



Economic costs of extreme heat on groundnut production in the Senegal Groundnut Basin

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ABSTRACT

Historical data show a rising trend in extreme heat in the past four decades in the Groundnut Basin of Senegal. We evaluate the economic costs of extreme heat on groundnut production in the region. Using temperature data from the ERA5 global climate reanalysis, we define extreme heat degree days (EHDDs) as the cumulative number of degree days above 35 °C during the groundnut growing season and estimate its effect on quasi-profits and yields at the person, household, and field levels utilizing a two-year panel data of 1,123 households. Our econometric estimations show that an additional EHDD reduces quasi-profits by 5,460 FCFA per hectare and significantly lowers yield by 2.5%. Further, rainfall interactions with EHDD generate compounding losses under high heat and rainfall. The findings highlight important and often unseen effects of increasing temperatures on agricultural practices in climate-vulnerable areas such as the Groundnut Basin and underscore the need for adaptation and mitigation strategies to cope with the impacts of climate change.

1. Introduction

Climate change, characterized by increasing temperatures and extreme weather events, poses a challenge to global agriculture with profound implications for food security, livelihoods, and economic stability (Kotir, 2011). Extensive research has highlighted the sensitivity of agricultural production to climate variables, including temperature. Previous studies by Schlenker and Roberts (2009) and Lobell and Field (2007) have established a robust relationship between rising temperatures and reduced crop yields. The problem is exacerbated in regions where agriculture is the main source of income and where the capacity to adapt to climate change is limited. Micro-level studies show smallholders shift inputs in season under heat stress, e.g. Jagnani et al. (2021) find Kenyan maize farmers facing hotter early-season conditions reduce fertilizer but increase pesticide use and weeding. Among the most affected places are the semi-arid regions in Africa, where increasing temperatures have begun to significantly impact agricultural productivity and economic well-being (Adhikari et al., 2015; Barrios et al., 2008).

A recent study by Lenton et al. (2023) finds that Senegal in West Africa is one of the countries most susceptible to the adverse heat impacts of global warming. Senegal has the third highest average temperature in the world, and in one of the most important agricultural regions of Senegal, the Groundnut Basin, temperatures oscillate between 20 °C and 45 °C throughout the year. Despite the strong

presence of high temperatures in Senegal and their impact on agriculture, research to understand the effects of increasing temperatures on agricultural outcomes in Senegal, and other Francophone African countries is largely underrepresented in the existing literature. Previous work on extreme heat in the Senegalese Groundnut Basin has mainly relied on simulation models and focused on cereals such as millet and sorghum (Faye et al., 2022; Ahmed et al., 2021). For the main cash crop of the country groundnuts, simulated projections also suggest climate-driven yield declines (Garcia, 2015; Alioune and Moctar, 2018). But empirical evidence on groundnut impacts remains limited, with most studies aggregating farm outcomes or focusing on cereals (Jarrett and Tackie, 2024; Emediegwu et al., 2022; Ayal, 2021).

In this paper, we estimate the impacts of extreme heat on groundnut production in the Groundnut Basin of Senegal. We first establish that extreme temperatures have been trending upward in the Groundnut Basin over the past four decades. Then we assess the impact of high temperatures on individual farmer groundnut production in this region. We use primary data from a two-year panel of 1123 households and temperature data from the ERA5 climate database to estimate the current economic costs of extreme temperatures for groundnut farmers in the region. Our findings reveal a relationship in which extreme temperatures are associated with substantial financial losses in groundnut production by farmers. Specifically, estimates from a fixed effects model indicate that an increase in one Extreme Heat Degree Day

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(EHDD) during the cropping season reduces quasi-profit per hectare by 5460 FCFA (approx. 9.33 USD) and yields by 2.5 percent. Over the past four decades, EHDDs in the Groundnut Basin have increased by about one additional day every five years on average, and in less than three years in some locations. Based on our estimates, this translates into decadal yield losses of approximately 5–8 percent. The rise in EHDDs is both rapid and compounding in its effects on productivity and quasi-profits.

Our results contribute to the existing literature by providing a detailed analysis of legume impacts that combines high-resolution temperatures data from a francophone region characterized by extreme heat with household-, person-, and field- level panel data.

The remainder of the paper is structured as follows. In Section 2, we provide context on the agricultural and climate conditions in the Groundnut Basin of Senegal. Section 3 describes the data sources and the sampling strategy for primary household data collected for our analysis. Section 4 elaborates the empirical strategy. In Section 5, we present the main findings. Section 6 discusses the implications of these findings for farmers in the Groundnut Basin, possible adaptation strategies, and policy recommendations.

2. Setting: The Senegal Groundnut Basin

The Groundnut Basin in Senegal (comprised of the regions of Diourbel, Kaolack, Kaffrine, Thiès, Louga and the Koumpentoum department) is one of the main agricultural regions in the country (Faye and Du, 2021). Agriculture is primarily rainfed and the predominant crops, groundnuts and millet, are grown on fields in successive years. The groundnut growing season typically runs from June to November, and production is primarily carried out by family-owned smallholder farmers.

Agricultural income represents 75% of total household income in the Groundnut Basin. Around 95% of farmers rely solely on rain as the main source of water for groundnuts, about 90% of households are poor (Gérard et al., 2020). Lately, young men migrate from the Basin because of low agricultural productivity and this migration serves as a coping strategy for households to escape cycles of poverty (Hathie et al., 2014). The heavy dependence on groundnut income increases the vulnerability of groundnut producers to environmental challenges (De-launay et al., 2020). According to World Food Program (2014), about 50% variability in groundnut yields can be explained by variations in seasonal rainfall. D'Alessandro et al. (2015) suggest that the poor performance of the groundnut sector is mainly related to climate variability and uncertain policies in the sector, which have generated a risky production environment. Similarly, Sall (2015) suggests that vulnerability to climate change is mainly due to the combination of increases in temperature and irregularities in rainfall. Some studies have also suggested that aggregate rainfall has decreased in recent years in the Groundnut Basin (Sall, 2015). However, empirical trends show more of an increase in irregular rainfall than reductions in aggregate levels.

