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Effects of climate variability and change on agricultural production: The case of small scale farmers in Kenya

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A B S T R A C T

Agriculture is the mainstay of the Kenyan economy, contributing to food security and employment of rural households. Climate variability and change have adversely affected this sector and the situation is expected to worsen in the future. We estimate the effect of climate variability and change on revenue from all crops, maize and tea separately, using a household fixed effects estimator. We find that climate variability and change affects agricultural production but effects differ across crops. Temperature has a negative effect on crop and maize revenues but a positive one on tea, while rainfall has a negative effect on tea. We find that tea relies on stable temperatures and consistent rainfall patterns and any excess would negatively affect production. Temperature has a greater impact on crop production than rainfall. Climate change will adversely affect agriculture in 2020, 2030 and 2040 with greater effects in the tea sector. Therefore, rethinking the likely harmful effects of rising temperatures and increasing rainfall uncertainty should be a priority in Kenya. Implementing adaptation measures at national, county and farm levels as well as putting in place policies that prevent destruction of the natural environment will assist to address the challenges posed by climate variability and change.

1. Introduction

Agriculture continues to be the mainstay of the Kenyan economy with an estimated gross domestic product (GDP) share of 25.9% [1] making it an important contributor to employment and food security of rural households. Climate change has significantly affected global agriculture in the 21st century and the Intergovernmental Panel on Climate Change (IPCC) assessment report indicates that most countries will experience an increase in average temperature, more frequent heat waves, more stressed water resources, desertification, and periods of heavy precipitation [2,3]. The past three decades have been the warmest in history, with each decade being warmer than the preceding period [3]. Further, the reports indicate that the African continent is warmer than it was 100 years ago [4]. Future impacts are projected to worsen as the temperature continues to rise and precipitation becomes more unreliable.

The rising temperature would expose millions of people to drought and hunger. Climatic variability and change have always presented a threat to food security in Kenya through their effect on rainfall, soil moisture and production. Since the early 1990s, Kenya has been affected by the droughts of 1991–2, 1992–3, 1995–6, 1998–2000 and 2004, the *El-Niño* rains that resulted in the floods of 1997–1998 [5] and the drought of 2008–9. Climatic variability and change directly affect agricultural production and food security given that most of the population in Kenya lives in the rural areas and relies on agriculture for its livelihoods. This is exacerbated by the fact that agriculture is predominantly rain-fed. The poor in Africa, particularly smallholder farmers, are highly vulnerable to climatic and environmental hazards as their options for diversifying their resources and income sources are limited. Their vulnerability is worsened by the spread of HIV/AIDS, lack of access to land due to the traditional land tenure systems, lack of adequate water, low levels of technology and education and institutional mismanagement [6]. This calls for clear response strategies in terms of mitigation and adaptation in order to deal with the threats posed by climate change.

In recognition of these climate change challenges, the Kenyan government put in place the National Climate Change Response Strategy (NCCRS) whose aim is to respond to the challenges and opportunities posed by climate change [7]. The objective of NCCRS is to strengthen nationwide focused actions towards adapting and mitigating against a changing climate, by ensuring commitment

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and engagement of the whole nation in combating the impacts of climate change, taking into account the vulnerable nature of the natural and ecological resources, and society as a whole. Environmental protection has been put in place as one of the important national priorities in the context of Kenya Vision 2030 (the country's development blueprint covering the period 2008–2030) and under its National Climate Change Action Plan (2013–2017) in order to address the threats of climate change in Kenya. In addition, the government identified irrigation as one of the ways of moderating the effects of climate change, and launched a flagship project, Galana Kulalu irrigation scheme in the Tana River area in the coastal region in January, 2014.

It has been recognized that adaptation measures can reduce negative impacts of global warming and climate change [8]. These measures comprise the growing of alternative crops, intercropping different crop varieties, use of drought tolerant seed varieties, employing irrigation and water harvesting techniques, crop insurance, early warning and monitoring systems, construction of dykes, human migration, changing planting dates, diversifying in and out of agriculture, reliance on safety nets and social networks and sale of assets. One constraint to adaptation has been that some of the adaptation technologies such as irrigation systems and dykes require huge capital outlays.

