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The heterogeneous effects of climate variability on cotton farming productivity in Burkina Faso

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Abstract

Burkina Faso, a West Africa's country, primarily relies on agriculture to drive its economic growth. However, in the country, this sector has not been consistently developed to deal with climate risks and market failures. Even though the cotton sector in Burkina Faso is well structured in a value chain, producers achieve low factor productivity. Given the complexity of cotton production, its high sensitivity to climate, and the uncertain and erratic weather conditions, it is relevant to analyze the heterogeneous effects of climate variability on farmers' productive performance. The study investigated this issue by estimating a mixed production translog function applied to Burkina Faso farmers' data using the feasible generalized least squares estimator and control function approach, and controlling for socioeconomic factors. The findings demonstrate that weather and climate fluctuations are the adverse effects on cotton output, contingent upon individual farmer characteristics and the specific agroclimatic context of production. These results underscore the heterogeneous nature of climate change effects, providing confirmation that the effects of rainfall, temperature, and wind variability are non-uniform and more crucial for agricultural activities in some regions. In this regard, strategic and localized agricultural policies emerge as indispensable tools for bolstering the resilience of agricultural systems in the face of shifting climatic paradigms. Thereby, the study recommends the need for water- and heat-stress-resilient crop varieties and region-specific climate-smart agricultural technologies at scale, including irrigation and sustainable innovation programs.

Keywords Burkina Faso · Climate variability · Cotton productivity · Heterogeneous effects

JEL Classification C33 · Q10 · Q54

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1 Introduction

Agriculture is the main driver of economic growth in most countries in the Sahel (Fuglie & Rada, 2012; Yobom & Le Gallo, 2022). According to Sarr et al. (2021), the sector contributes about 40% of the gross domestic product (GDP) in these countries and employs more than half of all workers. Despite its significant impact, this sector is struggling to develop. Indeed, the agricultural sector in Sahelian Africa has long been characterized by low productivity due mainly to poor soil porosity, lack of rainfall, and fertility (Bado et al., 2022; Frisvold & Ingram, 1995). According to Ragasa et al. (2018), agricultural productivity in these countries is the lowest in the world. This low global factor productivity recorded in the last three decades is closely related to the phenomenon of climate change, which has contributed to land degradation and rendered farmers' efforts futile (Sarr et al., 2021). The specialists of the Intergovernmental Panel on Climate Change (IPCC, 2021) define climate as a stable set of meteorological conditions that apply to a particular geographic environment over a long period. When this stability is disrupted over time for natural and/or anthropogenic reasons, we refer to it as climate change.

Empirical studies have highlighted factors that can negatively impact agricultural productivity in sub-Saharan Africa (SSA). They cite the inadequacy of agricultural policies pursued in these countries and institutional failures as important factors that may hinder the development of the agricultural sector (Johson & Evensohn, 2000; Partey et al., 2018). Others believe that the low level of investment in the sector, the accelerated degradation of soils, the re-emergence of climatic phenomena, the low level of adoption of new agricultural technologies, the low level of access to credit and improved seeds, and the lack of control over the use of fertilizers may explain this poor performance (Feder et al., 1985, 2004; Ragasa et al., 2018; Binswanger & Townsend, 2000).

Among these factors believed to negatively affect productivity, climate appears to be the most important determinant of agricultural production, especially in developing countries (Bedeke, 2023). According to London School theorists subscribing to David Pearce's views on environmental economics, contrary to neoclassical theories, the climate is a critical natural capital, the disturbance of which is harmful to both nature and humans because it affects agriculture (Pearce, 1987). The link between climate and economic activity was the subject of a relevant analysis by Nordhaus (1977). According to Nordhaus (2019), climate change affects all economic activities through a ripple effect, as it mainly affects agriculture and the energy sector, which are important and vulnerable sectors of the economy. The failure to take climate into account leads to the omission of a crucial variable in the economic analysis. Therefore, the climate appears as a crucial factor for economic growth, along with the factors mentioned in neoclassical theory (Nordhaus, 2019). In summary, climate change affects the economy, agricultural production, and income of cotton farmers in Burkina Faso.

Ongoing climate change is contributing to significant losses in agricultural productivity and incomes due to fluctuations in rainfall and average temperatures, as well as the intensity of extreme weather events, particularly in the Sahel region of Africa (Knox et al., 2012; Omotoso et al., 2023). Mendelshon et al. (1994) reason that agriculture is the economic activity most sensitive to climate variability. In their reports, IPCC specialists point to climatic shocks as the main cause of the decline in crop yields in Africa over the past two decades (IPCC, 2021). These climate-damaging impacts on agriculture lead to a decline in economic output and growth, as well as an increase in inequality and poverty rates in these developing countries (IPCC, 2021). According to Ncube et al. (2015), the main shocks caused by climate hazards are increased temperature extremes, rainfall variability, and drought. They argue that rising temperatures reduce crop yields and promote the spread of weeds and crop-damaging weeds. Regarding precipitation, its constant variability makes agricultural output very unpredictable (Abdi et al., 2023). These results clearly show that it is unthinkable to formalize a production model in countries with low irrigation capacity, such as Burkina Faso, without taking climatic conditions into account (Deschênes & Greenstone, 2007; Mendelshon & Dinar, 2003). In conclusion, the manifestations of climate change such as heat stress, drought and flood intensities, abnormal rainfall patterns, consequent shortage of water, and frequency of extreme events are directly affecting cotton production.

In Burkina Faso, as in most other countries in the Sahel, the agricultural sector is under the influence of climate shocks, as practiced agriculture is quasi-rain dependent due to limited irrigation capacity (Kurukulasuriya et al., 2006). According to Ouédraogo and Tiganadaba (2015), poor irrigation and geographic location (in the heart of the Sahara) make Burkinabe agriculture dependent on climatic shocks. Despite being an economic growth lever and the configuration of its value chain, the cotton sector is not immune to the negative impacts of climate change (Akouwérabou et al., 2022; Diarra et al., 2017). The sensitivity of cotton to climate variability (very demanding in terms of rainfall and thermal conditions) is a justifying factor for this situation, leading to lower cotton productivity and farmers' incomes (Ton, 2011; Vyankatrao, 2020). Ai et al. (2021) confirm that the increase in temperature, decrease in water availability, and increase in evapotranspiration arising from decreased precipitation and humidity levels are climate factors that make cotton cultivation complex.

Due to the above climate risks, the cotton sector in Burkina faces low productivity and high production costs (Gray et al., 2018). As a former African leader in the cotton sector and among the top ten cotton-producing countries in the World, Burkina Faso recorded a poor performance with a production of 464,000 tons of cotton for the 2019–2020 campaign, ranking behind Benin, Mali, and Côte d'Ivoire, which produced 714,714; 700,000; and 490,470 tons, respectively (Laouan, 2021). Seed cotton production decreased by 29% between 2018 and 2019, due to a decline in yields from 697 to 672 kg per hectare (MAAH, 2021). In a diagnostic study, Akouwerabou et al. (2017) demonstrated the fluctuation in cotton yields per hectare between 1996 and 2017. Productivity initially increased from 0.86 tons per hectare in 1996 to 1.06 in 2001 and 1.08 in 2007. However, it experienced a decline, reaching 0.96 tons in 2015 and further dropping to 0.69 tons in 2017. According to Vitale (2018), the pivotal constraints on cotton productivity growth in Burkina Faso are attributed to water scarcity, intensified pest pressure, soil degradation, and the quality of seeds. These factors collectively culminate in escalated production costs within the cotton sector.

The threats associated with climate hazards require the adoption of climate-smart agriculture (CSA) practices to prepare for and deal with potential shocks and uncertainties. CSA represents a comprehensive repertoire of agricultural practices, interventions, and technologies, all wielding the potential to serve as instrumental tools for both climate change adaptation and mitigation. These multifaceted innovations hold the promise of augmenting the economic well-being of farmers while concurrently bolstering food security (Teklu et al., 2023). Noteworthy among these advancements are a diverse array of strategies encompassing agronomy, agroforestry, livestock management, forestry practices, land use optimization, pasture management, water and soil resource management, adaptive shifts in planting schedules and growing seasons, and the harnessing of bioenergy sources. Unfortunately, Burkinabe farmers face financial constraints that prevent them from investing in their farms and coping with these shocks (Feder et al., 1985; Hansen et al., 2019). This effectiveness of climate change and the catalytic role of cotton in economic dynamics in Burkina Faso lead to a diagnosis of the impact of climate variability on cotton productivity.

