

Effects of rainfall and temperature variabilities on coffee (*Coffea arabica* L.) productivity in eastern Ethiopia

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**Effects of rainfall and temperature variabilities on coffee (*Coffea arabica* L.)
productivity in eastern Ethiopia**

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Abstract

Coffee production in eastern Ethiopia is highly sensitive to rainfall variability and rising temperatures. Understanding the relationship between seasonal climate characteristics and coffee yield is critical for sustaining livelihoods and export potential. This study examined rainfall and temperature patterns in Melka Balo, Bedeno, and Shenen Dugo districts, analyzing eighteen years of daily climate and yield data (2007–2024) and projected future trends (2026–2055) using CMIP6 models under the SSP2-4.5 scenario. Correlation analysis revealed that belg rainy days had a strong positive influence on coffee yield, while belg and kiremt rainfall totals, kiremt rainy days, and length of the growing period showed moderate positive effects. Conversely, delayed onset of rainfall reduced yield, and both belg and kiremt mean temperatures exhibited strong negative correlations. Regression models explained 82–92% of yield variation across districts, confirming rainfall reliability as a key driver of productivity. Projection results indicated that belg rainfall totals will decline sharply (~3.7–9.8 mm per year), kiremt rainfall totals will decrease slightly but variably (~0.5–9 mm per year), and annual rainfall will decline steadily (~4.6–9 mm per year). The onset of belg rainfall is expected to be delayed by 0.7–1.2 days per year, while the end date shifts earlier by ~2–4 days per year, shortening the growing period by ~0.7–6 days annually. Seasonal temperatures will rise consistently, with belg mean increasing by ~0.035–0.039 °C per year, kiremt mean by ~0.021–0.032 °C per year, and mean annual temperature by ~0.02–0.03 °C per year. Coffee yield is projected to decline steadily, averaging ~0.09–0.10 qt/ha loss per year. Climate variability, particularly rising belg and kiremt temperatures, declining rainfall totals, delayed onset, earlier cessation, and shortened growing periods, poses a severe threat to Arabica coffee production in eastern Ethiopia. Without adaptation, both livelihoods and export potential will be undermined. Urgent measures such as introducing drought and high temperature-resistant coffee varieties, expanding production to higher altitudes, integrating shade trees, and implementing soil and water conservation strategies are essential to sustain productivity under changing climate conditions.

Keywords: *Coffea arabica* L.; Rainfall and temperature variability; Productivity; East and west Hararghe

1. Introduction

Global Arabica coffee production is increasingly threatened by climate change, with rising temperatures, erratic rainfall, and extreme events reducing suitability in traditional growing regions [1, 2]. Beyond yield impacts, climate variability undermines the genetic diversity and cultural heritage of coffee, a crop deeply tied to local identities and global markets [3]. These challenges are magnified in Africa, where Sub-Saharan regions are recognized as among the most vulnerable to climate variability and climate change [4]. Recurrent droughts and floods have constrained economic development and livelihoods across the continent, intensifying risks for agriculture-dependent communities [5, 6].

Within this continental picture, Ethiopia occupies a unique position. Agriculture remains the backbone of its economy, yet its dependence on rain-fed systems makes it highly sensitive to rainfall variability and temperature extremes [7-9]. At the same time, Ethiopia is the center of origin of *Coffea arabica* and Africa's leading producer, ranking fifth globally in Arabica production and tenth in coffee exports [10]. Coffee is not only an economic pillar, contributing more than 25% of foreign exchange earnings, 5% of GDP, 12% of agricultural output, and 10% of government revenues [11] but also a cultural heritage crop deeply tied to Ethiopian identity and tradition.¹²

Despite this importance, climate pressures are already eroding Ethiopia's coffee sector. Rising temperatures, prolonged droughts, and intensified rainfall events have reduced productivity and increased pest and disease risks [12-14]. Empirical studies confirm Arabica's narrow climatic tolerance: Chemura et al. [15] showed warming trends narrowing its ecological range, while Megerssa et al. [16] documented heightened vulnerability to pests. While [17] found rainfall variability constrained yields, Mamuye et

¹ Rain-fed agriculture accounts for more than 95% of Ethiopia's cultivated land, making rainfall timing and reliability decisive for productivity.

² Coffee ceremonies are central to Ethiopian social life, symbolizing hospitality and cultural identity; this heritage dimension strengthens the crop's national importance beyond economics.

al. [18] identified rainfall variability as a driver of decline, Wakjira linked late cessation to smaller beans [19], and demonstrated that delayed onset reduces yield reliability [20]³.

In eastern Ethiopia, Hararghe coffee is globally prized for its flavor profile and genetic diversity, yet productivity remains low. Average yields of 512 kg/ha, and 546 kg/ha in West and east Hararghe respectively [21], below the national average of 619 kg/ha. Coffee marketing issues [22], trends and production challenges [23], while recent work warns of genetic erosion [24]. Climatic thresholds remain critical as Tesfaye reported Arabica coffee tolerance ranges annual precipitation between 700–2019 mm (optimum 1502–1854 mm) and mean temperatures between 14–27 °C (optimum 19–22 °C)[25]. More recent modeling confirms these ranges but stresses that deviations, particularly rising temperatures and moisture stress, are already reducing productivity [13, 16].⁴

While these studies provide valuable insights, most have concentrated on some parts of Ethiopia or national-level value chain impacts. District-specific projections in eastern Ethiopia remain scarce, particularly for Melka Balo, Bedeno, and Shenen Dugo, where coffee is central to household income but highly vulnerable to climate variability. Quantitative projections of belg and kiremt rainfall timing, seasonal temperature rise, and yield decline at district scale are largely absent. This study addresses that gap by analyzing historical climate–yield relationships (2007–2024) and projecting future coffee productivity (2026–2055) under CMIP6 SSP2-4.5 scenarios in Melka Balo, Bedeno, and Shenen Dugo. The findings provide localized evidence to guide adaptation strategies for sustaining Arabica coffee in eastern Ethiopia.

2. Materials and methods

2.1 Description of the Study Area

³ Arabica coffee thrives only within narrow temperature and rainfall ranges; small deviations increase risks of pests, diseases, and yield instability

⁴ Hararghe coffee is valued globally for its distinct flavor and genetic diversity, but its narrow climatic tolerance makes it highly vulnerable to rainfall variability and warming trends.

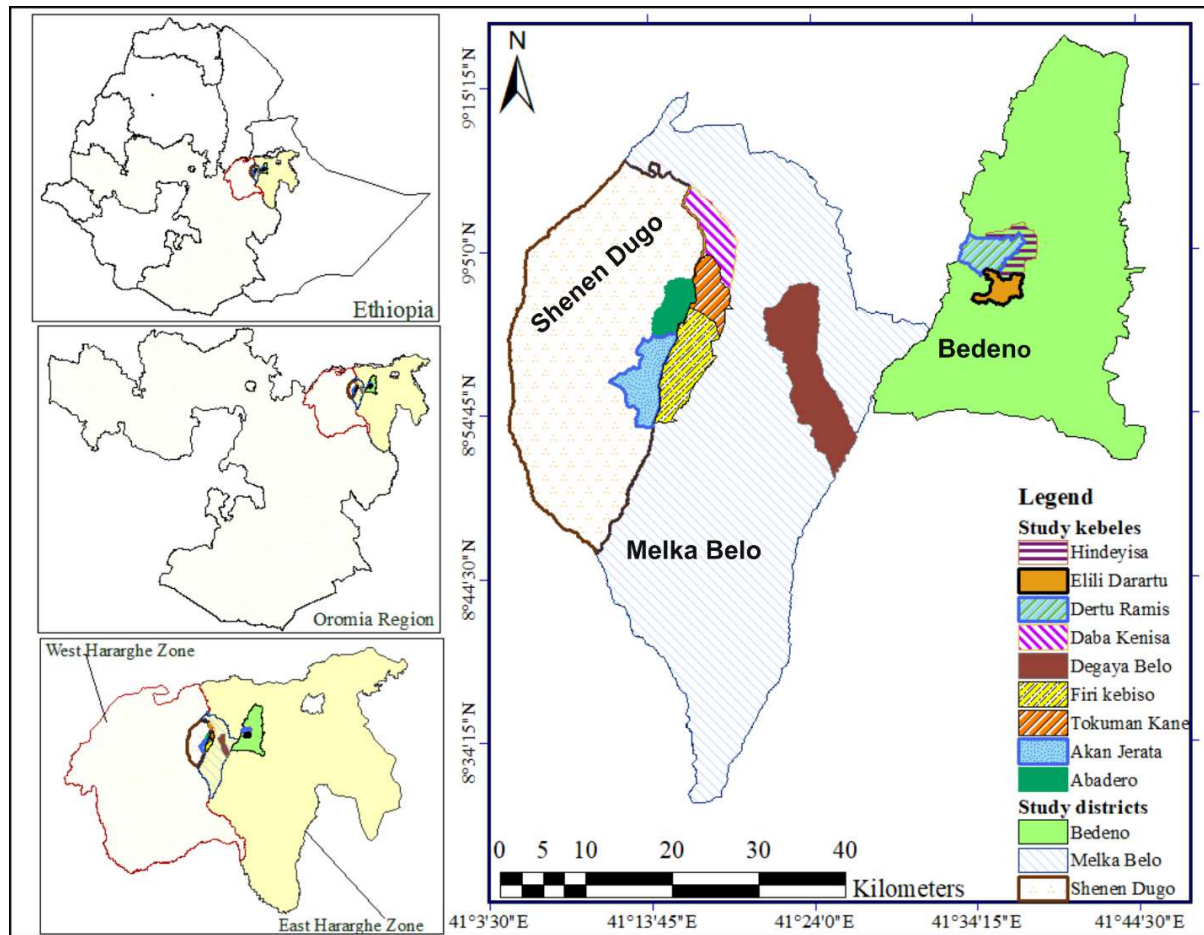
The study was conducted in coffee-producing districts of East and West Hararghe Zones, located in the eastern part of Oromia Regional State, Ethiopia. The zones lie approximately 525 km east of Addis Ababa, between 7°32'–9°44' N latitude and 41°10'–43°16' E longitude, covering a total area of about 26,311 km². Elevation ranges from 500 to 3,405 m.a.s.l., reflecting diverse agro-ecological conditions. Agro-climatically, the zones are divided into three major categories: lowland (60.32%), midland (32.24%), and highland (7.44%). Rainfall is bimodal, with the main rainy season (kiremt) occurring from June to September and the short rainy season (belg) from February to May [21]. Annual rainfall ranges between 400–1,010 mm, while mean annual temperatures vary from 14–25 °C.

