Optimizing Crop Management Practices for Cowpea (*Vigna Unguiculata* (L.) Under Climate Change in Tehuledere District, Eastern Amhara, Ethiopia

MSc Thesis

Abay Dessale Goshu

ABSTRACT

Climate change poses increasing risks to rainfed crop production in semi-arid regions of sub-Saharan Africa, where rising temperatures and climate variability threaten smallholder livelihoods. This study assessed climate risk to cowpea (Vigna unguiculata L. Walp) production in northeastern Ethiopia and evaluated management-based adaptation options using the DSSAT CROPGRO-Cowpea model. The model was calibrated and validated using field data and applied to simulate crop responses under historical conditions (1994–2023) and future climate scenarios (SSP2-4.5 and SSP5-8.5) for the mid-century (2050s) and late-century (2080s).

Results indicate that under the high-emission SSP5-8.5 scenario, cowpea production faces substantial climate risk due to accelerated phenological development, increased yield variability, and heightened vulnerability of rainfed systems. Although elevated atmospheric CO_2 partially enhanced biomass and yield through improved photosynthesis and water-use efficiency, CO_2 fertilization alone was insufficient to offset climate risk under extreme warming. In contrast, optimized sowing dates and supplemental irrigation during critical growth stages significantly reduced yield losses and variability across future scenarios, including SSP5-8.5.

Early sowing minimized exposure to terminal heat and moisture stress, while supplemental irrigation stabilized reproductive development and improved yield reliability. The combined application of early sowing and targeted irrigation consistently produced the lowest climate risk, outperforming reliance on physiological CO_2 effects alone.

These findings demonstrate that climate risk to cowpea production under future warming is manageable through practical, low-cost adaptation strategies. Integrating adaptive sowing calendars and small-scale irrigation into extension services and climate-smart agriculture policies can substantially enhance the resilience of cowpea-based farming systems in Ethiopia and similar semi-arid regions.

1. INTRODUCTION

Ethiopia is predominantly characterized by arid and semi-arid agro-ecological zones, covering approximately 66% of the country, where agriculture is highly vulnerable to climate variability (Ajadi et al., 2011; Dereje et al., 2012). The Tehuledere District, located in Eastern Amhara, falls under this classification. Farming systems in the region are largely mixed, with cereals as the main crops. However, soils are generally low in fertility, rainfall is erratic, and drought frequency is increasing, limiting agricultural productivity and exacerbating food insecurity. Consequently, many households rely on subsistence farming with limited alternative income sources, making them highly vulnerable to climate risks (Conway and Schipper, 2011).

Climate change, driven by increasing temperatures, changing rainfall patterns, and rising greenhouse gas concentrations, poses a major threat to global and regional food systems (Awoye et al., 2017; Kukal and Irmak, 2018; Hounnou et al., 2019). It affects crop growth and development by altering physiological and biochemical processes, reducing nutrient uptake, delaying flowering, accelerating senescence, and lowering yields (Fahad et al., 2017; Lamaoui et al., 2018; Srivastava et al., 2019). In rainfed systems, such as those in Tehuledere, climate variability is a key factor constraining food production, especially for smallholder farmers who have limited capacity to adapt (Challinor et al., 2014).

Grain legumes are vital for food security in Ethiopia, providing essential protein, minerals, and vitamins, particularly in semi-arid regions. Among these, cowpea (*Vigna unguiculata* (L.) Walp.) is widely cultivated due to its drought tolerance, adaptability to marginal soils, and ability to enhance soil fertility through biological nitrogen fixation (Alemu et al., 2016; Ravelombola et al., 2017). Cowpea contributes to rural livelihoods as a source of grain, fodder, and soil improvement, while also serving as a cover crop to suppress weeds, conserve soil moisture, and reduce erosion (Das et al., 2018; Olajide and Ilori, 2017; Cardona-Ayala et al., 2020). Its grain is nutritionally rich, containing 23–32% protein and essential amino acids, making it a key crop for addressing protein deficiency in rural communities (Carvalho et al., 2017; Gerrano et al., 2019).

Despite its potential, cowpea yields in Ethiopia remain below their genetic potential due to pests, low soil fertility, drought, poor agronomic management, and limited access to improved technologies (Belay et al., 2017; Walker et al., 2016). Improving management strategies is critical for enhancing productivity under changing climatic conditions. Simulation models, such as the Decision Support System for Agrotechnology Transfer (DSSAT) version 4.8.5, provide a powerful approach to assess crop responses to climate variability and evaluate adaptation options at the field and regional scales (Hoogenboom et al., 2017; Khaliq et al., 2007). Unlike traditional field trials, which are limited in time and scope, DSSAT allows integration of soil, climate, and management data to simulate crop growth, phenology, and yield under multiple scenarios (Boote et al., 2010).

Climate projections are widely available from global climate models (GCMs) such as the Coupled Model Intercomparison Project Phase 5 (CMIP5), which provide downscaled data for mid-century (2041–2069) and late-century (2071–2099) periods. In this study, future climate scenarios were downscaled for the study area using the MarkSim weather generator under Shared Socioeconomic Pathways (SSPs) 2–4.5 and 5–8.5 (Jones and Thornton, 2009, 2013; Hadgu et al., 2014). These scenarios allow assessment of climate-related risks to cowpea production and evaluation of adaptive management strategies such as optimized sowing dates and supplementary irrigation.

Previous studies in Ethiopia have largely focused on climate trends, with limited research addressing climate impacts on crop production and adaptation (Dereje et al., 2012; Adem et al., 2016). Where studies exist, such as for maize and chickpea, findings suggest that changes in sowing dates, cultivars, and irrigation can mitigate negative climate effects (Adem et al., 2016). However, similar analyses for cowpea, particularly in northeastern Ethiopia, remain scarce, highlighting the need for location-specific assessments that inform practical adaptation strategies.

Given the importance of cowpea as a climate-resilient crop and a critical protein source, this study aims to assess the impacts of projected climate change on its phenology, yield, and evapotranspiration in Tehuledere District. Additionally, it explores management practices, including sowing date adjustment and supplementary irrigation, to optimize production under future climate conditions. The study provides evidence-based guidance for smallholder farmers and policy makers to enhance food security and climate resilience in semi-arid Ethiopia.

1.1 Objectives

1.1.1 General Objective

- To calibrate and evaluate the CROPGRO-Cowpea model, assess the impact of climate change, and explore adaptation strategies for cowpea in Tehuledere District.