Therefore, aware of the idiosyncratic nature of the climate and the heterogeneity of farmers, the research question is: What can be the heterogeneous effects of climate and weather fluctuations on the agricultural productivity of cotton smallholders in Burkina Faso? Thus, this study aims to assess the heterogeneous effects of climate variability, as measured by precipitation, temperature, and wind, on cotton productivity in Burkina Faso. The IPCC (2021) report shows that depending on the region, changes in temperature and precipitation can have heterogenous effects on agricultural activities. Therefore, the first objective is to analyze the impact of the evolution of average rainfall on the productivity of cotton farmers across different agroclimatic regions in Burkina Faso. We then analyze the effects of average temperature variation and wind fluctuations on cotton productivity at the farm level. According to Bange (2007) and Drine (2011), extreme weather events affect agricultural productivity differently depending on the development period of cotton plants. The study hypothesizes that the rising of temperatures and wind variability, as well as rainfall instability during the growing season, negatively affect cotton productivity in Burkina Faso.

A few studies worldwide have highlighted the impact of climate change on agriculture in the country. These studies focused on the relationship between agricultural income and climate change and found a negative correlation (Ouédraogo et al., 2010; Somé et al., 2013; Ouédraogo, 2012). However, the use of productivity, i.e., the output obtained per unit of sown land, seems more appropriate as a dependent variable. Unlike income, it is independent of variable factor prices and measures the efficiency of agricultural practices. Moreover, previous literature does not consider the idiosyncratic nature of climate shocks and the specificity of cotton farming through data collection, which may lead to non-specific results. To address this gap in the literature, we used GPS precipitation data collected from individual plots and average temperatures recorded during the three phases of cotton production in Burkina Faso.

Taking the cotton sector as a case study is justified by the lack of climate-related risks literature about this crop in Burkina Faso even though it is an economically crucial element. To the best of our knowledge, so far, very few economic studies have explored the effects of climate change on cotton farming in Burkina Faso. Previous studies focused on climate change's impact on cereals production such as maize, sorghum, rice, millet, yam, cassava, and groundnuts which the livelihoods of a large proportion of the SSA's population currently depend on (Ouédraogo, 2012; Nana, 2019; Kogo et al., 2021; Carr et al., 2022). However, in Burkina Faso, cotton production contributes enormously to economic growth and is a reliable source of income used by farmers as a safety net to ensure their food supply (Gray et al., 2018). This highlights the importance of cotton and the need to assess the constraints that affect its productivity, including climate change and variability.

The importance of this study, therefore, is that it focuses on elucidating the heterogeneous impacts of climate change on farm households, which is a departure from previous research that has predominantly examined general and aggregate effects. Kumar and Khanna (2023) aptly note that many studies to date have neglected to consider climate-specific impacts on economic performance, which hinders the identification of precise adaptation strategies to mitigate these effects. To our knowledge, this critical issue has not yet been addressed in the context of Burkina Faso. Therefore, in order to conduct a comprehensive and robust analysis, it is essential to recognize the idiosyncratic nature of climate change and the inherent heterogeneity of households. In many ways, this study challenges development actors to formulate tailored, individualized household resilience strategies to effectively address the negative impacts of climate change. In academia, it adds to the literature already begun on the effects of climate change on vulnerable stakeholders in developing economies.

To test the basic hypotheses of the study, a translog production function with the control function approach (CF) and the feasible generalized least squares (FGLS) estimator are applied to cross-sectional data of 667 cotton farmers from Burkina Faso. Ginbo (2022) and Kumar et al. (2021) have previously used FGLS estimation to examine the heterogenous effects of climate change on crop yields across different crops in Ethiopia, and in lower-middle-income countries, respectively. Econometric results confirm a negative correlation between climatic irregularities and cotton production per hectare in Burkina Faso. This correlation tends to decrease with producer experience and the adoption of climate-resilient farming practices.

The remainder of the paper is organized as follows: The second section is devoted to the methodological approach. The third section describes the process of data generation and the statistics of the variables. Furthermore, this section presents the estimations and econometric validation tests, followed by a discussion of the results in the fourth section. The final section concludes the paper and provides policy implications.

2 Methodology

2.1 Theoretical framework

After the synthesis of the controversies between neoclassical thought and the London School, made possible by the fundamental contribution of Nordhaus (1977), who initiated the debate on the need to include climate in economic analysis, two main methods of analysis have emerged. These are the traditional production function approach and the Ricardian approach. The latter approach is called the Ricardian method because it is based on an observation by David Ricardo in 1817 that in a situation of pure and perfect competition, the value of land would reflect its level of productivity.

The production function approach is based on Mendelshon et al. (1994) an empirical production function that establishes the relationship between agricultural production and climate changes. Thus, this approach allows for measuring the impact of climatic phenomena on agricultural yields or productivity by varying the level of climatic stimuli (Mendelshon et al., 1996; Deressa & Hassan, 2009; Ouédraogo, 2012). Environmental variables such as precipitation, temperature, and the amount of carbon dioxide released into nature are included as production factors in the production function approach of Mendelshon et al. (1994). Authors such as Rosenzweig and Parry (1994), Barrios et al. (2008), and Ncube et al. (2015) used it to estimate the impact of climate change on agricultural production in Africa. One of the advantages of this model is its strong ability to reliably predict how climate change will affect agricultural yields (Deressa & Hassan, 2009). However, this approach has been criticized as biased because it omits adaptation options that farmers can implement to limit the damage of climate change on their farms. This omission tends to overestimate the damage to agricultural activities (Mendelshon et al., 1994). To better apply the production function approach, Dinar et al. (1998) suggest including potential adaptation measures in the model. Based on this critique, the Ricardian approach is developed.

To correct the bias attributed to the production function approach, Mendelshon et al. (1994) develop the Ricardian approach by including the potential for private adjustments by farmers. These adaptation measures include variations in sowing dates, the use of improved seeds and fertilizers, and irrigation. The theoretical basis of this approach is that producers adapt in the face of climate change by developing private initiatives to always maximize their profits (Wood & Mendelsohn, 2015). These adaptation actions generate costs and benefits that negatively or positively affect net income or farm value. To account for the costs or benefits of adjustment, the precursors of the Ricardian approach believe that the relevant dependent variable should be net income or land value rather than yield. Ouédraogo et al. (2006, 2010) and Kurukulasuriya et al. (2006) applied it to analyze the economic impacts of climate change on agriculture in Burkina Faso and Africa, respectively.

In addition to accounting for private adjustments, another advantage of this model is that its application does not suffer from difficulties because it uses cross-sectional secondary data that are relatively easy to collect (Mendelshon et al., 1996; Schlenker & Lobell, 2010). The limitations of this model are that it does not account for the effects of carbon prices and fertilization. In addition, according to Cline (1996), it is not based on proven experience by farms. The other major limitation of this approach is that its applicability in its original form is a serious problem in most developing countries due to the lack of an efficient land market (Sarker et al., 2014). In a recent study, Kumar et al. (2023) employed a fixed-effect quantile panel regression to explore variations in estimates across the spectrum of crop yield functions. This modeling approach proves advantageous for investigating the distinct impacts of climate change across different points of the yield distribution and specific geographic areas. However, it is worth noting that the successful application of this model necessitates access to panel data encompassing both individual household farms and climate-related variables. Regrettably, our study is constrained to utilizing solely cross-sectional data, limiting our capacity to leverage the full potential of this method.

Given these constraints and the low rate of new agricultural technologies' adoption in Burkina (Feder et al., 1985; Ouédraogo, 2012), in this study we reconcile the two approaches by adopting a mixed production function approach, following Yobom and Le Gallo (2022), which takes into account the possibility of adopting climate-smart agriculture (CSA) technologies as an adaptation measure. Climate-smart agriculture seeks to enhance the resilience of agricultural systems and livelihoods and to reduce the climate risks on production (Ogunyiola et al., 2022). It is a set of agricultural practices and technologies that help achieve sustainable development goals by mitigating climate risks such as drought, heat, flooding, and soil erosion. In Burkina Faso, these technologies include soil and water conservation techniques (Zaï, Stony cords, Half-moons pits), the use of animal or motorized traction, adoption of improved and drought-tolerance varieties, crop rotation, and mixed-cropping. Akouwérabou et al. (2022) show that these practices are very relevant to control the harmful effects of floods and droughts, reclaiming degraded land, and improving cotton productivity in Burkina Faso. In conclusion, this study uses a production function approach considering the above limits mentioned to perform the adapted model.