While several studies provide detailed accounts of the impacts of climate change in Kenya [8–10], a few critical gaps do, however, exist which we seek to address in the current paper. The existing studies mainly use cross-sectional data and we contribute to the discussion by using the Tegemeo panel survey data set which takes into account changes in household incomes, rainfall and temperature across both space and time, and thus enables the assessment of any variability across these key indicators over time. Secondly, while most studies model effects of climate on total crop revenue, we assess the effects on selected key crops in Kenya, maize and tea. Disaggregation of income by crop types sheds more light on the effects of climate variability and change on maize which is an important staple crop and tea, the leading export crop that contributes about 20% of the total foreign exchange earnings in Kenya.

The remainder of the paper is organized as follows. Section 2 includes a review of the literature on effects of climate change and variability on agriculture production. Section 3 presents our materials and methods which include data sources and estimation techniques. Findings and discussions are presented in Section 4 and the last section concludes and discusses policy implications.

2. Literature review

Climate change is arguably one of the most important challenges facing African countries, largely due to their geographic exposure,[1] low income, greater reliance on climate-sensitive sectors such as agriculture, and weak capacity to adapt to the changing climate [11]. However, there are limited studies that have documented adverse socio-economic impacts of extreme weather events specifically in Kenya. The effects have been felt on almost all sectors such as health, agriculture, livestock, environment, hydropower generation and tourism [12]. Kenya is adversely affected by climatic variability and change because of her dependency on rain-fed agriculture, with variability in rainfall and temperature directly affecting crop and livestock yields.

Empirical results show that climate variability has significant economic costs as a result of periodic floods and droughts, which lead to major macro-economic costs and reductions in economic growth [12]. Downing [13] explored the impact of climate change in Kenya and found that higher temperatures would have a positive impact in highland areas but a negative effect in lowland areas, and especially semi-arid ones. Therefore, potential food production would increase with rising temperature and rainfall, but in the semi-arid areas, yields would decline as a result of insufficient precipitation. Fischer and van Velthuizen [14] indicated that the overall impact of climate change on food production in Kenya would be positive but results would vary by region. They also asserted that the increase in production would arise from an increase in carbon dioxide and temperature, provided that there would be an increase in precipitation as well.

Adger [15] argued that social vulnerability to climate change is a key dimension in the constitution of vulnerability, and that it shifts emphasis onto the underlying, rather than the proximate causes of vulnerability. In Kenya, smallholder farmers have been found to respond to drought through diversification into off-farm employment activities [16]. Kabubo-Mariara and Karanja [8] also showed that adaptation measures in terms of micro-level farm adaptations, market responses, technological developments and institutional changes have a large potential in reducing negative impacts of global warming and climate change. Bilham, [10] found that temperature had more impact on crop yields than rainfall. Jones and Thornton [35] showed that maize production in Africa and Latin America would reduce by 10% by 2055 and recommended that climate change effects should be assessed at household level so that the poor who depend on agriculture can be targeted for advice.

Many studies in East Africa focus on the effects of one climate variable in isolation, usually rainfall for the specific data collection year. For instance, a study by Oremo [9], used only rainfall while Skoufias and Vinha [17] reported that temperature has received much less attention in climate change research. The two climate variables are often correlated, and so the inclusion of just one variable would lead to omitted variable bias. In this paper, we use both rainfall and temperature, and also cover most of the agro-ecological zones in Kenya. A study by Ndukhu et al. [18] showed that farmers in Kenya were aware of short-term climate changes, particularly an increase in temperatures, but their perceptions of these changes and the adaptations they used varied across agro-climatic zones. Oremo [9] showed that farmers' perceptions that Kitui County was getting drier and that rainfall decreased were consistent with the meteorological rainfall data. However, Oremo [9] used cross sectional data for the region to evaluate the relationship between rainfall and maize yields without considering temperature changes which would be equally important in influencing maize productivity.

One of the most comprehensive studies on climate change in Kenya is by Kabubo-Mariara and Karanja [8]. This study was conducted in 38 out of 46 former districts and analysed the economic impact of climate on crop agriculture, using a seasonal Ricardian model and a crop response simulation model. The analysis was based on different types of data: long-term mean seasonal temperature and precipitation data; long-term mean monthly hydrological data; main classes of soil types; and, cross-sectional household level data. The results showed that climate affects crop revenue, with increased winter (June-August) temperatures being associated with higher crop revenue, and increased summer (March-May) temperatures having a negative impact on revenue. Increased precipitation was positively correlated with net crop yield. The results also showed that there was a non-linear relationship between revenue and the temperature and precipitation variables.