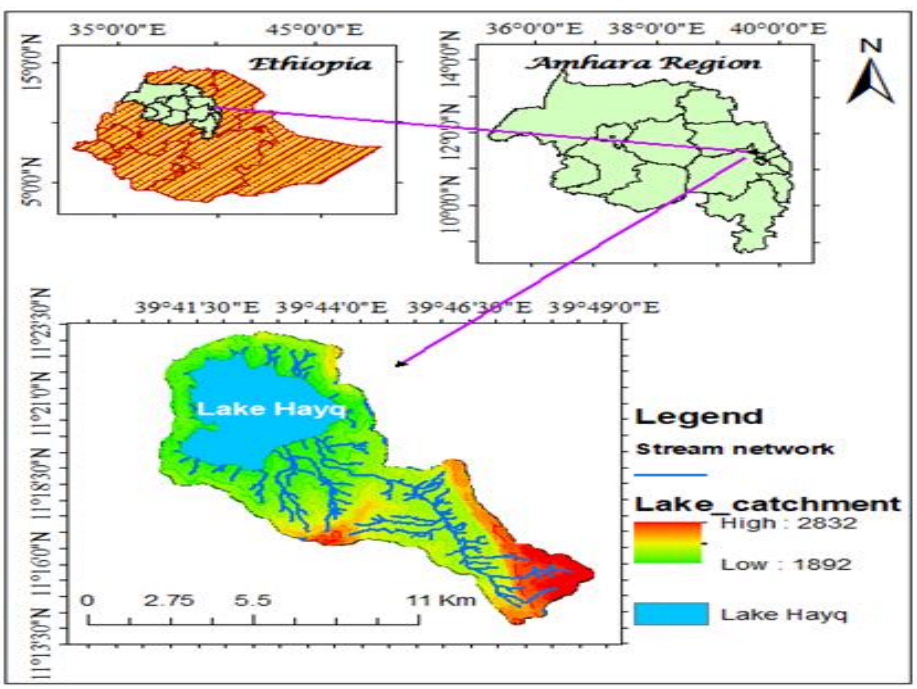
1.1.2 Specific Objectives

1. To calibrate and evaluate the CROPGRO-Cowpea model for simulating growth, phenology, and yield of cowpea.
2. To assess the impact of projected climate change on phenology, yield, and actual evapotranspiration.
3. To explore management practices, including sowing date optimization and supplementary irrigation, for sustainable cowpea production under climate change.

2. MATERIALS AND METHODS

2.1 Study Area

The study was conducted at Jari site, Tehuledere District, northeastern Ethiopia (11°45′N, 39°38′E; 1680 m above sea level), located 454 km from Addis Ababa and 33 km from Dessie city. The district falls under semi-arid agro-ecology with a bimodal rainfall pattern: the long rainy season (Kiremt) from June to September contributes ~80% of total annual rainfall, while the short rainy season (Belg) from March to May supports limited cropping. The mean annual maximum and minimum temperatures are 27.7 °C and 12.5 °C, respectively, with an annual rainfall of ~1098 mm. Moisture deficit, particularly during flowering and grain filling, is a major constraint to crop production. Soils are dominated by Vertisols, and the local farming system is mixed crop-livestock, with cereals (sorghum, teff, maize) and legumes (chickpea, mung bean, cowpea) as principal crops (Adem et al., 2016, 2017).



Figure; 1 map of study site

2.2 Field Experiment for Model Calibration and Evaluation

Field experiments were conducted during the 2022 and 2023 main cropping seasons on 10 m × 10 m plots arranged in a randomized complete block design (RCBD) with three replications. Two seeds per hill were sown and thinned to one plant 15 days after emergence. Fertilizer (20 kg N ha^{-1} as urea) was applied at sowing, and recommended agronomic practices were followed. Phenological data (days to flowering and physiological maturity) were recorded from ten randomly selected plants per plot, with flowering defined as the appearance of the first flower and physiological maturity when 75% of plants had matured. Grain yield and aboveground biomass were harvested from the central three rows, excluding border plants, and oven-dried at 80 °C for 48 h before weighing.

The CROPGRO-Cowpea model was calibrated using observed phenology, growth, and yield data under optimum conditions and evaluated with an independent dataset. Six planting dates (20 June, 1 July, 11 July, 21 July, 1 August, 10 August), supplemental irrigation (45 mm every 10 days from flowering), and their interactions were simulated to explore management scenarios.

2.3 Model Inputs

2.3.1 Crop Management Data

Crop management inputs included sowing date, sowing depth, intra- and inter-row spacing, cultivar selection, soil type, and simulation start date, obtained from field observations.

2.3.2 Soil Data

Soil samples were collected to 1.6 m depth two weeks prior to sowing. Laboratory analyses determined texture (Bouyoucos hydrometer method), pH (1:2.5 soil:water), organic carbon (Walkley-Black method), total nitrogen (Kjeldahl), available phosphorus (Olsen), and cation exchange capacity (Chapman, 1965). Soil water parameters, including drained upper limit (DUL), lower limit (LL), saturation (SAT), root growth factor (RGF), and saturated hydraulic conductivity (SKS), were estimated using DSSAT SBuild utility, based on pedotransfer functions incorporating texture, organic matter, and bulk density.

2.3.3 Weather Data

Daily maximum and minimum temperatures (°C), precipitation (mm), and solar radiation (MJ m^{-2} day^{-1}) were obtained from Kombolcha Meteorological Station (~53 km from the site). Solar radiation was estimated using the DSSAT WeatherMan utility based on recorded sunshine hours. Future climate projections were downscaled using the MarkSim GCM weather generator for mid-century (2041–2069) and late-century (2071–2099) under SSP2-4.5 and SSP5-8.5, based on CMIP5 ensemble outputs.

2.4 Data Collection

2.4.1 Phenology

Ten tagged plants per plot were monitored for emergence, flowering, and physiological maturity. Days to emergence was recorded when 50% of seedlings had emerged; days to physiological maturity when 75% of plants had matured.

2.4.2 Yield and Growth

Grain yield and aboveground biomass were harvested from the central three rows, oven-dried at 80 °C for 48 h, and weighed. Leaf area index (LAI) was calculated as:

$$\mathbf{LAI} = \frac{\mathbf{LA}}{\mathbf{A}}$$

Where:

- **LAI** = Leaf Area Index (dimensionless)
- **LA** = Total leaf area of the crop (m^2)
- **A** = Ground area occupied by the crop (m^2)

2.5 Model Calibration and Evaluation

The CROPGRO-Cowpea model was calibrated by adjusting genetic coefficients for phenology, growth, and yield using a trial-and-error approach, with each parameter modified incrementally

(~±5%) to align simulated outputs with observed data (Adem et al., 2016). Model evaluation used independent data for flowering, maturity, biomass, and grain yield. Predictive accuracy was assessed using:

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

Where

n = number of observations,

Pi = predicted value for the ith measurement and

Oi = observed value for the ith measurement.