2.2 Model specification

According to Deschênes and Greenstone (2007), the analysis of the effects of climate change on agricultural production can be performed using the following fitted production function:

$$y_i = \alpha_i + X_i'\beta + \sum_i \theta_i f_i\left(W_{i(t)}\right) + u_i \tag{1}$$

where y_i represents output per hectare of cultivated land, X_i' the socioeconomic characteristics of the household head and his farm, $W_{i(t)}$ a set of n climatic variables affecting farmer at time t, θ_i the climatic effect on productivity, and $f_i(.)$ a quadratic shape function. Equation (1) can therefore be specified by a transcendental logarithmic function or a translog production function since this functional form is general and flexible (Berndt & Christensen, 1973). Variables in the model are not in the same measurement units, and to control their excessive variation resulting from regional and farmers heterogeneity, it is necessary to translog the Eq. (1). Unlike the Cobb–Douglas production function, the translog form allows the analysis of the interaction between variables and is not subject to restrictions on marginal factor productivities and elasticities of substitution (Ochieng et al., 2016; Zepeda, 2001). In this study, however, it is useful to use a log–log functional form that accounts for the quadratic terms of the climatic variables.

Ochieng et al. (2016) justify the above specification by the existence of a nonlinear relationship between climatic variables and agricultural activity. Moreover, this form allows estimation and interpretation without too much difficulty. Similarly, when estimating, it is possible to directly obtain the elasticities of the variables whose squares are not included in the model. This is not the case with the translog specification, which always requires mathematical transformations after estimation to obtain any elasticity.

Starting from the production Eq. (1), we can write the new functional form, which we refer to here as an extended Cobb–Douglas form:

$$\ln Y_{ij} = \alpha_0 + \sum_{i,j=1}^{N,n} \beta_{ij} \ln X_{ij} + \sum_{i,j=1}^{N,n} \theta_{ij} \ln W_{ij} + \sum_{i,j=1}^{N,n} \gamma_{ij} \ln W_{ij}^2 + \sum_{i,j=1}^{N,n} \delta_{ij} \ln W_{ij} \ln Z_{ij} + \lambda_k D_k + \mu_{ij} \tag{2}$$

where are β_{ij} the elasticities of factors X_{ij}, D_k represents climate-smart agriculture technologies adoption (binary variable) and two dummy variables for the Sahel and the Sudanese zones, and Z_{ij} is the household's experience in cotton production. The elasticity of productivity for the climatic factors W can be obtained by a mathematical transformation of Eq. (2) as follows:

$$\varepsilon_{ij} = \frac{dY_{ij}}{dW_{ij}} * \frac{W_{ij}}{Y_{ij}} = \frac{\frac{dY_{ij}}{Y_{ij}}}{\frac{dW_{ij}}{W_{ij}}} = \frac{\partial \ln Y_{ij}}{\partial \ln W_{ij}} \tag{3}$$

The last term of Eq. (3) is possible because $\ln Y_{ij}$ is a continuous and derivable function. Then we can develop the function $\ln Y_{ij}$ to order N to derive the first part of the elasticity formula given by Eq. (3). From Eq. (2), we have:

$$\begin{aligned}\ln Y_{ij} = \alpha_0 + + \sum_{i,j=1}^{N,n} \beta_{ij} \ln X_{ij} + \theta_{1j} \ln W_{1j} + \theta_{2j} \ln W_{2j} + \cdots + \theta_{ij} \ln W_{ij} \\ + \cdots + \theta_{Nj} \ln W_{Nj} \gamma_{1j} \ln W_{1j}^2 + \cdots + \gamma_{ij} \ln W_{ij}^2 + \cdots + \gamma_{Nj} \ln W_{Nj}^2 \\ + \delta_{1j} \ln W_{1j} \ln Z_{1j} + \cdots + \delta_{ij} \ln W_{ij} \ln Z_{ij} + \cdots + \delta_{Nj} \ln W_{Nj} \ln Z_{Nj} \\ + \lambda_k D_k + \mu_{ij}\end{aligned} \tag{4}$$

We can now derivate $\frac{\partial \ln Y_{ij}}{\partial \ln W_{ij}}$ from Eq. (4) as:

$$\begin{aligned}\frac{\partial \ln Y_{ij}}{\partial W_{ij}} = \theta_{ij}\left(\frac{1}{W_{ij}}\right) + 2\gamma_{ij}\left(\frac{1}{W_{ij}}\right) + \delta_{ij} \ln Z_{ij}\left(\frac{1}{W_{ij}}\right) \Rightarrow \frac{\partial \ln Y_{ij}}{\partial W_{ij}} W_{ij} \\ = \theta_{ij} + 2\gamma_{ij} + \delta_{ij} \ln Z_{ij}\end{aligned} \tag{5}$$

Equation (6) can be rearranged to obtain:

$$\frac{\partial \ln Y_{ij}}{\frac{\partial W_{ij}}{W_{ij}}} = \theta_{ij} + 2\gamma_{ij} + \delta_{ij} \ln Z_{ij} \Rightarrow \frac{\partial \ln Y_{ij}}{\partial \ln W_{ij}} = \theta_{ij} + 2\gamma_{ij} + \delta_{ij} \ln \overline{Z}_{ij} = \varepsilon_{ij} \tag{6}$$

β_{ij}, θ_{ij}, γ_{ij} and δ_{ij} are parameters to be estimated.

2.3 Identification strategy

Equation (2) supposes that variables including in D_k are all exogenous. However, it is known that the adoption of CSA technologies depends on household socioeconomics and plot characteristics, the degree of farmers' risk aversion, access to climate information, institutional factors, and social norms (Jha et al., 2021). This variable is therefore endogenous, and the ordinary least squares (OLS) estimators are inconsistent. The problem must be addressed so that the parameter estimates reliably represent the population. In such a situation, Wooldridge (2015) recommends using the control function (CF) approach. Unlike Heckman's (1979) method based solely on observables through the use of Mills ratios, the CF approach takes into account both observable and unobservable factors that are sources of endogeneity in the data. It consists initially of modeling and estimating the decision to adopt CSA technologies by a probit model. Then, the generalized residuals of the model are retrieved and integrated into step 2 in Eq. (2) to obtain unbiased estimates. The specification used to address the endogeneity issue through the CF approach is presented as follows:

$$D_i = 1\left[\delta_i Z_i + \nu_i > 0\right] \tag{7}$$

where D_i represents the farmers' adoption decision of CSA; 1[.] is the binary indicator function, Z_i is a vector of variables that include farm and household characteristics; δ_i is a vector of parameters to be estimated, while ν_i is an error term. Equations (2) and (7) would assume that (μ_i, ν_i) are independent of Z.

Although the variables in the vectors X_i in Eq. (2) and Z_i in Eq. (7) are similar, it is important to note that for correct identification at least one variable in the vector X_i is excluded from Z_i. Here, we include specifically in Z_i variables related to age and experience of household, distance to market, off-farm activity participation, education, labor, and access to extension services. Intuitively, these variables may influence farmers' decision to adopt CSA technologies, but not necessarily cotton productivity.

If it assumes that $\nu_i \sim$ normal (0, 1), then D_i follows a probit model:

$$P(D = 1|Z) = \Phi(\delta Z), \tag{8}$$

where $\Phi(\bullet)$ is the standard normal cumulative distribution function.

The empirical probit model from Eq. (7) is specified as follows:

$$\begin{aligned} \text{CSA}_{\_\text{adopt}} = {} & \eta_0 + \eta_1 \ln(\text{Age}) + \eta_2 \ln(\text{Experience}) + \eta_3 \ln(\text{Distance to market}) \\ & + \eta_4 \text{Off\_farm\_activity} + \eta_5 \text{Education} + \eta_6 \ln(\text{Labor}) \\ & + \eta_7 \text{Extension\_agent\_contact} + \eta_8 \text{Farm\_size} + \upsilon \end{aligned} \tag{9}$$

According to Wooldridge (2015), the CF approach consists of the first estimate Eq. (9) and obtains "generalized residuals" whose mathematical expression is:

$$\hat{v}_i \equiv D_i \lambda\left(\hat{\delta}_i Z_i\right) - \left(1 - D_i\right) \lambda\left(-\hat{\delta}_i Z_i\right), \quad i = 1, \ldots, N \tag{10}$$

where $\lambda(\bullet) = \phi(\bullet)/\Phi(\bullet)$ is the inverse Mills ratio. The second step is to run the OLS regression of Eq. (2) above after incorporating the generalized residuals $\hat{v}_i$ and observed values of the CSA variable as covariates to address the endogeneity problem of CSA. The significance of the estimates of the generalized residuals at the first stage indicates evidence of simultaneity bias from the CSA variable (Wooldridge, 2015). However, to deal with heteroskedasticity in the sample the use of the feasible generalized least squares (FGLS) estimator at the second stage might be appropriate to obtain more consistent estimates.