Rising temperatures associated with climate change can also have a more negative impact on groundnut yields than on maize or rice in Senegal (Khouma et al., 2012). Several studies have underscored the sensitivity of groundnut yields to temperature variations and identified that production temperature range between 27 °C–30 °C as optimal (Ntare et al., 2001; Vara Prasad et al., 2003; Ketring, 1984). The interaction between temperature and drought-like conditions further exacerbates the reductions in groundnut yields. For example, pod yields decrease by 72% under high temperatures during drought conditions. Each phase of the development of groundnut plant is associated with a specific temperature range that determines the minimum, optimum, and maximum yield potential. However, the literature suggests that groundnut growth is generally inhibited by temperatures above 35 °C, highlighting the critical importance of managing temperature exposure throughout the life cycle of the crop (Kumar et al., 2012).

3. Data

The primary data come from a panel survey conducted with 1123 households in the months of February and March in 2020 and 2021 in the provinces of Kaolack, Kaffrine, and the department of Koumpentoum in Tambacounda. The data were collected through a proprietary household survey designed and implemented by our research team in collaboration with the Ecole Nationale Supérieure d'Agriculture (ENSA) and the Institut Sénégalais de Recherches Agricoles (ISRA), as part of the project 'Retaining Next Generation Farmers in the Senegalese Groundnut Basin', funded by the United State Agency for International Development (USAID) Peanut Innovation Lab.

The sampling technique for our primary data involved a two-stage process, an initial population-weighted random selection of 75 villages (with populations under 900 based on the 2014 Census) followed by random sampling of 15 groundnut growing households per village. Each household in the sample manages multiple agricultural fields, with plot-level data collected separately for each. A 'field' refers to a spatially distinct area cultivated with crops during the agricultural season. A 'person' is defined as the primary manager of a given field. Individuals can manage multiple fields, and each household typically has one or more field managers. The sampling structure yields a nested dataset: multiple fields per person, and multiple persons per household. We perform our analysis at the field, person, and household levels by aggregating outcomes, which is novel compared to previous research that primarily focused on whole farm composites.

GPS-enabled mapping of all household groundnut fields was conducted, leading to data on 5214 fields across both survey years. The person-level groundnut productivity data were estimated by the area-weighted aggregation of output and input metrics per hectare for groundnut fields managed by persons. The aggregation generated 4278 person-level groundnut growing data points over the two panel years. The person-level dataset is used as the primary sample for estimation, but the field- and household- level samples are also utilized to check for robustness of the estimates from person-level regressions.

The temperature data are extracted from the ERA5-Land hourly temperature datasets, which are produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) through Copernicus Climate Change Service (Muñoz Sabater, 2019). This product is chosen for its temporal granularity, long series, and spatial resolution, which are provided on a $0.1^\circ \times 0.1^\circ$ latitude–longitude grid. The data extraction occurred at the village levels from 1980 to 2020. The coordinates of each village were input into Google Earth Engine to extract temperature values. The reliability and applicability of the ERA5 data in the African context are supported by Gbode et al. (2023) and Gleixner et al. (2020).

Additional temperature data were obtained from Senegal's national agency for civil aviation and meteorology (ANACIM) for three locations: Kaolack, Kougheul, and Tambacounda. The dataset contains maximum temperature records for Kaolack (1980–2021), and both minimum and maximum temperature data for Kougheul (1990–2021) and Tambacounda (1969–2021). Although substantial missing values prevented a complete time series analysis with the station data, the maximum temperature values were used to compute EHDD (for years 2019 and 2020) as an alternative measure for robustness checks (presented in the appendix). Due the limited number of stations, the ANACIM data yielded only six EHDD observations (three stations per year) compared to 75 observations per year from ERA5 data.

Table 1 presents person-, household-, and field-level statistics for the variables utilized in the estimations. The household-level statistics represent aggregate data for entire households, encompassing all cultivated fields and the total input and output levels. Quasi-profit is defined as crop revenue per hectare minus variable input expenses excluding labor. We compute revenue as total harvest times the farm-gate price reported by each respondent then divided by the total cultivated area. Variable costs cover seed, fertilizer and phytosanitary products, valued at the purchase prices given in the survey. Labor costs are omitted since

Table 1
Household, person, and field level summary statistics.

	2019	2020
Household level		
n	806	740
Quasi-profit (FCFA/ha)	52,456	88,527
Total expenses (FCFA/ha)	105,273	116,659
Yield average (kg/ha)	611	692
Fertilizer rate (kg/ha)	46	53
Seed rate (kg/ha)	100	99
Avg. expenditure in phytosan product (FCFA/ha)	1871	2051
Total area grown (ha)	3.28	3.37
Person level		
n	1970	2369
Quasi-profit (FCFA/ha)	41,859	79,023
Total expenses (FCFA/ha)	128,487	141,632
Yield average (kg/ha)	715	739
Fertilizer rate (kg/ha)	51	60
Seed rate (kg/ha)	113	110
Avg. expenditure in phytosan product (FCFA/ha)	2265	2290
Area (ha)	1.57	1.28
Field level		
n	2530	2684
Quasi-profit (FCFA/ha)	56,684	81,522
Total expenses (FCFA/ha)	131,521	144,772
Yield average (kg/ha)	734	747
Fertilizer rate (kg/ha)	54	64
Seed rate (kg/ha)	115	112
Organic Fertilizer (Yes) %	19.3	24.3
Avg. expenditure in phytosan product (FCFA/ha)	2308	2058
Total area grown (ha)	1.34	1.19
% using seed market	47.37	38.9
EHDD (Village Level)		
n	75	75
Mean (SD)	29.78 (24.27)	12.8 (10.33)

the questionnaire did not collect labor input data. Consequently, our quasi-profit measure reflects net returns to material inputs but does not account for unpaid family or hired labor.

