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Managing climate risk through crop diversification in rural Kenya

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Abstract
Climatic variability and change continue to militate against efforts to increase agricultural productivity and food and nutrition security in many developing countries. Several studies propose crop diversification as a climate risk management strategy to increase production and food security. Most of the empirical studies are based on cross-sectional data that do not account for unobserved factors that may affect crop diversification. A disaggregated analysis of the influence of climatic variability and change on crop diversification by agroecological profiles is less explored. Panel studies also do not combine more than one climatic variability and change indicator as we do. We employ panel data models on farm household and 31-year rainfall and temperature data to analyze the effects of climatic variability and change on crop diversification among small-scale farmers disaggregated by agroecological zones in Kenya. We find widespread crop diversification among small farms in warmer regions as a risk management strategy. Results further show that smaller farm size, limited use of inorganic fertilizer, low household incomes, and limited access to off-farm livelihood options influence the decision to diversify crop production. However, crop diversification is not a one-size-fits-all strategy and should be adopted in situations where it gives maximum benefits, consistent with existing land use policies and known benefits of a specified crop portfolio. Crop diversification should not crowd-out specialization, particularly among resource-endowed farmers.

Keywords Climate change · Crop diversification · Panel data · Small-scale farms · Kenya

JEL classification C31 · Q24 · Q12 · Q54

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1 Introduction

The most recent report of the IPCC paints a gloomy picture of how climatic variability and change continue to militate against global efforts to ensure a sustainable and secure food system. This is through above normal increase in temperatures, frequent droughts, and increasingly unpredictable rainfall patterns (IPCC 2014). The adverse effects of climatic variability and change manifest more in agrarian areas of many developing countries. Coupled with rapid population growth, these effects are more pronounced in most hunger and malnutrition-prone regions of the developing world (Wheeler and von Braun 2013; FAO et al. 2018).

Faced with such climate adversities, small-scale farmers generally adopt various mitigation strategies. One of the most debated and widely practiced strategies is crop diversification, defined as increasing the number of crops or varieties of a crop (Bradshaw et al. 2004; Bezabih and Sarr 2012; Makate et al. 2016; Hitayezu et al. 2016). With the continued changes in rainfall patterns and depletion of water resources, less diversified cropping patterns are bound to be riskier under rain-fed agriculture. Hence, crop diversification among other strategies is more relevant to build resilience to climate change among resource-constrained small-scale farmers (Ngigi 2009). Seo (2010) forecasts that the number of diversified farms across Africa would increase, while the specialized ones will decrease by 2060.

Most rural households in Kenya depend on rain-fed small-scale farming as the main source of livelihood (Olwande et al. 2015). This exposes them to the negative effects of climate change (Ochieng et al. 2017). Climatic variability and change negatively impact on agricultural production (McCord et al. 2015; Ochieng et al. 2016). Kimenju and Tschirley (2008) recorded a drop in the share of crop income to the overall farm household income from 50% in 2000 to 44% in 2007, attributed to climatic variability and changes that reduced crop production. Climate change has also caused heavy rains (El Nino rains/floods) as well as prolonged dry spells in 2008–2009 in Kenya (ROK 2012). The challenges of climatic variability and change are amplified in scenarios of rain-fed agriculture.

Existing studies show that crop diversification could attenuate the likely negative impacts of climatic variability and change among small-scale farmers in developing countries (Bradshaw 2004; Lin 2011; Makate et al. 2016). Some of the merits of crop diversification include (1) providing insurance against the risk of crop failure and expanding the production possibility set for farmers thereby stabilizing crop incomes (Samuelson 1967; Meert et al. 2005), (2) improving environmental sustainability by reducing pests and controlling parasites and diseases (Lin 2011), (3) stabilizing yield, (4) improving soil fertility by decreasing nitrogen fertilizer use and fixing nitrogen to soils where legumes are intercropped (Krupinsky et al. 2002; Lin 2011), and (5) improving nutrition diversity and food availability (Lin 2011; Sibhatu et al. 2015; Makate et al. 2016). Research shows that impacts of climatic variability and change on small-scale farms depend on their cropping strategies in line with agroecology and robust knowledge transfer of best practices (Bindhumadhavan 2005; Lin 2007).