While the study by Kabubo-Mariara and Karanja [8], provides the most detailed and more recent account of the impacts of climate change in Kenya, a few critical gaps do, however, exist and which we seek to address in the current study. First, the Ricardian analysis that was used estimates the effect of climate on net crop revenue

[1] Most of the African countries are located on lower latitudes.

across space without incorporating a time dimension. Using the Tegemeo panel data set, our study takes into account the changes in household incomes, rainfall and temperature across both space and time. Secondly, while the study models the impact of climate on total crop revenue, the current study proposes to go further and assess the impacts on gross maize and tea revenue separately. Tea is an important cash crop mainly exported whereas maize is a major staple in Kenya.

3. Materials and methods

3.1. Data description

3.1.1. Farm household data

We use a balanced panel household-level dataset collected in 2000, 2004, 2007 and 2010, comprising of 1243 households across eight agro-regional zones in Kenya. The agro-regional zones include coastal lowlands, eastern lowlands, western lowlands, western transitional, the high potential maize zone, western and central highlands, and the marginal rain shadow zone. Agro-regional zones are a hybrid of broad agro-ecological zones and administrative boundaries [19]. The panel data is of high quality with the necessary quality control ensured in all the data collection waves by proper training and supervision of the enumerators.

The Tegemeo household survey covered 107 villages across eight agro-ecological zones in Kenya (Fig. 1). A detailed description of sampling design and collection procedure is found in Argwings-Kodhek et al. [19]. The sample excluded large farms with over 50 acres, while Nairobi and Northern regions were excluded because of urbanization, and aridity and migration nature of pastoralists, respectively. The data collected over the years is quite broad, covering several aspects of household livelihoods including crop yields and revenues. We measured crop production as the value of yields per acre in farm household because most small-scale farmers practice mixed cropping in one plot, making it difficult to accurately allocate area for each crop. Maize and tea revenue per unit of land was estimated given that most farmers grow them under mono-cropping system. Descriptive statistics of the climate and socio-economic data used in the econometric model are presented in Table 1.

3.1.2. Climate data

This study relies on climate data (rainfall and temperature) from Kenya Meteorological Services (KMS) weather stations across the country. The data obtained from KMS include temperature (°C) and rainfall (mm) from 1980 to 2010 for different regions in Kenya. These two parameters have the longest and widest data coverage in the country and are the most common climatic variables considered by many studies in Sub-Saharan Africa. We use temperature and rainfall for respective data collection years and their long term values, to capture climate variability and change, respectively, to estimate the short- and long-term effects of climate on agricultural revenues. A similar approach has been followed in previous studies such as Sarker et al. [20], Lobell et al. [21] and Kabubo-Mariara and Karanja [8].

We match household level data with climate variables. In this process, the households in different sub-locations are linked with climate data from the nearest weather stations in order to perform econometric analysis.

3.2. Estimation strategy

The impacts of climate change on agriculture have been mainly studied using the Ricardian approach, which involves regressing the value of land against climate variables and other control variables [22]. This approach assumes that land markets are functioning properly but existence of ill-defined property rights and tenure insecurity in some regions in Kenya makes its application less feasible. Besides, a major drawback of the method is that it does not account for price changes and also fails to fully control for the impact of other variables that affect agricultural farm incomes [23].

Based on this, we adopt an augmented production function as a general framework to model the effects of climate change on revenue from all crops and also separately for maize and tea revenues. The production function framework allows to control for economic variables [24], whereas the disadvantage is that it does not take farmers' responses to climate change into account. We specify a production function where revenue from all crops, maize and tea Y_{it} is a function of factors of production, farmer personal attributes and climate variability and change factors (Eq. (1)):

$$Y_{it} = f\left(\partial_{it}, \forall_{it}, \phi_{it}\right) \quad (1)$$

where ∂_{it} represents factors of production such as land and assets; $\forall_{it}$is a set of farmer personal attributes (gender and education of the household head, household size); and ϕ_{it} represents climate variability and change factors (temperature and rainfall in the respective survey year, and long term mean temperature and rainfall). In the estimation of effects of climate variables, we control for agricultural inputs, such as farm land, livestock, agricultural assets and fertilizers. This study also differs from earlier studies because we control for socio-economic information such as household size, gender and education of the farmers. These are important variables to include in the estimation as pointed out by De Salvo et al. [25]. The production function, where revenue from all crops, tea and maize obtained by farmer i at time t, is a function of production factors, socio-economic and climate factors is presented in Eq. (2).