Agriculture is the dominant economic activity and the primary source of livelihood for most residents. Farming is largely small-scale and mixed, combining crop and livestock production. Major crops include cereals (sorghum, maize, wheat, and barley), pulses, oilseeds, vegetables, and fruits. Cash crops such as coffee (*Coffea arabica* L.) and chat (*Catha edulis*) are particularly important, contributing significantly to household income and regional trade [22].⁵⁶

Figure 1. Map of the study area.

⁵Belg (February–May) and Kiremt (June–September) are Ethiopia's two principal rainy seasons; their timing and reliability are decisive for crop growth and coffee yield.

⁶Chat (*Catha edulis*) is a stimulant leaf widely cultivated in eastern Ethiopia; alongside coffee, it provides vital cash income and shapes regional trade dynamics.



Source=map was produced in ArcGIS 10.8

The map highlights the study districts (Bedeno, Melka Belo, and Shenen Dugo), with boundaries, a legend, a scale bar, and a north arrow included for orientation

2.2. Data and source

Historical daily rainfall and temperature records (2007–2024) were obtained from the National Meteorological Agency (NMA) and local weather stations in Bedeno, Melka Balo, and Shenen Dugo. Annual coffee yield data (qt/ha) were collected from District Agricultural and Marketing Offices.

Future rainfall and temperature projections were sourced from the Coupled Model Intercomparison Project Phase 6 (CMIP6) under the SSP2-4.5 scenario, representing an intermediate stabilization pathway [26, 27, 28]. Data were accessed through the Earth System Grid Federation (ESGF) portal (<https://esgf-node.llnl.gov/projects/cmip6/>). Model

selection considered experiment type, analysis period, resolution, and variant consistency, specifically the complete first ensemble member (r1i1p1f1). Two CMIP6 models (HadGEM3 GC31 LL and NorESM2 MM) were chosen for their completeness, diversity in spatial resolution and structural design, and proven performance in simulating East African climate (Table 1). Their inclusion also ensured representation from different modeling centers, minimizing systematic biases and enhancing robustness.⁷

Table 1. List of employed CMIP6 climate models for projection of climate data in eastern Ethiopia

CMIP6 model name	Country	Horizontal resolution (longitude × latitude)	Variant label	Key references
HadGEM3-GC31-LL	UK	1.875° × 1.25°	r1i1p1f1	[29]
NorESM2-MM	Norway	2.5° × 1.875°	r1i1p1f1	[30]

The study focused on the near-future period (2026–2055) under SSP2-4.5, reflecting short-term climate variations driven by current greenhouse gas concentrations and phenomena such as El Niño–Southern Oscillation (ENSO), making it critical for immediate adaptation and mitigation planning [31]. Model performance was evaluated by comparing simulated historical data against observed records during the 2015–2024 baseline. Annual rainfall and temperature values were plotted and visually inspected for consistency with observed climatology, following approaches used in East African climate assessments [32, 33]. Projected climate data (2026–2055) were then incorporated into regression models developed from observed climate–yield relationships to estimate future coffee productivity in East and West Hararghe.

2.3 Definitions of Climatic Variables

The start date of the rainy season was declared when a total rainfall of more than 20 mm recorded in three consecutive days that were not followed by greater than 10 days of dry

⁷ SSP2-4.5 is a mid-range scenario in CMIP6, representing moderate greenhouse gas emissions and socio-economic pathways; HadGEM3 and NorESM2 are widely used global climate models with demonstrated skill in East African rainfall simulation.

spell length within 30 days from planting day was used. No drier spell exceeding 10 days within the 30 days taken as extra criteria embedded in INSTAT (V 3.37) helps to avoid false onset. The end date of the rainy season was adopted in this case is defined as any day after the first of September, when the soil water balance reaches zero. In determining the end date, site-specific evapotranspiration was determined and a fixed 3.66 mm per day and 100 mm of plant-available soil water were considered [34]. Using the above definitions, Instant Statistical program Version 3.37 was used for analysis using January to December calendar. The length of the growing period was determined by subtracting *Belg* onset date from *Kiremt* end date of rainfall.

Finally, in determining the number of rainy days, multiple criteria are available for use. In the context of Ethiopia, Segele and Lamb employed three rainfall thresholds to define a rainy day (0.1 mm, 0.5 mm and 1 mm)[35]. However, Hadgu et al. defined a rainy day as, a day with 1 or more mm of rainfall amount [36]. In this study, 1 mm per 24 hrs, rainfall threshold was adopted. Seasonal rainfall amount was decided by adding the amount of rainfall recorded for both *belg* and *Kiremt* rainy season for this study area.⁸

2.4. Data quality control

Daily rainfall, minimum, and maximum temperature records were organized in Excel using day-of-year format. Quality control procedures included checks for completeness and temporal consistency. Missing values were imputed using a first-order Markov chain simulation model in INSTAT software, following established approaches [35]. The first-order approach was chosen because it avoids exaggeration and provides reliable estimates [37]. Outlier detection, homogeneity testing, and multicollinearity checks were conducted in SPSS to ensure dataset robustness prior to statistical analysis. These steps minimized bias and enhanced the reliability of subsequent correlation and regression models.⁹

⁸ The 1 mm threshold is widely accepted in Ethiopian agro-climatic studies as the minimum rainfall amount that contributes meaningfully to soil moisture and crop growth.

⁹ Multicollinearity checks ensure that explanatory climate variables (rainfall, temperature, onset, cessation) do not distort regression estimates of coffee yield sensitivity.

2.5. Data analysis

Observed rainfall, temperature, and coffee yield data (2007–2024) were analyzed using correlation and regression. The multiple regression model was developed to quantify the influence of climatic variables on coffee productivity:

$$Y = a + b_1x_1 + b_2x_2 + b_3x_3 + b_4x_4 + b_nx_n + e \quad \text{equationn (1)}$$

Where Y=the value of the dependent variable (Coffee yield in qt/ha), a =Y-intercept, b_1 , b_2 , b_3 , b_4 ,... b_n = regression coefficients (each b represents the amount of change in Y (yield) for one unit of change in the corresponding x-value when the other x values are held constant; x_1 , x_2 , x_3 , x_4 ,... x_n =the rainfall independent variables (i.e. rainfall onset, cessation, LGP, seasonal rainfall totals and number of rain days) and temperature-independent variables (i.e. *belg* mean temperature and *Kiremt* mean temperature), e : the error of estimate or residuals of the regression.¹⁰

Pearson correlation coefficients (r) were calculated to assess the strength and direction of relationships between coffee yield and individual climatic parameters. Values of r range from −1 to +1, with coefficients close to +1 indicating strong positive correlation, coefficients close to −1 indicating strong negative correlation, and values near 0 indicating no correlation. The coefficient of determination (R^2) was used to evaluate the proportion of yield variation explained jointly by rainfall and temperature variables. Statistical significance of predictors was tested using ANOVA at the 95% confidence level ($p \leq 0.05$). Student's t-tests were applied to assess the unique contribution of each independent variable. Multicollinearity was checked using Variance Inflation Factor (VIF) in SPSS; VIF values close to 1 indicate no collinearity, while values approaching 10 suggest serious collinearity problems [38].¹¹

3. Results

3.1 Correlation between Rainfall, Temperature, and Coffee Yield

¹⁰ This regression framework allows simultaneous estimation of rainfall and temperature effects, controlling for interdependence among climatic variables.

¹¹ Variance Inflation Factor (VIF) is a diagnostic tool that quantifies how much multicollinearity inflates the variance of regression coefficients; values above 10 are generally considered problematic.

