African Journal of
Agricultural and Resource Economics
Volume 18, Number 2 (2023), pp 152–170

The effect of climate change and agricultural diversification on the total value of agricultural output of farm households in Sub-Saharan Africa

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Received: March 2023
Accepted: October 2023

DOI: https://doi.org/10.53936/afjare.2023.18(2).10

Abstract

This study investigates the effect of temperature and precipitation on the economic value of agricultural output from farm households in six Sub-Saharan African countries: Ethiopia, Malawi, Niger, Nigeria, Tanzania and Uganda. Using a repeated cross-sectional dataset covering the period from 2008 to 2016, the study explores how the adverse effects of climate change vary among different levels of agricultural diversification. The findings reveal that a one-degree increase in temperature has a negative effect on the value of agricultural output. Nevertheless, households engaged in diversified production activities exhibit better adaptation to higher temperatures, leading to attenuated effects of climate change. Therefore, this study highlights the critical importance of diversification as a strategy to enhance the resilience of farm households in Sub-Saharan Africa.

Key words: agricultural diversification, agricultural households, climate change, climate resilience, sustainable agriculture

1. Introduction

Climate change is a globally recognised phenomenon that brings with it risks such as droughts and floods. The average global temperature has risen by almost one degree Celsius since 1901, and is projected to increase by two to five degrees Celsius by the end of the twenty-first century, contingent on efforts to reduce greenhouse gas emissions (USGCRP 2018; IPCC 2021). In Africa, the temperature rise is expected to occur faster than the global average, while the region is predicted to experience a long-term decline in precipitation (Nhemachena & Hassan 2007; Gannon *et al*. 2014). This scenario will lead to more frequent and severe extreme weather events in the future (IPCC 2014; Ault 2020).

Agriculture continues to play a crucial role as the primary economic sector in alleviating poverty and fostering prosperity in Sub-Saharan Africa (Kray *et al*. 2018). However, Africa is highly vulnerable to the risks of climate change, mainly due to the significant number of people engaged in agriculture, thereby making poverty eradication a challenge. The repercussions of climate change on farm households are likely to be amplified and expose them to even greater production and income risks. Previous studies have confirmed that climate change has created a loss to the agricultural sector around the world and the damage will be higher in the future, especially for developing countries (Mendelsohn *et al*. 1994; Attavanich & McCarl 2014; Brown *et al*. 2017). Moreover, several studies have shown that poor farmers with low levels of assets tend to have lower adaptation capacity to cope with climate shocks, such as those located in areas vulnerable to a drought or flood shock (Mano & Nhemachena 2007; Skoufias 2012; Hallegatte *et al*. 2016; Nikoloski *et al*. 2018; Sesmero *et al*. 2018; Chonabayashi *et al*. 2020; Chonabayashi 2021).

To address the risk of income loss, households often opt for low-risk, low-return strategies instead of more profitable options (Hallegatte *et al*. 2016). This choice can lead to a perpetual cycle of poverty across generations (Damania *et al*. 2017). For instance, extreme weather events severely affect vulnerable populations, and climate change exacerbates the effects. The income loss experienced by the bottom 40% of the population due to climate change is estimated to be 70% higher than that of the average population (Hallegatte & Rozenberg 2017), likely because climate shocks directly reduce agricultural income and increase food prices due to low crop yields. The repercussions of climate change for global food security are significant, with projections suggesting that it could force an additional 35 million and 122 million people into extreme poverty under optimistic and pessimistic scenarios (Mendelsohn *et al*. 2012).

Agricultural diversification often refers to crop diversification, using different varieties and mixed production, and is a good adaptation to climate risks. The adaptation strategies include promoting sustainable agricultural practices (IPCC 2014; Rosa *et al*. 2020, Zhang *et al*. 2021). Nhemachena *et al*. (2010) demonstrate that the mixed crop–livestock farms are less sensitive to climate variations than specialised farms. Prommawin *et al*. (2022) suggested that households engaged in diversified production activities enterprises are better adapted to higher temperature. Intercropping can increase rain-use efficiency and increase or stabilise crop yields (Kar *et al*. 2004; Agegnehu *et al*. 2008; Sileshi *et al*. 2011, 2012; Koskey *et al*. 2022). Drought-resistant crop varieties and other improved varieties are introduced in many studies as an effective strategy to deal with the negative rainfall shocks and stabilise agricultural production (Xiong & Tarnavsky 2020; Abou *et al*. 2021; Mwinkom *et al*. 2021; Kusiima 2023). Livestock is another common means of production for rural African households, though its contribution to the total household income is generally small (Bundala *et al*. 2020; Kaumbata *et al*. 2020; Giller *et al*. 2021; Sekaran *et al*. 2021). Sekaran *et al*. (2021) conclude that crop-livestock integration can improve agriculture production and address food insecurity.

