield (kg/ha)	3073.5	2957.8	0.85	307.4	4.6	0.91
Teshale	Anthesis day	81	82	0.83	1.3	0.57	0.93
	Maturity day	121	129	0.53	6.5	2.5	0.68
	Yield (kg/ha)	2956	3506.8	0.57	520.4	15.9	0.67

Notes: Obs: observed; Sim: simulated; RMSE: root mean squared error; nRMSE: normalize RMSE; d-stat: Wilmot index of agreement.

The performance of CERES-sorghum model was evaluated with independent set of data, 2023-2024 crop data. The findings indicated a good agreement between observed and simulated anthesis days for both Melkam and Teshale varieties, with d-stat of 0.78 and 0.82, respectively (Table 6). The highest indices of agreement were recorded on the days to maturity, with 0.88 for Melkam variety and 0.85 for Teshale variety, respectively. For these two statistical parameters, the R^2 values were above 0.6, indicating the similarity between observed and simulated data, and their nRMSE (%) were less than 10%. Regarding the grain yield, d-stat of 0.81 and 0.77 were respectively recorded for Melkam and Teshale variety, with R^2 values equal to 0.64 for Melkam variety and 0.79 for Teshale variety. The nRMSE (%) of grain yield for the two variety were also less than 10%, which indicates excellent performance evaluation for sorghum yield in the district (Table 6). Although all the sorghum varieties (Melkam and Teshale) presented good statistical indices for the three crop parameters, the level of acceptance (R^2) for Teshale variety was high as compared to that of Melkam variety. The validation of CERES-sorghum model was successful.

Similarly, APSIM-sorghum model was validated using 2023-204 crop data. The result, as reported by Table 7, revealed a similar accuracy of the model as compared to the outcomes of the model calibration. The model presented high coefficients of agreement between observed and simulated data for both Melkam and Teshale varieties regarding the three crop parameters: anthesis day, maturity day and yield (d-stat >0.7); with high values on the anthesis day, 0.84 for Melkam variety and 0.88 for Teshale variety. Similarly, the correlation between observed and simulated data was greater than 50% for all the crop parameters and for the two sorghum varieties. Anthesis day presented the highest correlation values (0.74 for Melkam and 0.78 for Teshale) and maturity day the lowest, 0.58 and 0.57 for Melkam and Teshale, respectively. For the grain yield, R^2 values were equal to 0.65 and 0.63 for Melkam and Teshale, respectively. The nRMSE (%) values of the two variety were less than 10% for anthesis and maturity day, while the grain yield presented nRMSE values between 10% and 20% (Table 7).

Table 6. CERES-sorghum validation for Melkam and Teshale varieties.

Varieties	Parameters	Obs	Sim	R^2	RMSE	nRMSE (%)	d-stat
Melkam	Anthesis day	75	86	0.72	1.68	1.13	0.78
	Maturity day	122	128	0.61	0.98	0.64	0.88
	Yield (kg/ha)	6280	5875.8	0.64	342.1	8.08	0.81

Teshale	Anthesis day	79	84	0.81	1.2	1.075	0.82
	Maturity day	124	130	0.67	1.45	1.22	0.85
	Yield (kg/ha)	5781	5664.7	0.79	128.3	4.09	0.77

Table 7. APSIM-sorghum validation for Melkam and Teshale varieties.

Varieties	Parameters	Obs	Sim	R^2	RMSE	nRMSE (%)	d-stat
Melkam	Anthesis day	75	72	0.74	5.5	2.9	0.84
	Maturity day	122	119	0.58	9.8	4.8	0.73
	Yield (kg/ha)	6280	5472	0.65	682.9	16.1	0.81
Teshale	Anthesis day	79	75	0.78	7.03	1.7	0.88
	Maturity day	124	129	0.57	8	3.4	0.72
	Yield (kg/ha)	5781	5225	0.63	319.3	12.4	0.78

Notes: Obs: observed; Sim: simulated; RMSE: root mean squared error; nRMSE: normalize RMSE; d-stat: Wilmot index of agreement.

3.2. Projected future climate and its impact on sorghum yield

Projected climate changes in Fedis district

The future annual and seasonal trends revealed a rise in rainfall, minimum and maximum temperature under SSP2-4.5 and SSP5-8.5 by 2050s and 2080s in the district (Tables 8 and 9). The annual rainfall is expected to increase from 577.04 mm (baseline) to 643.02 mm (+11.4%) under SSP2-4.5 scenario and 652.14 mm (+13.01%) under SSP5-8.5 scenario in 2050s. By the end of the century (2080s), the rainfall may reach 644 mm (+11.7%) under SSP2-4.5 scenario and 737.86 mm (+28.86%) under SSP5-8.5 scenario (Table 8). Regarding the seasonal rainfall, A significant increase in rainfall will be observed in June-July-August-September (JJAS) season. The seasonal mean rainfall will rise from 320.6 m to 360.6 mm (+12.35%) under SSP2-4.5 scenario and will reach 375.03 mm (+16.98%) under SSP5-8.5 scenario by 2050s, while rainfall will reach 357.7 mm (+11.55%) and 415.98 mm (+29.75%), respectively under SSP2-4.5 and SSP5-8.5 in 2080s (Table 9). For the future changes in temperature, the district may experience variation in both minimum and maximum temperature at the range of 2.28℃ to 3.453℃ under SSP2-4.5 and 3.02℃ to 5.26℃ for SSP5-8.5 in 2050s. The end-century will be characterized by high temperature variability, and this will range between 3.388℃ and 5,26℃ under both SSP2-4.5 and SSP5-8.5 scenarios (Table 8).

Table 8. Change in temperature and rainfall by 2050s and 2080s from baseline at Fedis District.

Scenarios	Period	Tmax (˚C)	Tmin (˚C)	ΔTmax (˚C)	ΔTmin (˚C)	RF during LGP in (mm)	ΔRF during LGP in %
Baseline	1992-2022	26.797	12.92	-	-	577.04	-
SSP2-4.5	Mid-century	29.48	15.35	2.28	2.43	643.02	+11.4
SSP2-4.5	End-century	30.25	16.31	3.45	3.39	644.6	+11.7
SSP5-8.5	Mid-century	29.85	15.94	3.053	3.02	652.14	+13.01
SSP5-8.5	End-century	31.77	18.18	4.97	5.26	737.78	+28.86

Note: LGP was considered from march to September, including MAM and JJAS seasons.

Table 9. Future projected changes in seasonal rainfall in %.