Across Melka Balo, Bedeno, and Shenen Dugo districts, rainfall reliability (rainy days and totals) consistently supported coffee yield, while rising seasonal temperatures and delayed onset of rainfall reduced productivity. In Melka Balo, as presented in Table 1.1, from rainfall variables *belg* rainy days ($r = 0.809$,) had the strongest positive correlation with yield, followed by *belg* rainfall total ($r = 0.736$,) and *kiremt* rainfall total ($r = 0.66$). *Kiremt* rainy days ($r = 0.461$), length of growing period ($r = 0.462$), and end date of rainfall ($r = 0.341$) also showed moderate positive associations. The onset date of rainfall ($r = -0.408$) had a moderate negative correlation, indicating that late onset reduced productivity. *Belg* and *kiremt* mean temperatures ($r = -0.838$ and $r = -0.801$, respectively) showed strong negative correlations, confirming that rising temperatures significantly reduced yield in the district during 2007-2024.¹²

Bedeno (Table 1.2): rainfall variables also showed positive associations, with *kiremt* rainfall total ($r = 0.881$, $p < 0.01$) and *kiremt* rainy days ($r = 0.684$) being the strongest predictors. *Belg* rainy days ($r = 0.604$) and *belg* rainfall total ($r = 0.525$) contributed moderately, while LGP showed a weak positive correlation ($r = 0.136$). Temperature variables *belg* mean ($r = -0.805$) and *kiremt* mean ($r = -0.792$) had strong negative correlations, and onset date ($r = -0.405$) was moderately negative. The end date of rain ($r = 0.032$) showed no meaningful correlation with yield but was strongly correlated with LGP ($r = 0.775$), suggesting redundancy.¹³

Shenen Dugo (Table 1.3): *Kiremt* rainfall total ($r = 0.635$) and *kiremt* rainy days ($r = 0.508$) were positively correlated with yield, while *belg* rainfall total ($r = 0.17$) and *belg* rainy days ($r = 0.044$) were weakly positive. Temperature variables *belg* mean ($r = -0.700$) and *kiremt* mean ($r = -0.642$) had strong negative correlations, and onset date ($r = -0.216$) was

¹² Strong negative correlations with temperature highlight the sensitivity of Arabica coffee to warming, particularly during *belg* and *kiremt* seasons.

¹³ The redundancy between end date and LGP suggests overlapping explanatory power; including both in regression models risks multicollinearity.

weakly negative. LGP was negatively but insignificantly correlated with yield ($r = -0.027$), though strongly correlated with end date ($r = 0.826^*$), indicating redundancy.¹⁴

Table 1.1. Pearson's lower triangular correlation matrix of rainfall and temperature characteristics and coffee yield in Melka Balo District 2007-2024

	Yield	BMT	KMT	OS	ED	BRD	KRD	BRT	KRT	LGP
Yield	1									
BMT	-0.838	1								
KMT	-0.801	0.753**	1							
OS	-0.408	0.343	0.027	1						
ED	0.341	-0.339	-0.247	-0.276	1					
BRD	0.809**	-0.663	-0.548*	-0.514*	0.305	1				
KRD	0.461*	-0.302	-0.598**	0.226	0.187	0.217	1			
BRT	0.736**	-0.597	-0.425	-0.697**	0.342	0.884**	0.013	1		
KRT	0.660**	-0.527	-0.794**	0.095	0.417	0.308	0.710**	0.182	1	
LGP	0.462*	-0.425	-0.187	-0.743	0.849**	0.495*	0.006	0.622**	0.239	1

**Correlation is significant at the 0.01 significant level; *Correlation is significant at the 0.05 significant level; BMT: Belg Mean Temperature; KMT: Kiremt Mean Temperature; OS: Onset of Rainy Season; ED: End Date of Rainy Season; BRD: Belg Rainy Day; KRD: Kiremt Rainy Day; KRFT: Kiremt Rainfall Total; BRFT: Belg Rainfall Total; LGP: Length of the Growing Period.

Table 1.2. Pearson's lower triangular correlation matrix of rainfall and temperature characteristics and coffee yield in Bedeno District

	Yield	BMT	KMT	OS	ED	BRD	KRD	BRFT	KRFT	LGP
Yield	1									
BMT	-0.805	1								
KMT	-0.792	0.563*	1							
OS	-0.405	0.205	0.347	1						
ED	0.032	0.159	-0.251	0.003	1					
BRD	0.604**	-0.519	-0.375	-0.155	0.193	1				
KRD	0.684**	-0.423	-0.76	-0.391	0.441	0.339	1			
BRFT	0.525*	-0.665**	-0.218	-0.07	0.079	0.692**	0.197	1		
KRFT	0.881**	-0.735**	-0.903	-0.349	0.242	0.465	0.813**	0.375	1	
LGP	0.136	0.104	-0.329	-0.37	0.775**	0.289	0.512*	0.001	0.299	1

**Correlation is significant at the 0.01 significant level; *Correlation is significant at the 0.05 significant level; BMT: Belg Mean Temperature; KMT: Kiremt Mean Temperature; OS: Onset of Rainy Season; ED: End Date of Rainy Season; BRD: Belg Rainy Day; KRD: Kiremt Rainy Day; KRFT: Kiremt Rainfall Total; BRFT: Belg Rainfall Total; LGP: Length of the Growing Period

Table 1.3. Pearson's lower triangular correlation matrix of rainfall and temperature characteristics and coffee yield in Shenen Dugo District 2007-2025

	Yield	BMT	KMT	OS	ED	BRD	KRD	KRT	BRT	LGP
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¹⁴ Shenen Dugo's weaker belg correlations may reflect localized rainfall variability or differences in soil water retention capacity.

Yield	1									
BMT	-0.700	1								
KMT	-0.642	0.418	1							
OS	-0.216	0.112	-0.213	1						
ED	-0.147	-0.082	-0.013	0.454	1					
BRD	0.044	-0.255	0.468*	-0.176	0.073	1				
KRD	0.508*	-0.156	-0.556*	-0.012	-0.268	-0.333	1			
KRT	0.635**	-0.309	-0.876**	0.193	-0.009	-0.454	0.470*	1		
BRT	0.170	-0.539	0.365	-0.493	-0.217	0.564*	-0.289	-0.425	1	
LGP	-0.027	-0.163	0.121	-0.128	0.826**	0.193	-0.291	-0.132	0.07	1

**Correlation is significant at the 0.01 significant level; *Correlation is significant at the 0.05 significant level; BMT: Belg Mean Temperature; KMT: Kiremt Mean Temperature; OS: Onset of Rainy Season; ED: End Date of Rainy Season; BRD: Belg Rainy Day; KRD: Kiremt Rainy Day; KRFT: Kiremt Rainfall Total; BRFT: Belg Rainfall Total; LGP: Length of the Growing Period

3.2 Regression Analysis and Coefficients across Districts

The multiple regression analyses confirmed that rainfall and temperature variables significantly influenced coffee yield in all three districts, though explanatory power varied. In Melka Belo (Table 2.1), the model was strongest, with $R^2=0.922$ and adjusted $R^2=0.860$, indicating that 92.2% of yield variation was explained by climatic parameters. The analysis of variance (ANOVA) revealed that the influence of climate variables on coffee yield was statistically significant ($p=0.001$), suggesting that rainfall and temperature characteristics are major determinant factors for coffee productivity in the district., and the standard error of the estimate was 1.14, suggesting a good fit. The end date of rain (ED) was excluded due to multicollinearity.

In Bedeno (Table 2.2), the regression model explained 89.7% of yield variation ($R^2=0.897$, adjusted $R^2=0.782$). The analysis of variance (ANOVA) confirmed statistical significance ($F = 7.774$, $p = 0.004$), with a standard error of 1.41. Although robust, the model was weaker than Melka Belo's was. In Shenan Dugo, the regression model explained 82.2% of yield variation ($R^2=0.822$, adjusted $R^2=0.679$) (Table 2.3). The analysis of variance (ANOVA) results were significant ($F = 5.768$, $p = 0.006$), with a standard error of 1.26. The model was moderately robust but weaker than those of Melka Balo and Bedeno, largely due to redundancy among rainfall variables. The end date of rain (ED) was removed from the regression model for this reason.

Table 2.1. Summary of regression values for rainfall and temperature characteristics and coffee yield (2007-2024) Melkabello district.

Model Summary				
Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	0.960 ^a	0.922	0.860	1.13968

a. Predictors: (Constant), LGP, KR D, BMT, BRD, KRT, OS, KMT, BRT

ANOVA ^a						
Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	154.441	8	19.305	14.863	0.001 ^b
	Residual	12.989	10	1.299		
	Total	167.429	18			

a. Dependent Variable: Yield

Table 2.2. Summary of regression values for rainfall and temperature characteristics and coffee yield 2007-2024

Model Summary				
Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	0.947 ^a	0.897	0.782	1.40978

a. Predictors: (Constant), LGP, BRFT, OS, KMT, BRD, KR D, BMT, ED, KRFT

ANOVA ^a						
		Sum of				
Model		Squares	df	Mean Square	F	Sig.
1	Regression	139.065	9	15.452	7.774	0.004 ^b
	Residual	15.900	8	1.987		
	Total	154.965	17			

a. Dependent Variable: Yield

Table 2.3. Summary of regression values for rainfall and temperature characteristics and coffee yield 2007-2024 in Shenen Dugo district.