One significant gap in the literature seems to be in relation to studies analysing the economic effect of climate change on agricultural households' production at the regional scale in Africa, despite many studies being conducted at the country scale. This may be due to a lack of household survey data with comparable information on agricultural livelihoods and climate change across countries. Some literature looks at the regional analysis of the nexus between climate resilience and agricultural diversification in Sub-Saharan Africa (SSA), drawing the national-level scientific research and policy dialogues into its regional implications (Kray *et al*. 2018; Ires & Jacobs-Mata 2022; Jacobs-Mata & Girvetz 2023).

This study endeavours to address the existing research gap by quantitatively assessing the economic effect of climate change and agricultural diversification on farm households in six Sub-Saharan African nations: Ethiopia, Malawi, Niger, Nigeria, Tanzania and Uganda. The analysis is based on a repeated cross-sectional pooling dataset from the Living Standards Measurement Study – Integrity Surveys on Agriculture (LSMS-ISA) conducted from 2008 to 2016. The primary focus is to understand how these factors influence the economic value of agricultural production in the selected countries.

To the best of the author's knowledge, this study represents the first regional analysis of the interplay between climate resilience and agricultural diversification in Sub-Saharan Africa. Utilising the nationally representative, agriculturally intensive, and cross-country comparable LSMS-ISA data, this study aims to explore the intricate relationship between climate change and agricultural diversification for farm households across Africa's agricultural landscape. The study sheds light on the role of agricultural diversification as an adaptation strategy for farm households in Sub-Saharan African countries. The regional scale of analysis could offer regional evidence for agricultural diversification as a climate resilience approach in Africa.

2. Methodology

This study investigated whether diversification of agricultural production increases farmers' economic resilience to climate change. The total value of agricultural output was used as an output measure of agricultural production. To identify diversification effects on economic resilience, the study regressed the total value of agricultural output on temperature and rainfall, among other control variables, with year and country fixed effects. In this setting, one can evaluate the differentiated climate change impacts on the household sub-samples *with* and *without* agricultural diversification.

This study considers a household as being diversified if it has either at least two agricultural activities or was categorised as being involved in both crops and livestock. This approach is similar in spirit to the studies by Lien *et al*. (2006), Birthal *et al*. (2013), Chonabayashi *et al*. (2020), Chonabayashi (2021) and Prommawin *et al*. (2022).

This study assumes that households manage their farm to maximise their output value from various agricultural enterprises, taking the observable climate as a given. Following Chonabayashi *et al*. (2020), the study considered the following equation to analyse the effects of temperature and rainfall on the output value of farm households:

$$\ln y = \beta_0 + \beta_{temp} temp + \beta_{temp^2} temp^2 + \beta_{precip} precip + \beta_{precip^2} precip^2 + \boldsymbol{\delta}' \boldsymbol{X} + \sum_{year} \beta_{year} \times I(year) + \sum_{country} \beta_{country} \times I(country) + u, \tag{1}$$

where y is a vector of total value of agricultural output from production activities, $temp$ and $precip$ are temperature and precipitation variables, $\boldsymbol{X}$ is a matrix of exogenous variables including observable characteristics such as labour and land inputs, physical capacity of farm and livelihood, and other household attributes. The control variables include spatial and temporal dummy variables, in which $I(\cdot)$ is the indicator function. The continuous explanatory variables have their square term to capture nonlinearity in their statistical associations with the output variable. The u is a vector of the stochastic disturbance component, assumed to be independently distributed by a normal distribution with zero mean and constant variance, or $u \overset{iid.}{\sim} N(0, \sigma_u^2)$.

The parameters β_0, β_{temp}, β_{temp^2}, β_{precip}, β_{precip^2}, $\boldsymbol{\delta}$, $\{\beta_{year}\}$, $\{\beta_{country}\}$ are the regression coefficients to be estimated. To account for heteroskedasticity and spatially correlated errors, the statistical inference employs cluster-robust standard errors, which allow intragroup correlation at the country-specific survey strata level, such as zone (in Ethiopia and Nigeria), traditional authority (TA) (in Malawi), grappe (in Niger), and district (in Uganda and Tanzania). To statistically represent the farmer populations, all calculations incorporate the households' stratified sampling weight.

To estimate the economic values of household enterprises *with* and *without* agricultural diversification, the study utilises the regression coefficients from each model to simulate the total value of agricultural output, using the average characteristics of each country in the most recent year available. Specifically, the year dummy variable is fixed at 2016, as it corresponds to the most recent year covered by the LSMS-ISA data used in this study. Consequently, the economic valuation of the effects of climate change and agricultural diversification on the total value of agricultural output will primarily be presented in terms of change in percentage points, facilitating a clear understanding of the effects of these factors on agricultural production.

3. Data

The study utilised nationally representative household-level data from the Living Standards Measurement Study – Integrity Surveys on Agriculture (LSMS-ISA) project. LSMS-ISA is a multi-round survey that collects detailed agricultural information at the plot and household level and includes geo-referenced enumeration location data. There is a growing body of literature that analyses the LSMS-ISA data to explore Africa's agricultural landscape (including Sheahan *et al*. 2014; Christiaensen 2017; Sheahan & Barrett 2017; Christiaensen & Demery 2018; Holden 2018). This study uses the cross-section datasets of six countries: Ethiopia, Malawi, Niger, Nigeria, Tanzania and Uganda from 2008 to 2016. The total number of surveys conducted for this study is 19, as outlined in the following details.