Scenarios	Period	RF in MAM (mm)	ΔRF in MAM (%)	RF in JJAS (mm)	ΔRF in JJAS (%)
Baseline	1992-2022	256.48	-	320.6	-
SSP2-4.5	Mid-century	282.8	+10.26	360.2	+12.35
SSP2-4.5	End-century	286.8	+11.82	357.7	+11.55
SSP5-8.5	Mid-century	277.1	+8.04	375.03	+16.98
SSP5-8.5	End-century	321.8	+25.47	415.98	+29.75

Projected climate change impact on sorghum yield

The simulated changes in days to flowering (DTF), days to maturity (DTM) and grain yield, using APSIM and DSSAT-CERES models, for two sorghum varieties (Melkam and Teshale) by 2050s and 2080s averaged over five GCMs under SSP2-4.5 and SSP5-8.5 scenarios are presented in Figure 2. Simulation results revealed that CERES-sorghum presented different results regarding the days to flowering and maturity day as compared to APSIM-sorghum. Under SSP2-4.5 scenario, the results from CERES-sorghum demonstrates decreases in DTF by 3.3% in 2050s and by 8.7% in 2080s for Melkam variety, while the DTF will decrease by 5.8% in 2050s and by 15.4% in 2080s for Teshale. The changes in DTM will be 1.5% and -4.7% respectively in 2050s and 2080s for Melkam, and 2.4% and -6.7% for Teshale. However, under the same scenario, APSIM-sorghum projected decreases in DTF for both Melkam (-6.7%) and Teshale (-8.9) in 2050s, and a decrease of this crop parameter in 2080s for the two varieties (-11.6% for Melkam and -17.2 for Teshale). A decrease in DTM is expected for the two sorghum varieties in the future, with -4.3% and -10.8%, respectively for Melkam and Teshale in 2050s; and -9.4% and -12.3% by 2080s (Figure 2).

Under SSP5-8.5 scenario, CERES-sorghum projected the DTF and DTM to decrease in 2050s and decrease in 2080s for the two varieties, at the range of -11.1% to -21.4% for DTF and -8.5% to -14.6% for DTM depending on variety. For APSIM-sorghum, the DTF and DTM will decrease in both 2050s and 2080s periods and for the two sorghum varieties under SSP2-4.5 and SSP5-8.5 scenarios. Melkam variety will record decreases in DTF and DTM by 6.7% and -4.3% in 2050s and 11.6% and 9.4% in 2080s under SSP2-4.5, while the decreases will reach 9.3% and 13.1% by 2050s and 18.1% and 14.4% by 2080s under SSP5-8.5, respectively. For Teshale variety, the DTF and DTM will decrease by 8.9% and 10.8% in 2050s and by 17.2% and 12.3% in 2080s under SSP2-4.5, while the two crop parameters will decrease by 17.2% and 12% in 2050s and by 24.1% and 17.4% in 2080s under SSP5-8.5 scenario (Figure 2).

In contrast to the days to flowering and maturity, the projected yields are expected to increase for both Melkam and Teshale variety in 2050s and 2080s under both SSP2-4.5 and SSP5-8.5 scenarios, and Melkam variety will perform well as compared to Teshale variety. Using CERES-sorghum model, the yield of Melkam variety is expected to increase by 37.3% in 2050s and by 29.8% in 2080s, while the increment will be 24.5% in 2050s and 27.2% in 2080s for Teshale under SSP2-4.5 scenario. Under SSP5-8.5 scenario, the yield of Melkam variety will increase by 41.8% in 2050s and by 44.4% in 2080s, while Teshale variety will record the yield increment of 31.3% by 2050s and 24.8% by 2080s. Similarly, Melkam variety presented high projected yields as compared to Teshale variety using APSIM-sorghum model. Under SSP2-4.5, the yield of Melkam variety is expected to increase by 34.8% in 2050s and 33.3% in 2080s, while the increment of 20.1 % and 24.1% will be observed for Teshale in 2050s and 2080s, respectively. Under SSP5-8.5, Melkam will record increases in yield by 36.6% in 2050s and 42.5% in 2080s, while the yield of Teshale will increase by 27.3% in 2050s and 25.3% in 2080s (Figure 2).

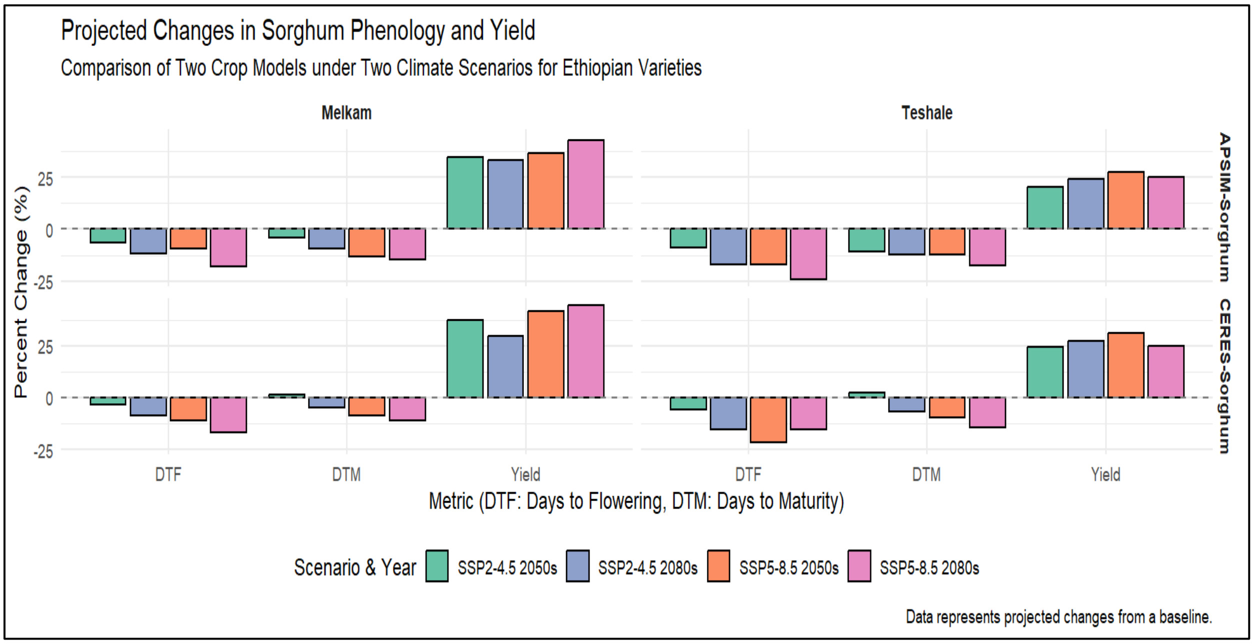

Figure 2. Change (in %) in days to flowering (DTF), days to maturity (DTM) and yield for Melkam and Teshale sorghum varieties under SSP2-4.5 and SSP5-8.5 in 2050s and 2080s compared to the base period yield in Fedis.