3 Descriptive data and statistics

3.1 Data

The data used in this research to test the hypotheses came from two sources. The cross-sectional data are used to capture rainfall at the plot scale, and the production and socio-economic environment of the household head. The other climate variables are secondary data collected by the Burkina Faso Meteorological Department.

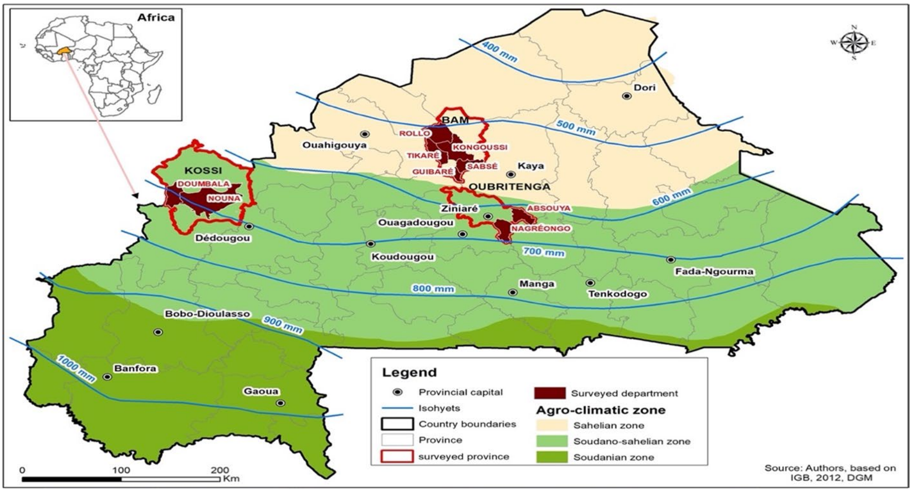
The cross-sectional data were collected in Burkina Faso in 2017 as part of Research Project No. 3, entitled "Pathways to Resilience in Semi-Arid Economies (PRISE)." This is collaborative research conducted simultaneously by researchers from the Overseas Development Institute (ODI), Innovations Environnement Développement (IED), and researchers from African and Asian universities. In Burkina Faso, the project is being carried out by researchers from the Economic department of University Thomas Sankara.

This project aims to analyze the impact of climate change on cotton farmers in arid and semiarid areas. The objective is to determine how farmers in these areas are affected by climatic shocks and at the same time to understand to what extent they are resilient. With this objective in mind, three provinces in the country belonging to two cotton societies were covered by the survey. It should be noted that in Burkina Faso, cotton growing areas are divided between three cotton companies, namely the "Société burkinabè des fibers et textiles (SOFITEX)" zone, the "Faso-Coton" zone, and "Société Cotonnière du Gourma (SOCOMA)" zone. The first two areas are the provinces of Oubritenga and Bam, which are in dry and low rainfall areas and are managed by the Faso-Coton Company.

However, the need to control the analysis of the impact of climate change on producers' yields has led to the retention of the province of Kossi (managed by SOFITTEX) as a control zone, where rainfall is slightly higher compared to the arid and semiarid areas. In this province, which served as a counterfactual variable, the number of households surveyed is lower because the weighting in terms of producers is made in favor of the arid and semiarid zones. No province was surveyed in the SOCOMA area because cotton is no longer grown in the arid and semiarid zones in this part of the country. The sample also included one province in each of the three climatic zones of the country (see Fig. 1). This is the Sudanian zone, which is the most irrigated zone in Burkina Faso (900–1200 mm annual rainfall), in which Kossi is located. Oubritenga province is in the Sudano-Sahelian zone (600–900 mm annual rainfall). Bam is in the least irrigated zone of the country, namely the Sahelian zone (400–600 mm annual rainfall).

A total of 678 cotton farmers were interviewed randomly as part of this project. In Oubritenga province, only two departments (Nagréongo and Absuya) with 160 cotton farmers were surveyed during the 2016/2017 growing season. In Bam province, there are five departments (Kongoussi, Rollo, Tikaré, Sabcé, and Guibaré) with 475 farmers who grew cotton during the survey period. In this province, 374 producers (78.74% of bam cotton producers) were randomly interviewed. In Kossi Province, which serves as the agroecological control region, 6033 farmers grew cotton in eight departments, while only 144 farmers (about 2.39%) were interviewed in Nouna and Doumbala departments, as the PRISE project focuses on arid and semiarid areas. However, due to the inconsistencies found at the end of the data processing, we kept 667 farmers, including 152 in Oubritenga (Sudano-Sahelian region), 371 in Bam (Sahelian region), and 144 in Kossi (Sudanian region).

The secondary data collected by the General Directorate of Meteorology of Burkina Faso are time series ranging from 1988 to 2017, i.e., a period of 30 years covering the periods of the agricultural campaigns, namely May to October. They refer to the monthly values of a few climatic variables provided by three meteorological stations, namely the Bourzanga, Ouagadougou Airport, and Dédougou stations, covering Bam, Oubritenga, and Kossi provinces, respectively. These variables are maximum temperatures and wind



Source: Authors, based on IGB, 2012, DGM

Fig. 1 Burkina Faso's agroclimatic regions and survey locations speeds. To illustrate the non-uniform distribution of precipitation, we also use precipitation data derived from GPS (Global Positioning System) coordinates of individual plots from the 2016/2017 growing season, which were also collected as part of the PRISE project. Utilizing the coefficients of variation for this variable allows us to effectively capture the heterogeneity within the rainfall distribution in our analyses.

3.2 Presentation of the variables and their descriptive statistics

Since the objective of this study is to show the potential effect of climate variability on cotton productivity, productivity (output obtained per hectare of cultivated land) is logically the dependent variable in the chosen model. According to the data in Table 1, the average productivity of the sample is 714.58 kg/ha. However, the analysis of individual productivity shows great differences, since the minimum productivity is 40 kg/ha, while the maximum is 2756 kg/ha. The explanatory variables were selected based on the theoretical and empirical literature presented previously. According to this literature, these variables can be divided into two main categories: socioeconomic factors and agroclimatic factors.

3.2.1 Socioeconomic variables

The professional experience acquired by the farmer is defended as a determinant that favors the improvement of agricultural production. The more years of experience the producer has in agricultural activity, the more he develops initiatives to increase his productivity level (Kaminski et al., 2011). The descriptive statistics of the sample show that cotton producer households have an average of 21 years of experience, which varies from 01 to 67 years depending on the individual. Theoretically, this large experience has a positive impact on productivity in Burkina Faso (Diarra et al., 2017).

In addition, the level of human capital, measured by education, is also a determining factor in agricultural production (Schultz, 1988). It is divided here into educated family labor and hired labor. The former reflects the number of working people in the household who are literate in any language. This category of labor is very useful to the farm because, in addition to its labor force, it can analyze and understand the challenges facing the farm and thus provide appropriate solutions. In Table 1, the educated family workforce consists of an average of 4 workers, while households employ an average of 11 workers to make up for the labor deficit on their farms. This deficit is further reduced when the household adopts climate-smart agricultural technologies.

The adoption of CSA technologies by farmers in Sahelian countries improves the productivity of their land (Nana & Thiombiano, 2018). In Burkina Faso for example, farmers who adopt soil and water conservation (SWC) technologies (Zaï and half-moons pits, stone cordon techniques), mechanization (tillage by traction animal, use of tractors and plows), crop rotation techniques, and improved crop varieties mitigate climate risks and significantly increase their agricultural productivity (Akouwérabou et al., 2022). The farm mechanization technology allows farmers to save time in preparing the soil for sowing, thus avoiding delays at the start of the campaign. The SWC allows to fight against soil erosion and water runoff, restore degraded, conserve water for plants, and control the harmful effects of climate risks such as floods and droughts (Norton & Alwang, 2020). In the sample, the average adoption of CSA adoption is 54.87%. This means that these technologies are moderately adopted in the cotton sector. In Africa, most agricultural land is degraded and less fertile (Ragasa et al., 2018). As a result, farmers are forced to add nutrients to