- Ethiopia: 2011, 2013, 2015
- Malawi: 2010, 2013, 2016
- Niger: 2011, 2014
- Nigeria: 2010, 2012, 2015
- Tanzania: 2008, 2010, 2012, 2014
- Uganda: 2009, 2010, 2011, 2013

Agricultural households are defined as those with at least one member involved in the following agricultural activities: crop cultivation, livestock or poultry ownership, or both. This study classifies households that engage in multiple activities as diversified. It also uses the number of agricultural activities as a proxy for agricultural diversification indicators to measure household climate resilience. To further distinguish between different types of agricultural engagements among farming households, this study categorises their activities as crop production, non-crop production, or a combination of both.

To assess the output of enterprises in the agricultural sector, this study employs the measure of agricultural value production, which is calculated by the value of the cultivation of crops and livestock production. All monetary values are converted into 2011 USD levels, using the consumer price index and purchasing power parity (PPP).

This study's definition of agricultural workers in a household includes self-employed and unpaid family workers in agriculture and hired non-family labour. Other explanatory variables include the size of land used for agricultural activities (in hectares), the agricultural wealth index, the index of access to infrastructure, the gender and age of the household head, and access to information – identified as cell phone ownership. Regarding the capacity of physical capital and the environment, this study considers both the agricultural wealth and infrastructure indexes given in the LSMS-ISA datasets. Both indexes give rise to the same conclusions in terms of positive or negative coefficient signs and relativity across farmers with different diversification types. This study furthermore uses the percentile of both indexes for ease of interpretation. The magnitude of changes from the percentage points of index distribution could be translated into output differentials. Following Mendelsohn *et al*. (1994), Fleischer *et al*. (2008) and Sanghi and Mendelsohn (2008), this study includes additional exogenous variables to capture the earth's location heterogeneity, including latitude, longitude and altitude.

The LSMS-ISA household data contains annual climate variables, such as temperature and precipitation, which are readily available in the survey datasets. This climate information was originally sourced from the UC Berkeley WorldClim dataset, providing global climate grids with a spatial resolution of approximately one square kilometre. The climate information covers the average annual temperature calculated from monthly climatology (°C), and total annual precipitation from monthly climatology (mm).

4. Results

This study investigates the effect of agricultural diversification on the output of agricultural households and their resilience to climate vulnerability. A key finding is that farmers who engage in agricultural diversification experience fewer effects from rising temperatures compared with those without diversification. The main regression results are presented in Table 1, which broadly covers two categories: (a) all households and (b) a sub-population of households categorised by their level of diversification in agricultural activities.

The first classification (a) involves a regression analysis of *all* households using different types of dummy variables for diversification:

(a1) All agricultural households with a dummy variable for two agricultural activities relative to one activity.

(a2) All agricultural households with two dummy variables, one for producing only livestock and the other for producing both crops and livestock – where both dummy variables are interpreted relative to producing crops only.

The second classification (b) covers four types of *sub-sample* agricultural households based on their diversification in agricultural activities:

(b1) Agricultural households producing only crops.
(b2) Agricultural households producing only livestock.
(b3) Agricultural households with only one activity, producing either only crops or only livestock.
(b4) Agricultural households with two activities, producing both crops and livestock.

4.1 Effects from temperature and precipitation

Table 1 shows that rising temperatures can have a substantially adverse effect on agricultural output value. Specifically, an increase in temperature of one degree Celsius can, on average, reduce the agricultural output value by 14% for all agricultural households.

However, when examining the effects of temperature on different types of farmers based on their agricultural diversification practices, it becomes apparent that households with diversified crops and activities experience fewer impacts on their output than those without diversification. This suggests that diversification can be an effective strategy to mitigate the negative effects of temperature increases on agricultural output.

In addition, this study reveals that the relationship between temperature and agricultural production value is almost non-linear, with a positive effect observed for temperature squared. However, the coefficients of temperature squared are relatively small, at less than one percent for an increase of one degree Celsius. This indicates that the economic losses resulting from an increase in temperature are significant and cumulative, and the positive coefficients of temperature squared are not sufficient to offset the decline in farmers' output.

Regarding precipitation, the study finds that it generally has a positive effect on agricultural output value. However, there are two exceptions: agricultural households that produce livestock exclusively, and those with only one activity (such as producing only crops or only livestock), experience a negative effect from precipitation. It is important to note that rainfall has the greatest positive effect on agricultural households with diversified crops and activities. Furthermore, the coefficients for rainfall squared are also negligible, as those of the temperature squared.

As demonstrated in Tables A1 and A2 in the Appendix, the sensitivity analysis utilising different sets of control variables validates that farmers who cultivate crops and practise activity diversification encounter fewer negative effects from rising temperature and experience a positive influence from rainfall.

4.2 Effects of labour, land, and physical capital capacity

Table 1 illustrates that an increase in either labour or land could have a positive effect on agricultural output value. However, the negative coefficients of their squared terms are relatively small.