Model Summary				
Model	R	R Square	Adjusted R Square	Std. Error of the Estimate

1	0.907 ^a	0.822	0.679	1.25602
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a. Predictors: (Constant), LGP, BRT, KMT, OS, KR, BRD, KRT, BMT

ANOVAa						
		Sum of Squares		Mean		
Model			df	Square	F	Sig.
1	Regression	72.796	8	9.099	5.768	0.006 ^b
	Residual	15.776	10	1.578		
	Total	88.571	18			

a. Dependent Variable: Yield

b. Predictors: (Constant), LGP, BRT, KMT, OS, KR, BRD, KRT, BMT

The regression coefficients further highlighted consistent patterns across districts. According to the estimated regression coefficients, Melka Balo district (Table 3.1) the variation in coffee yield (qt/ha) due to climatic variables as follow: *Belg* mean temperature (-1.335 qt/ha) had the strongest negative effect, reducing yield by ~1.34 qt/ha per unit increase, *kiremt* mean temperature (-0.191 qt/ha), onset date of rain (-0.019 qt/ha) reduced yield, whereas rainfall variables like *belg* rainy days (0.046 qt/ha), *kiremt* rainy days (0.031 qt/ha), *belg* rainfall total (0.005 qt/ha), *kiremt* rainfall total (0.010 qt/ha), length of growing period (-0.009 qt/ha).¹⁵ Thus, the regression equation can be expressed as:

$$\text{Yield} = 30.190 - 1.335X_1 - 0.191X_2 - 0.019X_3 + 0.046X_4 + 0.031X_5 + 0.005X_6 + 0.010X_7 - 0.009X_8$$

(equation 2)

In Bedeno (Table 3.2), *Belg* mean temperature (-1.049 qt/ha) and *kiremt* mean temperature (-0.817 qt/ha) both had strong negative effects, reducing yield significantly per unit increase. The onset date of rain (-0.019 qt/ha) also reduced productivity. Rainfall variables contributed positively: *belg* rainy days (0.087 qt/ha), *kiremt* rainy days (0.031 qt/ha), and *kiremt* rainfall total (0.007 qt/ha) supported yield, while *belg* rainfall total (0.001 qt/ha) had negligible impact. End date (-0.004 qt/ha) and length of growing period (-0.012 qt/ha), reflecting redundancy rather than true negative effects.¹⁶ Thus, the regression equation expressed as:

$$\text{Yield} = 42.294 - 1.049X_1 - 0.817X_2 - 0.019X_3 + 0.087X_4 + 0.031X_5 + 0.001X_6 + 0.007X_7 - 0.004X_8 - 0.012X_9$$

(equation 2)

¹⁵ Belg temperature sensitivity is strongest in Melka Balo, confirming early-season warming as a critical stressor.

¹⁶ Bedeno's yield is most supported by *kiremt* rainfall totals, highlighting main-season rainfall reliability.

In Shenen Dugo (Table 3.3), Belg mean temperature (-1.682 qt/ha) had the strongest effect among all districts, reducing yield by ~1.68 qt/ha per unit increase. Kiremt mean temperature (-0.377 qt/ha) was also negative but statistically insignificant, while onset date of rain (-0.021 qt/ha) reduced yield. While other rainfall variables contributed positively: belg rainy days (0.052 qt/ha), kiremt rainy days (0.044 qt/ha), and kiremt rainfall total (0.009 qt/ha) supported productivity, though belg rainfall total (0.001 qt/ha) was negligible. Length of growing period (-0.001 qt/ha), though correlation analysis confirmed its supportive role independently.¹⁷ Thus, the regression equation expressed as:

$$\text{Yield} = 41.612 - 1.682X_1 - 0.377X_2 - 0.021X_3 + 0.052X_4 + 0.044X_5 + 0.001X_6 + 0.009X_7 - 0.001X_8$$

(equation 2)

Overall, regression results across the three districts reinforce that rising seasonal temperatures (both belg and kiremt) are the most damaging factors for coffee yield, while rainfall reliability (rainy days and totals) plays a crucial role in sustaining productivity. Negative coefficients for onset date highlight the importance of timely rainfall onset, while the slight negative signs for LGP reflect statistical redundancy rather than true agronomic effects.

Table 3.1. Coefficients of regression analyses for the effect of rainfall and temperature characteristics on coffee yield 2007-2024

Model	Coefficients ^a		Standardized Coefficients	t	Sig.
	Unstandardized Coefficients				
	B	Std. Error	Beta		
(Constant)	30.190	21.421	-	1.409	0.189
Belg Mean Temperature (BMT)	-1.335	0.700	-0.311	-1.908	0.085
Kiremt Mean Temperature (KMT)	-0.191	1.072	-0.040	-0.178	0.862
Onset date of rain (ODR)	-0.019	0.017	-0.193	-1.126	0.286
Belg rainy day (BRD)	0.046	0.043	0.236	1.063	0.313
Kiremt rainy day (KRD)	0.031	0.047	0.090	0.659	0.525
Belg rainfall total (BRFT)	0.005	0.006	0.227	0.902	0.388
Kiremt rainfall total (KRFT)	0.010	0.006	0.343	1.792	0.103
Length of growing period (LGP)	-0.009	0.009	-0.162	-1.019	0.332

¹⁷ Shenen Dugo shows the highest belg temperature sensitivity, suggesting localized vulnerability to warming during early growth stages.

a. Dependent Variable: Yield

Table 3.2 Coefficients of regression analyses for the effect of rainfall and temperature characteristics on coffee yield 2007-2025

Model	Coefficients ^a				
	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
(Constant)	42.294	53.488	-	0.791	0.452
Belg Mean Temperature (BMT)	-1.049	1.803	-0.168	-0.582	0.577
Kiremt Mean Temperature (KMT)	-0.817	1.283	-0.182	-0.637	0.542
Onset date of rain (ODR)	-0.019	0.020	-0.148	-0.971	0.360
End date of rain (EDR)	-0.004	0.019	-0.055	-0.229	0.825
Belg rainy day (BRD)	0.087	0.065	0.246	1.344	0.216
Kiremt rainy day (KRD)	0.031	0.048	0.147	0.631	0.546
Belg rainfall total (BRFT)	0.001	0.006	0.032	0.145	0.888
Kiremt rainfall total (KRFT)	0.007	0.008	0.359	0.811	0.441
Length of growing period (LGP)	-0.012	0.017	-0.170	-0.689	0.510

a. Dependent Variable: Yield

Table 3.3. Coefficients of regression analyses for the effect of rainfall and temperature characteristics on coffee yield 2007-2025

Model	Coefficients ^a				
	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
(Constant)	41.612	36.986	-	1.125	0.287
Belg Mean Temperature (BMT)	-1.682	1.524	-0.351	-1.103	0.296
Kiremt Mean Temperature (KMT)	-0.377	1.346	-0.099	-0.280	0.785
Onset date of rain (ODR)	-0.021	0.017	-0.221	-1.230	0.247
Belg rainy day (BRD)	0.052	0.039	0.243	1.323	0.215
Kiremt rainy day (KRD)	0.044	0.031	0.258	1.422	0.185
Kiremt rainfall total (KRT)	0.009	0.006	0.494	1.663	0.127
Belg rainfall total (BRT)	0.001	0.007	0.056	0.165	0.872
Length of growing period (LGP)	-0.001	0.010	-0.011	-0.067	0.948

a. Dependent Variable: Yield

3.3. Projected Climate Trends and Future Coffee Yield

Projection analyses indicated a steady decline in coffee productivity across the study areas from 2026 to 2055, driven primarily by rising seasonal temperatures, later onset of

rainfall, shortened growing periods, and reduced rainy days. In Melka Belo, mean annual temperature is projected to rise from 21.25 °C to 22.14 °C, while annual rainfall declines from 980 mm to 706 mm (2026–2055). Belg rainfall decreases sharply from 493 mm to 220 mm (~9 mm per year, ~90 mm per decade), though with mid-term fluctuations (e.g., 621 mm in 2037, 837 mm in 2044, and lows of 145 mm in 2045) (Table 4.1). Kiremt rainfall totals remain relatively stable but highly variable, with peaks of 854 mm in 2047 and lows of 368 mm in 2051.¹⁸ The onset of belg rainfall is projected to be delayed, increasing from 102 days in 2026 to 138 days in 2055 (~1.2 days per year, ~12 days per decade). The end date shifts earlier by ~2 days per decade, shortening the effective rainy season. Consequently, the length of the growing period decreases from 208 days in 2026 to 111 days in 2055 (~3 days per year, ~30 days per decade).¹⁹

Projected belg mean temperature rises from 21.82 °C in 2026 to 22.96 °C in 2055 (+1.14 °C over 30 years, ~0.038 °C per year, ~0.38 °C per decade). Kiremt mean temperature rises from 20.69 °C to 21.33 °C (+0.64 °C, ~0.021 °C per year, ~0.21 °C per decade). Mean annual temperature increases steadily by ~0.02–0.03 °C per year (~0.2–0.3 °C per decade).²⁰ As a result, coffee yield in Melka Balo is projected to decline steadily. Reductions are modest in the early decades (4.75 qt/ha in 2026), but intensify toward mid-century, falling to 1.86 qt/ha in 2055 (~0.096 qt/ha per year) (Table 4.1). This confirms that climate variability and warming trends pose a significant threat to coffee production in the district.²¹

Bedeno district (Table 4.2): mean annual temperature 19.9-20.9 °C and rainfall 741.01-1002mm projected from 2026-2055. The result of projected belg and annual rainfall totals in Bedeno district indicated a slight but unstable decline. Belg rainfall decreases from 493

¹⁸ Annual rainfall decline is driven mainly by belg season reductions, underscoring the vulnerability of early-season water supply.

¹⁹ Delayed onset and earlier cessation shorten the growing period, reducing the window for coffee flowering and bean development.

²⁰ Temperature increases, though modest annually, accumulate to significant stress levels over decades, particularly during Belg.