3.3. Adaptation strategies

Planting date adjustment

Different planting windows were utilized to simulate and anticipate the yield of sorghum varieties (Melkam and Teshale) under future projected climate of Fedis district. The results revealed that early planting date (10-June) may be benefic for both Melkam and Teshale varieties by 2050s and 2080s under both SSP2-4.5 and SSP5-8.5 scenarios (Table 10). Due to this planting date, Melkam variety is expected to increase its grain yield by 53.6% and 46.2% respectively under SSP2-4.5 and SSP5-8.5 scenarios in 2050s, while Teshale may record an increment of 47.6% under SSP2-4.5 and 44.2% under SSP5-8.5 during the same period (2050s). By the end of the century (2080s), the grain yield of the different sorghum varieties may also increase due to early planting date, 38.7% under SSP2-4.5 and 26.3% under SSP5-8.5 for Melkam and 36.1% under SSP2-4.5 and 30.6% under SSP5-8.5 for Teshale. Using the normal planting date (20-June), the grain yield of the two varieties will also increase under all the climate scenarios and future periods, but will be low as compared to the changes provided by the early planting date. The late (02-July) and very late (12-July) planting dates will not be favorable for sorghum production in Fedis. These planting date may negatively affect the grain yield and the decline of the yield will be at the range of -15.3% to -41.3%, depending on the period, the climate scenario, and the variety (Table 10).

Table 10. Simulated yield change (%) for sorghum varieties under different planting windows.

Varieties	Baseline yield (kg/ha)	Planting windows	SSP2-4.5		SSP5-8.5	
			2050s	2080s	2050s	2080s
Melkam	3901.3	10-June early	+53.6	+38.7	+46.2	+26.3
		20-June normal	+26.5	+17.6	+21.5	+13,3
		02-July late	+10.3	-6.3	-13.2	-17.1
		12-July very late	-15.3	-24.7	-16.2	-41.8
Teshale	4352.26	10-June early	+47.6	+36.1	+44.2	+30.6
		20-June normal	+21.1	+14.4	+19.3	+14.9
		02-July late	+2.6	-11.2	+8.6	-28.6
		12-July very late	-26.3	-36.5	-28.3	-41.3

Planting density

Table 11 presents the projected changes in grain yield for Melkam and Teshale sorghum varieties relative to the baseline under different planting densities for the 2050s and 2080s, considering SSP2-4.5 and SSP5-8.5 climate scenarios. The results revealed that the density of 9 plants m^{-2} is expected to increase yields in both the 2050s and 2080s under SSP2-4.5 and SSP5-8.5 scenarios. The years 2050s might experience high changes in grain yield for both Melkam and Teshale varieties, respectively +52.3% and +33.4% under SSP2-4.5 and +41.5% and +28.3% under SSP5-8.5 due to the use of this planting density. During the end of century (2080s), the yield will also increase by 34.7% for Melkam and by 31.6% for Teshale under SSP2-4.5, while Melkam will increase by 36.6% and Teshale by 25.1% under SSP5-8.5 as a result of the density of 9 plants m^{-2}. The density of 11 plants m^{-2} is also expected to increase the yield of both Melkam and Teshale varieties in 2050s under SSP2-4.5, but the yield of the two varieties will decrease in 2080s and under SSP5-8.5 by 2050s and 2080s. However, the yield increment for this planting density by 2050s under SSP2-4.5 will be less than that of the density of 9 plants m^{-2}, meaning that there is not yield benefits from the use of the density of 11 plants m^{-2} (Table 11). Regarding the density of 7 plants m^{-2}, the projected yield is similar to that of figure 2 since this is the baseline in the region and this density was used for calibration and validation.

Table 11. Simulated yield change (%) for both sorghum varieties under different planting density.

Varieties	Baseline yield (kg/ha)	Planting density (plant m-2)	SSP2-4.5		SSP5-8.5	
			2050s	2080s	2050s	2080s
Melkam	3901.3	7	+36.1	+31.5	+39.2	+43.2
		9	+52.3	+34.7	+41.5	+36.6
		11	+9.4	-5.7	+2.3	-14.2
Teshale	4352.26	7	+22.3	+25.7	+29.3	+25.1
		9	+33.4	+31.6	+28.3	+29.5
		11	+6.2	-8.7	-10.5	-15.3

4. Discussion

4.1. Crop models calibration and validation

The crop models were calibrated and validated using the same data. Overall, both the APSIM-sorghum and CERES-sorghum models showed good performance in simulating the anthesis day, days to maturity and grain yield of sorghum in climate conditions of Fedis district. Anthesis day of the sorghum varieties studied was successfully simulated by the two crop models. The adjustments were made to obtain improved agreement between simulated and observed-values, d-stat > 0.75 for the two crop models and for both Melkam and Teshale varieties. The results showed that the model calibration datasets were consistent with the model evaluation datasets and the two models overestimated the anthesis day of sorghum. Good relationships were obtained between the simulated and observed anthesis day values (Figure 3). This indicated that both APSIM-sorghum and CERES-sorghum can be used to simulate the days to flowering of different sorghum varieties in the study area (Chisanga *et al*., 2021). For the maturity day, the CERES-sorghum model evaluation indices were better than those presented by APSIM-sorghum model for all varieties, with a low nRMSE value, high d-stat and R^2 values. CERES-sorghum can be used to simulate the maturity day with improved accuracy in Fedis than APSIM-sorghum model. Research has proven the performance of DSSAT-CERES in simulating the phenology of crops (Chisanga *et al*., 2021; Feleke *et al*., 2021; Liu *et al*., 2011; Shawon *et al*., 2025).

The findings from tables 6 and 7 revealed that the simulated grain yield agreed well with the observed data for the two sorghum varieties, d-stat equal to 0.81 and 0.77 for Melkam and Teshale varieties, respectively using CERES-sorghum; and 0.81 for Melkam and 0.78 for Teshale using APSIM-sorghum model. Additionally, both APSIM-sorghum and CERES-sorghum models underestimated sorghum yield (Figure 3). The model evaluation indices RMSE, d-stat and R^2 confirmed the good accuracy of DSSAT-CERES and APSIM models in simulating yield at semi-arid zones like Fedis. This result is partially in agreement with the findings of Feleke *et al*. (2021) who reported that only APSIM can underestimate the yield of cereal crops. The result is also similar to the finding of Berghuijs *et al.* (2021) who revealed that APSIM can overestimate the yield of certain crops and underestimate the yield of cereal crops like wheat.