For all households, a one-unit increase in agricultural workers is associated with a 3% increase in agricultural output value. However, the effect of labour on output value varies across different types of households. For households that exclusively produce crops, a one-unit increase in labour would lead to a 3% increase in output value. In contrast, for households that exclusively produce livestock, the output value would increase by 27% with the same increase in labour. This suggests that livestock production is more labour-intensive than crop production.

An increase of one hectare of land dedicated to agricultural activities is associated with a 15% increase in agricultural output value for all households. However, the effects of land size on households exclusively producing livestock are statistically insignificant, while an increase of one hectare for households exclusively producing crops would increase output by 17%. Thus, land appears to be more crucial for crop production than for livestock production.

This study also discovers positive effects from higher levels of the agricultural wealth index and the index of access to infrastructure. Specifically, an increase of one standard deviation in the agricultural wealth index would result in a 36% increase in the total value of agricultural output for all households. The effects of agricultural capital capacity are more significant for non-diversified households. However, the index of access to infrastructure has smaller and mostly statistically insignificant slope coefficients.

4.3 Effects of household characteristics

Farm households with a female head experience a lower agricultural output value. The age of the household head has a non-linear positive effect on output, with older heads of households leading to higher output values. Access to information, as measured by owning a cell phone, is associated with a 12% increase in output value for all agricultural households. However, the effects of cell phone ownership vary across different household groups, with or without diversification.

4.4. Effects of spatial heterogeneity

Latitude does not have a significant effect on agricultural output value. However, there are negative effects from longitude, indicating that agricultural households located further to the east in SSA tend to have higher agricultural output. In addition, this study finds that higher elevations have a negative effect on agricultural output. Furthermore, households located in rural areas tend to have higher output value. When comparing output values across countries, most countries have lower output value than Ethiopia, particularly farmers in Niger.

4.5 Effects of agricultural diversification

From the slope coefficients of the dummy variables for agricultural diversification in the regression model for *all* farm households, we can observe that the effects of diversification through being involved in economic activities of both producing crops and livestock are notably large. Specifically, households with diversification have a 50% higher output value than households with only one activity.

4.6 Economic values of agricultural diversification and climate change adaptation

As illustrated in Tables 2 and 3, the economic valuation reveals that agricultural households that engage in diversification experience fewer negative effects from increasing temperatures. A one-degree Celsius increase in temperature is associated with a 14% reduction in output for all agricultural households. However, households with agricultural diversification have a 50% higher output value than those engaged in only one activity. Furthermore, households that produce both crops and livestock experience lower effects from temperature increases. On the other hand, an increase in precipitation had the highest positive effect on output for households that engage in diversification.

Table 1: Regression results on log of total value of agricultural output

	All agricultural households		Subgroups of agricultural households			
	Control for diversification:					
Dependent variable: Log of total value of agricultural output	**a1) Two activities (relative to one activity)**	**a2) Livestock only or mixed (relative to crops only)**	**b1) Only crops**	**b2) Only livestock**	**b3) One activity (only crops or livestock)**	**b4) Two activities (both crops and livestock)**
Annual mean temperature (Celsius)	-0.145***	-0.144***	-0.170**	-0.207**	-0.262***	-0.131***
	(< 0.001)	(< 0.001)	(0.019)	(0.025)	(< 0.001)	(< 0.001)
Annual mean temperature (Celsius) squared	0.004***	0.003***	0.003*	0.005**	0.006***	0.003***
	(< 0.001)	(< 0.001)	(0.051)	(0.047)	(< 0.001)	(< 0.001)
Avg. 12-month total rainfall (mm/100)	0.044***	0.045***	0.063***	-0.089**	-0.032*	0.076***
	(< 0.001)	(< 0.001)	(0.002)	(0.012)	(0.055)	(< 0.001)
Avg. 12-month total rainfall (mm/100) squared	-0.002***	-0.002***	-0.003***	0.002	0.000	-0.003***
	(< 0.001)	(< 0.001)	(< 0.001)	(0.123)	(0.897)	(< 0.001)
Number of agricultural workers	0.026***	0.026***	0.029***	0.270***	0.032***	0.025***
	(< 0.001)	(< 0.001)	(< 0.001)	(< 0.001)	(< 0.001)	(< 0.001)
Number of agricultural workers squared	-0.000***	-0.000***	-0.000***	-0.010***	-0.000***	-0.000***
	(< 0.001)	(< 0.001)	(< 0.001)	(< 0.001)	(< 0.001)	(< 0.001)
Land used for agriculture (hectares)	0.149***	0.150***	0.174***	0.081	0.164***	0.150***
	(< 0.001)	(< 0.001)	(< 0.001)	(0.568)	(< 0.001)	(< 0.001)
Land used for agriculture (hectares) squared	-0.002***	-0.002***	-0.001***	-0.007	-0.001***	-0.002***
	(< 0.001)	(< 0.001)	(< 0.001)	(0.510)	(< 0.001)	(< 0.001)
Agricultural wealth index	0.363***	0.363***	0.511***	0.352**	0.471***	0.299***
	(< 0.001)	(< 0.001)	(< 0.001)	(0.014)	(< 0.001)	(< 0.001)
Index of access to infrastructure	0.043*	0.043*	-0.056	-0.039	-0.014	0.033
	(0.097)	(0.093)	(0.253)	(0.773)	(0.764)	(0.276)
Female head (relative to male head)	-0.269***	-0.269***	-0.230***	-0.066	-0.218***	-0.274***
	(< 0.001)	(< 0.001)	(< 0.001)	(0.467)	(< 0.001)	(< 0.001)
Age of head	0.021***	0.021***	0.023***	0.001	0.022***	0.020***
	(< 0.001)	(< 0.001)	(< 0.001)	(0.970)	(< 0.001)	(< 0.001)
Age of head squared	-0.000***	-0.000***	-0.000***	-0.000	-0.000***	-0.000***
	(< 0.001)	(< 0.001)	(< 0.001)	(0.839)	(< 0.001)	(< 0.001)
Household has a cell phone	0.114***	0.113***	0.117***	0.115	0.124***	0.111***
	(< 0.001)	(< 0.001)	(< 0.001)	(0.130)	(< 0.001)	(< 0.001)
EA latitude	-0.003	-0.003	0.009	-0.065***	-0.024***	0.007*
	(0.387)	(0.395)	(0.250)	(0.006)	(< 0.001)	(0.094)
EA latitude squared	-0.001***	-0.001***	0.001**	0.001	-0.001**	-0.000*