Table 1 Farm household characteristics and climate-related variables

Variables	Definitions	Means	Std. Dev	Prop. (%)	Min	Max	Sign
Dependent variable							
Production per hectare (kg/ha)	Cotton production per unit hectare of land	714.585	454.211	–	40	2,755.906	
Cofactors							
Age	Age of household head	49.135	12.384	–	18	88	±
Experience	Number of years the household has experience in cotton production	20.947	11.746	–	1	67	+
Education	1[if the farmer got formal education]	–	–	0.352	0	1	+
Educated labor force	Number of workers who are educated in the household	3.657	3.045	–	0	23	+
Hired labor	Number of workers hired per campaign	10.799	18.078	–	0	84	+
Organic fertilizer (kg)	Quantity of organic fertilizer used	2,746.17	2,345.212	–	0	9,000	+
Pesticides (liters)	Quantity of pesticides used in liters	6.991	5.18589	–	1.5	40	+
Farm size (in ha)	Farm area allocated to cotton production	1.373	1.075	–	0.2	9	+
Distance to market (in km)	Household distance from the nearest market	5.052	4.437	–	0.1	22	±
Off-farm activity	1[if the household has a non-farm activity]	–	–	0.631	0	1	
Physical capital (in FCFA*)	Amount invested in farm equipment	35,541.91	4,115.37	–	10,500	450,000	+
Climate-smart agriculture technology (dummy)	1[if the household adopts CSA technology]	–	–	0.5487	0	1	+
Contact to extension agents	1[if the farmer has access to extension services]	–	–	0.853	0	1	+
Coef. variation of rainfall	Coefficient of variation of the amount of precipitation on the plot in 2016	14.951	2.116	–	11.39	18.16	±
Coef. variation maximum temperature	Coefficient of variation of maximum temperatures from 1988 to 2017	0.377	0.357	–	0.136	0.297	±
Coef. var. of wind speed	Coefficient of variation of wind speed from 1988 to 2017	0.175	0.066	–	0.131	1.04	±
Sahelian zone	1[if the household is in the Sahel]	–	–	0.556	0	1	–
Sudan-Sahel zone	1[if the household is in Sudano-Sahelian zone]	–	–	0.216	0	1	±
Sudanian zone	1[if the household Sudanese zone]	–	–	0.228	0	1	+

Source: Data from PRISE's project/Burkina Faso, 2017

FCFA is the common currency of the West African Economic and Monetary Union countries. 1 USD is equivalent to 600 FCFA in 2017 the soil. Given the financial constraints faced by Burkinabè producers, the most accessible fertilizer is organic manure. This is confirmed by the data in Table 1, which shows that producers used an average of 2746.17 kg of organic fertilizer to fertilize their plots. This variable is expected to have a positive effect on soil productivity (Ochieng et al., 2016).

Moreover, cotton production requires regular treatment with pesticides to get rid of pests (Diarra et al., 2017). The statistics below show that farmers in the sample use an average of 6.99 L of pesticides to spray their farms for pests.

The expected effect of this variable when the dosage is controlled is positive (Bange, 2007). Another factor identified in the literature that positively affects productivity is physical capital (Fuglie & Rada, 2012). Investment in physical capital is the household's total expenditure on farm equipment, household furniture, and physical achievements on its farm to improve the productivity of the land. Our sample shows that households invest an average of FCFA 35,542 but with wide variation, as some may invest as much as FCFA 450,000.

3.2.2 Agroclimatic variables

The climate variables commonly used in the literature that are believed to affect agricultural productivity are temperature, precipitation, and wind speed (Santra et al., 2017; Ochieng et al., 2016; Chang, 2002; Mendelshon et al., 1994). Climate change manifests itself in the intertemporal and spatial variation of these variables, which directly affects agricultural activity (IPCC, 2021). Therefore, according to Asfaw et al. (2015) and Chang (2002), the use of coefficients of variation to study this climate variability is the best option. The coefficient of variation of a variable is obtained by calculating the ratio between its standard deviation and its mean i.e., $\text{CV(Coeffcient of Variation)} = \frac{\sigma}{\mu} = \frac{\text{Standard deviation}}{\text{mean}}$.

In this study, the coefficient of variation for precipitation was calculated for the short period. It refers to the precipitation data recorded on each plot during the 2016/2017 agricultural campaign. The coefficients of variation for temperature and wind were obtained by the quotient of the standard deviation and the mean of each of these variables during the period 1988 to 2017 in each of the three climatic zones covered by the survey. The locations considered are the Sahelian, the Sudano-Sahelian, and the Sudanian zones. Table 1 shows that on average, rainfall varies from one plot to another (14.95%). These fluctuations have different effects on agricultural productivity. The variation of maximum temperatures for the period 1988–2017 is 37.7 and that of wind speeds is 17.5%.

4 Results of the estimates

4.1 Robustness check

The quality of the specification of the quadratic translog model is checked by Ramsey's test for omitted variables. The results of the test, given in Table 3, do not allow for the rejection of the null hypothesis that the model does not suffer from the problem of omitted variables. Thus, the model is well-specified. To address the problem of multicollinearity that some climate variables exhibit, the model is estimated separately. This issue of multicollinearity is tested using the variance inflation factors (VIF) and the correlation matrix between the

Table 2 Variance inflation factor (VIF) of independent variables

Variable	VIF	Tolerance
Experience	1.23	0.8150
Educated labor force	1.16	0.8615
Hired labor force	1.14	0.8741
Organic fertilizer	1.46	0.6847
Pesticide	1.24	0.8075
Climate-smart agri. (CSA) technology	1.26	0.7953
Physical capital	1.24	0.8080
Coefficient of variation of rainfall	15.05	0.0664
Coefficient of variation of temperature	461.77	0.0022
Coefficient of variation of wind speed	364.07	0.0027

Caption: A VIF of 1 indicates not correlated, a VIF between 1 and 5 indicates a moderate correlation, and a VIF above 5 indicates a high correlation

Table 3 Elasticities of cotton productivity concerning explanatory variables

Variables	Model 1′	Model 2′	Model 3′
Experience	0.03	1.435**	
Educated labor force	0.041*	0.045	0.036
Hired labor	0.071***	0.059	0.067**
Organic fertilizer	0.025**	0.031**	0.028***
Pesticides		0.027	
Physical capital	0.0280***	0.035***	0.023***
Climate-smart agriculture	0.392**	0.434***	0.402**
Coefficient of variation of maximum temperature			-1.830***
Coefficient of variation of rainfall			16.137**
Coefficient of variation of wind speed		– 17.834***	

Source: From the authors' estimation results

independent variables, which are reported in Tables 2 and 6. Table 6 in Appendix shows that the correlation coefficients between the explanatory variables are moderately significant, and many are not statistically significant. However, Table 2 reports a high correlation between climate variables. The collinearity problem is addressed in estimating the model in three ways: first without including the climate variables (model 1), then considering the coefficient of variation of wind speed (model 2), and finally considering the coefficients of variation of precipitation and maximum temperature (model 3). Moreover, by altering the model's specifications, including or excluding variables, we perform sensitivity analyses. This helps verify the consistency of the results. In addition, the control function (CF) approach is used to test and solve the potential endogeneity problem of the CSA_adoption variable. The t-statistics show that the generalized residuals coefficients from the probit model at the first stage are statistically significant, proving that the CSA variable was indeed endogenous (Table 4).

To ensure the accuracy of our statistical conclusions, checking the assumption of heteroskedasticity in data is needed. Indeed, such an econometric problem occurs when the

Table 4 Effect of climate variability on cotton productivity (Dep. Var. Cotton output per hectare)

Variables	CF approach			CF and FGLS		
	(1)	(2)	(3)	(1′)	(2′)	(3′)
Socioeconomic factors						
ln(household experience)	– 0.007 (0.043)	0.615*** (0.208)		0.003 (0.039)	0.528** (0.210)	
ln (educated labor force)	0.071* (0.038)	0.086** (0.040	0.074** (0.037)	0.041 (0.036)	0.045 (0.039)	0.035 (0.036)
ln (hired labor force)	0.069 (0.045)	0.069 (0.046)	0.076* (0.045)	0.073** (0.034)	0.059 (0.037)	0.0674** (0.034)
ln (organic fertilizer)	0.021** (0.010)	0.029** (0.012)	0.023** (0.010)	0.025** (0.011)	0.031** (0.012)	0.028** (0.011)
ln(pesticide)		0.047 (0.044)			0.027 (0.034)	
Climate-smart agri. (CSA) technology	0.457* (0.236)	0.636** (0.240)	0.474** (0.236)	0.392** (0.155)	0.434*** (0.156)	0.402** (0.156)
Generalized Residuals $\hat{v}.CSA$	– 0.246* (0.141)	– 0.357** (0.144)	– 0.257* (0.141)	– 0.211** (0.086)	– 0.240** (0.088)	– 0.222** (0.087)
ln(Physical capital)	0.024*** (0.008)	0.032*** (0.009)	0.024*** (0.008)	0.028*** (0.008)	0.035*** (0.008)	0.023*** (0.008)
Agroclimatic factors						
ln (Coef. var. rainfall)			22.094 (15.506)			25.474** (12.050)
ln(Coef. var. rainfall) *ln (Coef. variation of rainfall)			– 4.258 (2.894)			– 4.752** (2.312)
ln (Coef. var. max. temperature)			– 0.842** (0.336)			– 1.100*** (0.257)
ln(Coef. var. max. temperature) *ln (Coef. var. max. temperature)			– 0.393** (0.181)			– 0.555*** (0.136)
ln (Coef. of variation of wind speed)		– 11.485** (1.867)			– 11.074*** (1.547)	