Despite the numerous studies on climatic variability and change as a driver of crop diversification, the conclusions have remained mixed. Most of the studies are also either at global, regional, or sub-regional levels with less disaggregated analysis, e.g., by agroecology or farm types. The questions about the broader context in which the strategy is appropriate and influence of such micro-level factors on crop diversification remain largely unanswered. Besides, there is a dearth of longitudinal studies that examine these questions in a broader way using more than one climate indicator. To analyze the interplay between climatic variability and change and crop diversification, we apply panel data models on spatially and temporally disaggregated data on rainfall and temperature patterns as well as on crop diversification from a sample of 1243 small-scale farmers.

This paper contributes to existing literature on climatic variability and change and adaptation strategies in the following ways. First, we exploit a more disaggregated 31-year geospatial climate dataset on short- and long-term rainfall and temperature patterns unlike many studies that use short-term data. Second, while many studies focus largely on the effects of one climate variable on crop diversification, our analysis explores the effects of more than one climate variable (rainfall and temperature). These factors may jointly influence crop diversification and therefore focusing on just one may bias estimates (Porter 2012; McCord et al. 2015). Third, we address the context specificity of climatic variability and change effects by explicitly analyzing the influence of agroecological heterogeneity through disaggregated analysis by agroecological zones (AEZs). Climatic variability affects farmers differently and therefore adaptation strategies are heterogenous (Wineman et al. 2017). Lastly, we control for farm and farmer characteristics over time to examine how they exogenously influence the decision to diversify crop production. These disaggregated micro-level analyses will supplement the existing macro-level analysis of the impacts of climatic variability and change on crop diversification.

The remainder of the paper is organized as follows. The next section provides an overview of the literature on climate change and climatic variability and crop diversification. Section 3 introduces the data sources, measurement of crop diversification, and the empirical approach. Section 4 discusses the results of the estimated models of crop diversification as a climatic variability and change adaptation strategy. Finally, Section 5 presents the conclusions and policy implications.

2 Literature review

A better understanding of the heterogenous impacts of climatic variability and change on farm production decisions is necessary for more targeted resilience-building approaches. With a plethora of studies on this topic, many continue to emerge on sustainable climate change adaptation strategies, particularly among resource poor small-scale farmers (Skoufias 2003; Ochieng et al. 2017). These farmers are more vulnerable to climatic variability because farming is their main source of livelihood, affecting their incomes, food security, and nutrition (Kabubo-Mariara and Karanja 2007; Wineman et al. 2017). There are numerous transmission channels through which climatic variability and change affect food security and nutrition from food production, marketing, and human health sides. From the production and marketing side, unpredictable and abnormally reduced (or increased) rainfall and increased temperature affect food availability through dwindling crop and livestock yields, especially in rain-fed production systems (Di Falco and Chavas 2008; Schlenker and Lobell 2010; Ochieng et al. 2016; Wineman et al. 2017).

On the one hand, reduced rainfall leads to reduced crop and livestock productivity through partial or total crop failures and reduced pasture availability (Jones and Thornton 2003; Tubiello et al. 2007; Mader et al. 2009; Knox et al. 2012; Rojas-Downing et al. 2017). On the other hand, abnormal increases in rainfall affect food security and nutrition through flash floods, which increase pest resurgence in warmer areas; cause rotting of tubers and root crops (Tefera 2012); delay planting and harvesting times and increases pre-harvest crop losses (Waha et al. 2012); increase post-harvest crop losses from poor storage and livestock deaths; and impede marketing of agricultural products among food surplus farm households and traders, thereby reducing their incomes (Bola et al. 2014; Udmale et al. 2014).