²¹ Yield decline projections highlight the combined effect of rainfall timing and temperature rise, reinforcing the need for adaptation strategies.

mm in 2026 to 200 mm in 2055, equivalent to ~9.8 mm per year (~98 mm per decade), though with sharp fluctuations (e.g., 510 mm in 2037, 832 mm in 2034, and lows of 103 mm in 2044). Kiremt rainfall totals remain highly variable, ranging from 183 mm in 2046 to 833 mm in 2034, a swing of nearly 650 mm, but the long-term trend is slightly downward (~5 mm per year). Consequently, annual rainfall totals decrease from 802 mm in 2026 to 558 mm in 2055, a reduction of ~4.8 mm per year (~48 mm per decade). Similarly, the onset of belg rainfall is projected to be delayed, increasing from 76 days in 2026 to 100 days in 2055, i.e. ~0.8 days per year (~8 days per decade). The end date of rainfall fluctuates between 246 days (most years) and 355 days (2046), showing instability in seasonal timing. However, the end date of rainfall shifts earlier by ~ 3.4 days per year. Consequently, the length of the growing period decreases sharply, from 259 days in 2026 to 50 days in 2055, a reduction of ~6 days per year (~60 days per decade).

Projected belg mean temperature rises from 20.46 °C in 2026 to 21.62 °C in 2055, an increase of +1.16 °C over 30 years, equivalent to ~0.039 °C per year (~0.39 °C per decade). Kiremt mean temperature rises from 19.30 °C in 2026 to 20.28 °C in 2055, an increase of +0.98 °C, or ~0.032 °C per year (~0.44 °C per decade) and annual 0.03 °C per year (Table 4.1). In the future, due to the combined impacts of rising temperatures, and variability in rainfall, coffee yield in Bedeno is projected to decline steadily. Yield reductions are modest in the early decades (6.27 qt/ha in 2026) (Table 4.2), but intensify toward mid-century, with productivity falling to 2.37 qt/ha in 2055, despite occasional spikes (e.g., 13.02 qt/ha in 2034, 8.80 qt/ha in 2042). This confirms that climate variability and warming trends pose a significant threat to coffee production in the district.

In Shenen Dugo (Table 4.3): mean annual temperature is projected to rise from 20.64-21.61 °C and while annual rainfall declines from 835 mm in 2026 to 698 mm in 2055. Belg rainfall decreases from 366 mm to 255 mm (~3.7 mm per year, ~37 mm per decade), though with sharp fluctuations (e.g., 461 mm in 2032, 565 mm in 2049, and lows of 142 mm in 2037). Kiremt rainfall totals also decline slightly, from 469 mm in 2026 to 442 mm in 2055 (~0.9 mm per year, ~9 mm per decade), but variability is high, with peaks of 821 mm in 2052 and lows of 172 mm in 2031. Consequently, annual rainfall totals decrease

from 835 mm to 698 mm, a reduction of ~4.6 mm per year (~46 mm per decade). Similarly, the onset of belg rainfall is projected to be delayed, increasing from 111 days in 2026 to 130 days in 2055, i.e. ~0.7 days per year (~6–7 days per decade). The end date of rainfall fluctuates between 249 days (most years) and 360 days (2043), showing instability in seasonal timing. However, shifts earlier by ~3.7 days per year. Consequently, the length of the growing period decreases from 138 days in 2026 to 119 days in 2055, a reduction of ~0.65 days per year (~6–7 days per decade).

Projected belg mean temperature rises from 21.20 °C in 2026 to 22.26 °C in 2055, an increase of +1.06 °C over 30 years, equivalent to ~0.035 °C per year (~0.35 °C per decade). Kiremt mean temperature rises from 20.08 °C in 2026 to 20.96 °C in 2055, an increase of +0.88 °C, or ~0.029 °C per year (~0.29 °C per decade) an increase of 0.032 °C per year for annual temperature show significant upward trends. In the future, due to the combined impacts of rising belg and kiremt mean temperatures, delayed onset of rainfall, shortened growing periods, and declining rainfall totals, coffee yield in Shenen Dugo is projected to decline steadily. Yield reductions are modest in the early decades (5.69 qt/ha in 2026), but intensify toward mid-century, with productivity falling to 2.63 qt/ha in 2055, despite occasional spikes (e.g., 7.09 qt/ha in 2032, 10.98 qt/ha in 2052). This confirms that climate variability and warming trends pose a significant threat to coffee production in the district.

Table 4.1. The predicted coffee yield based on projected rainfall and temperature characteristics

year	X1	X2	X3	X4	X5	X6	X7	X8	Yield (qt/ha)
2030	22.12	22.05	99	38	46	646.7	367.92	189	3.25
2035	22.32	22.37	99	39	46	644.9	362.84	190	2.90
2040	22.38	22.46	101	38	48	648.3	359.02	184	2.81
2045	22.41	22.52	107	36	50	646.5	356.95	187	2.56
2050	23.01	23.07	108	35	51	638.8	366.31	170	1.82
2055	23.12	23.15	108	35	50	638.5	344.51	170	1.41

X1: Belg Mean Temperature; X2: Kiremt Mean Temperature; X3: Onset of Rainy Season; X4: Belg Rainy Day; X5: Kiremt Rainy Day; X6: Kiremt Rainfall Total; X7: Belg Rainfall Total; X8: Length of the Growing Period

Table 4.2. The predicted coffee yield based on projected rainfall and temperature characteristics at the study area

Year	X1	X2	X3	X4	X5	X6	X7	X8	X9	Yield (qt/ha)
2030	22.57	22.64	96	288	35	43	625.1	348.9	192	3.60
2035	22.85	22.92	95	293	35	42	618.1	344.5	199	2.92
2040	22.98	22.97	99	292	36	42	620.3	344.3	193	2.84
2045	22.94	23.47	99	286	32	45	614.3	342.7	187	2.27
2050	23.43	23.61	101	284	32	47	610.6	332.0	183	1.69
2055	23.56	23.65	100	286	32	47	610.4	330.5	186	1.49

X1: Belg Mean Temperature; X2: Kiremt Mean Temperature; X3: Onset of Rainy Season; X4: End Date of Rainy Season; X5: Belg Rainy Day; X6: Kiremt Rainy Day; X7: Kiremt Rainfall Total; X8: Belg Rainfall Total; X9: Length of the Growing Period

Table 4.3. The predicted coffee yield based on projected rainfall and temperature characteristics at the study area

Year	X1	X2	X3	X4	X5	X6	X7	X8	YLD (qt/ha)
2030	22.17	22.32	98	34	42	616.6	324	199	3.40
2035	22.46	22.54	99	35	42	614.2	324	195	2.84
2040	22.54	22.57	102	34	46	616.4	326	186	2.78
2045	22.61	22.72	106	32	45	618.3	324.4	181	2.40
2050	23.02	23.03	109	32	46	615.4	320.5	180	1.54
2055	23.06	23.26	109	32	46	606.2	318.4	178	1.30

X1: Belg Mean Temperature; X2: Kiremt Mean Temperature; X3: Onset of Rainy Season; X4: Belg Rainy Day; X5: Kiremt Rainy Day; X6: Kiremt Rainfall Total; X7: Belg Rainfall Total; X8: Length of the Growing Period

4. Discussion

4.1 Climatic Determinants of Coffee Yield

Rainfall reliability measured through rainy days and seasonal totals consistently supported coffee yield across Melka Balo, Bedeno, and Shenen Dugo. Rising belg and kiremt mean temperatures showed strong negative correlations, confirming warming as the dominant stressor. These findings align with earlier studies [39, 40], which emphasized rainfall's supportive role and drought as a major limitation.

Regression models confirmed the significant influence of climate variables, strongest in Melka Balo ($R^2 = 0.922$), moderate in Bedeno ($R^2 = 0.897$), and weaker in Shenen Dugo ($R^2 = 0.822$). The lower adjusted values in Shenen Dugo highlight multicollinearity challenges, particularly between rainfall end date and length of growing period [41]. Negative coefficients for *belg* and *kiremt* mean temperatures were consistent across districts, while rainfall totals and rainy days contributed positively. These results echo

broader Ethiopian studies [42–44], which emphasized rainfall timing, growing period length, and bimodal rainfall systems shaping planting cycles. Globally, Arabica's narrow climatic tolerance has been confirmed, with warming trends exerting profoundly negative influences [45, 46].

4.2 Rainfall Patterns and Seasonal Timing

Rainfall onset and cessation are critical for coffee flowering and maturation. Belg onset has been delayed by ~0.2–0.3 days per year, consistent with findings in Habro [42] and in Jimma and Sidama [20]. Such delays reduce synchronization between rainfall and coffee phenology, leading to poor flowering and lower yields. Delayed onset, which can shorten the growing period for coffee [47, 48]. End date variability, though less influential, shortens maturation; in Shenen Dugo, early cessation has been linked to reduced bean size [19]. Early cessation can lead to water stress during the latter stages of coffee development, affecting bean quality and yield [47]. The variability in rainfall onset and cessation can disrupt the phenological stages of coffee, leading to reduced yields and quality. This is particularly concerning as coffee plants require consistent water supply during flowering and fruit development stages [17, 18].

Belg rainy days emerged as the most reliable predictor of yield, with strong positive correlations ($r \sim 0.53$ – 0.81). This finding is consistent with [49], who noted that frequency of rainfall events matters more than totals for coffee physiology, as evenly distributed rains sustain soil moisture and reduce stress. Kiremt rainy days were moderately positive but less influential, as excess wetness during kiremt can increase disease incidence, particularly coffee leaf rust [14]. The trend toward fewer rainy days but heavier events reflects broader East African climate patterns, increasing risks of both drought stress and disease outbreaks. A decreasing trend in rainfall has been noted, which, coupled with temperature increases, has negatively affected coffee production [50].

