Climate Variability and Coffee Yields in Brazil, Vietnam, and Ethiopia:

A Panel Data Analysis

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Abstract

Climate change poses a growing threat to agricultural production in tropical regions, where coffee cultivation is highly sensitive to temperature, precipitation, and extreme weather events. This study analyses how climate change affects coffee production in three of the world's most important coffee-producing countries: Brazil, Vietnam, and Ethiopia. Using a country-level panel dataset covering the period 1993–2023, the study examines the association between climate variables, average temperature, precipitation, and drought intensity and coffee yields. Climate exposure is measured using production-area weights of major coffee-growing regions to better capture the local agronomic conditions for coffee production. Fixed-effects panel regressions are employed to control for unobserved country-specific characteristics and global price dynamics. The findings of the study suggest that temperature has significant and robust effect on coffee yields even when controlling for other climate indicators and price variables.

Keywords: Coffee Yield, Coffee Production, Climate Change, Coffee Arabica, Coffee Robusta, Panel Fixed Effects, Supply.

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Abbreviations

Abbreviation	Description
CDD	Consecutive Dry Days
FAO	Food and Agriculture organization
Ha	Hectares
ICO	International Coffee Organisation
mm	Millimetre
USDA	The US. Department of Agriculture
WCR	World Coffee Research

1. Introduction

For many cultures around the world, coffee is a staple piece in every household kitchen. It is with a cup of hot coffee that many individuals start their day, collecting energy through their day or exchanging conversations and life stories. Coffee is a popular beverage and over 2.25 billion cups of coffee are consumed daily. Coffee stands as one of the world's most critical agricultural crops, it is the second largest traded commodity after oil and is mainly produced in developing countries.

Coffee producers, who rely on perennial cropping systems, are vulnerable to climate disruptions, since coffee cultivation requires long planning horizons and substantial upfront investment takes time to yield results. The slow establishment of coffee agroforestry systems limits farmers ability to quickly respond to climate shocks (Läderach et al. 2017). Smallholder farmers play a central role in global coffee production, with farms smaller than 5 ha supply 60% of the world´s coffee, while medium sized farms, 5-50 ha, contribute further 19% (Siles et al. 2022). Unpredictable rainfall, rising average temperatures, and more frequent extreme weather events act as negative shocks to the production process, reducing yields and threatening the economic viability of smallholder farmers, who are the most vulnerable to such disruptions (Davis et al. 2012). Furthermore USDA reports that global coffee stocks are expected to decrease in 2025/2026 for the fifth consecutive year, leading to coffee prices nearly tripling during this period (*Coffee: World Markets and Trade* 2025). Since coffee supply is price-inelastic in the short run, production cannot increase quickly in response to price increases because it takes several years for coffee trees to bear fruit. This means that even relatively small reductions in harvest volumes can lead to disproportionately large price increases on the world market (Bastianin et al. 2018). According to the World Coffee Research, WCR, the impact of adverse weather and climate shocks are threefold for coffee farmers as they are left with reduced quality on yield, reduced productivity and increased economic vulnerability (*World Coffee Research Strategy 2021-2025*. 2020.). Previous estimations show that if climate change continues on it´s current trend coffee cultivation areas could decrease by 95% (Lemma & Megersa 2021).

This study contributes by using a long-run cross-country panel dataset with the objective to examine how climate change affects coffee production within three pivotal countries: Brazil, Vietnam, and Ethiopia.

Using the theoretical lens of the production theory and by combining production-area-weighted climate indicators with yield and price data, the analysis provides a comparative assessment of climate impacts across countries with different agro-ecological conditions and coffee species, primarily Arabica and Robusta. These countries were selected due to their dominant roles in global coffee production and the differences in their agro-ecological conditions. Based on the USDA Global Market Analysis “Coffee: World Markets and Trade” (2025), Brazil is ranked as the biggest exporter and coffee production in the world, Second comes

Vietnam and on fifth place Ethiopia, after Colombia and Indonesia (*Coffee: World Markets and Trade* 2025). Vietnam and Brazil together account for 50% of the worlds coffee, with Brazil and Ethiopia predominantly producing Arabica while Vietnam is the biggest global producer of Robusta (FAO 2025). Using a country-level panel dataset covering the period of 1993–2023, the study seeks to estimate how key variables such as temperature, precipitation, and drought intensity influence annual coffee yields.

2. Background

The leading coffee producers are Brazil, Colombia, Vietnam, Indonesia and Ethiopia (Lemma & Megersa 2021), while the European Union and the United States share space as the largest consuming and importing markets, according to the Food and agricultural organization (FAO) (*Food Outlook – Biannual report on global food markets* 2025).

This global industry is fundamentally built upon the labour of millions of small-scale producers in low-income countries where coffee exports is an important source of revenue. There is more than 10 million coffee farms in the world and estimates show that about 95% of these farms are smallholdings, and these operations collectively produce a staggering 80% of the global coffee supply (*Kaffe* 2025). Not only does it create employment throughout the coffee value chain, global coffee export also helps generate foreign currency reserves which is crucial for low-income countries in order to secure access to global markets for import of goods and services (Amrouk et al. 2025).