Table 4 (continued)

Variables	CF approach			CF and FGLS		
	(1)	(2)	(3)	(1′)	(2′)	(3′)
ln(Coefficient variation of wind speed)*ln (Coef. var. wind speed)		− 3.492*** (0.575)			− 3.380*** (0.479)	
ln(Experience)*ln(Coef. variation of rainfall)			0.061** (0.029)			0.055* (0.030)
ln(Experience)*ln(Coef. variation of maximum temperature)			0.128** (0.048)			0.125** (0.051)
ln(Experience)*ln(Coef. variation of wind speed)		0.370*** (0.117)			0.317** (0.117)	
Sudano-Sahelian Region	0.780*** (0.080)			0.733*** (0.071)		
Sudanian region	0.699*** (0.099)			0.664*** (0.092)		
Constant	5.227*** (0.186)	− 3.609** (1.440)	− 23.151 (20.782)	5.218*** (0.187)	− 3.096** (1.230)	− 28.508* (15.734)
Adjusted R^2	0.260	0.289	0.268	0.332	0.335	0.347
F-test (P value = 0.0000)	26.75***	22.36***	21.12***	35.01***	27.04***	29.68***
White's heteroskedasticity test ($P > \text{chi}^2$)	73.52***	100.20***	97.79**			
Ramsey's RESET test	1.08	0.70	0.22	0.69	0.57	1.37
AIC	1354.14	1166.74	1349.94	1065.65	901.44	1039.44
BIC	1399.09	1219.07	1408.38	1110.61	953.76	1097.88
Sample size	662	579	662	662	579	662

Caption: Standard errors in parentheses; *$P < 0.10$, **$P < 0.05$, ***$P < 0.01$

variance of the error terms in the sample is not constant. In this case, the estimated coefficients remain valid but inefficient and the standard deviations are biased. This problem can be avoided using the Breusch Pagan or White (1980) tests. However, since the Breusch-Pagan test assumes normality of the errors, this study opts for the White test by regressing the squared residuals on the dependent variables, their squares, and their cross-products. The results of the White test do not allow to reject the alternative hypothesis of the presence of heteroskedasticity in data (see Table 4). In this case, the ordinary least squares estimator is inefficient. And since the functional form of heteroskedasticity is unknown and because of the endogeneity of the CSA variable, the Feasible Generalized Least Squares (FGLS) estimator combined with the CF approach is most appropriate. The study then applies White's (1980) robust variance–covariance matrix under FGLS estimator to the original quadratic translog model, incorporating the predicted values of the generalized residuals to correct for the potential endogeneity bias problem that may arise from observables and unobservable factors. Furthermore, the Akaike information criterion (AIC) and the Bayesian information criterion (BIC) are used to determine the appropriate models. The results show the lowest AIC and BIC values for models 1′, 2′ and 3′, suggesting a better fit to the data (see Table 4). By making estimates consistent, they can now be used for interpretations and policy implications.

4.2 Empirical results

The econometric results presented in Table 4 show that some climate variables including the variability of maximum temperatures and wind, affect cotton production in Burkina Faso in a negative linear fashion. As we can see in Table 4, a 1% increase in maximum temperatures leads to a 1.830% decrease in cotton output per hectare. The correlation is more pronounced when wind speed varies. In this regard, the results show that a 1% increase in wind speed leads to a significant decrease of about 17.834%. The negative effects of irregularities in precipitation, temperature, and wind are mitigated as farmers gain experience in cotton production (Table 4, columns 1′, 2′, and 3′ below).

However, concerning rainfall, the situation is different. The results show that the impact of rainfall variability on cotton productivity takes the form of an inverted U in the short term. This suggests the existence of a threshold effect at which rainfall becomes harmful to cotton. According to the findings, this threshold is a coefficient of variation of 14.83% outside of which a marginal increase or decrease in rainfall is devastating to cotton. However, the overall effect is positive, as Table 3 shows a positive elasticity of about 16.137, meaning that a 1% increase in rainfall variability results in a productivity increase of about 16.137%. The increase in cotton productivity is only possible when the rainfall fluctuation is low, as we can see in Fig. 2.

The previously mentioned effects of climatic variables on cotton productivity are confirmed by the results of the dummy variables of agroclimatic zones. Indeed, we find that growing cotton in the Sahelian zone of Burkina Faso reduces productivity performance (only 518.78 kg per hectare, see Table 5). This is not the case for farmers in the Sudanian zone (1014.920 kg per hectare). This later zone has a positive effect on production per hectare because the land is fertile, and rainfall and temperatures are favorable for production. Table 5 shows a significant gap of 441 kg per hectare of cotton output in the Sahelian region compared to the two others agroclimatic regions due to climate change effects. Climate variability is higher in the Sahelian zone than in other zones in Burkina Faso and

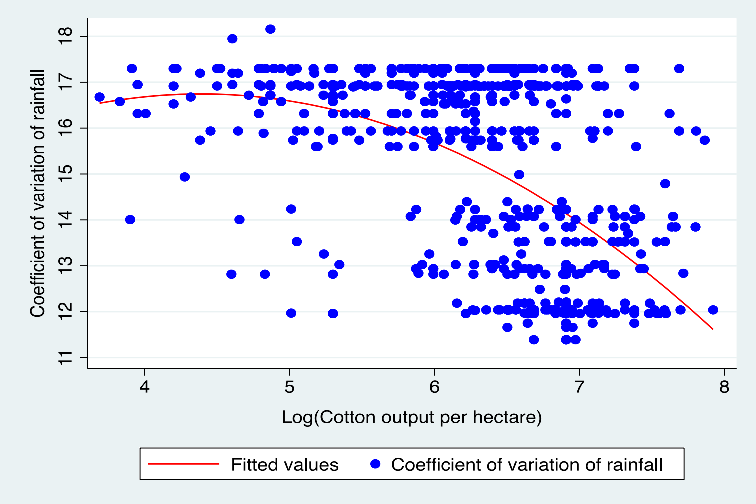


Fig. 2 Correlation between rainfall variability and cotton productivity. Source: Authors, from PRISE's data

Table 5 Characteristics of main variables for each ago-ecological region

Variables	Sudanian	Sudano-Sahelian	Sahelian	All regions
	Means	Means	Means	Means
Cotton productivity	1014.920 (368.52)	902.035 (473.910)	518.78 (374.104)	714.585 (454.211)
Coef. var. of rainfall	12.075 (0.435)	13.407 (0.665)	16.729 (0.561)	14.951 (2.116)
Coef. var. of temperature	0.336 (0.000)	1.040 (0.000)	0.136 (0.001)	0.377 (0.357)
Coef. var. of wind speed	0.336 (0.000)	0.297 (0.000)	0.131 (0.001)	0.175 (0.066)
Climate-smart agriculture practices adoption (%)	13.9 (0.347)	63.2 (0.484)	67.4 (0.469)	54.9 (0.498)

Standard deviations in brackets; the difference-in-means test reveals a significant difference of 441.223 kg per hectare in cotton productivity in the Sahel compared to the other agroclimatic zones

that constraints farmers to adopt more CSA technologies to cope with the climate risks (Table 5).

Regarding household experience in cotton cultivation, the results show a positive correlation with land productivity. The elasticity of this variable to production per hectare is 1.435 (Table 3, Model 2′). Similarly, variables such as the use of organic fertilizer, labor recruitment, and the adoption of climate-smart agricultural technologies are all positively correlated with productivity. Indeed, a 1% increase in the amount of organic manure used to fertilize the plot significantly improves cotton productivity by 0.025, 0.031, and 0.028% for models 1′, 2′, and 3′, respectively. The same is true for hired labor, which significantly increases cotton productivity by 0.071 and 0.067%, respectively, when increased by 1% (Table 3, columns 1′ and 3′). Concerning CSA technologies adoption, empirical results show a positive and significant correlation with cotton productivity.

Farmers who adopt these technologies or practices may improve their productive performance by 0.392, 0.434, and 0.402% according to estimates 1′, 2′, and 3′, respectively (Tables 3 and 4). However, the adoption rate for three regions surveyed is 54.9%, which is low concerning the prevalence of climate shocks in Burkina Faso.