Regional studies further illustrate variability. [51] Reported that increased belg rainy days enhanced productivity in Abaya and Gelana, whereas excessive kiremt rainy days often led to disease proliferation. Broader reviews [52] confirmed that rainfall variability;

including rainy day frequency is a central stressor threatening Ethiopia's coffee sector. Adaptive strategies such as rainwater harvesting and planting cycle adjustments are therefore essential to buffer against rainfall irregularity [53].

International evidence reinforces these findings: studies in Mexico, Tanzania, and Brazil all showed that rainfall timing and frequency strongly influence yield and quality [54, 55, 56]. Arabica's minimum rainfall requirement of 150 mm has been emphasized [57], while onset/cessation and rainy day frequency have been confirmed as key predictors of productivity in India and Vietnam [58, 59, 60].

4.3 Temperature Variability and Growing Periods

Belg mean temperature was the most influential variable across districts (Melka Balo: –1.335 qt/ha; Bedeno: –1.049 qt/ha; Shenen Dugo: –1.682 qt/ha). Rising *belg* and *kiremt* temperatures accelerated crop development, shortening the length of growing period (LGP) by ~0.7 days per year. This aligns with national projections of 15–20 day reductions by mid-century [61] and supports earlier findings [15], which emphasized Arabica's narrow climatic tolerance. Consistent with [12], coffee Arabica's optimum range (19–22 °C) was highlighted. Year-to-year increases (~0.03–0.04 °C) compound stress, particularly during flowering, leading to reduced fruit set. *Kiremt* warming also negatively affected yield, though slightly less severe, as cooler *kiremt* conditions partially buffered the impact. Global syntheses confirm that incremental warming across both *belg* and *kiremt* seasons will progressively erode Arabica suitability in Ethiopia [62].

Broader Ethiopian studies confirm these trends: continued rises in mean annual temperatures [63], increases in maximum and minimum temperatures compressing the diurnal range [64], and rising temperatures during critical growth periods adversely affecting yield and quality [43,65]. Spatiotemporal analyses further highlight localized variability, showing that temperature trends are not uniform but vary with land use and regional dynamics [66, 67].

Agronomic practices can partly mitigate these effects. For example, topping and vertical number management influenced growth and yield [68], while optimizing population density and pruning enhanced productivity [69]. These interventions suggest that management practices can extend or stabilize effective LGP, counteracting climatic constraints.

Globally, warm nights combined with rainfall events were found to influence flowering and ripening in Tanzania [70], while Robusta coffee yield sensitivity to altered flowering times under climate stress was demonstrated [71]. These parallels reinforce coffee Arabica's vulnerability to warming trends, where even modest increases in mean temperature can significantly reduce productivity.

4.4 Projected Climate Trends and Future Coffee Productivity

Across the study districts, climate projections reveal a marked reduction in the growing period from approximately 259 days to as few as 150 days in lowland areas. These shortened cycles reduce the time available for fruit maturation, leading to lower yields and compromised bean quality. Such contractions confirm that climate variability will not only reduce productivity but also destabilize the reliability of coffee harvests. These findings are consistent with earlier studies [72,19], which reported shrinking Arabica suitability in East Africa and emphasized that deviation from normal *kiremt* rainfall increases vulnerability among rain-fed farmers. The erratic rainfall patterns documented in the Kafa Zone mirror the instability observed in Bedeno and Shenen Dugo, reinforcing the broader trend of climatic unpredictability [64].

At the national scale, projected coffee productivity in Ethiopia is significantly shaped by ongoing and future climate change, with multiple studies highlighting both challenges and opportunities. Climatic conditions critically affect coffee suitability, with warmer conditions altering exposure to climate stresses and reducing yields [12]. Rainfall and temperature variability analyses in Habro district found that declining rainfall and shortened growing periods directly reduce productivity, with weakening *kiremt* rainfall underscoring

vulnerability [42]. Broader projections emphasize that climate trends could further diminish productivity, particularly in regions with ideal agroecological conditions [52], while persistent productivity gaps between potential and actual yields have been documented [73]. Together, these findings highlight the urgency of adaptation strategies to counteract climate-related declines and close Ethiopia's long-standing yield gap.

Modeling studies provide further insight into spatial shifts. Future scenarios could alter the distribution of suitable coffee growing areas in Jimma Zone [61], while projections of temperature increases of 2.6–4.8 °C across East Africa threaten both yield quantity and quality [72]. Climate analogue mapping similarly indicated that future conditions may shift optimal production zones, necessitating breeding programs for resilience and climate-smart agronomy [75]. Emerging evidence also points to potential opportunities: projected changes in bioclimatic suitability could enhance productivity in certain regions if adaptation measures are implemented [76]. Likewise, specialty coffee cultivation under changing climates may expand or shift, creating new market opportunities [15]. Similar projections reinforce Ethiopia's vulnerability, as Arabica's narrow climatic tolerance has long been emphasized [45], while even modest shifts in rainfall and temperature regimes could destabilize coffee systems [71]. These parallels highlight that Ethiopia's challenges are part of a wider global crisis in Arabica coffee production.

Given the projected decline in productivity, adaptation strategies are essential. Agronomic practices such as pruning, shade management, mulching, and soil moisture conservation can help buffer against climatic stress, combined with rainwater harvesting [53], use of drought-tolerant varieties, and intercropping with shade trees — all critical to sustain yields.

5. Adaptation Pathways and Policy Relevance

Projected declines in coffee productivity under rising seasonal temperatures and variable rainfall underscore the urgency of adaptation. In East and West Hararghe, coffee management practices such as pruning, mulching, and composting have declined due to the expansion of khat (*Catha edulis* FRISK), which requires less management and

provides short-cycle income. This shift highlights the need to re-invest in coffee adaptation strategies to sustain productivity and livelihoods.²²

Recommended measures

- Expanding coffee production to higher altitudes where cooler conditions buffer against warming²³
- Growing suitable shade trees to reduce heat stress and diversify income
- Strengthening farmer knowledge through participatory training and extension support
- Rainwater harvesting and improved water management
- Introduction of drought and high-temperature-tolerant coffee varieties
- Implementing soil and water conservation practices

Policy relevance

Policy interventions are essential to sustain Ethiopia's coffee sector, particularly in vulnerable areas such as East and West Hararghe where rainfall variability and warming trends are most pronounced. Strengthening extension services, promoting climate-smart agriculture programs, and supporting farmer training and institutional capacity will be critical to safeguard livelihoods and maintain Ethiopia's export potential.²⁴

6. Conclusion

This study provides robust evidence that rainfall reliability is a key driver of coffee yield in eastern Ethiopia, while rising belg and kiremt temperatures consistently undermine productivity. Correlation and regression analyses confirmed that delayed rainfall onset, shortened growing periods, and warming trends exert significant negative effects, whereas reliable rainy days and seasonal rainfall totals enhance yield. Future projections (2026–2055) indicate declining belg rainfall totals (~3.7–9.8 mm per year), modest reductions in kiremt rainfall (~0.5–9 mm per year), delayed onset (0.7–1.2 days per year), earlier cessation (2–4 days per year), and shortened growing periods (~0.7–6 days per

²² The expansion of khat reflects short-term income priorities but undermines long-term resilience of coffee systems.

²³ Altitude migration is a proven adaptation pathway, as cooler microclimates mitigate heat stress on Arabica coffee.

²⁴ Policy support ensures adaptation measures are scaled, institutionalized, and aligned with Ethiopia's export strategy.

year). Mean temperatures are expected to rise steadily (0.02–0.04 °C per year), leading to an average productivity decline of ~0.09–0.10 qt/ha annually. The importance of these findings lies in their direct relevance to Ethiopia’s coffee sector, which underpins rural livelihoods and national export earnings. By quantifying the sensitivity of Arabica yield to rainfall and temperature variability, this study highlights the vulnerability of Ethiopia’s globally prized coffee to climate change. The relevance to the field is twofold. First, it demonstrates how localized climate analyses can reveal district-specific risks, emphasizing the need for site-specific adaptation strategies. Second, it underscores the broader implications for climate–agriculture research: rising temperatures and shifting rainfall regimes threaten staple export crops, with cascading effects on food security, income stability, and global supply chains. Therefore, anticipatory adaptation measures including climate-resilient agronomic practices, improved water management, and high temperature-tolerant coffee varieties are urgently needed. At the policy level, integrated climate strategies, strengthened extension services, and investment in institutional capacity will be essential to safeguard livelihoods, stabilize production, and sustain Ethiopia’s competitiveness in Arabica coffee under changing climatic conditions.

7. Declaration

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7.3 Author contribution

Aliyi Jemal: Conceptualization, data collection, data analysis, manuscript drafting.

Zelalem Bekeko: Guidance on methodology, data interpretation, and manuscript revision.

Abdi Mohammed: Contributions to logistics support during data collection, manuscript revision, and final approval.

Abdulatif Ahmad: Manuscript revision, and final approval.

Bulti Tesso: Manuscript revision, and final approval.

7.4 Competing Interest

The authors declare that they have no competing interests

7.5 Ethics approval and consent to participate

Not applicable. Because does not involve human participants, animal subjects, or tissue samples

7.6 Consent for publication

Not applicable.