$$\begin{aligned} \ln NR_{it} &= \alpha_1 + \alpha_2 lnL_{it} + \alpha_3 lnA_{it} + \alpha_4 lnF_{it} + \alpha_5 CD_{it} + \alpha_6 G_{it} + \alpha_7 lnE_{it} + \alpha_8 lnHs_{it} \\ &+ \alpha_9 Temp_{it} + \alpha_{10}(Temp_{it})^2 + \alpha_{11} TempC_{it} + \alpha_{12}(TempC_{it})^2 + \alpha_{13} Rain_{it} \\ &+ \alpha_{14}(Rain_{it})^2 + \alpha_{15} RainC_{it} + \alpha_{16}(RainC_{it})^2 + \alpha_{17} TempC \times RainC_{it} + \emptyset_t \\ &+ \varepsilon_{it} \end{aligned} \quad (2)$$

where $\ln NR_i$ represents the natural logarithms of crop revenue,[4] maize and tea revenue for farmer *i*. The variables *lnL*, *lnA* and *lnF* represents the natural logarithms of farm size, total value of agricultural assets and fertilizer used, respectively, while *CD* is the crop diversification index. Socio-economic variables include education (*lnE*) and gender (*G*) of the household head and household size (*lnHs*). For climate variables, *Temp* and *Rain* denotes the mean annual temperature and mean monthly rainfall in the respective data collection years, while *TempC* and *RainC* represent long term temperature and rainfall (from 1980 to 2010), respectively. The study considers different agro-regional zones across many years

[2] Fertilizer in Kg is the sum of all types of inorganic fertilizers used by a given household.

[3] The crop diversification index (CDI) is calculated by subtracting the Herfindahl index (HI) from one $\left(CDI = 1 - \sum_{n=1}^{i} P_i^2 = 1 - HI\right)$, where P_i is the proportion of value of the *ith* crop relative to the overall area of land cultivated. The index ranges from zero, reflecting complete specialization (for example just one crop), to one, reflecting complete diversification (i.e., an infinite number of crops).

[4] The crops include maize, coffee cherries, beans, sorghum, millet, bananas, tea, wheat, cotton, sugarcane, pyrethrum, cowpeas, coconuts, cashew nuts, French beans, Irish potatoes, cassava tobacco, sunflower, rice, groundnuts, green grams, simsim, sweet potatoes, arrow roots, passion, tomato, Sukuma wiki, cabbage, spinach, watermelon, pumpkin, yams and snow peas.