Although it is a lucrative market, the global coffee production face an existential threat from climate changes (Lemma & Megersa 2021). The two most economically dominant species of coffee, Robusta and Arabica, make up for 99% of the global bean production. Both species are highly sensitive to temperature with Arabica requiring relatively cool and stable conditions (18-22 C) and Robusta, as the name suggests, are more robust to slightly higher temperatures (22-28 C). Deviations beyond these optimal conditions lead to reduced yields and declining bean quality (Lemma & Megersa 2021). This vulnerability is further compounded by the long productive lifespan of coffee plantations, which typically span over 30 years, exposing crops to prolonged and intensifying climate variability over time (Bunn et al. 2015a). According to FAO, major producing countries have faced production and supply difficulties in 2024 due to adverse weather and extreme climate indices. Vietnam faced prolonged drought which reduced coffee yields by approximately 20% in the 2023/2024 season, while exports declined as farmers withheld stocks amid rising domestic prices. In Brazil persistent dry and hot conditions led to downward revisions for production forecasts. These weather -related shocks, combined with rising shipping costs in 2024, exerted sustained upward pressure on global coffee prices, underscoring the sectors growing vulnerability to climate change (Amrouk et al. 2025).

The global food import bill produced by the FAO explains that climate change and adverse weather in major producing countries were the key drivers for the price surge that occurred for international prices of coffee in 2024 (*Food Outlook – Biannual report on global food markets* 2025). The prices for coffee increased in 2024 by 38% from their average level in 2023 and it is a high chance that the price for 2025 will rise even higher if key growing regions faces declines in significant production (Amrouk et al. 2025).

3. Literature review

Multiple scientific models and observations unambiguously show that rising temperatures and changed precipitation patterns already negatively affects coffee yields and diminishes suitable areas for coffee production (Davis et al. 2012). Davis et al show in their study that particularly vulnerable is Arabica coffee, the world's most widely grown species, which is highly climate sensitive and requires specific temperature ranges to produce high-quality beans (Davis et al. 2012). The same conclusion could be found in a study of Bunn et al (2015b), which estimated with global bioclimatic models a reduction in suitable sites of 65% to almost 100% by the year 2080 for both Arabica and Robusta. This threatens not only wild populations but also the crucial genetic diversity necessary to develop future climate-resilient coffee varieties (Bunn et al. 2015b). Bunn et al (2015b) also conducted agro-ecological zoning approaches, creating a nuanced understanding of climate impacts by classifying Arabica-growing regions into multiple agro-ecological zones and demonstrating that climate change affects these zones differently. Hot and dry zones are projected to experience greater losses, while relatively stable climates are limited and geographically constrained. This heterogeneity underscores the need for region-specific adaption strategies rather than uniform responses (Bunn et al. 2015b).

Similarly, the study made by Ovalle -Rivera et al (2015) projected substantial losses in Arabica suitability across major producing regions, with suitability shifting upwards as temperature rises. While some high-altitude regions may become more suitable, physical, ecological and socioeconomic constraints limit the feasibility of large-scale relocation (Ovalle-Rivera et al. 2015).

Using long-term data from Tanzania, Craparo et al (2015) find that rising minimum temperatures are strongly associated with declining Arabica yields, providing observational evidence that warming trends are negatively impacting coffee production (Craparo et al. 2015). These findings align with broader agricultural evidence showing nonlinear responses to temperature, where yields decline sharply once thermal thresholds are exceeded (Schlenker & Roberts 2009).

At the same time, certain studies highlight the role of interacting factors that may partially offset climate impacts. Verhage et al (2017) show that when CO2 fertilization effects are incorporated into crop models, projected yield losses for Arabica coffee in Brazil are reduced and may even become slightly positive under moderate emissions scenarios (Verhage et al. 2017).

Uncertainty and variability further complicate adaption planning. Estrada et al (2012) introduce a probabilistic risk assessment framework and demonstrate that climate variability alone can generate economic losses several times greater than the annual value of coffee production in Veracruz, Mexico (Estrada et al. 2012). The study highlights the importance of accounting for uncertainty and extreme outcomes rather than relying solely on average projections.

Lemma and Megersa (2021) project substantial declines in suitable coffee areas across East African countries under future scenarios, with suitability shifting toward higher elevations (Lemma & Megersa 2021). Lichtfouse (2018) further documents observed warming trends and increasing rainfall variability in Ethiopia, alongside pressures from deforestation and land use change, which combines climate risks and threaten genetic diversity (Lichtfouse 2018).

Climate impacts on coffee production does not only affect the yield or coffee growing areas, but it also directly results in economic consequences through supply disruptions and price volatility. Using a Vector Auto regression (VAR) model Bastianin et al (2018) show that climate variability associated with the El Nino southern Oscillation significantly affects coffee production, exports and prices in Colombia. (Bastianin et al. 2018)

Despite the expanding literature on climate change and coffee, empirical evidence on climate changes on coffee production remains fragmented across countries, time periods and methodologies. A key limitation highlighted in the literature is the lack of long-term time series of coffee yields across multiple contrasting environments, which is required for robust statistical assessments (Dinh et al. 2022). Most existing empirical studies rely on relatively short datasets, often less than 20 years, thereby limiting their ability to capture long-run climate effects and increasing the risk of model instability (Dinh et al. 2022).

Moreover, the geographical and varietal coverage of the literature is uneven. Most existing studies are concentrated in the Americas, particularly Central America, and focus almost exclusively on Arabica coffee. In contrast, research on coffee production in Asia is limited, despite Vietnam being the second largest coffee producing country globally. Pham et al (2019) further note that no study in their review exclusively focused on Robusta coffee despite its accounting for approximately 40% of global production. In addition, although drought represents one of the most critical climatic constraints on coffee production, relatively few studies explicitly analyse drought related effects, compared to more general temperature and precipitation variables (Pham et al. 2019). In addition, much of the literature linking climate variability to coffee prices relies on reduced form models that do not fully account for underlying supply and demand shocks, limiting the interpretation of climate-price relationships (Bastianin et al. 2018).

4. Theoretical Framework and Hypotheses

Agricultural production decisions are fundamentally shaped by economic principles governing costs, revenue and market incentives. In the context of climate change, these principles help explain how environmental conditions affect agricultural output through changes in biological productivity. Therefore, the theoretical foundation of this study draws primarily on production economics and supply-demand theory to understand how climate change affects coffee production decisions.