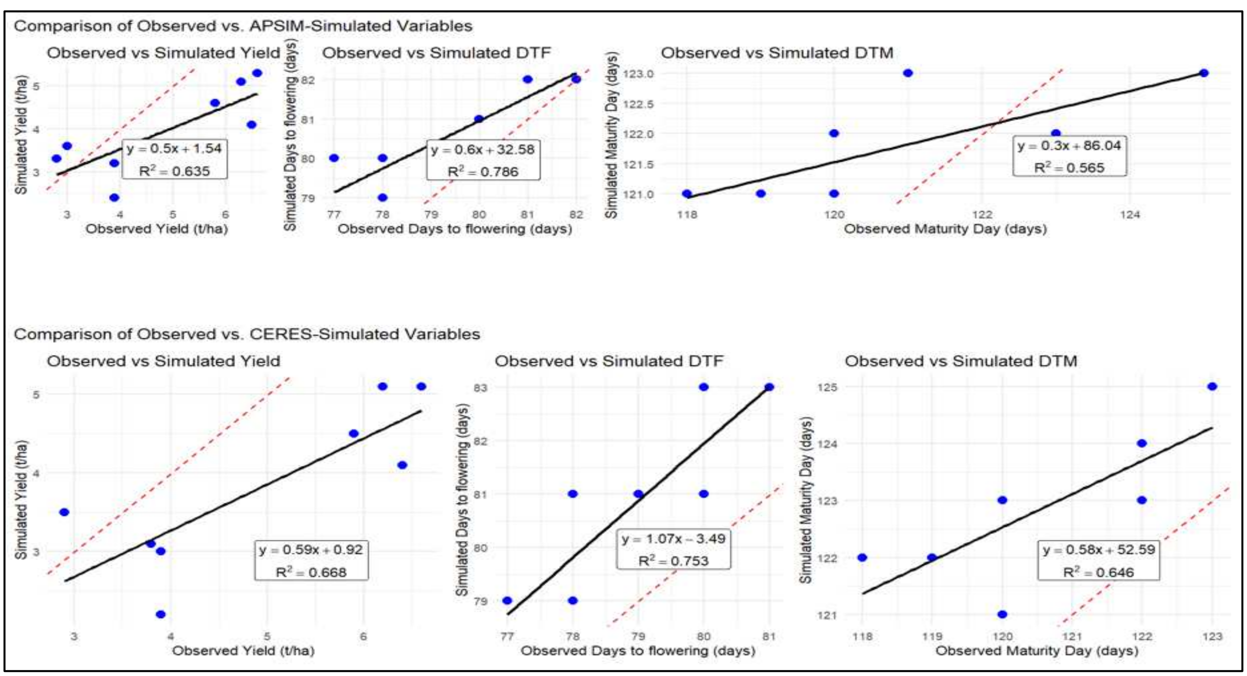

Figure 3. Comparison of observed and simulated crop variables from APSIM and DSSAT outcomes.

4.2. Future climate projection and impact assessment

According to our findings, the annual rainfall of Fedis district is expected to increase at the range of 11.4 to 28.86%, as compared to baseline (1992 to 2022) under both SSP2-4.5 and SSP5-8.5 scenarios in 2050s and 2080s. Regarding the seasonal rainfall, a significant increment may occur during the JJAS season at the range of 12.35 to 29.75%. These results are higher than the findings of Kebede *et al*. (2026) who reported that the annual rainfall is expected to increase by 7.77% and 13.74% under the SSP2-4.5 scenario and by 14.02% and 28.48% under the SSP5- 8.5 scenario for the 2040s and 2080s, respectively in northern Ethiopia. Similarly, Yisehak *et al*. (2021) reported that the rainfall is projected to increase at the range of 3.5 to 13.4 % over the semi-arid zones of Ethiopia under RCP 4.5 and RCP 8.5 scenarios. Fedis district may receive more rainfall than other semi-arid zones of the country by the mid and end of the century. However, the IPCC report of 2020 projected the rainfall of East African to increase by 20-30% the end of the century. Additionally, Gebrechorkos *et al*. (2023) reported that the annual rainfall is expected to increase by above 30% in East African countries, including Ethiopia; with hydrological extremes like floods. This rise in rainfall may profit the rain-fed agriculture and cereal crops like sorghum in Fedis, but some reductions in agricultural production are expected to appear due to hydrological extremes (Abdisa *et al*., 2022).

The results of the present study projected a high increase in both minimum and maximum temperature (2.28°C-5.26°C) by the mid and end of the century under SSP2-4.5 and SSP5-8.5 climate scenarios. These findings are almost similar to those of Kebede *et al*. (2026) who reported that Amhara region will record an increase in temperature at the range of 0.92°C to 4.48°C under the same climate scenarios and periods. These shifts in temperature may intensify extreme weather events, posing risks to agriculture. Therefore, there is a need of implementing adaptation strategies to mitigate potential impacts and enhance climate resilience in the district (Malhi *et al.*, 2021).

The impact assessment demonstrated low decreases in projected days to flowering and maturity of sorghum varieties (Melkam and Teshale) in Fedis district, while the grain yield is projected to increase to the range of 20.1 to 44.4%, depending on the crop model and variety. Unlike our results, researchers have predicted the decline of sorghum yield in Ethiopia due to climate change. For instance, Mohammed and Misganaw (2022) reported that sorghum yield might decrease by 2030s and 2050s under both RCP 4.5 and RCP 8.5 scenarios in Amhara region. In north Wollo, Hayelom and Kritika (2026) projected sorghum yield to reduce by 15-16% in mid-century and by 17-22% in late-century. Additionally, Tolosa *et al*. (2023) reported a decline in projected sorghum yield during the near term of the 21st century in Babile district, Eastern Ethiopia. According to these studies, the main causes of this decrease in sorghum yield include declining and disturbed rainfall, increases in minimum and maximum temperatures, and increase in evapotranspiration. In the context of our study, both rainfall and temperature are expected to increase. The increases in temperature and evapotranspiration will be compensated by increase in rainfall, which will increase the grain yield. Moreover, Stuch *et al*. (2021) revealed that the mean yields of tropical cereals will be more robust to climate change, apart from maize. This also support our findings and shows that sorghum can tolerate and produce under climate stress.