Then, there is a positive correlation between investment in physical capital and cotton production per hectare. The results show that a 1% increase in investment in agricultural infrastructure and equipment significantly improves producer productivity by 0.028, 0.035, and 0.023% for the three estimation cases, respectively (see Table 4).

5 Discussion

The findings show that climate variability has an overall negative and heterogeneous effects on cotton productivity across agricultural regions in Burkina Faso. Indeed, it appears that large variability in maximum temperatures during the period from May to October harms cotton productivity. This is because cotton growing requires special attention during these periods. Cotton is extremely sensitive to temperature and each stage of crop development and growth requires well-defined thermal conditions (Bange, 2007; Sharma et al., 2022; Ton, 2011). Thus, if there are major temperature fluctuations that do not meet the needs of the plants, especially during the period of seed germination and boll development, yields and fiber quality become very uncertain (Ullah et al., 2017). This result is consistent with the study conducted by Bange (2007) on cotton in Australia which shows high temperatures during critical stages of plant growth led to heat stress, which contributes significantly to lower cotton yields. Like our results, Diarra et al. (2017) find that outdoor temperatures negatively affect germination and vegetative stages of cotton growth in Burkina Faso, resulting in lower yields.

High temperatures during the growing season increase environmental stress by altering biodiversity, leading to a decline in crop production capacity (Di Falco & Chavas, 2008; Karahasan & Pinar, 2023). In the last thirty years, average maximum temperatures of 35.6 °C, 34.6 °C, and 34.4 °C have been recorded during the rainy season in the Sahelian, Sudano-Sahelian, and Sudanian regions of Burkina Faso, respectively. These temperatures are harmful to cotton cultivation, as the optimum is 32 °C (Bange, 2007; Ton, 2011). Photosynthesis, which is the main growth factor for cotton plants, is very sensitive to temperature and decreases significantly above 30 °C because of increased atmospheric evaporative (Ai et al., 2021). This fact, combined with the high-temperature stress, can damage crops and lead to a decrease in lint yield and quality, which partly explains the decline in cotton productivity in Burkina Faso. Similar effects are observed in the variability of rainfall.

In countries with limited irrigation capacity, rainfall is a major determinant of agricultural production. Therefore, rain-fed agriculture practiced in these regions is sensitive to any rainfall variability (Barrios et al., 2008; Ogundari & Onyeaghala, 2021). According to the findings, rainfall variability has a positive effect on cotton production up to a certain threshold, above which the effect becomes negative. This is like the effect observed using the environmental Kuznets curve, which illustrates an inverted U-shaped relationship between environmental degradation due to pollution and economic growth. Spatial and temporal variability of rainfall that corresponds to the cotton plants' need for 600–800 mm of water per year leads to better yields. However, when its variability exceeds the required threshold, a negative effect is observed.

This last case can be explained by two situations. First, in the case of a decrease in precipitation (or even drought), cotton plants enter a situation of water stress (Ton, 2011). This is not conducive to the development of the cotton plant, as this stress causes the plants to suffocate. Secondly, if the variability is positive so that flooding occurs, the roots of the plants are inundated. The runoff water deprives the bolls of the nutrients they need to mature properly (Diarra et al., 2017). These results confirm the findings of Kazianga and Udry (2006) that rainfall variability is the main cause of agricultural income variability in Burkina Faso due to its direct impact on yields. According to Welsh et al. (2022), during the critical developmental stages of the cotton plant, high climate variability in temperature, water availability, and moisture negatively affects cotton growth processes and results in reduced yield and fiber quality. These findings are consistent with ours because, in agroclimatic regions in which rainfall variability is high in Burkina Faso, farmers realize lower productive performance (see Table 5). It highlights the heterogeneity of climate change effects on cotton farming in Burkina Faso.

Another climatic factor affecting agricultural productivity is the wind which is one of the major contributors to soil erosion (Santra et al., 2017). Our findings show that increasingly violent winds harm cotton productivity in Burkina Faso. This result corroborates the findings of Warsame et al. (2022) that strong winds accelerate soil fertility loss through erosion and lead to reduced land productivity in Africa. Moreover, Ben Mohamed et al. (2002) reason that strong winds during the growth and flowering stages of the cotton plants cause wind erosion in Niger and crush the young plants with sand or dust. The heat emanating from these piles of soil particles deposited at the base of the seedlings prevents the plants from flowering. Similarly, strong winds during the flowering stage destroy the flowers and boll formation, which reduces the productivity of cotton due to boll shedding. Furthermore, the wind changes the temperature and moisture gradient around the cotton plant, resulting in a change in evaporative demand (Gwambene et al., 2022). These findings show that climatic extremes such as drought, rising temperatures, rainfall instability, and heavy winds are the main challenges for smallholders in cotton production in Burkina Faso.

The results in Table 4 show that the effect of climate variability on productivity is less in the Sudanian zone than in the Sahelian zone. These heterogeneous regional effects are logical because the Sudanian zone is the agroclimatic zone of Burkina Faso where the harmful effects of climate change are least felt. In this part of the country, rainfall is abundant (900–1200 mm per year, see Fig. 1), temperatures are pleasant, and the soil is fertile (Kaminski et al., 2011; Hauchart, 2008). In contrast, the Sahel receives less than 600 mm of rainfall per year, rainfall is very unstable (16.73% of variation level), and the soils there are very degraded. Maximum temperatures are usually highest in this agroclimatic region of Burkina Faso. Therefore, without irrigation, the possibilities of obtaining better yields in cotton cultivation are lower. The negative effects of climate change decrease as households gain experience. Indeed, results show a positive correlation between farmer experience and productivity on the one hand and a positive interaction between climatic variables and experience on the other (Table 4, columns 2′ and 3′). These results are explained by the fact that thanks to learning by doing acquired through experience, the producer manages to adapt to climate variability by adopting appropriate resilience strategies (Feder & Savastano, 2017). This helps mitigate climate risks and increase productivity.

Furthermore, the results show that traditional factors such as labor, organic fertilizer, physical capital endowment, and CSA technologies adoption positively influence cotton productivity. Indeed, the results show that the accumulation of human capital through the increase of literate workers in each language improves cotton productivity. This result reflects the need for non-formal education to benefit farmers. This is justified by the fact that when workers are educated, they have easier access to information regarding new sustainable farming techniques (Jha et al., 2021). The idea put forward by Schultz (1988) comes into play here, as he claims that non-formal education improves the knowledge of producers and makes them more productive. In a study of Indonesian farmers, Feder et al. (2004) reach a similar conclusion to ours. According to this study, farmers who have received specialized non-formal education and are literate are more proficient in pesticide use than those who are not educated. Thus, the ability to dose pesticides and fertilizers contributes to improving farmers' productivity (Ogundari & Onyeaghala, 2021).

The use of organic fertilizers in cotton farms has a positive effect on land productivity (Tables 3 and 4). In the context of climate change, characterized by continuous soil degradation, the use of organic materials that include compost, livestock manures, and crop residues is a sustainable solution for smallholder farmers to deal with poor soils conditions and improve agricultural productivity (Daadi & Latacz-Lohmann, 2021). Organic fertilizer as a substitute for chemical fertilizer has the advantage of having lower production costs and containing the nutrients necessary for plant growth and soil regeneration (Teklu et al., 2023). Therefore, this traditional agricultural practice can help protect the ecosystem and increase cotton yields. According to Sawadogo (2011), the minerals contained in compost and livestock manures improve the porosity, structure, and water retention capacity of the soil. Thus, the use of organic fertilizer promotes better conditions for plant development and thus increases the productivity of cotton. This result is consistent with that of Ouédraogo et al. (2010), for whom sorghum productivity in Burkina Faso improves greatly when farmers use organic materials.

In addition to family labor, which is commonly used in African agriculture, results suggest that the use of paid labor significantly improves the productivity of cotton production. Cotton farming is labor intensive (Hauchart, 2008; Kaminski et al., 2011), and as a result, farmers must rely on outside labor to support family labor (Husen et al., 2017). Effective allocation of this additional human capital on the farm allows for the pooling of efforts to facilitate the execution of production activities. When pay is based on the performance of each recruit, they are sometimes required to work diligently. This self-sacrifice then makes it possible to improve the productivity of the land using appropriate agricultural techniques. However, the cotton industry in Burkina Faso is struggling with problems related to exploited and poorly paid child labor. To address this problem, which is particularly prevalent in Africa and Asia where cotton production is labor intensive and dominated by smallholder farms, the CLEAR cotton project has been implemented thanks to the implication and collaboration of the Food and Agriculture Organization (FAO), European Union (EU) and International Labour Organization (ILO). The project aims to combat child and forced labor in the cotton value chain in target-producing countries. It promotes programs to accelerate the school reintegration of disadvantaged children and victims of forced labor. This project, which benefits children, will result in a shortage of labor for farmers and an increase in the cost of producing cotton in Burkina Faso, resulting in a further decrease in productivity.