Reduced incomes from sale of agricultural products hinder farm households' economic access to food, especially when food prices skyrocket (Devereux 2007; Brown and Kshirsagar 2015). Floods hamper distribution of food from surplus to decifit areas and also increase food prices and reduce food availability (Sen 1983; Kimenju and Tschirley 2008). From the health side, increased rainfall has also been associated with child malnutrition and spread of vector-borne diseases with negative long-term health effects (Paterson and Lima 2010; Cooper et al. 2019). Reduced rainfall and elevated temperatures increase water scarcity. Limited water access and intake negatively affect food utilization, thus contributing to malnutrition (Sasson 2012; Wheeler and von Braun 2013). Reduced livestock production also reduces availability of animal protein with adverse effects on human health (Barrett and Santos 2014).

Efforts to mitigate the adverse effects of climatic variability have been centered around building resilience of small-scale farmers to climate change through adoption of "climate smart" agricultural practices such as conservation agriculture and crop diversification to name only a few (Kabubo-Mariara and Karanja 2007; Ochieng et al. 2016). The success of these strategies depends on several exogenous factors that are often context specific. This context specificity has elicited intense inter-disciplinary debate among scholars and development practitioners to combat the problem (Guthrie 2019; Hsiang and Kopp 2018). Looking at crop diversification, the literature underscores the importance of climatic variability and change and how this influences farm diversification and the welfare effects at scale (Bradshaw 2004; Bradshaw et al. 2004). However, there is a lack of disaggregated analysis of the influence of climatic variability, agroecological and farm household heterogeneity on farmers' decisions to diversify crop production and the context in which such an adaptation strategy is beneficial.

Despite the importance of climatic variability and change in crop and livestock production, most studies estimate drivers of crop diversification without including these factors (e.g., Porter 2012; Sichoongwe et al. 2014; Hitayezu et al. 2016; Makate et al. 2016). Existing studies have either used climatic variability (either rainfall or temperature alone) or in rare cases both (e.g., Di Falco et al. 2010; Bezabih and Sarr 2012; McCord et al. 2015). These empirical studies so far present mixed evidence of the complex relationship between climatic variability and change and crop diversification. Some studies show that climatic variability and change such as rainfall and temperature are positively associated with crop diversification (Bezabih and Sarr 2012; McCord et al. 2015). Other studies show that climatic variability and change is negatively associated with crop diversification; for example, past rainfall is negatively correlated with crop diversity (Joshi et al. 2007; Di Falco et al. 2010; Acharya et al. 2011).

At the same time, there are many initiatives to intensify production in monoculture systems in developing countries. However, the belief that intensive systems are more productive than diversified systems is not always true, particularly in the case of predominantly subsistence production with limited marketable surpluses (Sileshi et al. 2012). Besides, the recent global report by the Global Commission on Adaptation emphasizes the need for resource-constrained farmers to diversify production (Manish et al. 2019). Other non-climate factors such as farmer and farm characteristics also influence the decision to diversify crop production. Existing studies document mixed conclusions on their influence on crop diversification. Some studies find a positive association between farmer characteristics such as age, household size, male gender, level of education and incomes, and farm characteristics such as farm sizes, levels of input use (e.g., fertilizer), and farm location and crop diversification (Sichoongwe et al. 2014;

Porter 2012; McCord et al. 2015; Makate et al. 2016) while others find negative associations (Kimenju and Tschirley 2008; Kasem and Thapa 2011; Hitayezu et al. 2016; Makate et al. 2016). Arguably, the association varies depending on context. For this reason, we also examine the influence of farm and farmer characteristics in our model estimations. Even though climatic variability and change and farmer and farm characteristics influence crop diversification, some studies show that a favorable agroecology may compensate for the obstacles to crop diversity (McCord et al. 2015; McCord et al. 2018). In this paper, we examine the interplay of climatic variability and change, farm and farmer characteristics, and adoption of crop diversification as an adaptation strategy under various agroecological contexts in Kenya.