4.1 Production Economic Theory

Production Economic theory models agricultural output as a function of inputs, technology and exogenous environmental conditions. Applied in this framework, climate variables like temperature, drought and precipitation enter the production function as productivity shifters which influences the efficiency with which inputs are transformed into output.

In this context climate change acts as a negative productivity shock in coffee production. Higher temperatures increase overall stress on the coffee plants growth and development, leading to lower yields per hectare. From an economic perspective this reduces total factor productivity and increases the marginal cost of production for a given level of inputs. As a result, even if farmers do not change their behaviour, coffee yields decline due to biological constraints inherent in the production process.

4.2 Supply - Demand Theory

The effects of climate change on coffee production can be further illustrated using a standard supply -demand framework. Adverse climatic conditions raise marginal production costs and reduce biological productivity. This leads to an upward or leftward shift of the supply curve, as seen in figure 1, implying that for any given market price of coffee a smaller quantity of coffee is supplied.

For perennial crops such as coffee supply is highly inelastic in the short-run because production is constrained by the existing stock of trees. Consequently, climate shocks primarily manifest as reductions in yield rather than immediate adjustments in production capacity. This is highlighted in Figure 1 panel (b).

Microeconomic theory highlights that weather shocks in major producing countries have a substantial effect on agricultural markets. Climatic shocks such as droughts or excessive precipitation have historically caused sharp but typically temporary increases in coffee prices through negative supply shocks.

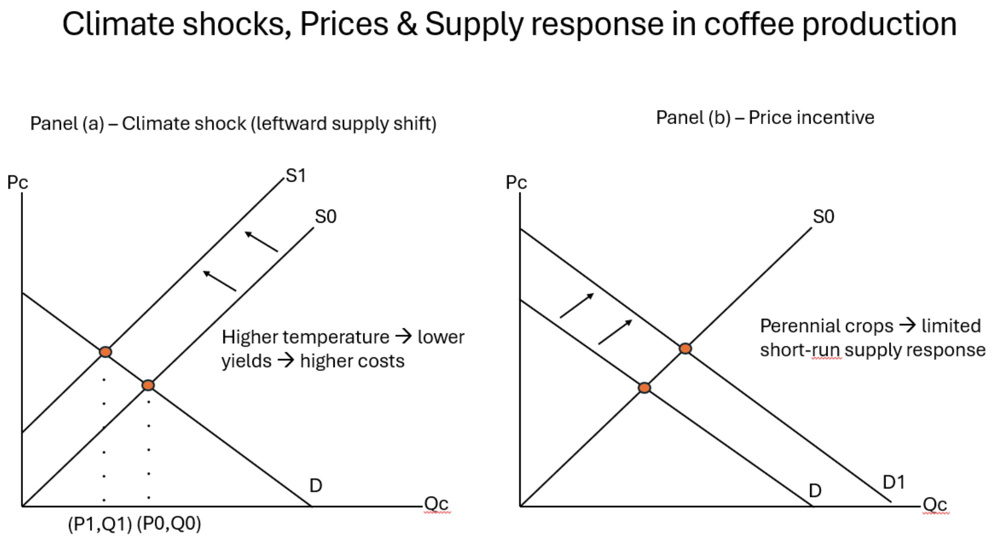

Figure 1.Demand & Supply curves

In Figure 1, the y-axis represents the price of coffee, and the x-axis represents the quantity of coffee. Panel (a) shows a leftward shift of the supply curve from S0 to S1, due to higher temperatures. At the equilibrium (P0, Q0), climate stress reduces yields and increasing marginal costs as equilibrium quantity falls from Q0 to Q1 while prices Increases from P0 to P1.

Panel (b) shows how prices indirectly affect yields, through producer incentives rather than immediate productivity changes. An outward shift in demand D to D1, raises the coffee price and creates incentives for producers to increase output.

4.3 Cobweb Theory

This analysis includes lagged export price as a control variable. The inclusion of lagged export prices is motivated by the cobweb theory, which explains production dynamics in markets where supply decisions are based on past prices due to production lags. In agriculture producers cannot adjust output prices because production decisions affect yields only after a time lag.

According to Cobweb Theory, prices observed in one period influence production outcomes in subsequent periods. Applied to coffee, higher export prices in the previous year may encourage investments in farm management and input use that affect current yields. In contrast, low past prices may reduce maintenance and input application, leading to lower yields.

4.4 Hypotheses

Guided by the chosen theoretical framework and literature review, this study tests several hypotheses regarding the determinants of coffee yields in major producing countries.

H1: Higher average temperature reduces annual coffee yields.

The coefficient for Temperature < 0

H2: The relationship between temperature and coffee yield is non-linear, with yield losses accelerating at higher temperatures.

The coefficient for $Temperature^2 < 0$

H3: Precipitation effect, lower annual precipitation and higher rainfall variability reduce annual coffee yields.

The coefficient for Precipitation < 0

H4: Drought effect measured by CDD, years with longer consecutive dry periods have significantly lower coffee yields.

The coefficient for CDD < 0

H5: Cross country heterogeneity. The magnitude and direction of climate impacts differ across countries due to species composition and agro-ecological conditions. In contrast to the above hypotheses, this hypothesis is a comparative one. It is examined by estimating fixed-effects regressions for each country and comparing the magnitude and significance of climate coefficients across specifications.

5. Data

This empirical analysis employs a strongly balanced country-level panel dataset covering the years 1993-2023 for Brazil, Vietnam and Ethiopia, as they are in the top five of the world's leading coffee producing countries. These countries together account for a substantial share of global coffee production and represent heterogeneous agro-ecological conditions and coffee species, with Arabica dominating production in Ethiopia, Robusta in Vietnam, and a mix of Arabica and Robusta in Brazil.