4.3. Adaptation options

According to our findings, early planting may ameliorate sorghum yield in future projected climate, especially in 2050s, and under both SSP2-4.5 and SSP5-8.5 scenarios. The reason behind this increment is the early start of rain in the future for JJAS season and the use of medium maturity varieties, Melkam and Teshale. Similar results have been reported by Hayelom and Kritika (2026) in north Wollo. They realized that due to early planting the sorghum yield was on average 3% and maximum up to 20% in 2050s as compared to the baseline. They also reported that late planting and longer maturity sorghum varieties may not provide yield benefits in the future periods. Early planting has many advantages, including reducing risks of terminal droughts, extending the growing seasons, and increasing rotation options (Morris *et al*., 2021).

Planting density adjustment showed a significant and positive effect on the yield of both Melkam and Teshale varieties across all scenarios and time periods. The density of 9 plants m^{-2} provided the highest and positive changes in yield, and unlike Teshale variety, Melkam will record the greatest increases in grain yield after adjusting the planting density. This result confirms the statement of Motsi *et al*. (2022) who reported that sorghum can still be high yielding at high plant densities under climatic stress in Sub-saharan Africa. Sorghum is a climate-resilient crop that is less sensitive to climate change vulnerabilities (Chadalavada *et al*., 2021).

5. Conclusion

Globally, agricultural production is negatively affected by climate change and variability, particularly in developing countries like Ethiopia, with more emphasize on the rainfed agriculture system. In Ethiopia, the productivity of major crops, including cereal crops is declining due to changes in climate patterns. This study simulated the impact of climate change on sorghum (*Sorghum bicolor* L.) yield in Fedis district, a semi-arid and agricultural zone located in Easter Ethiopia. Therefore, DSSAT-CERES and APSIM crop models were calibrated and validated to simulate sorghum yield, the impact of projected climate on sorghum yield was assessed, and the effectiveness of planting date adjustment and different planting densities was evaluated as adaptive strategies to anticipate sorghum yield in Fedis.

Observed climate data were obtained from the Ethiopian Meteorological Institute (EMI) for the period 1992-2022. For future climate, the Coupled Model Intercomparison Project Phase 6 (CMIP6) datasets of five GCMs were used under medium emission (SSP2-4.5) and high emission (SSP5-8.5) scenarios. Empirical Quantile Mapping (EQM) approach was used for future climate downscaling and bias correction. Crop data and soil samples were obtained from the Oromia Agricultural Research Institute site located at Fedis. CERES-sorghum model embedded in DSSAT and APSIM-sorghum were used to assess impacts of climate change on sorghum yield, while different planting dates and planting densities were evaluated as adaptation strategies to enhance sorghum yield in the district.

The crop models, calibrated and validated with field data for Melkam and Teshale varieties, demonstrated good performance in simulating the days to flowering, days to maturity and grain yield of sorghum in climate conditions of Fedis district. High coefficients of agreement between observed and simulated data (d-stat >0.66) for both Melkam and Teshale varieties were revealed by the two crop models for all the crop parameters. Similarly, the models presented R^2 values >0.6, except APSIM which simulated the days to maturity with R^2 value <0.6. Excellent performance of the crops models was shown for days to flowering and maturity (nRMSE <10%); while for the grain yield the nRMSE was between 10 and 20%, meaning a good performance.

The projected yields for Melkam and Teshale varieties are expected to increase in the 2050s and 2080s under both SSP2-4.5 and SSP5-8.5 scenarios, with Melkam demonstrating superior performance. Specifically, using CERES-sorghum model, the grain yield of Melkam variety is expected to rise by 37.3% in the 2050s and 29.8% in the 2080s, while Teshale will experience an increase by 24.5% and 27.2% respectively. Under SSP5-8.5, Melkam's yield is projected to increase by 41.8% in the 2050s and 44.4% in the 2080s, in contrast to Teshale which will record 31.3% and 24.8% increases. Similarly, the APSIM-sorghum model forecasted the yield of Melkam variety to rise by 34.8% in the 2050s and 33.3% in the 2080s under SSP2-4.5, compared to Teshale with 20.1% and 24.1% increases. Under SSP5-8.5, Melkam will record increases of 36.6% in 2050s and 42.5% in 2080s, while the yields of Teshale will rise by 27.3% and 25.3% in the respective periods.

Moreover, early planting date (10-June) and increased plants density (9 plants m^{-2}) may increase the sorghum yield in the district. Early planting will reduce the risk of terminal droughts and extending the growing seasons, while the density of 9 plants m^{-2} will allows to optimize the filed surface for better yield. Therefore, future studies should focus on testing other adaptation strategies, including fertilizer rates and climate smart agriculture practices for future sorghum production in Fedis district. Additionally, we recommend the use various climate and crop models to assess the impact on climate change on sorghum in order to formulate sustainable adaptive options.

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Data availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors assert the absence of any conflict of interest.

Clinical trial

Not applicable.

Ethics, Consent to Participate, and Consent to Publish declarations

Not applicable.

References

Abdisa, T. B., Diga, G. M., & Tolessa, A. R. (2022). Impact of climate variability on rain-fed maize and sorghum yield among smallholder farmers Impact of climate variability on rain-fed maize and sorghum yield among smallholder farmers. *Cogent Food & Agriculture*, *8*(1), 1–16. https://doi.org/10.1080/23311932.2022.2057656

Al-Shammary, A. A. G., Kouzani, A. Z., Kaynak, A., Khoo, S. Y., Norton, M., & Gates, W. (2018). Soil bulk density estimation methods: A review. *Pedosphere*, *28*(4), 581–596.

Alimagham, S., van Loon, M. P., Ramirez-Villegas, J., Adjei-Nsiah, S., Baijukya, F., Bala, A., Chikowo, R., Silva, J. V., Soulé, A. M., Taulya, G., Tenorio, F. A., Tesfaye, K., & van Ittersum, M. K. (2024). Climate change impact and adaptation of rainfed cereal crops in sub-Saharan Africa. *European Journal of Agronomy*, *155*(June 2023). https://doi.org/10.1016/j.eja.2024.127137

Amelework, B. A., Shimelis, H. A., Tongoona, P., Mengistu, F., Laing, M. D., & Ayele, D. G. (2016). Sorghum production systems and constraints, and coping strategies under drought-prone agro-ecologies of Ethiopia. *South African Journal of Plant and Soil*, *33*(3), 207–217. https://doi.org/10.1080/02571862.2016.1143043

Anega, D. (2024). Sorghum Production in Ethiopia: An Overview of Advances, Successes, and Challenges. *International Journal of Food Science and Biotechnology*, *9*(4), 107–113. https://doi.org/10.11648/j.ijfsb.20240904.15

Asefa Bogale, G. (2023). Analysis the characterization of climate change and its impacts on smallholder farmers in Eastern Ethiopia. *Heliyon*, *9*(10), e20293. https://doi.org/10.1016/j.heliyon.2023.e20293

Asfew, M., & Bedemo, A. (2022). Impact of Climate Change on Cereal Crops Production in Ethiopia. *Advances in Agriculture*, *2022*. https://doi.org/10.1155/2022/2208694

Assefa, K., Geremu, T., & Duguma, M. S. (2021). *2021 Oromia Agricultural Research Instit Regional Review Workshop on Completed Research Activities Proceedings of Review Workshop on Completed Research Activities of Natural Resource Research Directorate Held at Batu Fishery and Other Aquatic Life Researc*. *December 2020*.