In 2020, there was a noticeable increase in quasi-profits per hectare compared to 2019 along with a corresponding increase in total expenses and yields. At the person level, data are aggregated to reflect individual farmers' performance, particularly those who manage multiple fields. Similarly, 2019 and 2020 trends in quasi-profits, total revenues, and yields are found at the household- and person- levels. Interestingly, average acreage cultivated per person decreased from 2019 to 2020. This may be in part due to the higher number of people in the sample cultivating groundnuts. Field-level statistics provide a more granular view of agricultural inputs and outputs with similar trends over the two survey years.

In 2019, the mean EHDD of 29.78 (Standard deviation = 24.27) indicates that farmers faced significant heat stress during the cropping season, with substantial variability across villages. In 2020, the mean EHDD is considerably lower at 12.8 (SD = 10.33), which reflects a less intense, but still variable, exposure to heat. The reduction likely eased some of the pressures on crop production, although persistent variability shows the ongoing risk posed by extreme temperatures. Lower 2020 temperatures may also have contributed in part to higher profits and yields.

4. Empirical framework

We present the empirical frameworks that we utilize to estimate EHDDs, the trends in exposure to extreme heat from 1980 to 2020 in the Groundnut Basin, and the effects of extreme heat on quasi-profits and yields from groundnut cultivation in the 2019 and 2020 growing seasons.

4.1. Analyzing extreme heat degree days

Based on a review of the agronomic literature, plant growth depends on cumulative exposure to heat and precipitation during the growing season. Furthermore, the impacts of temperature are non-linear. For temperature modeling, the standard approach is to convert daily temperatures into degree-days. The plant response to accumulated heat follows a non-linear pattern: temperatures up to a certain threshold promote growth, but beyond this upper temperature threshold, additional heat becomes detrimental to plant development (Deschênes and Greenstone, 2007).

The heat degree-day is defined as the number of degrees within the day that the temperature is above an upper threshold (Schlenker et al., 2006; Burke and Emerick, 2016; Auffhammer and Schlenker, 2014; Schlenker and Roberts, 2009; Hsiang, 2016; Roberts et al., 2013). For most large cultivated plants, heat absorption increases almost linearly up to a threshold of 32 °C, and above this threshold there is no more heat absorption (Burke and Emerick, 2016). Groundnuts have some heat tolerance, but plant growth is inhibited above 35 °C. The EHDD variable within a growing season is calculated by adding the daily measures of EHDD throughout the entire growing season (Burke and Emerick, 2016; Roberts et al., 2013; Deschênes and Greenstone, 2007).

We use the hourly temperature data. Following Lobell et al. (2013), the formula for computing the EHDD method is as follows:

$$EHDD = \sum_{i=1}^N DD_{35,t}, \quad \text{where} \quad DD_{35,t} = \begin{cases} 0 & \text{if } T_t < 35 \text{ }^\circ\text{C} \\ \frac{(T_t - 35)}{24} & \text{if } T_t \geq 35 \text{ }^\circ\text{C} \end{cases}$$

where DD represents the EHDD for each hour t between June 10th and November 20th. This formula sums the daily degree-day contributions that exceed the 35 °C base temperature. Each day's contribution is calculated as the sum of the hourly average temperature above 35 °C. The EHDD metric captures both the intensity and the duration of the heat that exceeds the baseline threshold.

4.2. Trends in EHDDs

Subsequently, we conduct the following linear regression to identify a trend in EHDDs over the years 1980 to 2020:

$$EHDD_{\text{year}} = \beta_0 + \beta_1 \times \text{trend}_{\text{year}} + \epsilon_{\text{year}}$$

where $EHDD_{\text{year}}$ denotes the extreme heat degree days for the growing season in a year, trend is a linear time trend variable, and ϵ_{year} is the error term.

4.3. Impact of short-term temperature variation on groundnut production

We estimate the effects of extreme heat on groundnut production outcomes using panel data collected in 2020 and 2021. The analysis focuses on two dependent variables: quasi-profit and log yield. All specifications control for person- or household- level fixed effects, and standard errors are clustered using 10 km \times 10 km spatial blocks to account for spatial autocorrelation. Spatial blocks are constructed from village GPS coordinates, and we use 1000 spatial block bootstrap replications. We add a time-invariant proxy for field quality built from multi-year Sentinel-2 NDVI (mean of annual peak NDVI, June–November from 2000 to 2019) at 10 m resolution, computed in Google Earth Engine. We include this NDVI proxy as robustness checks in the appendix (Tables A.1, A.2, and A.3).

4.3.1. Quasi-profits regressions

Our main specification for quasi-profit is a fixed-effects model at the person level:

$$\pi_{it} = \beta_1 EHDD_{it} + \beta_2 Rain_{it}^{std} + \beta_3 (Rain_{it}^{std})^2 + \beta_4 (EHDD_{it} \times Rain_{it}^{std}) + a_i + \epsilon_{it}$$

Here, π_{it} is quasi-profit for person i in year t ; $EHDD_{it}$ is the number of extreme heat degree days; $Rain_{it}^{std}$ is standardized rainfall; and a_i captures unobserved time-invariant individual traits.

We also estimate a household-level version of this model with household fixed effects and a field-level version by OLS with village fixed effects

4.3.2. Yield regressions

To complement the profit results, we estimate the same model using the log of yield as the dependent variable. We include farmer-managed input in the log-yield specification but not the quasi-profit specification, as they are embedded in the measure of quasi-profit. At the person and household levels, the model is:

$$\log(Yield_{it}) = \beta_1 EHDD_{it} + z_{it}\beta_2 + \beta_3 Rain_{it}^{std} + \beta_4 (Rain_{it}^{std})^2 + \beta_5 (EHDD_{it} \times Rain_{it}^{std}) + a_i + \epsilon_{it}$$

where z_{it} includes farmer-managed inputs such as seed use and fertilizer application.

At the field level, we use an Ordinary Least Squares model with village fixed effects:

$$\log(Yield_{it}) = \beta_1 EHDD_{it} + z_{it}\beta_2 + \beta_3 Rain_{it}^{std} + \beta_4 (Rain_{it}^{std})^2 + \beta_5 (EHDD_{it} \times Rain_{it}^{std}) + \gamma_v + \epsilon_{it}$$

where γ_v captures village-level fixed effects to absorb local factors that may influence yield outcomes.