Dependent variable: Log of total value of agricultural output	**All agricultural households**		**Subgroups of agricultural households**			
	Control for diversification:					
	a1) Two activities (relative to one activity)	**a2) Livestock only or mixed (relative to crops only)**	**b1) Only crops**	**b2) Only livestock**	**b3) One activity (only crops or livestock)**	**b4) Two activities (both crops and livestock)**
	(0.002)	(0.002)	(0.048)	(0.580)	(0.024)	(0.055)
EA longitude	-0.025***	-0.026***	-0.053***	0.004	-0.030**	-0.013
	(0.001)	(0.001)	(0.001)	(0.916)	(0.047)	(0.125)
EA longitude squared	0.001***	0.001***	0.001***	0.000	0.000	0.001***
	(< 0.001)	(< 0.001)	(0.009)	(0.693)	(0.137)	(0.001)
Log of elevation (m)	-0.316***	-0.314***	-0.211	-0.386*	-0.297**	-0.343***
	(< 0.001)	(< 0.001)	(0.125)	(0.086)	(0.010)	(0.008)
Log of elevation (m) squared	0.035***	0.035***	0.023	0.033	0.037***	0.037***
	(< 0.001)	(< 0.001)	(0.124)	(0.257)	(0.005)	(0.004)
Rural (relative to urban)	0.425***	0.428***	0.377***	0.344***	0.427***	0.385***
	(< 0.001)	(< 0.001)	(< 0.001)	(0.001)	(< 0.001)	(< 0.001)
Malawi (relative to Ethiopia)	-0.218**	-0.214**	0.242	-2.332***	-0.542***	0.067
	(0.021)	(0.024)	(0.242)	(< 0.001)	(0.002)	(0.536)
Niger (relative to Ethiopia)	-0.885***	-0.881***	-1.337***	0.260	-1.292***	-0.495***
	(< 0.001)	(< 0.001)	(< 0.001)	(0.764)	(< 0.001)	(0.005)
Nigeria (relative to Ethiopia)	-0.094	-0.091	0.266	0.406	0.172	0.082
	(0.472)	(0.489)	(0.332)	(0.577)	(0.500)	(0.591)
Tanzania (relative to Ethiopia)	-0.217***	-0.209***	0.375**	-1.504***	-0.487***	0.035
	(0.001)	(0.002)	(0.025)	(< 0.001)	(< 0.001)	(0.657)
Uganda (relative to Ethiopia)	-0.245***	-0.240***	0.186	-0.353	-0.374***	-0.050
	(< 0.001)	(< 0.001)	(0.233)	(0.281)	(0.004)	(0.468)
Year of survey conducted = 2010 (relative to 2008)	0.068**	0.069**	-0.052	0.222	-0.035	0.093**
	(0.035)	(0.033)	(0.383)	(0.372)	(0.551)	(0.013)
Year of survey conducted = 2011 (relative to 2008)	0.435***	0.437***	0.499***	0.190	0.489***	0.408***
	(< 0.001)	(< 0.001)	(< 0.001)	(0.608)	(< 0.001)	(< 0.001)
Year of survey conducted = 2012 (relative to 2008)	-0.075**	-0.075**	-0.078	0.079	-0.027	-0.016
	(0.020)	(0.020)	(0.183)	(0.748)	(0.643)	(0.672)
Year of survey conducted = 2013 (relative to 2008)	0.008	0.010	0.093	-0.222	0.017	0.033
	(0.835)	(0.805)	(0.284)	(0.393)	(0.829)	(0.454)
Year of survey conducted = 2015 (relative to 2008)	0.352***	0.353***	0.190**	-0.198	0.150**	0.380***
	(< 0.001)	(< 0.001)	(0.011)	(0.457)	(0.036)	(< 0.001)
Year of survey conducted = 2016 (relative to 2008)	-0.524***	-0.523***	-0.544***	-0.311	-0.567***	-0.466***