3 Data and methods

3.1 Data description

3.1.1 Farm household survey data

The study used panel survey data collected from rural farm households in Kenya. Data was collected by the Tegemeo Institute of Agricultural Policy and Development, Egerton University in collaboration with Michigan State University. The nationally representative data was collected in five waves, beginning with a baseline in 1997 and subsequent follow-ups in 2000, 2004, 2007, and 2010. The baseline sampling frame and sampling procedure were developed in consultation with the Kenya National Bureau of Statistics (see Argwings-Kodhek et al. (1999) for details). The study covered the eight original AEZs in Kenya, namely coastal lowlands, eastern lowlands, western lowlands, western transitional zone, high potential maize zone, western highlands, central highlands, and marginal rain shadow (Fig. 1). The AEZs are a hybrid of broad AEZs, administrative and political boundaries (Argwings-Kodhek et al. 1999). The households were interviewed using a semi-structured questionnaire. We excluded the 1997 data from our analysis due to data gaps in some of the key variables. Hence, our analysis was based on a balanced panel of 1243 farm households. The survey covered 22 administrative districts, 37 divisions and 107 villages. Nairobi and North Eastern regions were excluded from the sample because of urbanization and aridity leading to limited crop production, respectively. This also means that our sample excluded pastoral households in northern Kenya who are likely to be most vulnerable to climate and weather shocks. It is important to note that about 10% of Kenya's population do not predominantly engage in crop production reside in arid and semi-arid lands (Kirkbride and Grahn 2008). Hence, the farm household survey data set is representative of the farming populations in rural Kenya.

3.1.2 Climate data

We use a combination of rainfall and temperature data collected by the Kenya Meteorological Service (KMS) over a period of 31 years (1980–2010). The data were collected from 29 weather stations nearest to the interviewed farm households and comprised mean annual rainfall and temperatures that capture climatic variability and the long-term rainfall and temperature means that capture climate change. The climate data have also been used in previous studies that investigated the effects of climate change on small-scale agriculture in Kenya (Kabubo-Mariara and Karanja 2007; Ochieng et al. 2016). In this paper, we aggregated