Thus, lower value indicates good fit of the model

$$NRMSE = \frac{RMSE}{N} x\ 100$$

Where NRMSE is normalized root mean square error express in percent. RMSE is root mean square error. N is the mean of the observed variable. Normalized RMSE gives a measure (%) of the relative difference of simulated versus observed data. The simulation is considered excellent when a normalized RMSE is less than 10%, good if the normalized RMSE is greater than 10 and less than 20%, fair if the normalized RMSE is greater than 20% and less than 30%, and poor if the normalized RMSE is greater than 30% (Jamieson *et al.,* 1991).

$$D = 1 - [\frac{\sum_{i=1}^{n}(Pi-Oi)^2}{\sum_{i=0}^{n}(|Pi-O|)+(|oi-O|)^2}]\ 0<d<1$$

The d-statistic was calculated as ($0 \leq d \leq 1$). The more values close to unity are regarded as best agreement between the predicted and observed data (Musongaleli et al. 2014). When d = 1 indicates excellent. Where n: number of observations, Oi and Pi are the observed and predicted values, respectively for the ith data pair; and O is the mean of the observed values.

2.6 Predicting Future Climate Impact

The CROPGRO-Cowpea model used daily climate (temperature, precipitation, solar radiation), soil profile, crop management, and genetic coefficients to simulate future phenology and yield. Baseline data from Kombolcha station served to calibrate the model. Future climate scenarios (2050s and 2080s) under SSP2-4.5 and SSP5-8.5 were downscaled using MarkSim. Simulations began on 5 July each year, corresponding to typical sowing dates. Percentage changes in phenology and grain yield were calculated as:

Change in phenology $(\%) = \frac{Xpredicted - Xbase}{Xbase} * 100$

= where, X is phenology of the crop

Change in grain yield (%) = $\frac{Y\,predicted - Ybase}{Ybase} * 100$

Where, y is grain yield of the crop.

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2.7 Crop Management Scenarios

Six sowing dates (SD1–SD6) and two irrigation levels (rainfed and supplemental irrigation) were simulated individually and in combination. Supplemental irrigation (3 × 100 mm at 10-day intervals starting at flowering) was applied to reduce terminal drought stress. Simulation outputs across multiple years were analyzed using ANOVA in SAS 2008, treating years as replications. Treatment means were compared at 5% probability using LSD, and descriptive statistics (mean, percentile) were reported.

3. RESULTS AND DISCUSSION

3.1 Soil Characteristics of the Study Site

The soil profile at Jari site exhibited clear vertical variation in physical and chemical properties across four depth intervals (0–30, 30–60, 60–120, and 120–160 cm; Table 1). The surface layer (0–30 cm) provided favorable conditions for cowpea growth, characterized by relatively low bulk density (1.21 g cm^{-3}), neutral pH (7.32), high plant available water (PAW = 0.115 cm^3 cm^{-3}), and high organic carbon (1.33%) and total nitrogen (0.10%). The root growth factor (RGF = 1.0) indicates minimal physical restriction to root penetration.

With increasing depth, soil fertility and root growth potential declined markedly. Although PAW remained relatively high in subsoil layers (0.129–0.137 cm^3 cm^{-3}), bulk density and clay content increased, while organic carbon and nitrogen declined substantially. Below 60 cm, very low RGF values (≤ 0.06) indicate severe physical constraints to deep rooting despite adequate moisture retention. Similar depth-related constraints have been reported for Vertisols in semi-arid Ethiopia and are known to limit effective water uptake during terminal drought periods.

Overall, the soil profile suggests that cowpea growth in the study area depends primarily on topsoil water and nutrient availability, reinforcing the importance of optimized sowing dates and supplemental irrigation under climate variability.

Table 1. Soil physio-chemical characteristics of the studied site

Soil depth (cm)	LL (cm^{3}/cm^{3}	DUL (c^{3}/cm^{-3}	SAT (cm^3 cm^{-3})	RGF (0-1	BD (g/cm^3)	SA	CL	SI	PH	OC (%)	TN (%)
0-30	0.288	0.403	0.514	1.00	1.210	25	38.6	36.3	7.32	1.33	0.10
30-60	0.241	0.378	0.483	0.20	1.340	23.1	39	37.9	7.22	1.14	0.17
60-120	0.224	0.356	0.456	0.06	1.360	22	39	42	7.34	0.82	0.08
120-160	0.202	0.331	0.463	0.03	1.320	22.67	32	45.3	7.41	0.34	0.04

***** LL- Lower limit, DUL- Drained Upper limit, SAT- Saturation, RGF- Root growth factor, , BD- Bulk Density, SA- sand, SI-silt, CL-clay, OC- Organic Carbon, TN- Total Nitrogen,

3.2 Genetic Coefficients for Model Calibration

The calibrated genetic coefficients for the cowpea cultivar *Bekur* are presented in Table 2. These coefficients regulate key phenological processes, biomass accumulation, and assimilate partitioning within the CROPGRO-Cowpea model. The calibrated values fall within biologically realistic ranges reported for cowpea cultivars in semi-arid environments and were effective in reproducing observed crop behavior under field conditions.