Dependent variable: Log of total value of agricultural output	**All agricultural households**		**Subgroups of agricultural households**			
	Control for diversification:					
	a1) Two activities (relative to one activity)	**a2) Livestock only or mixed (relative to crops only)**	**b1) Only crops**	**b2) Only livestock**	**b3) One activity (only crops or livestock)**	**b4) Two activities (both crops and livestock)**
	(< 0.001)	(< 0.001)	(< 0.001)	(0.298)	(< 0.001)	(< 0.001)
Two activities (relative to one activity)	0.490***					
	(< 0.001)					
Livestock only (relative to crops only)		0.046				
		(0.336)				
Mixed (relative to crops only)		0.496***				
		(< 0.001)				
Constant	7.262***	7.233***	7.481***	9.642***	9.014***	7.047***
	(< 0.001)	(< 0.001)	(< 0.001)	(< 0.001)	(< 0.001)	(< 0.001)
Number of observations	46 270	46 270	15 683	2 553	18 236	28 034
R-squared	0.268	0.268	0.210	0.243	0.187	0.213
Adjusted R-squared	0.267	0.267	0.209	0.234	0.185	0.212

Note: Coefficients are the estimates of the standard linear regression using household-level data from the LSMS-ISA, which covers Ethiopia, Malawi, Niger, Nigeria, Tanzania, and Uganda from 2008 to 2016. Standard errors are clustered at the level of the country-specific strata. Estimated coefficients with the cluster-robust p-values in parentheses (* p<0.05, ** p<0.01, *** p<0.001).

Table 2: Economic valuation of effects of climate and diversification to total value of agricultural output (million USD, 2011 PPP)

	Baseline: current practice of agricultural diversification		Simulation: updated practice of agricultural diversification			
	Control for diversification:					
	a1) Two activities (relative to one activity)	a2) Livestock only or Mixed (relative to crops only)	b1) Only crops	b2) Only livestock	b3) One activity (only crops or livestock)	b4) Two activities (both crops and livestock)
Agricultural output (million USD at 2011 PPP)	116 892	116 935	25 039	8 037	29 622	88 525
Increase in annual mean temperature (Celsius)						
0.50	-8 249.5	-8 185.2	-2 075.2	-768.8	-3 786.5	-5 618.1
1.00	-16 499.0	-16 370.5	-4 150.4	-1 537.6	-7 573.0	-11 236.2
1.50	-24 748.5	-24 555.7	-6 225.7	-2 306.4	-11 359.5	-16 854.3
2.00	-32 998.0	-32 740.9	-8 300.9	-3 075.2	-15 146.0	-22 472.4
Increase in avg. 12-month total rainfall (mm/100)						
0.50	2 414.0	2 495.7	704.3	-357.3	-526.8	3 277.3
1.00	4 828.0	4 991.4	1 408.6	-714.5	-1 053.6	6 554.6
1.50	7 242.0	7 487.1	2 112.8	-1 071.8	-1 580.5	9 831.9
2.00	9 655.9	9 982.8	2 817.1	-1 429.0	-2 107.3	13 109.2
Two activities (relative to one activity)	57 441.0					
Livestock only (relative to crops only)		5 435.3				
Mixed (relative to crops only)		58 246.2				

Table 3: Effects of climate and diversification on total value of agricultural output (as % changed)

	Baseline: current practice of agricultural diversification		Simulation: updated practice of agricultural diversification			
	Control for diversification:					
	a1) Two activities (relative to one activity)	a2) Livestock only or mixed (relative to crops only)	b1) Only crops	b2) Only livestock	b3) One activity (only crops or livestock)	b4) Two activities (both crops and livestock)
Increase in annual mean temperature (Celsius)						
0.50	-7.1%	-7.0%	-8.3%	-9.6%	-12.8%	-6.3%
1.00	-14.1%	-14.0%	-16.6%	-19.1%	-25.6%	-12.7%
1.50	-21.2%	-21.0%	-24.9%	-28.7%	-38.3%	-19.0%
2.00	-28.2%	-28.0%	-33.2%	-38.3%	-51.1%	-25.4%
Increase in avg. 12-month total rainfall (mm/100)						
0.50	2.1%	2.1%	2.8%	-4.4%	-1.8%	3.7%
1.00	4.1%	4.3%	5.6%	-8.9%	-3.6%	7.4%
1.50	6.2%	6.4%	8.4%	-13.3%	-5.3%	11.1%
2.00	8.3%	8.5%	11.3%	-17.8%	-7.1%	14.8%
Two activities (relative to one activity)	49.1%					
Livestock only (relative to crops only)		4.6%				
Mixed (relative to crops only)		49.8%				

5. Conclusions and recommendations

Climate change is a pressing issue that poses risks such as drought and flooding. Extreme weather events have adverse effects on the economy, leading to economic losses and hampering growth. Vulnerable populations, such as poor farmers, are particularly susceptible to income loss, potentially leading to a lifelong cycle of poverty. Climate change is expected to increase the frequency of severe weather events, leading to greater economic damage. Despite numerous studies being conducted at the country scale, there is a lack of research analysing the economic effect of climate change and agricultural diversification on agricultural households' livelihoods at the regional scale in Africa. A multi-country study is necessary to assess the effects of weather shocks and climate resilience on the region more comprehensively.