Aweke, C. S., & Lahiff, E. (2020). The contribution of agriculture to household dietary diversity : evidence from smallholders in East Hararghe , Ethiopia. *Food Security*, *12*, 625–636. https://doi.org/https://doi.org/10.1007/s12571-020-01027-w

Baker, D. E., Rayment, G. E., & Reid, R. E. (1983). Predictive relationships between pH and sodicity in soils of tropical Queensland. *Communications in Soil Science and Plant Analysis*, *14*(11), 1063–1073.

Bekuma Abdisa, T., Mamo Diga, G., & Regassa Tolessa, A. (2022). Impact of climate variability on rain-fed maize and sorghum yield among smallholder farmers. *Cogent Food and Agriculture*, *8*(1). https://doi.org/10.1080/23311932.2022.2057656

Belay, A., Demissie, T., Recha, J. W., Oludhe, C., Osano, P. M., Olaka, L. A., Solomon, D., & Berhane, Z. (2021). Analysis of climate variability and trends in Southern Ethiopia. *Climate*, *9*(6), 1–17. https://doi.org/10.3390/cli9060096

Berghuijs, H. N. C., Weih, M., Werf, W. Van Der, Karley, A. J., Kiær, L. P., Newton, A. C., Adam, E., Scherber, C., Tavoletti, S., & Vico, G. (2021). *Field Crops Research Calibrating and testing APSIM for wheat-faba bean pure cultures and intercrops across Europe*. *264*(February). https://doi.org/10.1016/j.fcr.2021.108088

Cao, H. X., Hanan, J. S., Liu, Y., Liu, Y. X., Yue, Y. Bin, Zhu, D. W., Lu, J. F., Sun, J. Y., Shi, C. L., Ge, D. K., Wei, X. F., Yao, A. Q., Tian, P. P., & Bao, T. L. (2012). Comparison of Crop Model Validation Methods. *Journal of Integrative Agriculture*, *11*(8), 1274–1285. https://doi.org/10.1016/S2095-

3119(12)60124-5

Chadalavada, K., Kumari, B. D. R., & Kumar, T. S. (2021). Sorghum mitigates climate variability and change on crop yield and quality. *Planta*, *253*(5), 1–19. https://doi.org/10.1007/s00425-021-03631-2

Chekole, Y., Moges, G., & Moges, S. (2024). Heliyon Implementation and application of APSIM for crop modelling in Ethiopia : A comprehensive review. *Heliyon*, *10*(10), e31612. https://doi.org/10.1016/j.heliyon.2024.e31612

Chisanga, C. B., Phiri, E., & Chinene, V. R. N. (2021). Evaluating APSIM-and-DSSAT-CERES-Maize Models under Rainfed Conditions Using Zambian Rainfed Maize Cultivars. *Nitrogen (Switzerland)*, *2*(4), 392–414. https://doi.org/10.3390/nitrogen2040027

Day, P. R. (1965). Particle Fractionation and Particle-Size Analysis. *In Methods of Soil Analysis, C.A. Black (Ed.)*. https://doi.org/10.2134/agronmonogr9.1.c43

Degebasa, L., Tessema, T., Bekeko, Z., & Belete, K. (2022). Prevalence and Socioeconomic Impact of Striga (Striga hermonthica) in Sorghum Producing Areas of East and West Hararghe Zones, Oromia, Ethiopia. *International Journal of Agronomy*, *2022*. https://doi.org/10.1155/2022/8402280

Degife, A. W., Zabel, F., & Mauser, W. (2021). Climate change impacts on potential maize yields in Gambella Region, Ethiopia. *Regional Environmental Change*, *21*(2). https://doi.org/10.1007/s10113-021-01773-3

Dubache, G., Ogwang, B. A., Ongoma, V., & Towfiqul Islam, A. R. M. (2019). The effect of Indian Ocean on Ethiopian seasonal rainfall. *Meteorology and Atmospheric Physics*, *131*(6), 1753–1761. https://doi.org/10.1007/s00703-019-00667-8

Etana, D., Snelder, D. J. R. M., van Wesenbeeck, C. F. A., & Buning, T. de C. (2020). Trends of climate change and variability in three agro-ecological settings in central Ethiopia: Contrasts of meteorological data and farmers' perceptions. *Climate*, *8*(11), 1–27. https://doi.org/10.3390/cli8110121

Farooq, A., Farooq, N., Akbar, H., Hassan, Z. U., & Gheewala, S. H. (2023). *A Critical Review of Climate Change Impact at a Global Scale on Cereal Crop Production*. 1–19.

Feleke, H. G., Savage, M. J., & Tesfaye, K. (2021). *Calibration and validation of APSIM – Maize , DSSAT CERES – Maize and AquaCrop models for Ethiopian tropical environments Calibration and validation of APSIM – Maize , DSSAT CERES – Maize and AquaCrop models for Ethiopian tropical environments*. *1862*. https://doi.org/10.1080/02571862.2020.1837271

Gardi, M. W., Zewdu, E., & Sida, T. S. (2025). Modeling sorghum yield response to climate change in the semi-arid environment of Ethiopia. *Journal of Agriculture and Food Research*, *22*(June), 102143. https://doi.org/10.1016/j.jafr.2025.102143

Gavasso-Rita, Y. L., Papalexiou, S. M., Li, Y., Elshorbagy, A., Li, Z., & Schuster-Wallace, C. (2024). Crop models and their use in assessing crop production and food security: A review. *Food and Energy Security*, *13*(1). https://doi.org/10.1002/fes3.503

Gebrechorkos, S. H., Taye, M. T., Birhanu, B., Solomon, D., & Demissie, T. (2023). Future Changes in Climate and Hydroclimate Extremes in East Africa Earth ' s Future. *Earth's Future*, 1–21. https://doi.org/10.1029/2022EF003011