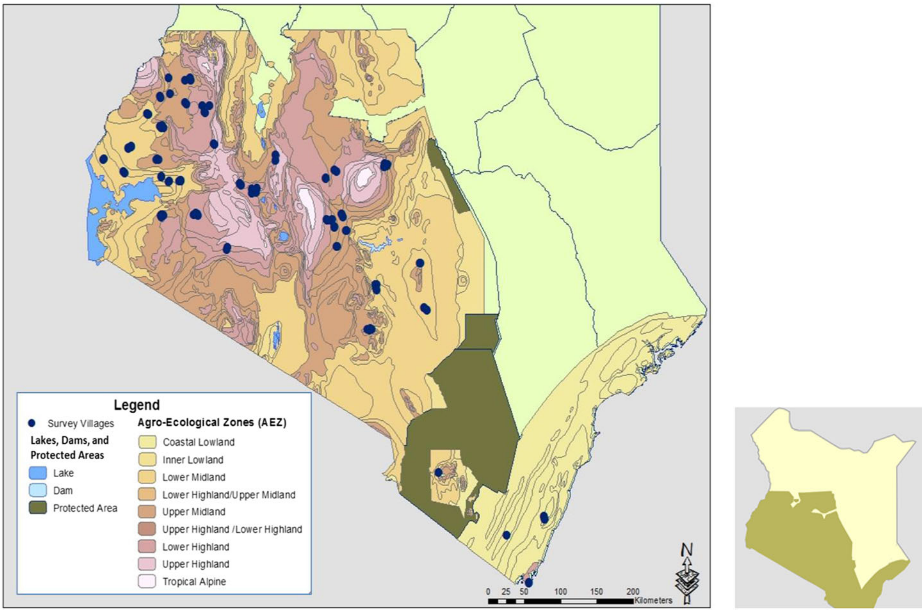

Fig. 1 Tegemeo survey villages and AEZs. Source: Ochieng et al. 2016

AEZs into three groups based on the maximum temperature thresholds for optimal growth of common crops in Kenya. The AEZ groups were as follows: lowlands (coastal and inner lowlands); midlands (lower midland, lower highland/upper midland, and upper midland); and highlands (lower highland, upper highland/lower highland, and upper highland) (see Fig. 1). From the KMS data, the mean and maximum annual temperatures were as follows: coastal lowland (> 24 °C, with maximum < 31 °C), inner lowland (> 24 °C, with maximum > 31 °C), lower midland (21–24 °C), upper midland (18–21 °C), and lower highland (15–18 °C), and upper highland (10–15 °C).

3.2 Measurement of crop diversification

There are several ways of measuring crop diversification ranging from simple counts of the number of crops grown to complex ones such as Shannon index, Simpson diversity index, and Herfindahl index (Duelli and Obrist 2003; Di Falco and Perrings 2005; Sichoongwe et al. 2014; Makate et al. 2016; Rajendran et al. 2017). The major crops grown by the sampled farmers are presented in Table 1A in the online supplementary material. To provide a more precise measure of crop diversity based on proportions rather than absolute counts, we used Simpson's crop diversification index (CDI) calculated for each farmer per panel year based on the relative composition of crops cultivated. The index ranges from zero to one. Zero means that farmers specialize in one crop while one means they are fully diversified and grown infinite number of crops. CDI is calculated as one minus Herfindahl index:

$$CDI = 1 - \sum_{n=1}^{i} P_i^2 = 1 - HI \tag{1}$$

where Pi is the proportion of area under ith crop relative to overall cropped area and HI is the Herfindahl index computed as

$$HI = \sum_{n=1}^{i} P_i^2 \tag{2}$$

We calculated the average score for the CDI for all farmers and farm categories. We adopt farm categories from Afari-Sefa et al. (2016) as follows: small farms (≤ 5 acres), medium farms (5–10 acres), and large farms (> 10 acres). Based on this criterion, the majority of farmers in our sample have small farms (66%). Medium and large farms constitute about 20% and 14% of the sample, respectively. The CDI is used as dependent variable in the model to analyze factors influencing adoption of crop diversification as a climate change adaptation strategy.

3.3 Modeling the effect of climatic variability and change on crop diversification

Fixed effects (FE) and random effects (RE) estimators are the workhorses of panel data analysis. The FE model is often preferred for controlling for unobserved time-variant heterogeneity. However, in our case, the outcome variable (CDI) is non-linear and hence, it is not possible to use FE estimator. Besides, the RE estimator is more efficient in estimating variables that have minimal longitudinal variance and retains time-constant covariates that would otherwise be dropped in FE regressions. Nonetheless, for a robustness test of our estimates, we separately fit a correlated random effect (CRE) model or Mundlak-Chamberlain (MC) procedure, which is a hybrid of RE and FE estimators (Mundlak 1978; Chamberlain 1984) and extends the RE analysis by modeling unobserved heterogeneity using the household means of time-varying variables. Notably, MC yields the same estimates for time-varying variables as FE, while at the same time modeling heterogeneity to explain differences across farm households. The model(s) are then estimated using Tobit since the crop diversification index is censored at zero. The model is specified in Eq. 3 below.

$$\begin{aligned} &{y_{it}}^{*} = X_{it}\beta + \mu_i,\ \mu|\chi\sim\text{Normal}\ (0, \sigma 2) \\ &Y_i = 0\ if y_i^{*} \geq 0 \\ &Y_i = y_i^{*}\ if y_i^{*} > 0 \end{aligned} \tag{3}$$