Each country is observed for 31 consecutive years making the final estimation sample consist of 93 country-year observations, which are reduced to 90 observations in regressions that include lagged price variables. The dataset used includes economic and non-economic variables.

Coffee production data are obtained from The Food and Agriculture Organization statistics FAOSTAT, while climate variables are sourced from the World Bank Climate Knowledge Portal, based on ERA5 reanalysis. Price data are drawn from FAOSTAT and the World Bank Commodity Price Data ("Pink Sheet").

5.1 Key Dependent Variable

The dependent variable is coffee yield, measured as kilograms per hectare (kg/ha), this variable was later log-transformed to stabilize variance and allow coefficient interpretation in percentage terms. Covering 31 years for each of the three countries. These variable captures productivity independent of changes in cultivated area. Yield data are obtained from FAOSTAT, using the Crops and Livestock Products domain. Yield is calculated by FAOSTAT as total production divided by harvested area.

5.2 Key Independent Variables

Mean temperature: Data on annual average temperature for the two largest producing regions in each country are obtained from the World Bank climate knowledge portal, based on the historical climate ERA5 reanalysis dataset which uses gridded data at 0.25 x 0.25-degree resolution. These are later used together with percentage of harvested area data from FAOSTAT to calculate the mean temperature. For Vietnam the two chosen regions make up for 100% of the country´s coffee production area and so follow the equation:
Mean temperature = (Region a temperature*proportion of production area of a + region b temperature *proportion of production area of b).
But for Brazil and Ethiopia this equation creates a smaller mean temperature than for each region, this is because the chosen regions do not make up for 100% of the country's coffee production area and so we must make an extension of the

equation as follows: Mean temperature = (Region a temperature*proportion of production area of a + region b temperature *proportion of production area of b)/ (proportion of production area of a+ proportion of production area of b)

This adjustment ensures that the constructed temperature measure accurately reflects climatic conditions in coffee-producing regions even when the selected regions do not cover 100% of national production.

Temperature² (non-linearity): A squared temperature term is included to allow for non-linear temperature effects. This inclusion of a quadratic specification is motivated by agronomic and empirical studies documenting narrow optimal temperature ranges for coffee and accelerating yield

Following earlier climate-economic literature, temperature is modelled nonlinearly to allow for disproportionate yield responses at higher temperature levels (Schlenker & Roberts 2009). To capture nonlinear temperature effects while reducing multicollinearity between linear and squared terms, the weighted mean temperature and the squared temperature is centered within each country by subtracting the country-specific mean temperature over the sample period. The centered temperature variable is then used to construct the squared temperature term included in the regression analysis.

This approach improves numerical stability in the estimation and allows for a clearer interpretation of nonlinear temperature effects on coffee yields.

Precipitation (mm): Annual Precipitation data are obtained from the World Bank climate knowledge portal, based on the ERA5 reanalysis dataset. These variables help capture long-run changes in mean climate conditions.

Drought (CDD): Drought intensity is measured using the annual number of consecutive dry days (CDD). This data is obtained from the World Bank Climate Knowledge Portal. Based on the ERA5 reanalysis dataset. CDD captures the duration of dry spells rather than total rainfall thus providing a more accurate indicator of crop water stress. This shows that prolonged dry periods are a key driver of yield losses in coffee production.

Flood & drought dummies (Disaster dummies): Dummy variables indicating the annual occurrence of major flood and drought events are constructed using regional disaster records from the World Bank Climate Knowledge Portal. The regions selected were the two biggest producing regions in each country whereas one was dropped since the disaster occurrences matched perfectly. They are numbered as 1 if either drought or flood has occurred within the country and 0 if no flood or drought has occurred. These variables capture extreme climate shocks that may not be fully reflected in continuous climate measures.

Export prices: Coffee export prices are obtained from FAOSTAT and complemented by global benchmark prices for Arabica and Robusta coffee from the World Bank Commodity Price Data (“Pink Sheet”). Export prices are used as the baseline price variable due to their availability and consistency across countries and years.

Lagged prices: To mitigate simultaneity concerns, price variables enter the regression with a one-year lag, reflecting the fact that coffee production decisions respond to expected rather than contemporaneous prices. The inclusion of lagged export prices is theoretically motivated by the cobweb theorem (Ezekiel 1938), which describes markets in which production decisions are based on past price information due to biological or technological production lags. Coffee production is characterized by long adjustment periods and limited short-run supply flexibility, implying that producers respond to price signals with a delay rather than instantaneously. Consequently, export prices from the previous period are more relevant for explaining current yield outcomes than contemporaneous prices.

Data	mean	sd	min	max	Count
Log yield	7.09	0.53	6.21	8.00	90
Temperature	0.02	0.39	-0.68	1.09	90
Precipitation	1206.69	445.16	640.63	2265.73	90
Consecutive dry days	49.64	19.94	15.40	91.00	90
Log export price ~1	7.66	0.52	6.04	8.62	90
Observations	90				

Table 1. Descriptive Statistics

6. Method

In order to examine the relationship between climatic conditions and coffee yield, a panel data approach is used. A fixed effects model (panel FE) was constructed to exploit within-country variation over time while controlling for unobserved, time invariant country characteristics that may be correlated with climatic variables such as geography and agroecological conditions (Wooldridge 2010). Furthermore, coffee yield is modelled as a function of temperature, precipitation and drought intensity, allowing for nonlinear temperature effects to capture potential biological thresholds.