Gebresamuel, G., Abrha, H., Hagos, H., Elias, E., & Haile, M. (2022). Empirical modeling of the impact of climate change on altitudinal shift of major cereal crops in South Tigray, Northern Ethiopia. *Journal of Crop Improvement*, *36*(2), 169–192. https://doi.org/10.1080/15427528.2021.1931608

Gleixner, S., Keenlyside, N., Viste, E., & Korecha, D. (2017). The El Niño effect on Ethiopian summer rainfall. *Climate Dynamics*, *49*(5–6), 1865–1883. https://doi.org/10.1007/s00382-016-3421-z

Gunawat, A., Sharma, D., Sharma, A., & Dubey, S. K. (2022). Assessment of climate change impact and potential adaptation measures on wheat yield using the DSSAT model in the semi-arid environment. *Natural Hazards*, *111*(2), 2077–2096. https://doi.org/10.1007/s11069-021-05130-9

Hailu, H., & Geremu, T. (2021). Effect of Sorghum-Legume Intercropping Patterns on Selected Soil Chemical Properties and Yield of Sorghum at Midland Areas of West Hararghe Zone of Oromia Regional State, Eastern Ethiopia. *Irrigation and Drainage Systems Engineering* , *10*(5), 1–8. https://www.researchgate.net/publication/352211063

Hayelom, K., & Kritika, A. (2026). Assessing future climate change impacts and adaptation strategies for sorghum yield in North Wollo , Ethiopia. *Theoretical and Applied Climatology*, *1*, 1–24.

Hendershot, W. H., Lalande, H., & Duquette, M. (1993). Ion exchange and exchangeable cations. *Soil Sampling and Methods of Analysis*, *19*, 167–176.

Jackson, M. L. (1973). Soil chemical analysis, pentice hall of India Pvt. *Ltd., New Delhi, India*, *498*, 151–154.

Janová, J. (2012). Crop planning optimization model: The validation and verification processes. *Central European Journal of Operations Research*, *20*(3), 451–462. https://doi.org/10.1007/s10100-011-0205-8

Jiang, R., He, W., He, L., Yang, J. Y., Qian, B., Zhou, W., & He, P. (2021). Modelling adaptation strategies to reduce adverse impacts of climate change on maize cropping system in Northeast China. *Scientific Reports*, *11*(1), 1–13. https://doi.org/10.1038/s41598-020-79988-3

Kebede, M. H., & Legesse, S. A. (2026). Projections of Precipitation and Temperature Changes and Trends Using CMIP6 Global Climate Models in the Eastern. *Meteorological Applications*, *33*(e70145), 1–24. https://doi.org/10.1002/met.70145

Kloss, S., Pushpalatha, R., Kamoyo, K. J., & Schütze, N. (2012). *Evaluation of Crop Models for Simulating and Optimizing Deficit Irrigation Systems in Arid and Semi-arid Countries Under Climate Variability*. 997–1014. https://doi.org/10.1007/s11269-011-9906-y

Legates, D. R., & McCabe, G. J. (1999). Evaluating the use of "goodness-of-fit" measures in hydrologic and hydroclimatic model validation. *Water Resources Research*, *35*(1), 233–241. https://doi.org/10.1029/1998WR900018

Liu, H. L., Yang, J. Y., Drury, C. F., Reynolds, W. D., Tan, C. S., Bai, Y. L., He, P., Jin, J., & Hoogenboom, G. (2011). Using the DSSAT-CERES-Maize model to simulate crop yield and nitrogen cycling in fields under long-term continuous maize production. *Nutrient Cycling in Agroecosystems*, *89*(3), 313–328. https://doi.org/10.1007/s10705-010-9396-y

Lobell, D. B., Sibley, A., & Ivan Ortiz-Monasterio, J. (2012). Extreme heat effects on wheat senescence in India. *Nature Climate Change*, *2*(3), 186–189. https://doi.org/10.1038/nclimate1356

Malhi, G. S., & Kaur, M. (2021). Impact of Climate Change on Agriculture and Its Mitigation Strategies : A Review. *Sustainability*, 1–21.

Mann, M. L., Warner, J. M., & Malik, A. S. (2019). Predicting high-magnitude, low-frequency crop losses using machine learning: an application to cereal crops in Ethiopia. *Climatic Change*, *154*(1–2), 211–227. https://doi.org/10.1007/s10584-019-02432-7

Mohammed, A., & Misganaw, A. (2022). Modeling future climate change impacts on sorghum (Sorghum bicolor) production with best management options in Amhara Region, Ethiopia. *CABI Agriculture and Bioscience*, *3*(1), 1–17. https://doi.org/10.1186/s43170-022-00092-9

Morris, G. P., Sexton-bowser, S., & Ciampitti, I. A. (2021). Crop modeling defines opportunities and challenges for drought escape , water capture , and yield increase using chilling-tolerant sorghum.

Frontiers in Plant Science, *August*, 1–16. https://doi.org/10.1002/pld3.349

Motsi, H., Molapo, M., & Phiri, E. E. (2022). South African Journal of Botany A review on sweet sorghum adaptive capacity on improving food security and poverty alleviation in sub-Saharan Africa. *South African Journal of Botany*, *150*, 323–329. https://doi.org/10.1016/j.sajb.2022.07.040

Muluken Bayable and Alemayehu Assefa (eds.). (2024). Proceeding of the 15th Annual Regional Conference on Completed Crop Research Activities, 21-23 October 2022*, Amhara Agricultural Research Institute, Bahir Dar, Ethiopia*. *October 2022*, 21–23.

Nelson, D. W., & Sommers, L. E. (1996). Total carbon, organic carbon, and organic matter. *Methods of Soil Analysis: Part 3 Chemical Methods*, *5*, 961–1010.