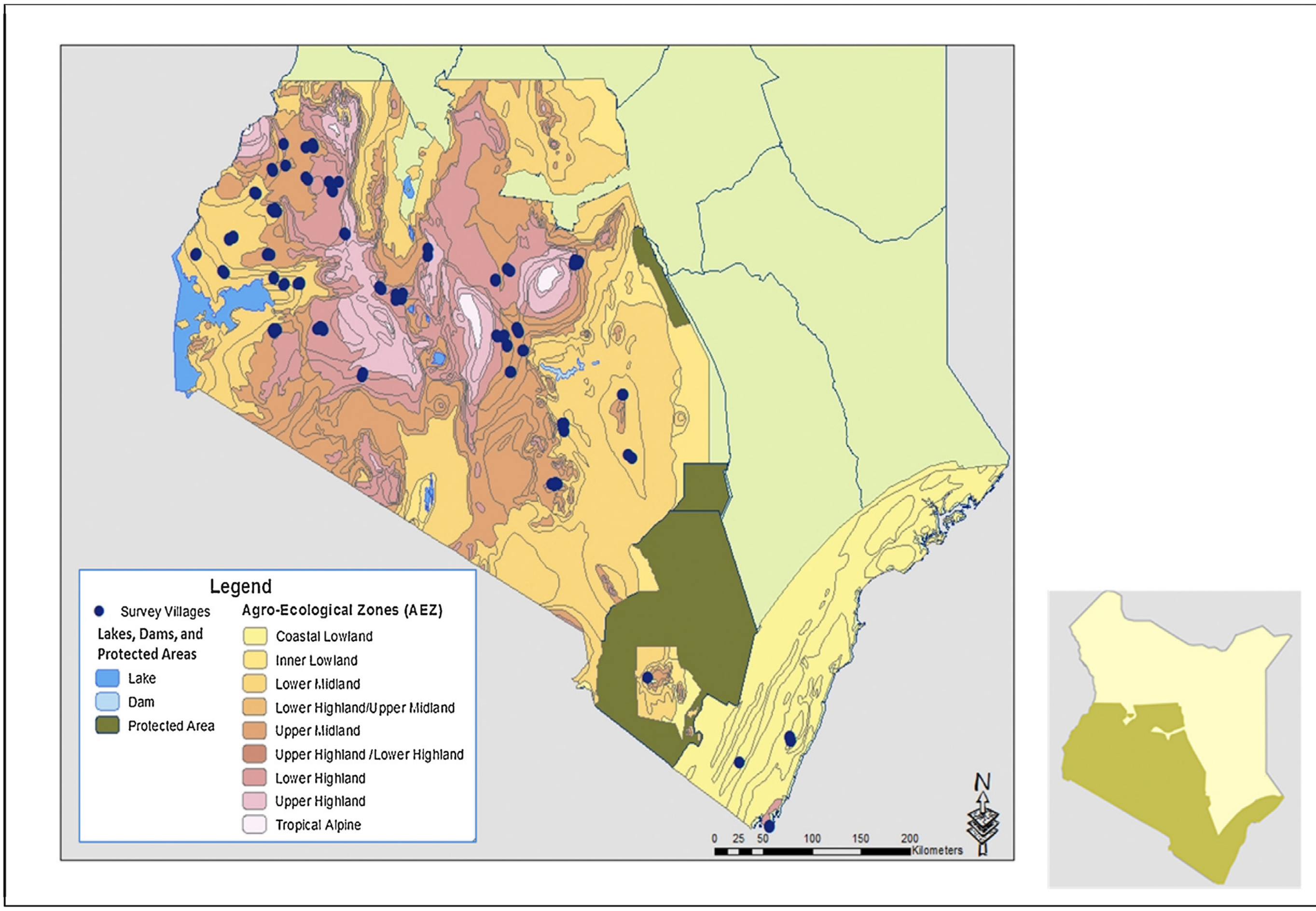

Fig. 1. Tegemeo survey villages and agro-ecological zones.

Table 1
Descriptive statistics of the variables included in the econometric model.

Variable	Description	Mean	Std. Dev.
Dependent variables			
Crop revenue	Gross revenue in Ksh/acre/year	23046.36	23581.39
Tea revenue	Gross tea revenue in Ksh/acre/year	103806.7	180888.7
Maize revenue	Gross maize revenue in Ksh/acre/year	23145.55	58237.26
Climate variables			
Rainfall	Mean monthly rainfall (mm/mo) for data collection year	126.331	61.229
Long term mean rainfall	Long term moving mean rainfall (mm/mo) 1980–2010	100.436	28.532
Mean temperature (°C)	Mean annual air temperature (°C) for data collection year	20.775	2.860
Long term mean temperature (°C)	Long term moving mean of air temperature (°C) 1980–2010	20.806	3.014
Rainfall × temperature	Interaction term of long term rainfall and temperature	2119.146	669.778
Other variables			
Gender	1 if household head is male	0.794	0.405
Education	Years of schooling of the household head	7.043	4.603
Household size	Number of household members	5.999	3.023
Fertilizer used in all crops	Inorganic fertilizer in kg per acre[2]	59.847	120.963
Fertilizer used in maize	Inorganic fertilizer in kg per acre	42.406	95.883
Fertilizer used in tea	Inorganic fertilizer in kg per acre	336.277	307.708
Farm size	Size of land in acres	5.802	9.032
Crop diversification	Crop diversification index[3]	0.728	0.191
Assets	Value of total assets in Ksh	247166.7	434666.7

Notes: Ksh-Kenya shillings.

(2000–2010) and so the analysis captures regional and temporal scale variations. Eq. (2) is estimated using the household fixed effects estimator which captures the time varying effects ϕ_t using time dummies associated with each year while α_i are the coefficients to be estimated.

Since the input variables in the model are expressed in natural logarithms, their coefficients are interpreted as elasticities of agricultural incomes with respect to each input. The squared variables have been included to take into account the non-linear relationship between agricultural income and climate factors. The results from crop research show that yield response to weather and climate is highly non-linear and there are significant interaction effects between temperature and rainfall [26]. We have, therefore, included interaction terms between annual temperature and rainfall as independent variables in the production function model. As observed by Fezzi and Bateman [27], most Ricardian studies in Kenya (e.g., Kabubo-Mariara and Karanja, [8]) do not account for such interaction between temperature and rainfall. In order to simulate the effects of climate change, we use future rainfall predictions from Kenya Meteorological Services (KMS) and temperature predictions from the literature, which have been obtained using different climate models. The different climate change scenarios were employed to project the changes in farm revenues due to changes in temperature and rainfall in Kenya.