The baseline model:
$\ln(yield_{it})=\beta_1 T^{C}_{it}+\beta_2(T^{c}_{it})^2+\beta_3 Precip_{it}+\beta_4 CDD_{it}+\beta_5 \ln(ExportPrice_{i,t-1})+\beta_6 Year_t+ \mu_i + \varepsilon_{it}$

Where *i* indexes countries and *t* years, climate variables enter nonlinearly, time trend capture gradual productivity and adaption.
u_i are country fixed effects, T^{c}_{it} is weighted mean temperature that´s been centered. ε_{it} is the error term capturing the unobserved variation not explained by the model.

Year fixed effects are not included in the baseline specification. Given the small number of cross-sectional units (N=3) and a long-time dimension (T=31), year dummies would absorb nearly all common temporal variation, including long-run trends in technology management practices and global market conditions. This would substantially reduce the identifying variation available for climate variables.

Instead, a linear time trend (c.year) is included to control for gradual technological progress and structural changes in coffee production over time. The inclusion of a linear time trend allows preservation of variation to identify the effects of temperature, precipitation, drought stress and prices.
Dell et al (2012) confirms that the inclusion of time trends is a robust way to remove background noise from technical and structural developments, allowing for a clearer view of how specific weather factors affect production (Dell et al. 2012). This is strengthened further by the study of Schlenker and Roberts who emphasizes the importance of using year-to-year variations to identify causal effects on economic results. (Schlenker & Roberts 2009).

Model selection is supported by Hausman tests favouring fixed effects, diagnostic tests are conducted on the final specification including test for groupwise heteroskedasticity, autocorrelation and cross- sectional dependence.
Robustness checks include alternative price measures (world Arabica and Robusta Prices), climate disaster dummy variables and country specific fixed-effects regressions.

6.1 Model Assumptions and Diagnostic Tests

All diagnostic tests were conducted on the final model specification including centered temperature, lagged export prices and a linear time trend.

6.1.1 Hausman Test

A key assumption in panel data modelling concerns whether unobserved country-specific effects are correlated with the explanatory variables. The presence of correlation collapses the use of random effects as their estimates are inconsistent, and fixed-effects estimation is required. But given N = 3 countries, this test is not meaningful and since coffee-producing countries differ systematically in agro-ecological conditions and institutional structures that are likely correlated with climate variables, a fixed effects estimation is ultimately chosen.

6.1.2 Heteroskedasticity

Classic linear regression assumes homoscedastic errors, meaning that the variance of the error term is constant across cross-sectional units. Groupwise heteroskedasticity is tested using the Modified Wald test for fixed effects models. The null hypothesis assumes homoscedastic errors across countries.

The test results reject the null hypothesis (x^2 =25.12, $p<0,01$) indicating the presence of heteroskedasticity across panel units as shown in figure 2. However, this result is unsurprising in cross-country agricultural data, where countries differ substantially in production scale, climate variability and institutional capacity. Dell et al (2012) notes that when working with fewer observations, statistical precision decreases significantly, and the results must be interpreted with great caution (Dell et al. 2012). However, since I only investigate 3 countries, cluster robust standard errors are not valid for hypothesis testing.

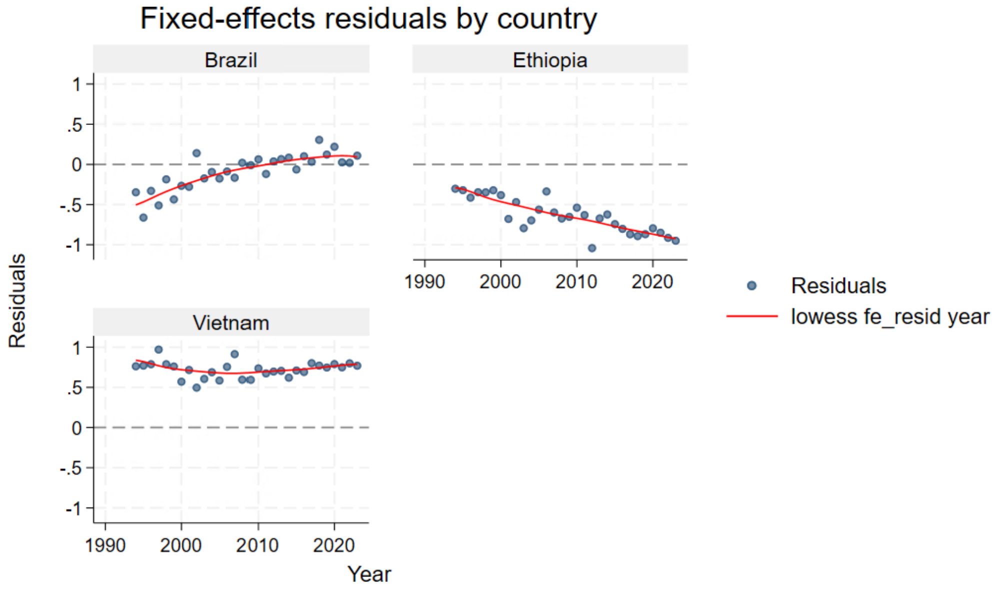

Figure 2.Modified Wald test for groupwise heteroskedasticity by country

Figure 2 presents fixed effects regression residuals over time by country as a visual diagnostic for heteroskedasticity. The plots reveal non-constant variance both over time and across countries, indicating the presence of heteroscedasticity in the error structure.

6.1.3 Serial correlation

Serial correlation was assessed using the Wooldridge test for autocorrelation in panel data. Since year fixed effects absorbs serial correlation mechanically the variable c.year is excluded from the model before running the test, since inclusion of such variables invalidates the results (Drukker 2003).

The test fails to reject the null hypothesis of no first-order autocorrelation (F (1,2) =0,068, p=0,8181), suggesting that serial correlation in the idiosyncratic error term is not a concern in the fixed-effect specification (Wooldridge 2010).