Table 2 the calibrated genetic coefficients in the model for cultivar Bekur

Coefficients	Definition	Cultivar (*Bekur*)
CSDL	Critical Short-Day Length below which reproductive development progresses with no day length effect (for short day plants) (hour)	12.80
PPSEN	Slope of the relative response of development to photoperiod with time (positive for short day plants) (1/hour)	0.294
EM-FL	Time between plant emergence and flower appearance (R1) (photo thermal days)	34.14
FL-SH	Time between first flower and first pod (R3) (photo thermal days)	3.0
FL-SD	Time between first flower and first seed (R5) (photo thermal days)	6.0
SD-PM	Time between first seed (R5) and physiological maturity (R7) (photo thermal days)	20.0
FL-LF	Time between first flower (R1) and end of leaf expansion (photo thermal days)	17.0
LFMAX	Maximum leaf photosynthesis rate at 30 C, 350 vpm CO2, and high lightm (mg CO2/m2-s)	1.0
SLAVR	Specific leaf area of cultivar under standard growth conditions (cm2/g)	325
SIZLF	Maximum size of full leaf (three leaflets) (cm2)	150
XFRT	Maximum fraction of daily growth that is partitioned to seed + shell	1.0

WTPSD	Maximum weight per seed (g)	0.60
SFDUR	Seed filling duration for pod cohort at standard growth conditions (photothermal days)	8.0
SDPDV	Average seed per pod under standard growing conditions (#/pod)	3.5
PODUR	Time required for cultivar to reach final pod load under optimal conditions (photo thermal days)	14.0
THRESH	The maximum ratio of (seed/ (seed+shell)) at maturity. Causes seed to stop growing as their dry weight increase until shells are filled in a cohort. (Threshing percentage).	82.0
SDPRO	Fraction protein in seeds (g(protein)/g(seed))	0.30
SDLIP	Fraction oil in seeds (g(oil)/g(seed))	0.065

3.3 Model Calibration Performance

The CROPGRO-Cowpea model showed excellent agreement between simulated and observed phenological and yield variables during calibration (Table 3). Flowering and physiological maturity were simulated with RMSE values of 2 and 4 days, respectively, corresponding to nRMSE values below 5%, indicating excellent model performance. Grain yield and aboveground biomass were simulated with acceptable accuracy, with nRMSE values of 13.83% and 7.75%, respectively.

The slightly higher error for grain yield compared to biomass likely reflects the greater sensitivity of reproductive processes to short-term stresses during flowering and pod filling, which are difficult to capture precisely in simulation models under rainfed conditions. Nevertheless, overall model performance meets accepted thresholds for climate impact studies and confirms the suitability of the CROPGRO-Cowpea model for scenario analysis in semi-arid Ethiopia. Comparable calibration accuracy has been reported in similar DSSAT-based studies on legumes in sub-Saharan Africa.

Table 3. Comparison between simulated and observed values of key cowpea growth parameters during model calibration

Parameters	Simulated	Observed	RMSE	nRMSE

Flowering (days)	52	54	2	3.7
Physiological maturity (days)	95	99	4	4.4
seed yield (kg ha^{-1})	2068	2400	332	13.83
Aboveground biomass yield (kg ha^{-1})	5350	4965	385	7.75%

3.4 Model Evaluation

Model evaluation using independent data further confirmed the robustness of the CROPGRO-Cowpea model (Table 4). Phenological stages were predicted with very high accuracy ($R^2 > 0.99$; d-index > 0.99), while seed yield and biomass yield showed strong agreement with observed values ($R^2 \geq 0.97$). These results are consistent with previous evaluations of CROPGRO-Cowpea under Ethiopian and West African conditions and demonstrate the model's reliability for assessing climate change impacts and adaptation options.

Table 4 Model evaluation statistics for simulated versus observed cowpea parameters using the CROPGRO-Dry Bean model.

Parameter	Simulated	Observed	RMSE	R^2	D-index
Flowering (days)	52	54	2.00	0.9999	0.9998
Physiological Maturity (days)	95	99	4.00	0.9998	0.9997
Seed Yield (kg ha^{-1})	2068	2400	332.00	0.9800	0.9900
Aboveground Biomass Yield (kg ha^{-1})	5350	4965	385.00	0.9700	0.9850

3.5 Projected Climate Change in the Study Area

Climate projections indicate an overall increase in annual rainfall and a consistent warming trend for the Tehuledere District under both SSP2-4.5 and SSP5-8.5 scenarios (Figures 2 and 3). Annual rainfall is projected to increase by approximately 9–10% by the 2050s relative to the baseline, with slightly lower but still elevated totals by the 2080s. These projections align with regional climate assessments for East Africa, which attribute increasing rainfall to intensified monsoon dynamics.

Both minimum and maximum temperatures are projected to increase substantially, with mean temperature rises approaching 3 °C by the late century under SSP5-8.5. Such warming is expected to accelerate crop phenology, increase evaporative demand, and intensify heat stress during sensitive growth stages, highlighting the need for adaptive crop management strategies.