In data censoring cases, the latent variable $y*$ should have homoscedastic normal distribution with linear conditional mean; X_i is a vector of known exogenous variables in the model while β is a vector of unknown parameters and μ_i is the error term assumed to be independent and normally distributed as $\mu_i \sim N\,(0, \sigma^2)$. The outcome variable Y_{it} is the crop diversification index. The exogenous variables (X_i) include climate data (rainfall and temperature). The crop diversity function that we estimated is as follows:

$$\begin{aligned} Y_{it} = {} & \beta_0 + \beta_1 \times R_{it} + \beta_2 \times T_{it} + \beta_2 \times RC_{it} + \beta_2 \times TC_{it} + \beta_3 \times HC_{it} + \beta_4 \times FC_{it} \\ & + \beta_5 \times AEZ_{ii} + \beta_6 \times Year_{it} \\ & + \varepsilon_{it} \end{aligned} \tag{4}$$

where Y_{it}= crop diversity index for household i at time t. R_{it} and T_{it} respectively represent the rainfall and temperature for the respective data collection years. RC_{it} and TC_{it} represent long-term temperature and rainfall (from 1980 to 2010), respectively. HC_{it} denotes the household head characteristics (age measured in years, sex which equals one if head is male and years of education). While FC_{it} represents the farm characteristics which include farm size, inorganic fertilizer use, household access to off-farm income, distance to input seller and to the motorable road in kilometers, and total household income.

We consider changes in the adoption of crop diversification strategy over the years ($Year_{it}$) as well AEZs (AEZ_{ii}) to capture regional and temporal scale variations within the country. Adaptation to climatic variability and change is context specific and assumed to vary by AEZs. We therefore estimated Eq. 5 for each AEZ.

$$Y_{it} = \beta_0 + \beta_1 \times R_{it} + \beta_2 \times T_{it} + \beta_2 \times RC_{it} + \beta_2 \times TC_{it} + \beta_3 \times HC_{it} + \beta_4 \times FC_{it} + \beta_5 \times Year_{it} + \varepsilon_{it} \tag{5}$$

Before, estimating Eq. 5, we tested for equality of regression coefficients that are generated from three different regressions for each AEZ. The results show that the coefficients are significantly different across the three AEZs and imply that it is worth estimating Eq. 5 for each AEZ (lowlands, midlands, and highlands) (Table 2A in the online supplementary material).

Farmers' decision to opt for more diversified systems would be highly influenced by the ability of the diversification to support household's resilience by accessing food and income during times of extreme climate risks. Thus, we hypothesize that declining rainfall and increasing temperatures lead to greater crop diversification among small-scale farmers. For example, declining rainfall patterns often force farmers to shield themselves against potential crop failure by diversifying crop production. Detailed measurements of these climatic variables are presented in Table 1. We also consider three AEZs (lowlands, midlands, and highlands) across four waves. This is important because households across these three AEZs exhibit varying livelihood strategies and face different climatic conditions. On the one hand, the highlands receive more rainfall, are cooler, more densely populated, and better connected to markets than other AEZs (columns 1, 2, and 3 of Table 1). Some parts of the highlands have cash crops such as coffee and tea, which are major sources of income. Farmers in the highlands also have larger farm and household sizes and have access to better road networks and input markets. On the other hand, lowlands are drier with an average temperature of 26 °C, sparsely populated and households from these areas depend on tourism, fishing and mixed farming (crop and livestock). Midlands experience lower temperatures than lowlands and households are more geographically dispersed and rely on food crop production (i.e., maize) as the main source of income. Farm households in the sparsely populated lowlands have the least access to markets and motorable roads than their counterparts in the midlands and highlands. Lowlands experience prolonged dry spells receive low rainfall and have shallow and infertile soils that have mainly develop from sedimentary rocks (Ochieng et al. 2017). This implies higher vulnerability to climatic variability and change. Regarding crop diversification, lowland farmers are the most diversified (CDI = 0.77) followed by midlands (CDI = 0.76) and highlands (CDI = 0.59) (Table 1).