6.1.4 Cross Sectional-Dependence

Cross-Sectional dependence was examined using Pesaran´s CD test, which evaluates whether residuals are correlated over cross-sectional units. The test statistic (Z =-2.917, p=0.0035) fail to reject the null hypothesis of cross- sectional independence. This indicates that unobserved shocks across countries do not significantly bias the error structure in the final model.

6.1.5 Multicollinearity

To test for multicollinearity, variance inflation factors (VIF) are computed from a pooled specification with identical regressors in the fixed effects model. Following standard econometric practice, multicollinearity is considered problematic when VIF values exceed 10. By centering temp_c and $temp\_c^2$ collinearity between temperature and it´s squared term is reduced. After centering all VIF values were well below conventional thresholds, with a mean VIF of 1.94. Indicating that multicollinearity does not distort coefficient estimates in the final model.

7. Results

Table 2. Estimation result of the baseline model for the pool sample (n=90)

	(1)
	ln_yield
Centered mean temperature	-0.130**
	(0.067)
Centered temperature^2	0.134**
	(0.0268)
(mean) precip_mm	-0.0000466
	(0.000139)
CDD	0.00267
	(0.00305)
L.Log export unit value (US$/tonne)	0.0713
	(0.0645)
year	0.0176
	(0.0031)
Constant	-28.80
	(6.00011.)
Observations	90
Within R squared	0.4205

*Standard errors in parentheses * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. Regression with country fixed effects.*

Table 3.Estimation results of extended models for the pool sample (n=90)

	(1)	(2)	(3)	(4)	(5)
	ln_yield	ln_yied	ln_yield	ln_yield	ln_yield
Centered mean temperature	-0.132** (0.0665)	-0.132** (0.067)	-0.134** (0.0667)	-0.136** (0.0673)	-0.133** (0.0669)
Centered temperature^2	0.114* (0.1168)	0.150* (0.119)	0.130 (0.119)	0.148*** (0.0116)	0.136** (0.0116)
(mean) precip_mm	-0.0000 (0.000)	-0.0000 (0.000)	-0.0000 (0.000)	-0.0000 (0.000)	-0.0000 (0.000)
CDD	0.0026 (0.0030)	0.002 (0.003)	0.002 (0.0031)	0.00248 (0.0031)	0.00278 (0.0031)
flood dummy	0.0988 (0.069)		0.0986 (0.0692)		
L.Log export unit value (US$/tonne)	0.081 (0.058)	0.072 (0.058)	0.081 (0.058)		
year	0.0173*** (0.003)	0.018*** (0.003)	0.0173** (0.0030)	0.0176*** (0.0031)	0.0182*** (0.0124)
drought_dummy		0.037 (0.048)	0.0367 (0.0338)		
L.ln_world_arabica				0.0728 (0.0641)	
L.ln_world_robusta					0.0745 (0.0557)
Constant	-28.45*** (5.967)	-28.85*** (6.016)	-28.49*** (5.983)	-28.51*** (6.187)	-29.54*** (5.767)
Observations	90	90	90	90	90
Within R squared	0,4349	0.4247	0.4391	0,4188	0.4224

*Standard errors in parentheses * p < 0.10, ** p < 0.05, *** p < 0.01. Regression with country fixed effects including dummies. (1) Estimation with flood dummy. (2) Estimation with drought dummy. (3) Estimation with both flood & drought dummies. (4) Estimation with world price of arabica. (5) Estimation with world price of robusta.*

Table 4.Estimation results for each studied country

	Brazil	Ethiopia	Vietnam
	ln_yield	ln_yield	ln_yield
Centered temperature	0.0404	0.00887	-0.0242
	(0.073)	(0.097)	(-0.059)
Centered temperature ^2	-0.0658	0.0213	-0.0792
	(0.099)	(0.164)	(0.14)
(mean) precip_mm	0.000165	0.000220	0.00000521
	(0.002)	(0.000)	(0.000)
CDD	-0.00235	0.000604	0.00124
	(0.0034)	(0.0041)	(0.0031)
L.Log export unit value (US$/tonne)	-0.0240	0.0869	0.192**
	(0.5722)	(0.084)	(0.054)
Year	0.0422***	-0.00754	0.0130***
	(0.0034)	(0,0034)	(0.0026)
Constant	-77.62***	20.74*	-19.88***
	(6.51)	(7.90)	(5.18)
Observations	30	30	30
Within R squared	0.9190	0.2324	0.7998

*Standard errors in parentheses * p < 0.10, ** p < 0.05, *** p < 0.01*

8. Result Interpretation and Discussion

8.1 Fixed Effect Estimation of the Baseline Model

Table 2 presents the main results of the baseline model, the dependent variable in all specifications is the natural logarithm of coffee yield (kg/ha). This model, as well as the other ones, include country fixed effects and a linear time trend to account for unobserved country- specific heterogeneity and long- run technological change.

The central result is that the centered mean temperature shows a negative and statistically significant effect on coffee yields in the baseline specification. This result provides strong support for H1, which hypothesized that higher temperatures reduce coffee yields. In table 2 it is shown that a one-degree Celsius increase in centered mean temperature is associated with approximately 13% reduction in coffee yield, holding other factors constant. This result is robust throughout the other model specifications shown in table 3 and table 4, thus it supports the hypothesis of temperature stress reducing coffee productivity. This indicates that increases in temperature relative to a country's historical norm reduce coffee productivity. The magnitude and sign of this effect are consistent with prior empirical evidence documenting adverse yield responses to rising temperatures in coffee-producing regions (Dinh et al. 2022) (Koh et al. 2020) (Dell et al. 2012) (Schlenker & Roberts 2009).