5. Results

We begin by establishing the trend in extreme heat over time. We then examine the association between extreme heat and groundnut production outcomes.

5.1. Time-series regression

We regress 41-year time series (1980–2020) on EHDD for the groundnut growing season on a time trend variable. The results show that the EHDD increased with time in two of the three provinces of the Groundnut Basin, with an overall increase of 0.21 EHDDs per year (Table 2). Fig. 1 shows the temporal evolution of EHDD across the three provinces. There is considerable difference in the growths in EHDDs by regions. The largest increase in EHDD is observed in Tambacounda, where EHDDs in a groundnut season have been increasing by approximately 0.37 EHDDs every year. In contrast, the lowest estimated increase in EHDD is found in Kaolack, where temperatures are somewhat moderated by the breeze from the Atlantic ocean, and there is a rise of 0.01 EHDDs per year, which is not statistically different from zero. The variation in the rate of increase in EHDDs across the region highlights the varying degrees of vulnerability to rising temperatures among groundnut farmers in the Groundnut Basin. The results also demonstrate that groundnut production is increasingly exposed to high temperature (above 35 °C) during the growing season. We present estimation results on the effects of EHDD on groundnut quasi-profits and log-yields in the next subsection.

Table 2
Time series regression of the seasonal values for EHDD.

	EHDD KL	EHDD KF	EHDD TB	EHDD GB
(Intercept)	5.00*** (0.91)	10.72*** (1.88)	18.88*** (2.77)	11.53*** (1.64)
Trend	0.01 (0.04)	0.25** (0.08)	0.37** (0.12)	0.21** (0.07)
R ²	0.00	0.20	0.21	0.19
Adj. R ²	-0.02	0.18	0.19	0.17
Sigma	2.85	5.90	8.71	5.15
Statistic	0.04	9.95	10.15	9.21
P Value	0.85	0.00	0.00	0.00
DF	1.00	1.00	1.00	1.00
Log Likelihood	-100.02	-129.93	-145.91	-124.37
AIC	206.05	265.87	297.82	254.74
BIC	211.19	271.01	302.96	259.88
Deviance	315.72	1358.16	2960.58	1035.49
DF Resid.	39	39	39	39
nobs	41	41	41	41

$p < 0.001$; ** $p < 0.01$; * $p < 0.05$.

5.2. EHDD on groundnut outcomes

Fixed effects and OLS models are estimated to examine the impact of short-term temperature change on groundnut quasi-profits and on log-yields. Table 3 presents the results for the preferred person-level specification in a fixed-effects model. The extreme heat degree days variable is negatively associated with quasi-profits and yield in the person-level fixed-effects model. The EHDD parameter estimates suggest that after controlling for individual fixed effects, an increase in one EHDD during the cropping season reduces quasi-profit per hectare by 5460 FCFA (≈ 10 USD). For yield, each additional EHDD reduces log yield by 0.025, which translates to approximately a 2.5% decline in groundnut yield per hectare.

Table 3
Effect of extreme heat on groundnut production person level.

	Dependent variable:	
	Quasi-profit (1000s CFA Francs) (1)	Log (Yield) (2)
EHDD	-5.46** (2.22)	-0.025** (0.012)
Seed quantity		0.002*** (0.0004)
Fertilizer quantity		-0.0002 (0.001)
Rainfall (standardized)	42.89*** (11.27)	0.208*** (0.073)
Rainfall squared	-36.58*** (10.03)	-0.177*** (0.063)
EHDD × Rainfall	-3.17*** (1.10)	-0.015** (0.006)
Individual fixed effects	Yes	Yes
Observations	4261	4267
R ²	0.06	0.22
Adjusted R ²	-2.43	-1.86
F Statistic	19.95*** (df = 4; 1161)	54.99*** (df = 6; 1163)

Note: Spatial bootstrap standard errors in parentheses.

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 4 presents alternative model estimates of EHDD effects under household-level fixed effect and field-level OLS models. A similar negative relationship between EHDDs and quasi-profits is found, though with lower magnitudes in the field-level OLS specification. Similarly,

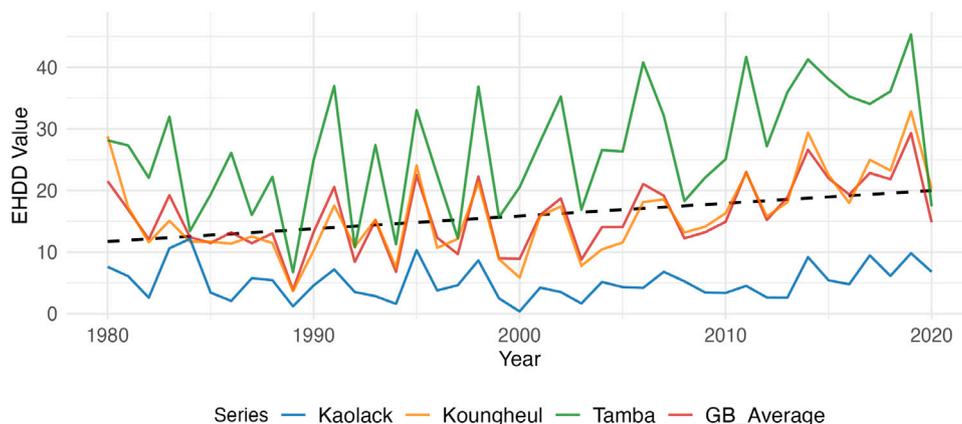


Fig. 1. Extreme Heat Degree Days (EHDD) in the Groundnut Basin,1980–2020.

Table 5 presents the results of the effects of EHDD on household and field log of yield. Each additional EHDD is associated with a 3.2% decrease in the household-level model and a 2.9% decline in the field-level model.

Table 4
Effect of extreme heat on groundnut quasi-profits.