Table 1 Basic household characteristics

Variable	Description	All households		Lowlands (1)		Midlands (2)		Highlands (3)		Tests[1]		
		Mean	SD	Mean	SD	Mean	SD	Mean	SD	1 = 2	1 = 3	2 = 3
Dependent variable												
Simpsons' CDI[2]	1-Herfindhal index	0.73	0.19	0.77	0.19	0.76	0.17	0.59	0.20	ns	***	***
Climate variables												
Rainfall	Mean monthly rainfall (total yearly/12(mm/mo) in a year	126.30	61.20	87.78	73.37	131.05	62.59	128.03	41.78	***	***	ns
Long-term rainfall	Long-term mean monthly rainfall (total yearly/12(mm/mo), 1980–2010	100.40	28.50	81.55	13.36	106.65	31.06	101.78	21.64	***	***	***
Temperature average	Mean annual air temperature (°C) in a year	20.70	2.90	26.23	0.78	20.94	2.18	17.83	0.89	***	***	***
Long-term temperature	Long-term mean air temperature (1980–2010)	20.80	3.00	24.14	4.05	21.12	2.28	18.11	0.74	***	***	***
Farmer and farm characteristics												
Age	Age of the head (years)	57.39	13.52	56.33	13.68	57.75	13.40	56.68	13.82	ns	ns	*
Sex	Sex of head (1 = male)	0.79	0.41	0.83	0.38	0.77	0.42	0.85	0.36	***	ns	***
Education	Years of schooling of the head	7.04	4.60	5.87	4.52	7.15	4.62	7.16	4.52	***	***	ns
Household size	Number of household members	6.00	3.02	7.49	4.27	5.78	2.84	6.06	2.75	***	***	**
Farm size	Total land owned(acres)	5.80	9.03	5.53	7.08	4.54	6.99	10.13	13.36	ns	***	***
Inorganic fertilizer use	Quantity of fertilizer (kilograms per acre)	59.85	120.96	4.72	21.13	57.69	134.85	91.32	83.52	***	***	***
Access to off-farm income sources	1 = access to off-farm income	0.74	0.44	0.79	0.41	0.76	0.43	0.66	0.47	ns	***	***
Distance to input seller	Distance from homestead to input seller in kilometers	4.24	6.34	11.57	14.30	3.39	4.17	3.70	3.91	***	***	ns
Distance to motorable road	Distance from homestead to motorable road in kilometers	0.83	1.47	1.46	2.58	0.74	1.15	0.84	1.63	***	***	ns
Net household income per adult equivalent (AE) ('000' KSh)	Net household income in Ksh per AE	62.83	84.38	43.77	63.96	57.85	73.08	87.56	115.88	ns	***	***
Number of observations		4972		468		3448		1056				

Notes: [1] Asterisks denote the level of significance for a *t*/χ-test difference in means, ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$ and *ns* not significant. [2] *CDI*, crop diversity index; *Ksh*, Kenyan Shilling; °*C*, degrees Celsius; *mm*, millimeters; *mo*, month; *AE*, adult equivalent

4 Results and discussion

4.1 Crop diversification, rainfall, and temperature trends by AEZs in Kenya

Figures 2 and 3 present the trends in crop diversification by AEZs and farms types, respectively, from 2000 to 2010. During this period, crop diversification increased in the lowlands (Fig. 2). Lowlands are relatively drier and households there tend to grow several crops to reduce risks from climatic variability and change as shown in Table 1A in the online supplementary material. As expected, crop production in the highlands was less diversified and farmers grew fewer crops (CDI = 0.59). The crop diversification trends show that diversification peaked in the highlands in 2004 and declined afterwards. The highlands have relatively fertile soils and receive higher rainfall (1400–1800 mm) than other AEZs, which can accommodate two cropping seasons. Long rain season starts from mid-March to July while short rain season lasts from mid-October to December and therefore highland farmers get better harvests.