The plausible alternative for farmers to address this labor shortage problem and the negative effects of climate variability is the adoption of climate-smart agricultural technologies (Ogunyiola et al., 2022). The findings show that farmers who adopt at least one of the CSA technologies studied such as SWC techniques, and animal or motorized traction, improved crop varieties significantly improve the cotton land productivity than those who do not adopt them. Farmers in the Sahelian and Sudano-Sahelian zones of Burkina Faso have a greater need to adopt them because of the harmful effect of climate change in these regions, as shown in Table 5. CSA adoption seeks to enhance not only the resilience of agricultural systems and livelihoods but also to mitigate greenhouse gas emissions, which in turn allows to control and reduce climate risks such as floods and droughts, to reclaim degraded land, and thus improve cotton productivity in Burkina Faso (Akouwérabou et al., 2022). Sardar et al. (2021) found that Pakistani farmers who embrace a comprehensive set of CSA practices experience a remarkable 32% increase in cotton yield (kg/ha). This boost in yield subsequently results in a substantial 45% rise in farm income (in US dollars). However, effective implementation of these technologies depends on household and farm characteristics including the age and experience of the household, distance to market, off-farm work participation, education, labor, access to extension services, and a prior endowment of financial and physical capital.

Investment in physical capital through the acquisition of farm equipment, land, livestock, transport, and storage facilities is a necessary condition for the adoption of certain innovative agricultural practices (Ragasa et al., 2018; Feder et al., 2004). This explains the positive correlation between physical capital and land productivity that emerges from our results (Tables 3 and 4). Physical capital accumulation improves agricultural productivity because it provides the technology needed for production. Norton and Alwang (2020) argue that the return to physical capital is clear in the form of improved factor productivity for large and wealthy producers, who are less risk-averse than poor farmers. Therefore, growers who can invest in agricultural infrastructure are the most productive. These results confirm the findings of Zakaria et al. (2019), which show in the case of South Asia that improvements in farmers' productivity are related to their endowment of physical capital.

6 Conclusion and policy implications

The study aims to investigate the heterogeneity effect of climate variability on cotton production in the Sahel region, Sudan-Sahel region, and Sudanian region in Burkina Faso. The results of the FGLS-CF estimations show that climate variability affects household productivity differently depending on the agroclimatic zone and farmers' resilience. Farmers in the Sahel are more affected than farmers in the Sudanian zone because of soil degradation, rainfall scarcity, and rising temperatures that are more pronounced in the Sahel than in other parts of Burkina Faso. Other findings suggest that high variability in maximum temperatures (above 32 °C) from May to October negatively affects cotton productivity in Burkina Faso. Moderate rainfall variability during the growing period has a positive effect on cotton productivity, but this effect becomes negative when variability leads to droughts or floods. The strong winds during the flowering period destroy the blossoms and destroy the boll formation, which reduces the productivity of cotton. These negative effects of climate variability are mitigated by experienced farmers adopting a private and appropriate resilience strategy, such as sustainable and productive agricultural technologies to manage climatic risks. Thus, this study contributes to providing new literature on climate change's effect on cotton farming in Burkina Faso and to an in-depth understanding of the heterogeneity and nonlinearity in climate variability assessment due to the idiosyncratic effect of climate conditions, climate-related risks do not have the same impact on farmers depending on the agroclimatic region.

Stakeholders must combine their efforts to mitigate the above negative effects of climate change in the cotton value chain, especially by supporting the weakest link in adaptation. To build resilience and manage climate risks, farmers in the Sahel and Sudano-Sahel regions need to widely adopt CSA technologies such as organic fertilizers, heat- and drought-resistant cotton varieties, SWC techniques, and precision agriculture based on local knowledge that is more accessible. Given the climatic disadvantage of the Sahel, it is imperative that producers in this region practice mixed rain-fed and irrigated agriculture and invest sufficiently in their farms to accumulate the necessary physical capital to restore degraded soils and protect their farmland from erosion. However, given their difficult economic conditions, this recommendation is feasible through a system of community mutual aid, as is common in some regions of Burkina Faso.

Second, cotton companies need to implement targeted technical and material support and training activities in CSA for the benefit of farmers in the Sahel and Sudano-Sahel zones, which are highly affected by extreme climatic events. Furthermore, for environmentally conscious agricultural development, they need to train and finance farmers in manure pit construction based on local knowledge. The compost and crop manure from these pits will fertilize agricultural fields while protecting the environment.

As the results show that temperature variability negatively affects productivity, the government of Burkina Faso could fund CSA technologies acquisition and agricultural research to develop temperature- and pest-resistant transgenic cotton varieties to improve farmers' resilience and adaptation to climate risks. These plans can be funded through a structural program for the local processing of raw cotton. By increasing the share of locally processed cotton before exports, which is currently around 1%, the cotton sector can become self-financing through the additional value-added and tax revenues generated by the creation of new jobs. The financial resources generated by this policy will be used to acquire new technologies to increase resilience to climate shocks and further organize the cotton sector to improve farmers' competitiveness. Due to the uncertain rainfall, cotton sector leaders and the Burkinabe government also need to develop index-based agricultural insurance and encourage farmers to purchase such insurance. Taking out such insurance will allow each producer to be compensated according to their exposure.

One of the major limitations of this study is the use of cross-sectional data, which does not allow for dynamic and intertemporal analyses of climate change effects in individual agroclimatic regions. The use of panel data or repeated cross-sectional data could be an avenue for future research. Panel data could allow to assess the long-run dynamic effects of climatic fluctuations on the output of cotton and provide more robust insights for policy decision making.

Appendix

See Table 6.

Table 6 Correlation matrix of independent variables

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(70	(8)	(9)	(10)	(11)	(12)
(1) Experience	1											
(2) Educated labor force	− 0.008 (0.840)	1										
(3) Hired labor force	− 0.088** (0.024)	− 0.121*** (0.002)	1									
(4) Organic fertilizer	0.112*** (0.010)	− 0.170*** (0.000)	0.440* (0.000)	1								
(5) Pesticide	− 0.095** (0.022)	0.100* (0.016)	0.204*** (0.000)	0.145*** (0.002)	1							
(6) Climate-smart agri	0.170*** (0.000)	− 0.036 (0.353)	− 0.260*** (0.000)	− 0.034 (0.435)	− 0.092** (0.026)	1						
(7) Physical capital	0.024 (0.681)	− 0.035 (0.550)	− 0.005 (0.928)	0.139** (0.034)	0.040 (0.500)	− 0.050 (0.385)	1					
(8) Rainfall	− 0.015 (0.701)	0.259* (0.000)	− 0.415*** (0.000)	− 0.435*** (0.000)	− 0.251*** (0.000)	0.206*** (0.000)	− 0.165*** (0.004)	1				
(9)Temperature maximum	− 0.215*** (0.000)	− 0.083* (0.031)	0.589*** (0.000)	0.398*** (0.000)	0.323*** (0.000)	− 0.429*** (0.000)	0.054 (0.357)	− 0.573*** (0.000)	1			
(10) Wind speed	− 0.215*** (0.000)	− 0.084* (0.030)	0.589*** (0.000)	0.399*** (0.000)	0.323*** (0.000)	− 0.429*** (0.000)	0.054 (0.354)	− 0.574*** (0.000)	1.000*** (0.000)	1		
(11) Sudan Region	− 0.247*** (0.000)	− 0.020 (0.609)	0.544*** (0.000)	0.227*** (0.000)	0.295*** (0.000)	− 0.432*** (0.000)	0.011 (0.847)	− 0.383*** (0.000)	0.974*** (0.000)	0.974*** (0.000)	1	
(12) Sudano–Sahelian	0.181*** (0.000)	− 0.268* (0.000)	0.097** (0.012)	0.397*** (0.000)	0.048 (0.246)	0.090** (0.019)	0.134** (0.020)	− 0.739*** (0.000)	− 0.062* (0.110)	− 0.060 (0.120)	− 0.285** (0.000)	1

P values are in parenthesis; $***P<0.01$, $**P<0.05$, $*P<0.1$

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Declarations

Compliance with the pre-publication policy The material in the manuscript has not been published, is not being published or considered for publication elsewhere, and will not be submitted for publication elsewhere unless rejected by the journal editor or withdrawn by the authors.

Conflict of interest Authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.

Data and code availability Authors are available to permanently share data and code for replication according to the Data and Documentation Policy.

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