	Dependent variable: Quasi-profit (1000s CFA Francs)	
	Household level (1)	Field level (2)
EHDD	-5.474*** (1.528)	-3.921** (1.730)
Rainfall (standardized)	42.29*** (7.244)	29.643*** (11.179)
Rainfall squared	-32.50*** (7.485)	-30.517*** (8.795)
EHDD × Rainfall	-3.215*** (0.791)	-2.350*** (0.882)
Constant		15.219 (55.168)
Fixed effects	Household	Village
Observations	1495	5179
R ²	0.70	0.094
Within/Adjusted R ²	0.09	0.081
Residual Std. Error		179.556 (df = 5101)
F Statistic		6.899*** (df = 77; 5101)

Note: *p < 0.1; **p < 0.05; ***p < 0.01. Spatial bootstrap standard errors in parentheses.

The interaction between EHDD and rainfall is negative and statistically significant in all specifications. Each additional EHDD combined with high rainfall further reduces quasi-profits and yields. This suggests that under high-heat conditions, the productivity benefits of rainfall decline, and losses from heat intensify.

Our estimates rely on two panel years. To address concerns that short panels confound site quality with weather, we control for a field-quality proxy from NDVI and include year fixed effects. The EHDD coefficients remain stable under this alternative specification (Tables A.1, A.2, and A.3).

Regression results using ground station temperature measures from the ANACIM dataset are presented in Table A.4. The EHDD parameter estimates are again negative and significant across person, household and field specifications. The estimated effects are smaller in magnitude

Table 5
Effect of extreme heat on groundnut yields.

	Dependent variable: Log (Yield)	
	Household level (1)	Field level (2)
EHDD	-0.032*** (0.010)	-0.029*** (0.010)
Seed quantity	0.003*** (0.001)	0.002*** (0.0003)
Fertilizer quantity	0.001* (0.001)	0.0005* (0.0003)
Organic fertilizer		0.172*** (0.036)
Rainfall (standardized)	0.264*** (0.067)	0.216*** (0.075)
Rainfall squared	-0.177*** (0.045)	-0.173*** (0.059)
EHDD × Rainfall	-0.019*** (0.005)	-0.016*** (0.006)
Constant		5.256*** (0.478)
Fixed effects	Household	Village
Observations	1506	5214
R ²	0.78	0.275
Within/Adjusted R ²	0.24	0.264
Residual Std. Error		0.877 (df = 5133)
F Statistic		24.324*** (df = 80; 5133)

Note: *p < 0.1; **p < 0.05; ***p < 0.01. Spatial bootstrap standard errors in parentheses.

compared to those using ERA5 data. This likely reflects the limited spatial variation in the ANACIM data, which comes from only three stations and may not capture micro-climatic differences across villages.

6. Discussion

Increasing temperatures and extreme heat variability are having notable impacts on agricultural production in the Senegal Groundnut Basin, especially on groundnut cultivation. Our results highlight the importance of generating effective adaptation strategies, as long-term projections suggest that extreme heat has been increasing and will continue to increase.

The negative correlation between EHDDs above 35 °C and groundnut quasi-profits aligns with previous studies asserting that high temperatures negatively affect crop yields (Schlenker and Lobell, 2010). Historical climate records show a steady increase in the number of extreme heat degree days (EHDD) over the past four decades in the Groundnut Basin. Climate model projections (such as CMIP6) indicate that this trend is expected to continue, with rising EHDD during the cropping season. Under the assumption that production systems remain vulnerable to heat, continued exposure will likely amplify the economic pressures we document.

EHDD has increased by about one extra EHDD every ~5 years on average since the early 1980s, and by less than 3 years in some locations. Combining this trend with our marginal yield effect implies decadal yield losses on the order of 5%–8%, with comparable declines in profits when applying the profit elasticities. These approximated figures support the interpretation that warming-related extreme heat stand to meaningfully lower farm outcomes in this region.

In this setting, land use and crop mix are set before planting and remain fixed during the season. Input adjustments within the season are limited; for example. We find no association between EHDD and fertilizer use in our data. Labor may adjust to EHDD, but we do not observe labor inputs in the survey. Thus yield and quasi-profit response can be interpreted as short-term responses with labor being the only variable input.

Effective adaptation to the changing climate demands a broader proactive approach that not only safeguards the livelihoods of farming communities, but also ensures food security and economic stability. Comprehensive adaptive strategy components likely involve development and promotion of heat-tolerant groundnut varieties that can withstand higher temperatures during critical growth stages. Additionally, the adoption of improved irrigation systems and water management practices can help counteract the increased risk of water stress caused by elevated temperatures. Further, agricultural extension services play a vital role in disseminating knowledge about climate-smart farming practices that focus on optimal planting dates, crop rotation, and soil conservation techniques. Diversifying income sources beyond agriculture through alternative livelihoods and rural entrepreneurship can reduce communities' reliance on groundnut production and enhance overall resilience to climate-related shocks. These solutions all require significant research and development investments from governmental and non-governmental organizations (Bryan et al., 2013; Rosenzweig and Parry, 1994).

When considering financial and technical support for farmer adaptation, it is also important to address the accountability principle in the context of extreme heat. The regions of the Groundnut Basin, and Senegal more broadly, are among the world's most vulnerable regions to temperature change (Lenton et al., 2023). But these same regions have contributed little in terms of greenhouse gas emissions that are spurring climate change (Lenton et al., 2023). This north-south dichotomy raises ethical considerations in terms of who should bear the costs of adaptation. Subsidies to promote adaptation can serve to reallocate costs from those who are disproportionately affected by climate change, but less responsible for its causes, to those economies that have most contributed to the problem and who have a greater capacity to bear the financial burden. This complexity implies that policy discussions must include considerations of justice and equity in climate finance, in addition to economic efficiency.