The purpose of this study was to document the nexus of climate change and agricultural diversification as an adaptation strategy for farm households in six Sub-Saharan African countries across the Africa continent. In summary, this study highlights the importance of agricultural diversification to mitigate the negative effects of climate change on agricultural output in Sub-Saharan Africa. The findings suggest that promoting diversified farming practices could be a critical strategy to improve the resilience of farm households in the region, particularly as the effects of climate change continue to worsen. This study reveals that an increase in temperature of one degree Celsius is linked to a 14% decline in agricultural output for all households. However, households that engage in agricultural diversification are expected to have about 50% higher agricultural output compared to the overall average, all other things held constant (ceteris paribus), indicating that diversification can help mitigate the negative effects of climate change.

Even though there are large cross-country variations, such as agricultural intensification and fertiliser use (Holden 2018), indicating that policies should be country-specific, Furthermore, Sheahan *et al*. (2014) and Sheahan and Barrett (2017) documented variations in within-country heterogeneity, especially in some large countries such as Ethiopia and Nigeria. Nevertheless, the African scenarios of an increase in temperature and a decline in precipitation, with more frequent and severe extreme weather events, are more likely, and poor farmers in Africa have limited adaptation capacity to cope with climate shocks. The regional scale of analysis could provide insightful evidence to confirm the use of agricultural adaptation as a climate resilience strategy for the continent.

Following Kray *et al*. (2018), policies for productive diversification are broadly grouped into six categories: (1) subsidies and agricultural public expenditure; (2) rural infrastructure and markets; (3) agricultural research and seed systems; (4) agricultural advisory services, skills development, and agripreneurship; (5) natural capital, land and water tenure; and (6) nutrition, health and social protection. The allocation of limited resources requires the deliberation on the local context and evidence-based research. Kray *et al*. (2018) also point out that agricultural input support programmes often have resulted in increased agricultural specialisation, but in turn have sacrificed agroecosystem resilience and nutritional diversity.

There are some cautions for policy interpretations that arise from this study. If the farm is situated in a natural setting that promotes the growth of specific staple crops, either due to soil composition or a unique pattern of rainfall and temperature, and it has access to well-functioning markets to sell its products and can acquire a variety of nutritious foods, then opting for specialisation could be a more favourable choice (Kray *et al*., 2018).

Econometrically, the author suggests taking into account the non-stationarity of climate change, as is evident on the continent (Gosoniu *et al*. 2009; Karambiri *et al*. 2011; Djibo *et al*. 2015; Garcia-

Aristizabal *et al*. 2015; De Paola *et al*. 2018; McBride *et al*. 2022). A reviewer of this manuscript highly recommended using variations from the mean for temperature and rainfall as key explanatory variables to capture the long-term variability of climate change. Lastly, to connect economic interactions at the micro- and macro-levels, the aggregation of the farming systems *with* and *without* agricultural diversification could be addressed for individual heterogeneity, such as applying the methodological framework of an impact assessment to balance the farmer characteristics between cohorts. Please note that the estimation of economic values of households *with* and *without* agricultural diversification in this study already has a fixed characteristic pattern for each country.

Even so, the findings of this study highlight the need for policies and interventions that encourage farmers to diversify their agricultural production, such as promoting the cultivation of multiple crops and the use of integrated farming systems. Therefore, this study underscores the urgent need for effective strategies to help farmers in Sub-Saharan Africa cope with the effects of climate change.

By promoting agricultural diversification and other resilience-building measures, governments and other stakeholders can help to build a more sustainable and resilient agricultural sector in the region. The desirable incentives to promote agricultural diversification should incorporate the goals of poverty reduction and sustainable development, which in turn will enhance climate resilience in Sub-Saharan Africa, which covers about one-fifth of the total land surface of Earth and where 60% of the global poor live under the extreme poverty line.

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Appendix

Table A1: Sensitivity analysis of temperature effects on log of total value of agricultural output