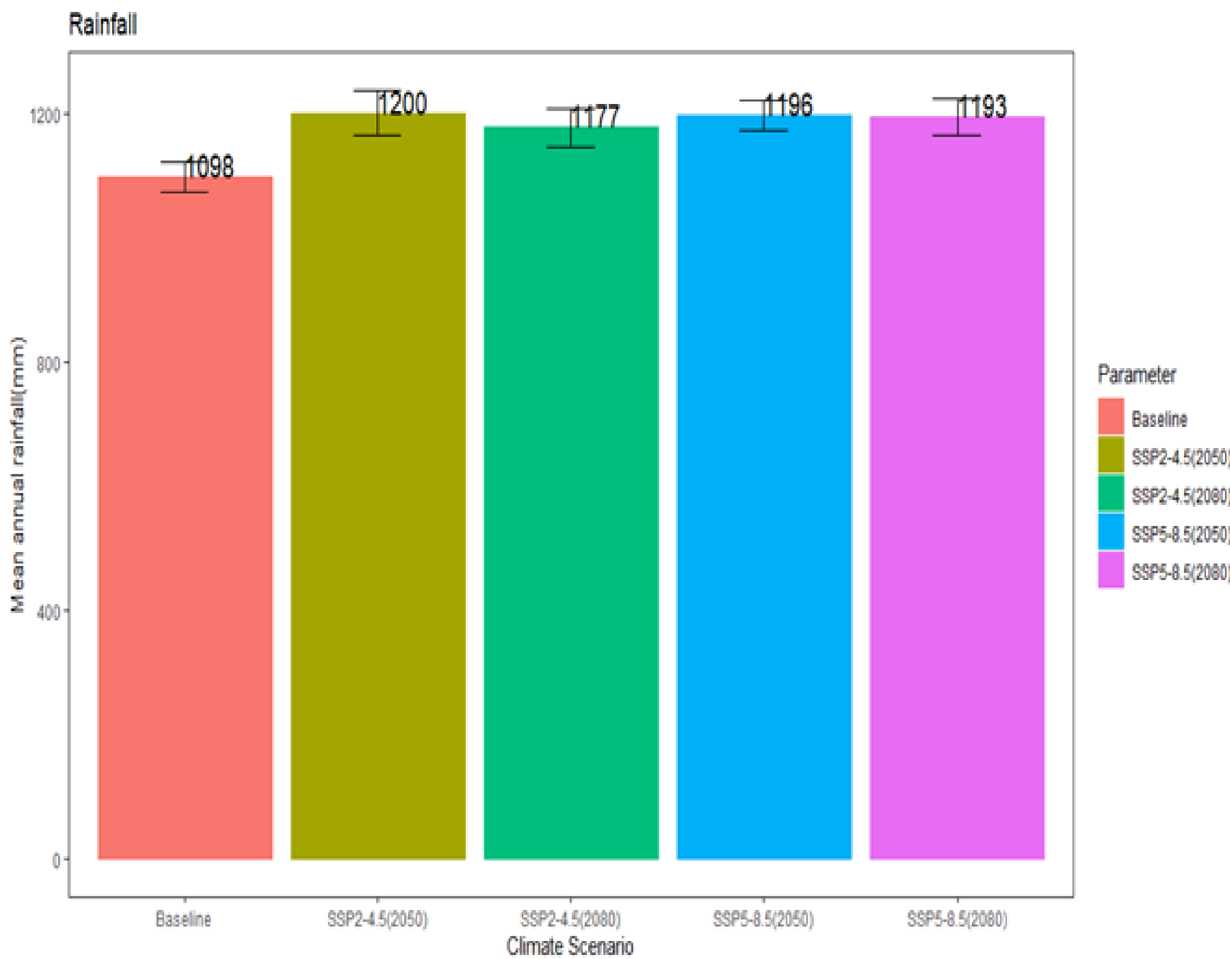

Figure. 2. Mean total annual rainfall in the base period, in 2050s and 2080s under SSP2.4.5 and SSP5.8.5 scenarios

3.6 Impact of Future Climate on Cowpea Phenology and Yield

3.6.1 With CO_2 Fertilization

Under future climate scenarios including CO_2 fertilization, cowpea phenology was significantly accelerated, with flowering and maturity occurring 9–22 days earlier than the baseline (Table 5). Despite shorter growth duration, aboveground biomass and seed yield increased substantially, particularly under SSP5-8.5. Seed yield more than doubled by the 2080s, primarily due to enhanced photosynthesis, improved water-use efficiency, and increased assimilate partitioning to grain under elevated CO_2.

The harvest index increased from 0.28 to approximately 0.36, indicating more efficient conversion of biomass into grain. Leaf area index also increased markedly, suggesting enhanced canopy development and radiation interception. These findings are consistent with well-documented CO_2 fertilization effects in C_3 legumes and demonstrate the potential for CO_2 to partially offset negative thermal effects under future climates.

Table 5 Projected Changes in Cowpea Growth Parameters under Future Climate Scenarios with co_2 fertilization

Trt	FD	MD	ABGY	SY	PW	HI	LAI
baseline (1994-2023)	59.1[c]	103[d]	4263[d]	1235.1[d]	1508[d]	0.2788[b]	3.5733[e]
SSP 2.4.5(2050)	49.8[b]	85.33[c]	5328.7[c]	1920[c]	2329.2[c]	0.3523[a]	4.51[d]
SSP5.8.5(2050)	48.33[a]	81.77[a]	5849.5[b]	2129.8[b]	2582.4[b]	0.3579[a]	5.33[b]
SSP2.4.5(2080)	47.567[a]	82.5[ab]	5388.7[c]	1984.5[c]	2406.4[c]	0.3613[a]	4.7867[c]
SSP5.8.5(2080)	48.6[ab]	83.57[b]	6644.9[a]	2431.2[a]	2950.9[a]	0.3602[a]	6.3733[a]
GM	50.68	87.233	5495	1940.1	2355.4	0.3421	4.9147
CV	5.06	3.03	6.25	8.78	8.77	5.3	5.86
LSD	1.3115	1.3517	175.68	87.084	105.64	0.009277	0.1472

**DF, days to flowering DM, days to maturity ABGY, above ground biomass yield, SY. Seed yield PW, pod weight HI, harvest index

3.6.2 Without CO_2 Fertilization

When CO_2 fertilization was excluded (Table 6), accelerated phenology remained evident, but biomass responses were minimal and yield gains were modest. Seed yield increased by only 15–38% relative to the baseline, largely due to improved harvest index rather than increased biomass. These results indicate that temperature-driven phenological escape can sustain yields to some extent, but CO_2 fertilization is critical for realizing substantial productivity gains under future climates.

Table 6 Projected Changes in Cowpea Growth Parameters under Future Climate Scenarios without co2 fertilization

Trt	FD	MD	ABGY	SY	PW	HI	LAI
baseline (1994-2023)	59.13[d]	103[d]	4265[b]	1235.1[c]	1508[c]	0.279[c]	3.57[cd]
SSP 2.4.5(2050)	49.8[c]	85.37[c]	4221.4[b]	1564.6[b]	1898.4[b]	0.36[b]	3.49[d]
SSP5.8.5(2050)	48.33[a]	81.77[a]	4192.4[b]	1595.8[b]	1935.5[b]	0.37[a]	3.72[b]
SSP2.4.5(2080)	48.57[ab]	82.5[ab]	4184.1[b]	1591.8[b]	1930.7[b]	0.373[a]	3.64b[c]
SSP5.8.5(2080)	49.27[bc]	83.87[b]	4474.8[a]	1706.6[a]	2072.4[a]	0.375[a]	4.29[a]
GM	51.0	87.3	4267.1	1538.8	1869.0	0.4	3.7
CV	2.7	3.1	7.8	8.9	8.9	5.3	6.8
LSD	0.7	1.4	170.5	70.3	85.2	0.0	0.1

**DF, days to flowering DM, days to maturity ABGY, above ground biomass yield, SY. Seed yield PW, pod weight HI, harvest index

3.7 Effect of Future Climate on Seasonal Evapotranspiration

Projected seasonal evapotranspiration (ET) declined under mid-century scenarios due to shortened crop duration and improved water-use efficiency, particularly under elevated CO_2. By the late century, ET partially recovered under SSP5-8.5, reflecting compensatory effects of increased canopy size and rainfall. These dynamics highlight the complex interaction between phenology, canopy development, and atmospheric demand in determining future crop water requirements.