It is also worth noting that extreme heat has implications not just for agricultural productivity, but also for broader issues of human habitation. In some regions like Tambacounda, temperatures are reaching the limits of human tolerance and the costs of losses cannot be calculated solely in the context of current farming practices. More drastic adaptive measures may be required, potentially up to and including migration or significant changes to lifestyles and livelihoods. Issues such as widespread lack of air conditioning further exacerbate the human impact of extreme heat. As noted by Dell et al. (2014), the

overall impacts of heat on people need to be considered alongside the direct effects on agriculture, adding another layer of complexity to the challenges posed by climate change. Further, climate impacts are not uniformly experienced; they differ based on factors such as gender, age, and vulnerability levels due to distinct societal roles, responsibilities, and resource access. Adaptation strategies must be tailored to ensure equitable outcomes and enhance overall effectiveness. This comprehensive view of the impacts of rising temperatures calls for a broader range of solutions, extending beyond agriculture and into the domains of urban planning, infrastructure development, and social policy. Recognizing these broader issues can foster the development of strategies that address both the economic and human aspects of climate change. The projected future costs highlights the need for more decisive commitments from nations to curb greenhouse gas emissions and broader global cooperation in addressing the challenge (Masson-Delmotte et al., 2022). Even the limited set of impacts examined in this paper highlight the need for future research on effective adaptation strategies that support community-wide adaptation.

CRedit authorship contribution statement

Maguette Sembene: Writing – original draft, Visualization, Software, Formal analysis, Data curation, Conceptualization. **Bradford Mills:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Anubhab Gupta:** Writing – review & editing, Supervision, Conceptualization.

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Appendix

Table A.1
Effect of extreme heat on groundnut production - Person level.

	Dependent variable:	
	Quasi-profit (1000s CFA Francs) (1)	Log (Yield)) (2)
EHDD	-8.256*** (2.327)	-0.0453*** (0.0133)
Seed quantity		0.0038*** (0.0004)
Fertilizer quantity		0.0009** (0.0004)
Rainfall (standardized)	31.17* (15.84)	0.2375** (0.0957)
NDVI field quality score	13.85 (45.11)	-0.2909 (0.2519)
Rainfall squared	-32.67** (12.60)	-0.2458*** (0.0748)
EHDD × Rainfall	-4.222*** (1.229)	-0.0242*** (0.0073)
Fixed effects	Person	Person
Observations	2591	2597
R ²	0.88019	0.91618
Within R ²	0.05763	0.34719

Note: *p < 0.1; **p < 0.05; ***p < 0.01.
Spatial bootstrap standard errors in parentheses.

Table A.2
Effect of extreme heat on groundnut quasi-profits.

	Dependent variable: Quasi-profit (1000s CFA Francs)	
	Household level (1)	Field level (2)
EHDD	-6.654*** (2.063)	-7.237*** (1.751)
Rainfall (standardized)	33.83** (12.73)	26.954*** (8.785)
NDVI field quality score	-60.55 (56.77)	52.903* (28.731)
Rainfall squared	-32.44*** (10.04)	-36.319*** (6.837)
EHDD × Rainfall	-3.562*** (1.055)	-3.727*** (0.826)
Constant		-9.588 (44.213)
Fixed effects	Household	Village
Observations	1142	3082
R ²	0.80825	0.104
Within/Adjusted R ²	0.10165	0.081
Residual Std. Error		185.724 (df = 3003)
F Statistic		4.473*** (df = 78; 3003)

Note: *p < 0.1; **p < 0.05; ***p < 0.01.
Spatial bootstrap standard errors in parentheses.

Table A.3
Effect of extreme heat on groundnut yields.

	Dependent variable: Log (Yield)	
	Household level (1)	Field level (2)
EHDD	-0.0425*** (0.0111)	-0.041*** (0.008)
Seed quantity	0.0043*** (0.0006)	0.003*** (0.0001)
Fertilizer quantity	0.0018*** (0.0004)	0.001*** (0.0001)
Organic fertilizer		0.159*** (0.041)
Rainfall (standardized)	0.2467** (0.0992)	0.206*** (0.042)
NDVI field quality score	-0.3387 (0.2674)	0.065 (0.136)
Rainfall squared	-0.1934*** (0.0588)	-0.190*** (0.032)
EHDD × Rainfall	-0.0239*** (0.0058)	-0.022*** (0.004)
Constant		4.579*** (0.209)
Fixed effects	Household	Village
Observations	1150	3,106
R ²	0.85981	0.314
Within/Adjusted R ²	0.34150	0.295
Residual Std. Error		0.882 (df = 3024)
F Statistic		17.074*** (df = 81; 3024)

Note: *p < 0.1; **p < 0.05; ***p < 0.01.
Spatial bootstrap standard errors in parentheses.

Table A.4
Effect of extreme heat on groundnut quasi-profits (ANACIM Station Data)

	Dependent variable: Quasi-profit (1000s CFA Francs)		
	Person	Household	Field
EHDD (Station)	-0.559*** (0.147)	-0.393*** (0.104)	-0.347*** (0.078)
Constant			53.050*** (19.417)
Fixed effects	Person	Household	Village
Observations	4261	1495	5,179
R ²	0.143	0.134	0.086
Within/Adjusted R ²	0.026	0.020	0.073

Note: *p < 0.1; **p < 0.05; ***p < 0.01.

Table A.5
Effect of extreme heat on groundnut yields (ANACIM Station Data).

	Dependent variable: Log (Yield)		
	Person	Household	Field
EHDD (Station)	-0.0029*** (0.0008)	-0.0021** (0.0008)	-0.0025** (0.0009)
Seed quantity	0.0021*** (0.0003)	0.0026*** (0.0007)	0.0023*** (0.0004)
Fertilizer quantity	-0.00003 (0.0005)	0.0010 (0.0006)	0.0005 (0.0003)
Organic fertilizer			0.1719*** (0.0244)
Fixed effects	Person	Household	Village
Observations	4267	1506	5185
R ²	0.822	0.761	0.312
Within R ²	0.208	0.168	0.219

Note: *p < 0.1; **p < 0.05; ***p < 0.01.