Simulations of the effects of climate change are done based on elasticities computed from Eq. (2). The average elasticities of climate variables on crop, maize and tea revenues are evaluated at the mean. Elasticities are the partial derivatives of agricultural revenues with respect to factors of production, farmer-specific characteristics and climate variables shown in Eq. (2). Elasticities are derived from marginal effects[5] (Eq. (3)) using the chain rule.

$$E\frac{\partial Y_i}{\partial x_i} = \alpha_i E(x_i) \times E(x_i) \tag{3}$$

Both sides of Eq. (3) are multiplied by $\frac{x}{Y}$ to obtain the elasticity as shown in Eq. (4).

$$E\frac{\partial Y_i/Y_i}{\partial x_i/x_i} = \alpha_i E(x_i) \times E(x_i) \tag{4}$$

where α_i is a linear term coefficient for independent variables (x_i) including the quadratic coefficients for long term rainfall and temperature variables. We use the predicted climate change values and compare with the 1980–2010 base average to simulate the effect of rainfall and temperature on revenue from all crops as well as that from maize and tea.

4. Results and discussion

4.1. Effects of climate variability and change on agriculture production

Econometric results presented in Table 2 shows that rainfall has a positive effect on revenues from all crops grown and maize as well, but has a negative effect on tea revenue. Temperature has a negative effect on all crops revenue but a positive effect on tea revenue. The negative coefficient and significant quadratic terms suggest that excess temperature would be detrimental to tea production. Similarly, rainfall exhibits a negative relationship with tea and has a positive quadratic term, which indicates that very little rainfall is not useful for tea production. In tea production, severe frost due to lower temperatures mainly at night leads to scorching of plants. The low temperatures cause water in the cell sap to expand and rapture the cell wall resulting into chemical reactions normally associated with green leaf fermentation and leaves turn brown [28]. The findings point out that long-term effects of climate change (in relation to temperature) on crop production are larger than short-term effects, an indication that farmers need to adapt effectively to reduce extreme effects of climate variability. This is because as they adapt to dealing with effects of climate variability, which they experience year after year, they will be effectively slowing down the potential effects of climate change. Our results clearly indicate that climate has a non-linear relationship with revenue from all crops, maize and tea, which is consistent with other findings [8,11,27]. Also the findings show that the coefficients associated with temperature are much larger than those for rainfall, thus temperature has a greater impact on production compared to rainfall. This confirms the findings that temperature is a more important contributor to climate change impact than rainfall and that temperatures will be a significant factor for Kenyan crop yields in future [8,10,29]. The interaction term (long term rainfall and temperature) has a negative correlation with crop and maize revenues, but a positive one with tea revenue though not significant. Tea exhibits a positive interaction between rainfall and temperature because its production depends on stable temperatures and consistent rainfall patterns. Previous studies such as Monteith [30] clearly indicate that the amount of water required for plant development increases with temperature, implying a positive rather than negative interaction. With this kind of scenario, we conclude that, with smallholder farm level data, there is a climate change effect on crop and maize revenue without a strong interaction between rainfall and temperature.

Crop diversification has a negative and significant effect on revenue from all crops meaning that farmers earn less revenue from cropping activities as their crop production systems become more diversified. This may be because large number of crops will provide disincentives to farmers to invest in yield enhancing inputs such as improved seed varieties and fertilizers, leading to crop failure and poor yields.

We also estimate the effects of socio economic factors which show that size of land owned, use of chemical fertilizers and agricultural assets owned have a significant role in improving agricultural performance. Although, unexpected, size of land owned negatively and significantly influences crop revenue. This finding indicates that households with larger land sizes attain lower revenues from all crops grown. This could be consistent with the finding in literature of an inverse relationship between farm size and crop revenue. This scenario may arise, first due to market failures, which imply that due to high unemployment, smaller farms which may have more labor per acre of land than larger farms may be forced to use more labor than is optimal on their farms, resulting in higher yields for smaller farms. Secondly, this scenario could be due to omitted variables, such as soil quality, in the econometric analysis [31]. Third, this may occur when small-scale farmers over-report land size, while relatively larger farmers under-estimating their land holdings, thus leading to a spurious inverse relationship between farm size and crop revenue. As a way to address this problem, Savastano et al. [32] proposes that taking land size using global positioning system (GPS) is more appropriate. However, land size positively and significantly influences maize and tea revenues.