The squared temperature term was included to evaluate H2, which hypothesized a non-linear relationship between temperature and yield, where yield losses accelerate at higher temperatures. However, the estimated coefficient $temperature^2$ is positive and statistically significant across the baseline model and in models 4 and 5 in table 3. This indicates a convex (U-shaped) relationship between temperature and yield, rather than the hypothesized concave form.

Based on the estimated coefficients and given the estimated specification:
$\ln(yield) = 0.134 * Temp^2 - 0.130\ Temp + ..$

Yield reaches a minimum at approximately 0.49 above the sample mean temperature. For temperature levels below this point, increases in temperatures reduce yields, while beyond this threshold further increases in temperature are associated with higher yields. Thus, the results do not support H2. Instead of accelerating losses at higher temperatures, the estimated relationship suggests that the marginal increase in yield becomes larger at high temperature. This pattern may reflect cross-country heterogeneity, adaption effects, or the use of annual mean temperature rather than measures capturing extreme heat exposure.

The annual precipitation, in contrast to the temperature variables, show no statistically significant association with coffee yields. Therefore, the H3 hypothesis is rejected. The coefficient for annual precipitation is close to zero and remain insignificant across all specifications. This suggests that, at the annual level, total rainfall does not capture the relevant moisture dynamics affecting coffee production, especially during the flowering period of coffee trees, potentially reflecting the importance of rainfall timing rather than aggregated amounts.

Likewise, Consecutive dry days (CDD), shows similar results in the output as it does not have a statistically significant effect on yields in the baseline model. While the estimated coefficients are positive, they are small and imprecisely estimated. This result indicates that moderate variation in drought duration may be less influential for yields than sustained changes in temperature, particularly when producers can partially adapt through irrigation or farm management practices.

Lagged export prices, show a positive relationship with coffee yields, although the estimated coefficients are not statistically significant in the baseline model. The positive sign suggests that higher prices may encourage investment and improved management in productivity enhancing inputs, but the lack of precision implies that yield responses are constrained in the shoer run due to the biological rigidity of coffee production. Coffee trees require several years to mature, which reduces the short-run elasticity of supply with respect to prices.

The time trend shows positive and highly significant results across all models. This reflects substantial long-run productivity growth in coffee production, likely driven by technological progress, improved agronomic practices, and structural changes in the coffee sector.

Lastly the constant term in the baseline specification is positive and statistically significant. In a fixed-effects framework with a time trend, the constant represents the baseline log yield level when all explanatory variables are evaluated at their reference values. Economically this captures the average productivity level driven by structural factors such as soil quality, institutional conditions, and accumulated production knowledge that are not explicitly modelled but are common across the sample once country fixed effects are accounted for. The significance of the constant indicates that these underlying production

8.2 Robustness Check using Climate Disaster as Dummy Variables

While the baseline specification captures the main climate-yield relationship, several alternative mechanisms could potentially influence the results. Robustness checks are therefore necessary to ensure that the estimated temperature effect is not driven by model specification, omitted variables or particular measurement choices. Table 3 and 4 systematically addresses these concerns by addressing alternative climate indicators, price measures and country specific estimations.

Table 3 extends the baseline specification by including binary indicators for major flood and drought events, both separately and jointly. These robustness checks are motivated by the concern that discrete extreme events, rather than average climate conditions, may drive yield variation. If omitted, such events could bias the estimated coefficients on continuous climate variables. The inclusion of these disaster dummies does not materially alter the estimated coefficients on the core climate variables.

The flood dummy enters with a positive coefficient but remains statistically insignificant, this suggests that extreme flood events do not systematically reduce average annual yields once temperature and precipitation are controlled for.

The drought dummy, likewise, is statistically insignificant and small in magnitude. These results indicate that continuous climate measures, particularly temperature captures yield- relevant climate variation more effectively than discrete disaster indicators, at least at the national level.

Importantly, the negative and statistically significant effect of centered mean temperature remains stable across all disaster specifications, this reinforces the robustness of the baseline temperature result.

8.3 World Price Robustness: Arabica vs. Robusta

Table 3 also evaluates the sensitivity of the results to alternative global price measures by replacing export prices with lagged world Arabica and Robusta Prices, respectively. This robustness check is important because domestic prices may reflect country-specific conditions, while world prices capture global market signals faced by producers.

Both Arabica and Robusta world prices enter the regression with positive coefficients indicating that higher global prices are associated with increased coffee yields. The effect is somewhat larger for Arabica prices than for Robusta prices, although neither coefficient is significant at the 5% level. This suggests that global price signals may influence production incentives, but their effect on yields is weaker than that of local climatic conditions.

Crucially, the estimated effect of centred mean temperature remains negative and statistically significant across both world price specifications, confirming that the temperature-yield relationship is independent of the chosen price proxy.

This finding aligns with supply response theory for perennial crops, while higher prices may raise expected profitability, biological constraints limit the speed and magnitude of yield responses. Climate-induced constractions therefore dominate price-induced supply expansions in the short run.

8.4 Country-Specific Results

Table 4 presents country specific regressions for Brazil, Ethiopia and Vietnam. These regressions are estimated separately for each country to explore heterogeneity in climate responses and to examine H5 that hypnotised that the magnitude of climate impacts differ across countries due to agro-ecological conditions and coffee species composition. The results reveal substantial heterogeneity in both climate sensitivity and price responsiveness.

For Brazil neither temperature nor precipitation variables are statistically significant, while the coefficient on consecutive dry days is negative but insignificant. The time trend, however, is strongly positive and highly significant, highlighting rapid productivity growth driven by technological adoption and large-scale mechanization.