3.7.1 Effect of future climate on seasonal evapotranspiration with co_2 fertilization

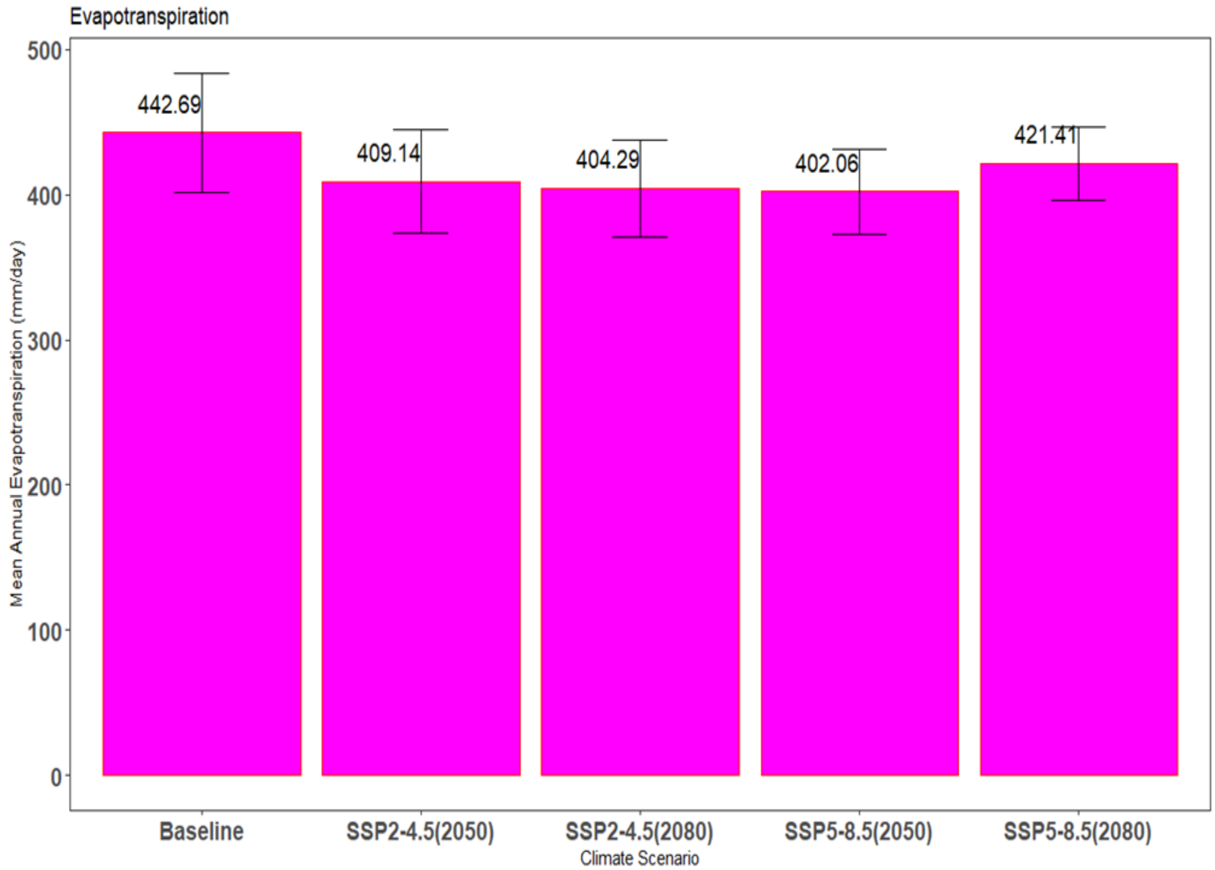

Figure 4 impact of future climate on evapotranspiration with co_2 fertilization

3.7. 2 Effect of future climate on seasonal evapotranspiration without co_2 fertilization

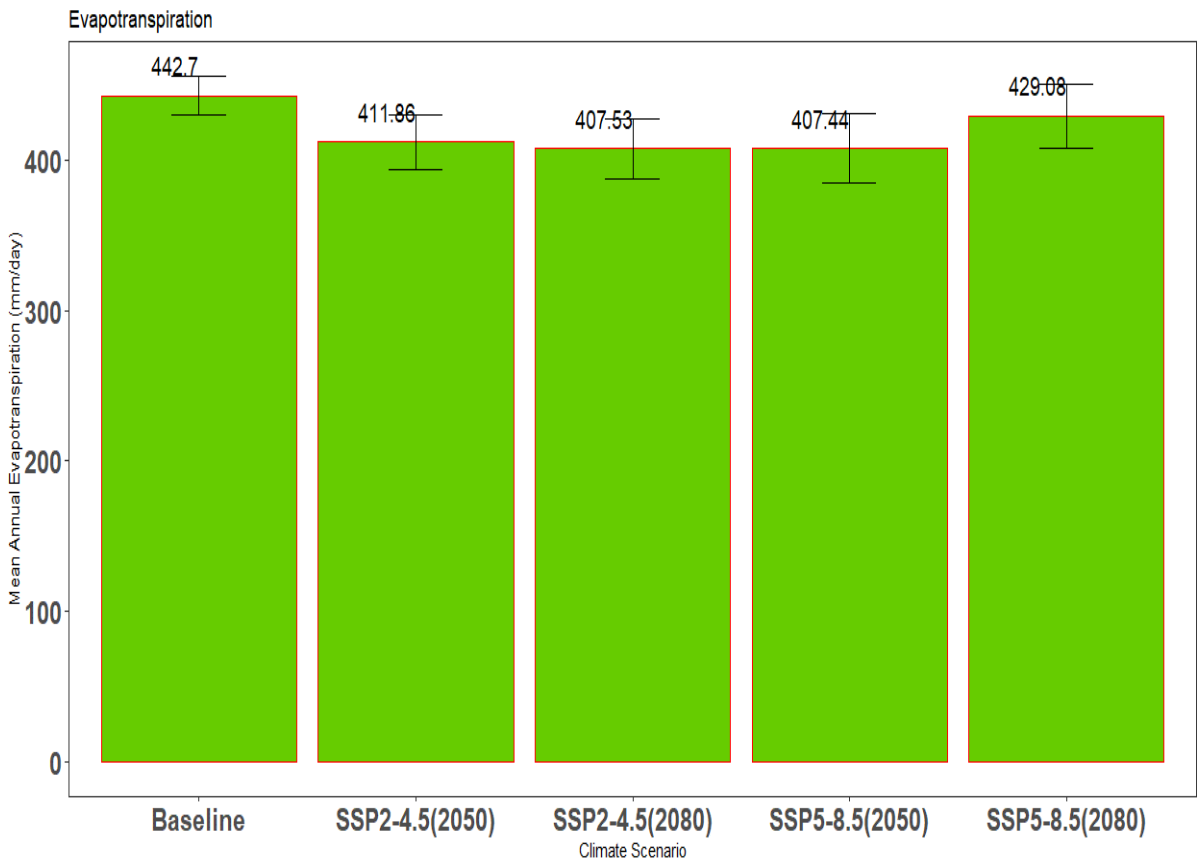

Figure 5 impact of future climate on evapotranspiration without co_2 fertilization

3.8 Climate Change Adaptation Options for Cowpea

3.8.1 Sowing Date Adjustment

Early sowing (SD1–SD2) consistently produced higher biomass, seed yield, and LAI compared to late sowing (Table 7). Delayed planting exposed crops to terminal heat and moisture stress, reducing seed yield by more than 80% in the latest sowing dates. Optimizing sowing time emerged as a low-cost and highly effective adaptation strategy under future climate conditions.