	Subgroups of agricultural households				**Control variables of regression fitting**				
	Only crops	**Only livestock**	**One activity (only crops or livestock)**	**Two activities (both crops and livestock)**	**Year and country**	**Geographical coordinates**	**Rural**	**Physical capacity**	**Household characteristics**
Average temperature	-0.170**	-0.207**	-0.262***	-0.131***	**o**	**o**	**o**	**o**	**o**
	(0.019)	(0.025)	(< 0.001)	(< 0.001)					
Average temperature squared	0.003*	0.005**	0.006***	0.003***					
	(0.051)	(0.047)	(< 0.001)	(< 0.001)					
Average temperature	-0.201***	-0.221***	-0.242***	-0.131***	**o**		**o**	**o**	**o**
	(0.003)	(0.010)	(< 0.001)	(< 0.001)					
Average temperature squared	0.004**	0.005**	0.005***	0.003***					
	(0.010)	(0.011)	(< 0.001)	(< 0.001)					
Average temperature	-0.172**	-0.251***	-0.239***	-0.128***	**o**	**o**		**o**	**o**
	(0.014)	(0.005)	(< 0.001)	(< 0.001)					
Average temperature squared	0.003*	0.006***	0.005***	0.003***					
	(0.051)	(0.008)	(< 0.001)	(< 0.001)					
Average temperature	-0.142*	-0.297***	-0.216***	-0.123***	**o**	**o**	**o**		**o**
	(0.057)	(0.002)	(< 0.001)	(< 0.001)					
Average temperature squared	0.003	0.006***	0.005***	0.003***					
	(0.119)	(0.004)	(0.001)	(< 0.001)					
Average temperature	-0.167**	-0.242***	-0.230***	-0.118***	**o**	**o**	**o**	**o**	
	(0.016)	(0.006)	(< 0.001)	(< 0.001)					
Average temperature squared	0.003*	0.005***	0.005***	0.002***					
	(0.058)	(0.008)	(< 0.001)	(< 0.001)					
Average temperature	-0.151**	-0.297***	-0.209***	-0.102***	**o**				
	(0.036)	(0.002)	(< 0.001)	(< 0.001)					
Average temperature squared	0.003*	0.007***	0.005***	0.002***					
	(0.073)	(0.002)	(0.001)	(0.001)					

Note: The table shows the ordinary least square coefficients of annual mean temperature (Celsius) on the log of the total value of agricultural output. The common control variables in all models are year and country dummy variables. The geographical coordinates cover latitude, longitude, elevation, and their squared terms. The rural control variable is a dummy variable relative to urban areas. The physical capacity covers number of agricultural workers and its squared, land used for agricultural activities in hectares and its squared, agricultural wealth index, and index of access to infrastructure. The household characteristics cover female head dummy variable, age of head and its squared, and the dummy variable whether the household owns a cell phone.

Table A2: Sensitivity analysis of precipitation impacts on log of total value of agricultural output

	Subgroups of agricultural households				Control variables of regression fitting				
	Only crops	**Only livestock**	**One activity (only crops or livestock)**	**Two activities (both crops and livestock)**	**Year and country**	**Geographical coordinates**	**Rural**	**Physical capacity**	**Household characteristics**
Average total rainfall	0.063***	-0.089**	-0.032*	0.076***	**o**	**o**	**o**	**o**	**o**
	(0.002)	(0.012)	(0.055)	(< 0.001)					
Average total rainfall squared	-0.003***	0.002	0.000	-0.003***					
	(< 0.001)	(0.123)	(0.897)	(< 0.001)					
Average total rainfall	0.061***	-0.133***	-0.020	0.059***	**o**		**o**	**o**	**o**
	(0.001)	(< 0.001)	(0.226)	(< 0.001)					
Average total rainfall squared	-0.003***	0.005***	-0.000	-0.002***					
	(< 0.001)	(< 0.001)	(0.900)	(< 0.001)					
Average total rainfall	0.065***	-0.105***	-0.036**	0.080***	**o**	**o**		**o**	**o**
	(0.002)	(0.002)	(0.038)	(< 0.001)					
Average total rainfall squared	-0.003***	0.003**	0.000	-0.003***					
	(0.001)	(0.021)	(0.854)	(< 0.001)					
Average total rainfall	0.056***	-0.079**	-0.017	0.093***	**o**	**o**	**o**		**o**
	(0.006)	(0.030)	(0.308)	(< 0.001)					
Average total rainfall squared	-0.003***	0.002	-0.001	-0.004***					
	(< 0.001)	(0.283)	(0.158)	(< 0.001)					
Average total rainfall	0.055***	-0.076**	-0.040**	0.076***	**o**	**o**	**o**	**o**	
	(0.008)	(0.031)	(0.020)	(< 0.001)					
Average total rainfall squared	-0.002***	0.002	0.000	-0.003***					
	(0.003)	(0.125)	(0.692)	(< 0.001)					
Average total rainfall	0.061***	-0.145***	0.002	0.082***	**o**				
	(0.002)	(< 0.001)	(0.903)	(< 0.001)					
Average total rainfall squared	-0.004***	0.005***	-0.001**	-0.004***					
	(< 0.001)	(<0.001)	(0.041)	(< 0.001)					

Note: The table shows the ordinary least square coefficients of average 12-month total rainfall (mm/100) on log of total value of agricultural output. The common control variables in all models are year and country dummy variables. The geographical coordinates cover latitude, longitude, elevation, and their squared terms. The rural control variable is a dummy variable relative to urban areas. The physical capacity covers number of agricultural workers and its squared, land used for agricultural activities in hectare and its squared, agricultural wealth index, and index of access to infrastructure. The household characteristics cover female head dummy variable, age of head and its squared, and dummy variable whether the household owns a cell phone.