Nelson, G., Bogard, J., Lividini, K., Arsenault, J., Riley, M., Sulser, T. B., Mason-D'Croz, D., Power, B., Gustafson, D., Herrero, M., Wiebe, K., Cooper, K., Remans, R., & Rosegrant, M. (2018). Income growth and climate change effects on global nutrition security to mid-century. *Nature Sustainability*, *1*(12), 773–781. https://doi.org/10.1038/s41893-018-0192-z

Pansu, M., & Gautheyrou, J. (2006). Chapter 26: Cation Exchange Capacity. In *Handbook of Soil Analysis: Mineralogical, Organic and Inorganic Methods.* http://dx.doi.org/10.1007/978-3-540-31211-6_26

Richetti, J., Lawes, R. A., Whan, A., Gaydon, D. S., & Thorburn, P. J. (2024). How well does APSIM NextGen simulate wheat yields across Australia using gridded input data ? Validating Continental-Scale Crop Model Simulations. *European Journal of Agronomy*, *158*(March), 127212. https://doi.org/10.1016/j.eja.2024.127212

Savary, S., Ficke, A., & Hollier, C. A. (2025). Impacts of global change on crop production and food security. *Global Environmental Change*, 379–387. https://doi.org/10.1007/978-94-007-5784-4_8

Schüller, H. (1969). Die CAL-Methode, eine neue Methode zur Bestimmung des pflanzenverfügbaren Phosphates in Böden. *Zeitschrift Für Pflanzenernährung Und Bodenkunde*, *123*(1), 48–63.

Serur, A. B., & Kebira, H. M. (2025). Drought risk assessment and mapping under changing climate: the East Hararge Zone in Ethiopia. In *Journal of Water and Climate Change* (Vol. 16, Issue 5). https://doi.org/10.2166/wcc.2025.602

Shawon, A. R., Attia, A., Ko, J., Memic, E., Uptmoor, R., Hackauf, B., & Feike, T. (2025). Impact of calibration strategy and data on wheat simulation with the DSSAT-Nwheat model. *Agronomy Journal*, *117*(4), 1–26. https://doi.org/10.1002/agj2.70111

Shawul, A. A., & Chakma, S. (2020). Trend of extreme precipitation indices and analysis of long-term climate variability in the Upper Awash basin, Ethiopia. *Theoretical and Applied Climatology*, *140*(1–2), 635–652. https://doi.org/10.1007/s00704-020-03112-8

Sime, C. H., & Demissie, T. A. (2022). Assessment and prediction of the climate change impact on crop yield, in Jimma Zone Upper Gilgel Gibe Districts, Ethiopia. *Arabian Journal of Geosciences*, *15*(3). https://doi.org/10.1007/s12517-022-09605-2

Stuch, B., Alcamo, J., & Schaldach, R. (2021). Projected climate change impacts on mean and year-to-year variability of yield of key smallholder crops in Sub-Saharan Africa. *Climate and Development*, *5529*. https://doi.org/10.1080/17565529.2020.1760771

Summer, M. E., Miller, W. P., & Sparks, D. L. (1996). *Methods of Soil Analysis: Part 3-Chemical Methods, Chapter 40*.

Temesgen, B., & Hailu, G. (2021). Evaluation and participatory variety selection of improved highland sorghum varieties for smallholder farm at west hararghe zone. *International Journal of Agricultural Science and Food Technology*, *January*, 374–380. https://doi.org/10.17352/2455-815x.000135

Tirfessa, A., Getachew, F., McLean, G., van Oosterom, E., Jordan, D., & Hammer, G. (2023). Modeling adaptation of sorghum in Ethiopia with APSIM—opportunities with G×E×M. *Agronomy for Sustainable Development*, *43*(1). https://doi.org/10.1007/s13593-023-00869-w

Tolosa, A. A., Dadi, D. K., Mirkena, L. W., Erena, Z. B., & Liban, F. M. (2023). Impacts of Climate Variability and Change on Sorghum Crop Yield in the Babile District of Eastern Ethiopia. *Climate*, *11*(5). https://doi.org/10.3390/cli11050099

Tolossa, A. A., Dadi, D. K., Mirkena, L. W., Erena, Z. B., & Liben, F. M. (2024). Impacts of climate change and variability on drought characteristics and challenges on sorghum productivity in Babile District, Eastern Ethiopia. *Journal of Water and Climate Change*, *15*(9), 4278–4292. https://doi.org/10.2166/wcc.2024.012

Wajid, A., Hussain, K., Ilyas, A., Habib-ur-Rahman, M., Shakil, Q., & Hoogenboom, G. (2021). Crop models: Important tools in decision support system to manage wheat production under vulnerable environments. *Agriculture*, *11*(11), 1166. https://doi.org/10.3390/agriculture11111166

Wang, J., Vanga, S. K., Saxena, R., Orsat, V., & Raghavan, V. (2018). Effect of climate change on the yield of cereal crops: A review. *Climate*, *6*(2). https://doi.org/10.3390/cli6020041

Watanabe, F. S., & Olsen, S. R. (1965). Test of an ascorbic acid method for determining phosphorus in water and NaHCO3 extracts from soil. *Soil Science Society of America Journal*, *29*(6), 677–678.

Winn, C. A., Archontoulis, S., & Edwards, J. (2023). *Calibration of a crop growth model in APSIM for 15 publicly available corn hybrids in North America*. *December 2021*, 511–534. https://doi.org/10.1002/csc2.20857

Worede, F., Mamo, M., Assefa, S., Gebremariam, T., & Beze, Y. (2020). Yield stability and adaptability of lowland sorghum (Sorghum bicolor (L.) Moench) in moisture-deficit areas of Northeast Ethiopia. *Cogent Food and Agriculture*, *6*(1). https://doi.org/10.1080/23311932.2020.1736865

Xing, B., & Veneman, P. L. M. (1998). Microwave digestion for analysis of metals in soil. *Communications in Soil Science and Plant Analysis*, *29*(7–8), 923–930. https://doi.org/10.1080/00103629809369996

Yen, N., Vo, N., Palacios-Lopez, A., Christiaensen, L., Kilic, T., Buehren, N., Goldstein, M., Gonzalez, P., Hagos, A., Kirkwood, D., Paskov, P., Poulin, M., Raja, C., CSA, Komikouma, A. W. N., Tnsue, G., Kaiyu, L., Thioulouse, J., Dufour, A. B., … Pavoine, S. (2023). Ethiopia Socioeconomic Panel Survey 2021/22 SURVEY REPORT. *Journal of Development and Agricultural Economics*, *67*(September), 130. http://dx.doi.org/10.1016/j.foodpol.2016.09.017

Yisehak, B., Shiferaw, H., Abrha, H., Gebremedhin, A., Hagos, H., Adhana, K., & Bezabh, T. (2021). Spatio - temporal characteristics of meteorological drought under changing climate in semi - arid region of northern Ethiopia. *Environmental Systems Research*, 10–21. https://doi.org/10.1186/s40068-021-00226-4

Zeleke, T., Beyene, F., Deressa, T., Yousuf, J., & Kebede, T. (2021). Vulnerability of smallholder farmers to climate change-induced shocks in east hararghe zone, ethiopia. *Sustainability (Switzerland)*, *13*(4), 1–19. https://doi.org/10.3390/su13042162