Although fertilizer is a major determinant of crop yields, results show that fertilizer use does not significantly affect tea and maize revenues. This may be because the application rates are low. However, it has also been argued that although, chemical fertilizer enhances crop productivity, it also releases greenhouse gases into the atmosphere contributing to global warming. For instance, a study by Sarker et al. [20] concluded that in order to reduce climate change challenges, it is important to reduce chemical fertilizer use and increase usage of organic materials in crop production. The assets owned by the household are significantly associated with higher crop revenues, because wealthier households have higher capacity to invest in crop production. The yearly fixed effects are significant, which implies that differences in the crop revenues exist over the years, probably due to varying market conditions such as prices, policy and technology over the study period.

[5] Marginal effects summarize how change in a response is related to change in a covariate. Marginal effects are used to obtain elasticities used in the simulation.

Table 2
Effect of climate variability and change parameters on agricultural revenue.

Variables	Crop revenue (1)		Tea revenue (2)		Maize revenue (3)	
Rainfall	0.007***	(0.001)	−0.022***	(0.005)	0.004***	(0.001)
Rainfall sq.	−0.000***	(0.000)	0.000***	(0.000)	−0.000***	(0.000)
Long term rainfall	0.033	(0.085)	−0.128	(0.290)	0.091	(0.098)
Long term rainfall sq.	0.000	(0.000)	0.001	(0.001)	0.000	(0.000)
Mean temperatures	−0.574***	(0.160)	1.037**	(0.505)	0.041	(0.208)
Mean temperatures sq.	0.016***	(0.004)	−0.025*	(0.015)	0.003	(0.005)
Long term mean temperature	−8.239***	(2.493)	8.900*	(4.730)	−9.800***	(3.232)
Long term mean temperature sq.	0.153**	(0.062)	−0.154	(0.124)	0.286***	(0.078)
Rainfall × temperature	−0.006	(0.003)	0.001	(0.011)	−0.006	(0.004)
Gender of household head	−0.078	(0.077)	−0.316	(0.204)	0.065	(0.115)
Education	0.063	(0.048)	0.108	(0.092)	0.063	(0.056)
Household size	0.017	(0.047)	−0.185*	(0.101)	0.025	(0.059)
Crop diversification index	−1.324***	(0.154)				
lnland size	−0.090***	(0.027)	0.281***	(0.080)	0.257***	(0.042)
lnfertilizer used on crop	0.118***	(0.025)				
lnfertilizer used in tea			0.0380	(0.051)		
lnfertilizer used in maize					−0.001	(0.025)
lntotal value of asset	0.068***	(0.020)	0.0826*	(0.049)	0.161***	(0.024)
Yearly FE	Yes		Yes		Yes	
Constant	−82.65***	(25.80)	−104.63*	(53.832)	88.83***	(33.988)
Observations	2662		587		2430	
R-squared	0.228		0.331		0.128	
Chi^2 of Hausman test	97.34	p = 0.000	99.14	p = 0.000	193.7	p = 0.000
Wald heteroscedasticity test (χ^2)	5.4e + 06	p = 0.000	3.3e + 05	p = 0.000	1.5e + 29	p = 0.000
Autocorrelation test (F-statistic)	14.817	p = 0.000	0.207	p = 0.650	14.31	p = 0.000

Notes: robust standard errors in parentheses ***p < 0.01, **p < 0.05, *p < 0.1.
The Hausman test rejects the null hypothesis, indicating that using fixed effects over random effects model is appropriate for all the equations.
The Wald test indicates presence of heteroscedasticity in the error terms which we have partly addressed by obtaining the transformations of independent variables and reporting robust standard errors.

Table 3
Predicted values of mean monthly rainfall and annual temperature by 2020–2040 compared to base year.

Climate variables	1980–2010	2020	2030	2040
Mean monthly rainfall (mm)	100.4	111.6	126.8	130.3
Mean annual temperature (°C)	20.8	21.8	22.8	23.3
% change in mean monthly rainfall	–	11.2	26.3	29.8

Notes: temperature values have been calculated based on previous literature

4.2. Predicted climate change and simulation results

Belloumi [11] predicted that the future climate of Southern and Eastern Africa (including Kenya) will be hotter and drier. Overall, our analysis shows that rainfall will increase between 2020 and 2040. This confirms findings reported by CIAT [33] that rainfall is likely to increase in Kenya by 2020 and 2050. Projections from KMS data indicate that annual rainfall will increase by 11.2, 26.3 and 29.8 percent in 2020, 2030 and 2040, respectively (Table 3). Recent predictions such as by CIAT [33] and KMS show that rainfall in Kenya will increase in the future, but those from Canadian Climate Model (CCC) reported by Kabubo-Mariara and Karanja [8] predict a 20% fall in rainfall by 2030. Their study used climate data from 1988 to 2003, while recent studies use data from 1980 to 2010, thus we think that the type of data as well as the characteristics of the model used might have led to the observed differences.