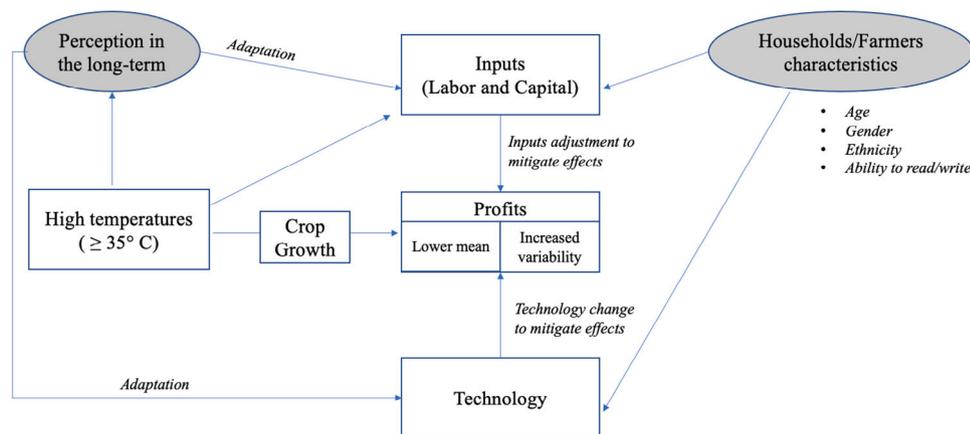


Fig. A.1. Framework for the impacts of extreme heat on Groundnut production.

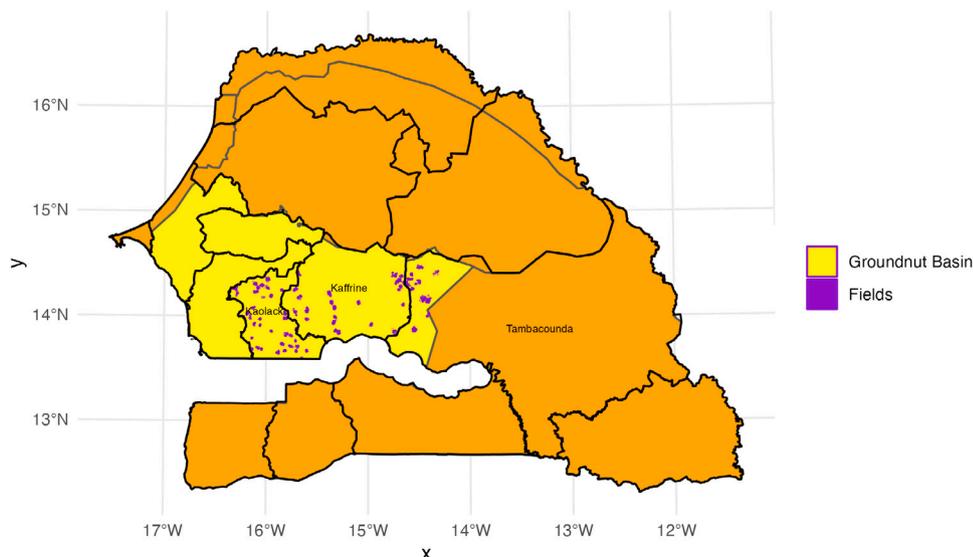


Fig. A.2. Map of the Groundnut Basin with the groundnut fields.

References

Adhikari, U., Nejadhashemi, A.P., Woznicki, S.A., 2015. Climate change and eastern africa: a review of impact on major crops. *Food Energy Secur.* 4 (2), 110–132.

Ahmed, A., Suleiman, M., Abubakar, M.J., Saleh, A., 2021. Impacts of climate change on agriculture in Senegal: A systematic review. *J. Sustain. Environ. Peace* 4 (1), 30–38.

Alioune, B.S., Moctar, C., 2018. Simulation of the impact of climate change on peanut yield in Senegal. *Int. J. Phys. Sci.* 13 (5), 79–89.

Auffhammer, M., Schlenker, W., 2014. Empirical studies on agricultural impacts and adaptation. *Energy Econ.* 46, 555–561.

Ayal, D.Y., 2021. Climate change and human heat stress exposure in sub-Saharan Africa. *CABI Rev.* (2021).

Barrios, S., Ouattara, B., Strobl, E., 2008. The impact of climatic change on agricultural production: Is it different for Africa? *Food Policy* 33 (4), 287–298.

Bryan, E., Ringler, C., Okoba, B., Roncoli, C., Silvestri, S., Herrero, M., 2013. Adapting agriculture to climate change in Kenya: Household strategies and determinants. *J. Environ. Manag.* 114, 26–35.

Burke, M., Emerick, K., 2016. Adaptation to climate change: Evidence from US agriculture. *Am. Econ. J.: Econ. Policy* 8 (3), 106–140.

D’Alessandro, S., Fall, A.A., Grey, G., Simpkin, S., Wane, A., 2015. Senegal. *Agricultural sector risk assessment.*

Delaunay, V., Desclaux, A., Sokhna, C., et al., 2020. Niakhar, Mémoires et Perspectives: Recherches Pluridisciplinaires sur le Changement en Afrique. IRD Éditions.

Dell, M., Jones, B.F., Olken, B.A., 2014. What do we learn from the weather? The new Climate-Economy literature. *J. Econ. Lit.* 52 (3), 740–798.

Deschênes, O., Greenstone, M., 2007. The economic impacts of climate change: evidence from agricultural output and random fluctuations in weather. *Am. Econ. Rev.* 97 (1), 354–385.

Emediegwu, L.E., Wossink, A., Hall, A., 2022. The impacts of climate change on agriculture in sub-Saharan Africa: a spatial panel data approach. *World Dev.* 158, 105967.

Faye, A., Camara, I., Diop, M., OuryDiallo, A., Sine, B., Noblet, M., Faye, B., Defrance, D., Sultan, B., Ndour, N.Y.B., 2022. Millet and sorghum yield simulations under climate change scenarios in Senegal. *Reg. Environ. Chang.* 22 (3), 1–11.

Faye, B., Du, G., 2021. Agricultural land transition in the “Groundnut Basin” of Senegal: 2009 to 2018. *Land* 10 (10), 996.