Table 7 Effect of Sowing Date on Cowpea Growth and Yield Components

Trt	FD	MD	ABGY	SY	PW	HI	LAI
SD1	50.133[a]	93.47[a]	7016.7[a]	1959.2[a]	2382[a]	0.3656[a]	4.89[a]
SD2	51.167[a]	91.97[a]	6392.3[b]	1771.9[b]	2160.4[b]	0.366[a]	4.8367[a]
SD3	51.233[a]	89.23[a]	5217.9[c]	1478.1[c]	1809.8[c]	0.3682[a]	4.7433[a]
SD4	52.8[ab]	91[a]	3561.7[d]	996.6[d]	1220.4[d]	0.3781[a]	4.25[b]
SD5	56.3[b]	95.77[ab]	2250.1[e]	559[e]	685.4[e]	0.3758[a]	3.1267[c]
SD6	53.6[ab]	103.9[b]	1560.1[f]	339.7[f]	417.4[f]	0.3712[a]	2.38[d]
GM	52.539	94.222	1184.1	1445.9	1445.9	0.3709	4.0378
CV	18	18.56	21.49	21.36	21.36	12.03	12.83
LSD	4.8263	8.9232	401.62	129.88	157.6	0.0228	0.2643

**DF, days to flowering DM, days to maturity ABGY, above ground biomass yield, SY. Seed yield PW, pod weight HI, harvest index,

3.8.2 Rainfed versus Irrigated Conditions

Supplemental irrigation significantly increased biomass and seed yield by 35–43% compared to rainfed conditions (Table 8), while extending crop duration and reducing drought stress during reproductive stages. Harvest index remained stable, indicating that irrigation primarily enhanced overall growth rather than altering biomass partitioning.

Table 8 Comparative Analysis of Cowpea Growth and Yield under Rainfed and Irrigated Conditions.

Parameter	RF	IR	Mean	CV (%)	LSD (0.05)
DF	51.1[a]	51.1[a]	51.1	-	-
DM	86.06[a]	92.46[b]	89.26	3.7	0.51
ABGY	2859.3[b]	4074.36[a]	3466.83	43.3	1.88
SY	766.7[b]	1037.93[a]	902.32	35.1	1.66
PW	940.5[b]	1265.0[a]	1102.75	34.6	1.62
HI	0337[a]	0.337[a]	0.337	-	-

**DF, days to flowering DM, days to maturity ABGY, above ground biomass yield, SY. Seed yield PW, pod weight HI, harvest index, RF, rainfed and IR, irrigatted

3.8.3 Combined Effects of Sowing Date and Irrigation

The interaction between early sowing and supplemental irrigation produced the highest yields and biomass (Table 9). Early-planted, irrigated treatments more than doubled seed yield compared to late-planted, rainfed treatments. These results confirm that aligning sowing dates with favorable climatic windows and providing limited irrigation during critical stages are highly effective climate-smart strategies for cowpea production in semi-arid environments.

Table 9 effects of Sowing date*supplementary irrigation on cowpea yield

Trt	FD (days)	MD (days)	ABY (kg/ha)	SY (kg/ha)	PW (kg/ha)	HI
SD1 (RF)	49.367^{ab}	93.63^{a}	7016.7^{a}	1959.2^{a}	2382^{a}	0.3658^{b}
SD2 (RF)	50.567^{abc}	95.47^{ab}	6392.3^{c}	1771.9^{b}	2160.4^{b}	0.366^{b}
SD3 (RF)	51.533^{bcd}	95.37^{ab}	5217.9^{e}	1478.1^{d}	1809.8^{d}	0.3682^{b}
SD4 (RF)	51.6b^{cd}	96.4^{ab}	3561.7^{f}	996.6^{f}	1220.4^{f}	0.3781^{ab}
SD5 (RF)	54.833^{e}	101.87^{c}	2250.1^{g}	559^{h}	685.4^{h}	0.3758^{ab}
SD6 (RF)	54.5^{e}	111.87^{d}	1560.1^{h}	339.7^{i}	417.4^{i}	0.3712^{ab}
SD1 (IR)	48.433^{a}	93.83^{a}	7145.1^{a}	1971.2^{a}	2396.3^{a}	0.365^{b}
SD2 (IR)	50.967^{abc}	95.17^{ab}	6920^{ab}	1786.7^{b}	2175.7^{b}	0.3667^{b}
SD3 (IR)	49.867^{ab}	98.27^{b}	6643.4^{bc}	1593.1^{c}	1941.5^{c}	0.3725^{ab}
SD4 (IR)	52.733^{cde}	104.27^{c}	6273.3^{c}	1336.8^{e}	1628.4^{e}	0.3786^{ab}
SD5 (IR)	53.9d^{e}	110.2^{d}	5837.9^{d}	1067.3^{f}	1301.3^{f}	0.3806^{ab}
SD6 (IR)	58^{f}	115.7^{e}	5395.3^{e}	856.1^{g}	1044.2^{g}	0.3896^{a}
GM	52.192	101	5351.1	1309.6	1596.9	0.3732
CV	9.99	6.08	13.69	16.28	16.19	11.17
LSD	2.647	3.1185	372.2	108.32	131.3	0.0212

DF, days to flowering DM, days to maturity ABGY, above ground biomass yield, SY. Seed yield PW, pod weight HI, harvest index,**

4. DISCUSSION

4.1 Climate Risk to Cowpea Production under SSP5-8.5

The results clearly demonstrate that climate risk to cowpea production in northeastern Ethiopia intensifies substantially under the high-emission SSP5-8.5 scenario. Although projected rainfall increases moderately, rising temperatures—particularly during the reproductive phase—pose a significant threat by accelerating crop phenology and shortening grain filling duration. The advancement of flowering and physiological maturity by up to three weeks under late-century SSP5-8.5 reflects increasing thermal stress and aligns with regional projections for semi-arid sub-Saharan Africa (SSA).