In Ethiopia, there is limited responsiveness to both climate and prices as none of the climate variables are statistically significant and the time trend is weak and negative. This pattern suggests limited productivity growth and weaker climate responsiveness, consistent with structural constraints faced by smallholder systems and lower adaptive capacity in Ethiopian coffee production

In contrast Vietnam exhibits a statistically significant and positive effect of lagged export prices on yields, indicating that price incentives play a more important role in yield dynamics. The time trend is also positive and significant, reflecting rapid productivity growth during the expansion of Vietnam´s coffee sector.

These differences support H5 and underscore that at county-level, climate impacts are mediated by institutional and technological contexts, an important insight that would be obscured without country-specific robustness checks.

The inclusion of all robustness tables demonstrates that the core findings are stable across specifications. Temperature consistently emerges as the dominant climatic constraint on coffee yields, while the constant term highlights the continued importance of structural production conditions.

9. Policy recommendations

The empirical results from this study indicate that climate change and in particular rising temperatures, is the most persistent and robust constraint on coffee yields in Brazil, Ethiopia and Vietnam, even when controlling for prices, precipitation and drought indicators. At the same time, price variables exhibit limited and heterogenous effects across countries. Therefore, it is suggested that future effective adaption policies must combine climate-resilient technologies with long-term investments in production systems.

Due to the robust and negative impact from rising temperatures on coffee yields in all countries, policies should prioritise measures that enhance the climate resilience of coffee production systems. Investments in adaption are particularly important for perennial crops such as coffee, where biological constraints limit short-run adjustments. World Coffee Research emphasizes that preserving genetic diversity and developing climate resilient coffee varieties are essential for maintaining productivity under increasing heat and climate variability (*World Coffee Research Strategy 2021-2025*. 2020). The WCR cooperates with national research institutes like WASI in Vietnam and JARC in Ethiopia in the Innovea global breeding network initiative to contribute to modernise production practices of coffee. Thus, securing the development and spreading of heat-tolerant coffee varieties, improved farm management techniques and production systems that reduce exposure to thermal stress, such as agroforestry and shade-grown coffee.

Policy initiatives should continue to support long-term research programmes targeting climate resilience in coffee production as well as mechanisms that facilitate the transfer of knowledge and technology to producers. Strengthening extension services is especially important in regions dominated by smallholder farmers, where access to information and innovation remains limited.

In countries dominated by smallholding farms, producers ability to adapt to climate change is constrained by limited access to credit, inputs and risk management tools. To reduce vulnerability and increase adaptive capacity, policy measures should be aimed at improving access to finance, strengthening producer organisations and enhancing institutional support. Through Resolution 465, ICO is working to address the structural problem of low producers prices and ensure that small holders can cover their production costs (*International Coffee organization. Annual Review 2017/18*). Which aligns with the global goal 8 of decent work and economic growth. This is particularly relevant in light of the results which shows that lagged export prices have limited direct effects on returns in the short-term. Furthermore, ICO also stresses that reducing gender gaps in the coffee sector is not only a matter of equity but also productivity and estimates that closing the gap could increase global coffee production. This is directly in line with Global goal 5 of gender equality.

For coffee importing countries such as Sweden and other EU member states, the findings underscore the importance of viewing climate adaption in producer countries as a matter of supply security. Reduced yields in major producing regions can lead to long-term supply constraints that cannot be fully offset through higher prices. Importing countries and private actors therefore have an incentive to support adaption efforts upstream in the supply chain. This may include long-term sourcing agreements, partnerships with producer organisations and co-financing of adaption investments.

10. Limitations

It is important to note that this study is subjected to several limitations that should be considered when interpreting the results.

First, the analysis is based on a small number of countries (N=3) combined with a relatively long time period (T=31 years). While this structure is suitable for fixed-effect estimation and allows the model to control for time-invariant country characteristics, it limits the reliability of inference methods that usually rely on a large number of cross-sectional units. In particular, cluster robust standard errors at the country level are not appropriate with so few clusters, this is because their asymptotic properties do not hold. It is for this reason that the study reports conventional fixed-effects standard errors. Statistical significance should therefore be interpreted with caution, and greater emphasis is placed on the sign, magnitude and consistency of the estimated coefficients across the model specifications.

Second, although the fixed-effect framework controls for unobserved, time-invariant heterogeneity across countries, it cannot fully account for time-varying omitted factors such as technological change, policy interventions or structural changes in coffee production systems. To partially address this issue, the analysis includes a linear time trend, but this does not mean that it will capture more complex or country-specific developments over time.

Third, the climate variables used in the analysis are based on annual averages, which may obscure important seasonal dynamics in coffee production. For example, coffee yields are particularly sensitive to climatic conditions during flowering but due to data limitations this is not modelled here. As a result, estimated climate effects may understate the true impact of short-term or seasonal climate shocks.

Finally, the country-specific regressions are estimated separately for each country. Knowing this, these results should be interpreted as descriptive comparisons across countries, rather than as precise causal estimates

11. Conclusion

The focus of this study was to investigate how climate change affects coffee production in three of the world's most important producing countries, Brazil, Ethiopia and Vietnam using a country level data set. The results show that rising temperatures were the most affecting variable on coffee yields which is consistent with previous studies. In contrast, price effects show limited and heterogenous effect across countries this suggests that market signals alone cannot compensate for climate related productivity losses.

These findings highlight the structural vulnerability of coffee production to climate change, especially for perennial crops with limited short-run adjustment capacity. The results underscore the importance of long-term adaption strategies in coffee producing countries. From an international perspective the study also suggests that climate adaption in coffee producing countries is not only a local development issue but a matter of long-term supply stability for importing regions.

Due to the limitations of the study and it´s effect on the interpretation of the results, future research could use region or farm- level panel data, including seasonal climate indicators and examine additional adaption strategies.

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