7.7. Data availability

All data supporting the findings of this study are publicly available from their respective sources. Downscaled rainfall and temperature projections were derived from the Coupled Model Intercomparison Project Phase 6 (CMIP6) under the SSP2-4.5 scenario, accessed via the Earth System Grid Federation (ESGF) portal: <https://esgf-node.llnl.gov/projects/cmip6/>. Historical rainfall, temperature, and yield records were obtained from the National Meteorological Agency (NMA) and District Agricultural Offices and are available from the corresponding author upon request.

8. References

1. Grüter R, Trachsel T, Laube P, Jaisli I (2022) Expected global suitability of coffee, cashew, and avocado due to climate change. *PLoS One* 17:1–24. doi:10.1371/journal.pone.0261976
2. Mulinde C, Majaliwa JGM, Twinomuhangi R et al. (2022) Projected climate in coffee-based farming systems: Implications for crop suitability in Uganda. *Reg Environ Change* 22(83):1–19. doi:10.1007/s10113-022-01930-2

3. PdS T, Giarolla A, Chou SC, Silva AJP, Lyra AA (2018) Climate change impact on the potential yield of Arabica coffee in Southeast Brazil. *Reg Environ Change* 18:873–883. doi:10.1007/s10113-017-1236-z
4. IPCC (2022) *Climate Change 2022: Impacts, Adaptation, and Vulnerability*. Cambridge University Press, Cambridge.
5. Gebrehiwot B, Gessesse B, Melgani F (2019) Characterizing the spatiotemporal distribution of meteorological drought as a response to climate variability: The case of Rift Valley Lakes Basin of Ethiopia. *Weather Clim Extremes* 26:100237. doi:10.1016/j.wace.2019.100237
6. USAID (2022) Climate change impacts on Ethiopia's coffee sector. *J Coffee Sustain* 1:1–45
7. FAO (2021) *The State of Food and Agriculture 2021*. Food and Agriculture Organization of the United Nations, Rome. doi:10.4060/cb4476en
8. Wakweya RB (2025) Impacts of climate change on crop production and food security in Ethiopia. *Discov Sustain* 6:158. doi:10.1007/s43621-025-00830-9
9. Ouko J (2021) Climate change impacts on rain-fed agriculture in East Africa. *Environ Res Lett* 16(12):124012. <https://doi.org/10.13140/RG.2.2.15009.74082>
10. ICO (International Coffee Organization) (2023) Coffee Market Report. ICO, London. Available at: <https://www.icocoffee.org>
11. Minten B, Tamru S, Kuma T (2014) Coffee value chains on the move: Evidence from Ethiopia. *Food Policy* 47:117–130. doi:10.1016/j.foodpol.2014.05.001
12. Moat J, Williams J, Baena S, Wilkinson T, Gole TW, Challa ZK, Davis AP (2017) Resilience potential of the Ethiopian coffee sector under climate change. *Nat Plants* 3(8):17081. doi:10.1038/nplants.2017.81
13. Etana D, Merga D (2023) The current climate change impacts in Arabica coffee production and mitigation option in case of Ethiopia: A review. *Int J Environ Monit Anal* 11(4):80–88. doi:10.11648/j.ijema.20231104.11
14. Benti DB, Tack A, Nemomissa S, Lemessa D, Dullo BW, Hylander K (2023) Prevalence of major pests and diseases in wild and cultivated coffee in Ethiopia. *Basic Appl Ecol* 73(1). doi:10.1016/j.baae.2023.06.005
15. Chemura A, van der Velde M, van Ittersum M (2021) Climate change and Arabica coffee: Impacts and adaptation. *Clim Change* 166(1–2):59–73. doi:10.1007/s10584-021-03104-6

16. Megerssa GR, Garedew W, Jespersen K, Grabs J, Bekele AE (2025) Impact of climate change on Ethiopian Arabica coffee production and current challenges it poses to the coffee value chain. *Sustain Futures* 10:101459. doi:10.1016/j.sftr.2025.101459
17. Zerihun J (2023) Climate variability and its implications on the production of Arabica coffee in Abe Dongoro district of Horro Guduru Wollega zone, Oromia, Ethiopia. doi:10.20372/afnr.v11i1.625
18. Mamuye M, Gallemore C, Jespersen K, Kasongi N, Berecha G (2024) Changing rainfall and temperature trends and variability at different spatiotemporal scales threaten coffee production in certain elevations. *Environ Challenges* 15:100950. doi:10.1016/j.envc.2024.100950
19. Wakjira MT (2024) Understanding the impacts of climate variability and change on rainfed crop production in Ethiopia. doi:10.3929/ethz-b-000672129
20. Tsega ZN et al. (2022) Climate variability on coffee yield and adaptation strategies in Gomma district, Jimma zone of Oromia national region, Ethiopia. Haramaya University Repository.
21. Central Statistical Agency of Ethiopia (CSA) (2024) Agricultural sample survey: Area and production of major crops. CSA official website. Available at: <https://www.csa.gov.et> Accessed 19 Nov 2025
22. Kibret K, Solomon A, Husein A, Abdulaziz T (2023) Assessment of coffee production and marketing system in East Hararghe Zone of Oromia Region, Ethiopia. *Glob J Agric Sci* 23: Article 103636. doi:10.15651/2408-6886.23.11.019
23. Hailu A, Kedir K (2024) Analysis of Arabica coffee production trend and major production constraints in East and West Hararghe Zones, Ethiopia. *J Coffee Sustain* 1(3):129–145. doi:10.21776/ub.jcs.2024.01.03.05
24. Aliyi I, Yusuf Z, Petros Y (2025) On farm diversity, farmers' practices and status of genetic erosion of Harar coffee (*Coffea arabica* L.). *Discov Life* 55(23). doi:10.1007/s11084-024-09672-3
25. Tesfaye G, Woldemariam T, Tenywa M, Kansiime F (2010) Predicting climate change impacts on the distribution of *Coffee arabica* in Ethiopia.
26. Eyring V, Bony S, Meehl GA, Senior CA, Stevens B, Stouffer RJ, Taylor KE (2016) Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6). *Geosci Model Dev* 9(5):1937–1958. doi:10.5194/gmd-9-1937-2016

27. O'Neill BC, Tebaldi C, Sanderson BM, et al. (2017) The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP6. *Geosci Model Dev* 9(9):3461–3482. doi:10.5194/gmd-9-3461-2016
28. Alaminie AA, Tilahun SA, Legesse SA, Zimale FA, Tarkegn GB, Jury MR (2021) Evaluation of past and future climate trends under CMIP6 scenarios for the UBNB (Abay), Ethiopia. *Water* 13(15). doi:10.3390/w13152110
29. Kuhlbrodt T, Jones CG, Sellar A, Storkey D, Blockley E, Stringer M, Hill R, Graham T, Ridley J, Blaker A et al. (2018) The low resolution version of HadGEM3 GC3.1: Development and evaluation for global climate. *J Adv Model Earth Syst* 10(11):2865–2888. doi:10.1029/2018MS001370
30. Seland Ø, Bentsen M, Olivie D, Toniazzo T, Gjermundsen A, Graff LS et al. (2020) Overview of the Norwegian Earth System Model (NorESM2) and key climate response of CMIP6 DECK, historical, and scenario simulations. *Geosci Model Dev* 13(12):6165–6200. doi:10.5194/gmd-13-6165-2020
31. Bitew AB, Minale AS (2025) Evaluation of past and future trends of temperature and rainfall under CMIP6 scenarios for the Ayehu watershed, Upper Blue Nile Basin, Ethiopia. *J Water Clim Change* 16(6):2153–2184. doi:10.2166/wcc.2025.03
32. Gebrechorkos SH, Hülsmann S, Bernhofer C (2019) Long-term trends in rainfall and temperature using high-resolution climate datasets in East Africa. *Sci Rep* 9:11376. doi:10.1038/s41598-019-47933-8
33. Dinku T, Faniriantsoa R, Cousin R, Khomyakov I, Vadillo A, Hansen JW, Grossi A (2022) ENACTS: Advancing climate services across Africa. *Front Clim* 3:787683. doi:10.3389/fclim.2021.787683
34. Yang W, Seager R, Cane M (2014) The East African long rains in observations and models. *J Clim* 27:7185–7202
35. Segele ZT, Lamb PJ (2005) Characterization and variability of *Kiremt* rainy season over Ethiopia. *Meteorol Atmos Phys* 89:153–180
36. Hadgu G, Tesfaye K, Mamo G, Kassa B (2013) Trend and variability of rainfall in Tigray, Northern Ethiopia: Analysis of meteorological data and farmers' perception. *Acad J Environ Sci* 1:159–171
37. Jones PG, Thornton PK (2013) Generating down-scaled weather data from a suite of climate models for agricultural modeling applications. *Agric Syst* 114:1–5
38. Odekunle TO, Orinmoogunje IO, Ayalande A (2007) Application of GIS to assess rainfall variability impact on crop yield in Guinea Savanna part of Nigeria. *J Biotechnol* 6:2100–2113
39. Koge T (2019) Rainfall variability and coffee productivity in Ethiopia. *Ethiop J Agric Sci* 29(1):77–89