Earlier phenological development under SSP5-8.5 reduces the time available for biomass accumulation and exposes cowpea to higher vapor pressure deficit and heat stress during pod filling. These findings confirm that temperature, rather than rainfall, is the dominant climate risk driver, consistent with previous modeling studies in Ethiopia and SSA that identify warming as the primary constraint on legume productivity under future climates. The increased inter-annual variability simulated under SSP5-8.5 further heightens production risk, making rainfed cowpea systems increasingly vulnerable without targeted adaptation measures.

4.2 Limits of CO_2 Fertilization as a Buffer Against Climate Stress

While elevated atmospheric CO_2 substantially increased biomass and grain yield in simulations, the results indicate that CO_2 fertilization alone cannot be relied upon as a long-term buffer against climate risk, particularly under SSP5-8.5. Yield gains under elevated CO_2 were largely driven by enhanced photosynthesis, increased leaf area development, and improved water-use efficiency—responses typical of C_3 legumes such as cowpea.

However, when CO_2 fertilization effects were excluded, yield gains were sharply reduced despite similar temperature and rainfall conditions. This divergence highlights the conditional nature of CO_2 benefits, which are constrained by nutrient availability, soil physical limitations, and increasing heat stress. In Vertisol-dominated soils with shallow effective rooting depth, the capacity of crops to fully exploit CO_2-induced growth stimulation is inherently limited.

Furthermore, rising temperatures under SSP5-8.5 partially offset CO_2 benefits by accelerating phenology and increasing maintenance respiration costs. Similar limitations of CO_2 fertilization have been reported in modeling studies on maize, chickpea, and common bean in Ethiopia and West Africa, suggesting that CO_2 fertilization should be viewed as a temporary and uncertain advantage rather than a guaranteed adaptation pathway.

4.3 Why Irrigation and Sowing Date Adjustment Reduce Climate Vulnerability

The strong yield response to sowing date adjustment and supplemental irrigation demonstrates that management-based adaptation is more reliable than physiological CO_2 effects in reducing climate vulnerability. Early sowing aligned crop development with periods of lower temperature and more reliable soil moisture, thereby reducing exposure to terminal heat and drought stress—two dominant risks under SSP5-8.5.

Supplemental irrigation applied during flowering and grain filling consistently reduced yield variability and extended crop duration, allowing better utilization of available radiation and soil nutrients. Importantly, irrigation did not alter harvest index substantially, indicating that its primary role is stabilizing biomass production under climate stress rather than changing assimilate partitioning.

The combined effect of early sowing and supplemental irrigation was particularly effective, producing the highest yields across both baseline and future scenarios. This interaction confirms that climate risk in semi-arid systems is best addressed through integrated water and time-based management strategies, which directly target the most climate-sensitive growth stages.

4.4 Comparison with Ethiopia and Sub-Saharan Africa Studies

The findings are consistent with climate impact assessments conducted across Ethiopia and SSA. Studies on chickpea, maize, and sorghum in Ethiopia have similarly reported accelerated phenology, moderate rainfall increases, and yield sensitivity to temperature under future climates. In particular, earlier studies in the Rift Valley and northeastern highlands identified sowing date optimization and supplemental irrigation as the most effective adaptation options under warming scenarios.

Across SSA, DSSAT-based analyses of cowpea and other legumes report comparable CO_2 fertilization responses, but also emphasize that benefits decline under extreme warming conditions. The present study extends this literature by explicitly quantifying how management interventions can offset climate risk even under SSP5-8.5, a scenario rarely explored in Ethiopian legume studies.

By focusing on cowpea—a climate-resilient but under-researched legume—this study contributes new evidence to the regional understanding of legume-based climate adaptation strategies in semi-arid environments.

4.5 Implications for Climate-Smart Agriculture and Policy

The results have direct implications for climate-smart agriculture (CSA) policies in Ethiopia. First, adjusting sowing calendars represents a low-cost, immediately deployable adaptation strategy that can be scaled through extension services. Second, targeted supplemental irrigation, even at modest levels, can substantially reduce yield risk under high-emission scenarios and should be prioritized in small-scale water development programs.

Third, reliance on CO_2 fertilization as a passive adaptation mechanism is risky and should not substitute for proactive management and investment in water infrastructure. National adaptation plans should integrate crop modeling outputs into extension advisories to support evidence-based decision-making at the farm level.

Finally, promoting cowpea within diversified cropping systems aligns with Ethiopia's broader resilience goals by improving soil fertility, dietary protein supply, and income stability under increasing climate uncertainty. The integration of simulation-based risk assessments into agricultural planning can strengthen the country's capacity to anticipate and manage future climate risks.

5. CONCLUSIONS AND IMPLICATIONS

Cowpea production in semi-arid northeastern Ethiopia faces increasing climate risk, particularly under the high-emission SSP5-8.5 scenario. Rising temperatures accelerate crop phenology, shorten grain-filling duration, and increase yield variability, especially in rainfed systems. Although projected rainfall increases slightly, warming remains the dominant risk driver, exposing smallholder farmers to heightened production and income uncertainty.

Elevated atmospheric CO_2 partially offsets climate stress by enhancing biomass production and water-use efficiency; however, CO_2 fertilization alone is an unreliable and insufficient buffer against climate risk under extreme warming. Its effectiveness is constrained by soil limitations, nutrient availability, and increasing heat stress, indicating that passive physiological responses cannot substitute for active adaptation.

In contrast, management-based adaptation strategies proved effective in reducing climate-induced yield risk. Optimized sowing dates reduced exposure to terminal heat and moisture stress, while supplemental irrigation during flowering and grain filling stabilized yields and reduced inter-annual variability. The combined application of early sowing and limited supplemental irrigation consistently produced the lowest climate risk across both mid- and late-century scenarios, including SSP5-8.5.

These findings have clear implications for climate-smart agriculture and policy. Planners should prioritize adaptive sowing calendars and small-scale water management over reliance on CO_2 fertilization benefits. Extension services should promote early planting windows aligned with projected climate trends and support targeted supplemental irrigation during critical growth stages. For farmers, adjusting planting time and strategically applying limited irrigation represent low-cost, high-impact actions to reduce climate vulnerability.

Overall, the study demonstrates that while future climate change poses substantial risk to cowpea production, this risk is manageable through timely, location-specific management interventions, providing a practical pathway for sustaining legume-based livelihoods under increasing climate uncertainty.