Garcia, L., 2015. Impact du Changement Climatique sur les Rendements du Mil et de L’arachide au Sénégal: approche par Expérimentation Virtuelle (Ph.D. thesis). Montpellier SupAgro.

- Gbode, I.E., Babalola, T.E., Diro, G.T., Intsiful, J.D., 2023. Assessment of ERA5 and ERA-interim in reproducing mean and extreme climates over West Africa. *Adv. Atmos. Sci.* 40 (4), 570–586.
- Gérard, F., Affholder, F., Mane, N.F., Sall, M., 2020. Impact de différentes politiques publiques sur l'intensification agroécologique et les inégalités de revenu dans le bassin arachidier du Sénégal. In: *Impact de Différentes Politiques Publiques sur L'intensification Agroécologique et les Inégalités de Revenu dans Le Bassin Arachidier du Sénégal*. Agence française de développement, pp. 1–76.
- Gleixner, S., Demissie, T., Diro, G.T., 2020. Did ERA5 improve temperature and precipitation reanalysis over East Africa? *Atmosphere* 11 (9), 996.
- Hathie, I., Wade, I., Niang, A., Ba, S., Niang, M., Sow, M., Ndione, Y., Ba, C., 2014. Jeunes ruraux à la recherche de la productivité. *Doc. Trav. IPAR*.
- Hsiang, S., 2016. Climate econometrics. *Annu. Rev. Resour. Econ.* 8, 43–75.
- Jagnani, M., Barrett, C.B., Liu, Y., You, L., 2021. Within-season producer response to warmer temperatures: Defensive investments by Kenyan farmers. *Econ. J.* 131 (633), 392–419.
- Jarrett, U., Tackie, Y., 2024. Re-examining the effect of heat and water stress on agricultural output growth: How is Sub-Saharan Africa different? *Agricult. Econ.* 55 (3), 515–530.
- Ketring, D., 1984. Temperature effects on vegetative and reproductive development of peanut 1, 2. *Crop. Sci.* 24 (5), 877–882.
- Khouma, M., Jalloh, A., Thomas, T.S., 2012. West African agriculture and climate change: a comprehensive Analysis-Senegal.
- Kotir, J.H., 2011. Climate change and variability in Sub-Saharan Africa: a review of current and future trends and impacts on agriculture and food security. *Environ. Dev. Sustain.* 13, 587–605.
- Kumar, U., Singh, P., Boote, K., 2012. In: Sparks, D.L. (Ed.), Chapter two - Effect of Climate Change Factors on Processes of Crop Growth and Development and Yield of Groundnut (*Arachis hypogaea* L.). In: *Advances in Agronomy*, Vol. 116, Academic Press, pp. 41–69.
- Lenton, T.M., Xu, C., Abrams, J.F., Ghadiali, A., Loriani, S., Sakschewski, B., Zimm, C., Ebi, K.L., Dunn, R.R., Svenning, J.-C., et al., 2023. Quantifying the human cost of global warming. *Nat. Sustain.* 1–11.
- Lobell, D.B., Field, C.B., 2007. Global scale climate–crop yield relationships and the impacts of recent warming. *Environ. Res. Lett.* 2 (1), 014002.
- Lobell, D.B., Hammer, G.L., McLean, G., Messina, C., Roberts, M.J., Schlenker, W., 2013. The critical role of extreme heat for maize production in the United States. *Nat. Clim. Chang.* 3 (5), 497–501.
- Masson-Delmotte, V., Zhai, P., Pörtner, H.-O., Roberts, D., Skea, J., Shukla, P.R., et al., 2022. Global Warming of 1.5° C: IPCC Special Report on Impacts of Global Warming of 1.5° C above Pre-industrial Levels in Context of Strengthening Response to Climate Change, Sustainable Development, and Efforts to Eradicate Poverty. Cambridge University Press.
- Muñoz Sabater, J., 2019. ERA5-Land Monthly Averaged Data from 1981 to Present. Copernicus Climate Change Service (C3S) Climate Data Store (CDS), (Accessed January 2023).
- Ntare, B., Williams, J., Dougbedji, F., 2001. Evaluation of groundnut genotypes for heat tolerance under field conditions in a Sahelian environment using a simple physiological model for yield. *J. Agric. Sci.* 136 (1), 81–88.
- Roberts, M.J., Schlenker, W., Eyer, J., 2013. Agronomic weather measures in econometric models of crop yield with implications for climate change. *Am. J. Agric. Econ.* 95 (2), 236–243.
- Rosenzweig, C., Parry, M.L., 1994. Potential impact of climate change on world food supply. *Nature* 367 (6459), 133–138.
- Sall, M., 2015. Les Exploitations Agricoles Familiales Face Aux Risques Agricoles et Climatiques: Stratégies Développées et Assurances Agricoles (Ph.D. thesis). Université Toulouse le Mirail-Toulouse II.
- Schlenker, W., Hanemann, W.M., Fisher, A.C., 2006. The impact of global warming on US agriculture: an econometric analysis of optimal growing conditions. *Rev. Econ. Stat.* 88 (1), 113–125.
- Schlenker, W., Lobell, D.B., 2010. Robust negative impacts of climate change on African agriculture. *Environ. Res. Lett.* 5 (1), 014010.
- Schlenker, W., Roberts, M.J., 2009. Nonlinear temperature effects indicate severe damages to US crop yields under climate change. *Proc. Natl. Acad. Sci.* 106 (37), 15594–15598.
- Vara Prasad, P., Boote, K.J., Hartwell Allen Jr., L., Thomas, J.M., 2003. Super-optimal temperatures are detrimental to peanut (*Arachis hypogaea* L.) reproductive processes and yield at both ambient and elevated carbon dioxide. *Global Change Biol.* 9 (12), 1775–1787.
- World Food Program, 2014. Climate Risk and Food Security in Senegal: Analysis of Climate Impacts on Food Security and Livelihoods. Technical Report, World Food Program, Rome.