- 844 40. Legesse A (2019) Climate variability and coffee production challenges in Ethiopia. *J*
- 845 *Agric Res Dev* 11(2):45–56
- 846
- 847 41. Regassa G, Gebisa T (2024) Multicollinearity challenges in climate–yield regression
- 848 models: Evidence from Ethiopian coffee districts. *J Clim Agric* 12(2):145–158
- 849
- 850 42. Gizaw W, Mengesha M, Nigatu L (2021) Analysis of rainfall and temperature
- 851 variability impacts on coffee productivity in Habro District, West Harerghe Zone,
- 852 Eastern Ethiopia. *J Climatol Weather Forecast* 9:283
- 853
- 854 43. Nigussie Z (2024) Climate and coffee production in Ethiopia: A review. *Int J Energy*
- 855 *Environ Sci* 9(5):98–106. doi:10.11648/j.ijees.20240905.12
- 856
- 857 44. Mulugeta T, Alemayhu G, Ademe D, Mohamed A, Tadele A, Kassaye (2026)
- 858 Spatiotemporal variability and trends in rainfall and temperature and their
- 859 implications for rain-fed crop production in Wollo and the Oromia Special Zone,
- 860 Northeastern Ethiopian Highlands. *Theor Appl Climatol* 157:220.
- 861 doi:10.1007/s00704-026-06131-z
- 862
- 863 45. Davis AP, Gole TW, Baena S, Moat J (2012) The impact of climate change on
- 864 indigenous Arabica coffee (*Coffea arabica*): Predicting future trends and identifying
- 865 priorities. *PLoS One* 7(11):e47981. doi:10.1371/journal.pone.0047981
- 866
- 867 46. Jaramillo J, Muchugu E, Vega FE, Davis A, Borgemeister C, Chabi-Olaye A (2011)
- 868 Climate change or coffee crisis? Predicted impact of climate change on coffee
- 869 supply. *Clim Change* 105(1–2):163–179. doi:10.1007/s10584-010-9881-4
- 870
- 871 47. Omay PO, Muthama NJ, Oludhe C, Kinama JM, Artan G, Atheru Z (2024) Changes
- 872 and variability in rainfall onset, cessation and length of rainy season in the IGAD
- 873 region of Eastern Africa. doi:10.60692/h175q-9rb93
- 874
- 875 48. Tesema TG, Bimrew G, Aniley E, Wubu T, Asaye TS (2025) Analysis and future
- 876 rainfall characteristics of the main rainy season over western region, Ethiopia.
- 877 *Preprints*. doi:10.20944/preprints202508.0898.v1
- 878
- 879 49. Legese EB, Diga GM, Tolossa AR et al (2026) Spatiotemporal analysis of extreme
- 880 precipitation and temperature variability, trends, and vulnerability hotspots in coffee
- 881 growing districts of Ilubabor zone, Ethiopia. *Theor Appl Climatol* 157:205.
- 882 doi:10.1007/s00704-026-06081-6
- 883
- 884 50. Leta Jima Desta (2023) Analysis of climatic change and variability and its effect on
- 885 coffee production in Mattu District, Southwest Ethiopia. *Sustain Clim Change*.
- 886 doi:10.1089/scc.2023.0091
- 887
- 888 51. Deresse T, Tolessa T, Mamo S, Bohnett E, Engdaw D (2025) Spatiotemporal trends
- 889 of climate change and variability: Impacts on coffee production in Abaya and Gelana

- Woredas, Southern Ethiopia. *Environ Monit Assess*. doi:10.1007/s10661/025/14414-7
52. Bekele TT (2025) Climate change impacts and adaptation strategies for Ethiopia's coffee sector: A review. *J Coffee Sustain* 2(1):48–58. doi:10.21776/ub.jcs.2025.02.01.05
53. Ayala G, Muleta B, Bulti A (2022) Evaluation of in situ rain water harvesting as an adaptation strategy to climate change for coffee production in Daro Lebu district, West Harerghe, Oromia, Ethiopia. *Irrig Drain Syst Eng* 11. doi:10.37421/2168-9768.2022.11.359
54. Parada PC, Carlos R, Perez CJC (2025) Impact of climate on water status, growth, yield, and phenology of coffee (*Coffea arabica*) plants in the central region of the state of Veracruz, Mexico. *PLoS One* 20(4). doi:10.1371/journal.pone.0319670
55. Wagner S, Jassogne L, Price E, Jones M, Preziosi R (2021) Impact of climate change on the production of *Coffea arabica* at Mt. Kilimanjaro, Tanzania. *Agriculture* 11(1):53. doi:10.3390/agriculture11010053
56. Soares LD, Rezende TT, Beijo LA, Silva K (2021) Interaction between climate, flowering and production of dry coffee (*Coffea arabica* L.) in Minas Gerais. *Coffee Sci* 16:e161786. doi:10.25186/v16i.1786
57. Torres GAL, Campos C, Salomon MV, Almeida J, Pantano AP (2021) *Coffea arabica* L: History, phenology and climatic aptitude of the state of São Paulo, Brazil. *Arq Inst Biol* 88. doi:10.1590/1808-1657000602020
58. Patil S, Devasia J, Daniel G, Rao NSP (2022) Influence of elevation and rainfall on leaf growth, bean characteristics and yield components of Arabica and Robusta coffee under changing climatic conditions in Karnataka state, India. *J Plant Crops* 50(2):78–84. doi:10.25081/jpc.2022.v50.i2.7981
59. Kouadio L, Tixier P, Byrareddy VM, Marcssen T, Mushtaq S, Rapidel B, Stone R (2021) Performance of a process-based model for predicting Robusta coffee yield at the regional scale in Vietnam. *Ecol Model* 443:109469. doi:10.1016/j.ecolmodel.2021.109469
60. Dinh TLA, Aires F, Rahn E (2022) Statistical analysis of the weather impact on Robusta coffee yield in Vietnam. *Front Environ Sci* 10:820916. doi:10.3389/fenvs.2022.820916
61. Chalchissa FB, Lemessa DT, Megersa TT (2022) Modeling the responses of coffee (*Coffea arabica* L.) distribution to current and future climate change in Jimma Zone, Ethiopia. *Soil Sci Agroclimatol J* 19(1):1–12. doi:10.20961/stjssa.v19i1.54885

62. Richardson D, Kath J, Byrareddy VM, Monselesan DP, Risbey JS, Squire DT et al (2023) Synchronous climate hazards pose an increasing challenge to global coffee production. *PLoS Clim* 2(3):e0000134. doi:10.1371/journal.pclm.0000134
63. Alemayehu ZY, Minale AS, Legesse SA (2022) Spatiotemporal rainfall and temperature variability in Suha watershed, Upper Blue Nile Basin, Northwest Ethiopia. *Environ Monit Assess* 194(8). doi:10.1007/s10661-022-10165-x
64. Amsalu A, Tizazu A, Bedhadha ST, Gameda DS (2026) Spatiotemporal trends in temperature and rainfall within the Coffea arabica landscapes of Gimbo and Decha districts in the Kafa Zone, Southwest Ethiopia. *Sci Rep*. doi:10.1038/s41598-026-54593-y
65. Tashebo GB, Zeleke TT, Cholo BE (2026) Spatiotemporal variability and trends of precipitation and temperature in relation to sea surface temperature teleconnections over Central Ethiopia's regional state. *Ethiop J Water Sci Technol* 12(2):77–95. doi:10.1234/ejwst.2026.850
66. Engda A, Yimer F, Mekuyie M, Tadesse M (2024) Spatiotemporal analysis of climate variability and trends in West Arsi Zone, South Central Ethiopia. *Adv Meteorol* 2024:1–14. doi:10.1155/adme/8708922
67. Bikeko SS, Venkatesham E (2024) Land use land cover change as a causal factor for climate variability and trends in the Bilate watershed, Ethiopia. *Environ Monit Assess* 196(3):1250. doi:10.1007/s10661-024-13435-y
68. Gebisa LA (2023) Effects of vertical number and topping practice on growth and yields of stumped coffee (Coffea arabica L.) at Awada, South Ethiopia. *Am J Plant Biol* 8(1):1–5. doi:10.11648/j.ajpb.20230801.11
69. Yilma A, Kejela A, Tamirat W, Etana D, Beza T, Kufa T, Aman M, Woldemichael (2023) Determination of appropriate population density and pruning methods for hybrid coffee in Southwest Ethiopia. In: Proceedings of Crops Improvement and Management Research Results, pp 294–304
70. Craparo ACW, Van Asten PJA, Läderach P, Jassogne LT, Grab SW (2021) Warm nights drive Coffea arabica ripening in Tanzania. *Int J Biometeorol* 65:181–192. doi:10.1007/s00484-020-02016-6
71. Kath J, Byrareddy VM, Reardon-Smith K, Mushtaq S (2023) Early flowering changes Robusta coffee yield responses to climate stress and management. *Sci Total Environ* 856(Pt 1):158836. doi:10.1016/j.scitotenv.2022.158836
72. Lemma DT, Megersa TT (2021) Impact of climate change on East African coffee production and its mitigation strategies. *World J Agric Sci* 17(2):81–89. doi:10.5829/idosi.wjas.2021.81.89

- 981
982 73. Ayele A, Lemma DT, Megersa TT (2021) Trend, instability and decomposition
983 analysis of coffee production in Ethiopia (1993–2019). *Heliyon* 7(8):e08022.
984 doi:10.1016/j.heliyon.2021.e08022
985 74. Mohammed H, Girma A, Kalifa N (2021) Climate analogue mapping for coffee
986 production in Ethiopia. *Int J Afr Asian Stud* 74:25–34. doi:10.7176/JAAS/74-03
987
988 75. Adane A (2024) Analysis of current and future bioclimatic suitability for *Coffea*
989 *arabica* production in Ethiopia. *PLoS One* 19(10):e0310945.
990 doi:10.1371/journal.pone.0310945
991