Due to the inability to obtain predicted temperatures from KMS, we adopted predictions from previous studies in Kenya [33] and in Southern and Eastern Africa [11]. Following CIAT and KMS predictions that the temperature in Kenya is likely to increase by between 1 °C and 2.5 °C on average, we assume that the annual temperature will increase by 1 °C in 2020 and 2 °C and 2.5 °C in 2030 and 2040, respectively. Simulation results show that a change in the temperature component of global warming is much more important than change in rainfall in Kenya (Table 4), which is consistent with the findings reported by Kabubo-Mariara and Karanja [8]. Rainfall increase in Kenya will have a positive and significant effect on crop and maize revenue, but will negatively affect tea revenue by 2020, 2030 and 2040 (Table 4). Holding all other factors constant, 1 °C increase in temperature would reduce crop revenue by 14% but increase tea revenue by 2.3% by 2020. In addition, 30% increase in rainfall in 2040 would reduce tea revenue by 9%. Tea as a crop is very sensitive to both rainfall and temperature and any excess would negatively affect production patterns. A study by FAO [34] has also predicted that the tea production in Kenya would decrease because of changes in rainfall and rises in air temperatures beyond the maximum threshold of 23.5 °C.

5. Conclusions and policy implications

This paper presents the effects of climate variability and change on total crop revenue, maize and tea revenues among small-scale farmers in Kenya. We focus on maize and tea production because they play an important role as food staple and foreign exchange earner in Kenya, respectively. Overall, the results show that climate change has the potential to significantly affect small-scale farmers' livelihoods by either decreasing or increasing the crop revenues.

We find that temperature has a negative effect on crop and maize revenues but a positive one on tea revenue. Rainfall has a positive effect on crop and maize revenues but a negative effect on tea revenue. Long-term effects of temperature on crop production are larger than short-term effects, thus farmers need to adapt effectively to reduce effects of climate variability and build their resilience. Tea production strongly depends on stable rainfall and temperature compared to other crops including maize. Small-scale farmers are still motivated to diversify cropping activities in order to reduce the downside risk (e.g., by spreading the risk across available crops) caused by persistent climatic variability and change. Small-scale farmers are affected by several market failures including underdeveloped input and output markets as well as poor or expensive crop insurance, and thus they rely on crop diversification as an alternative risk-coping mechanism.

Predictions for the future effects of climate change show that agriculture will be adversely affected by 2020, 2030 and 2040 if

Table 4
Predicted effect of climate change on agricultural production.

Year	Increase level (%/°C)	Climate variable	Rainfall and temperature increase effect (in%)		
			Crop revenue	Maize revenue	Tea revenue
2020	11%	Rainfall	0.8	0.6	−2.5
	1 °C	Temperature	−14.2	1.1	2.3
2030	26%	Rainfall	0.9	1.2	−5.5
	2 °C	Temperature	−14.8	2.2	2.4
2040	30%	Rainfall	1.0	1.9	−8.8
	2.5 °C	Temperature	−15.2	3.3	2.5

nothing is done and the strongest effect will be felt in the Kenyan tea sector. Our findings further indicate that temperature as an indicator of global warming is much more important than rainfall in Kenya as also reported by Kabubo-Mariara and Karanja [8], Bilham [10], and Dinar et al. [29]. Thus, there is need to rethink the likely harmful effect of climate change in the future and integrate this into agricultural and environmental policy formulation processes.

More effort should be put in consolidating and implementing policies particularly those that prevent destruction of natural environments and ensure that crop insurance as a risk coping mechanism has a solid framework that can help to enhance its uptake by farmers in different agro-regional zones. Given that human activities are the major drivers of climate variability and change, it is necessary to invest in adaptation measures at national, county and farm level especially in the tea growing regions, as a way of building farmers' resilience. In this regard, farmers should adopt an integrated approach that includes adaptation measures such as growing drought tolerant crop varieties, increasing investment in agriculture and using sustainable farm management practices.

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