A similar trend was observed in the midlands with a slight decline in crop diversification from 2007 onwards. This suggests that densely populated areas with greater agroecological potential and access to markets and road networks like the highlands were less diversified than other AEZs. The results also indicate that small-scale farmers still have the incentive to diversify production to meet their subsistence and market needs.

In contrast, lowland farmers were the most diversified. This is plausible given that these areas are drier and farm households have limited options to adapt. Often, water harvesting strategies and irrigation infrastructure do not provide sufficient water for continuous cultivation during dry periods (McCord et al. 2015). This leaves lowland farmers with crop diversification as the cheapest livelihood strategy.

Overall, crop diversity per farm increased between 2000 and 2004 from 10 to 14 crops but then declined in subsequent years (Fig. 3). Such a high level of farm diversity is typical among smallholder farmers in Kenya as also noted in other studies (Kimenju and Tschirley 2008; Ogutu et al. 2019). Larger farms increased crop diversity to 13 crops between 2000 and 2004 but this also dropped in subsequent years, showing that farmers moved towards specialization over time. A similar trend is observed among farmers with medium and small land holdings when using the number of crops grown (Fig. 1A in the online supplementary material). A more precise measure of the crop diversity index (CDI) based on the proportions of cropped areas

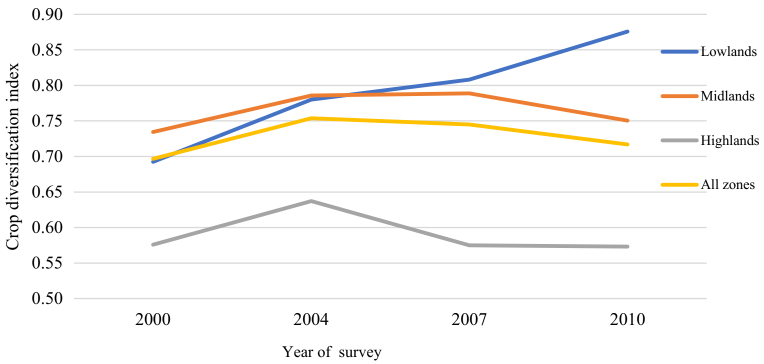

Fig. 2 Crop diversification trends by agroecological zones between years 2000 and 2010

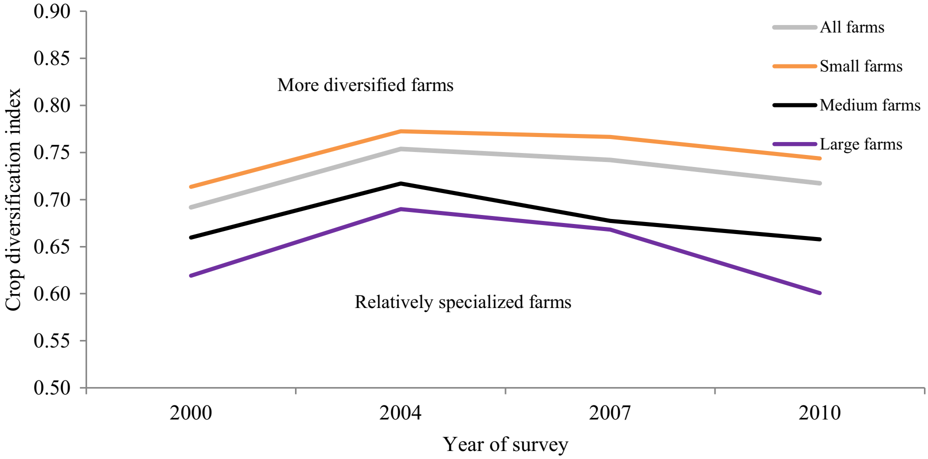

Fig. 3 Crop diversification trends by farm categories between years 2000 and 2010

rather than an absolute count of crops grown also shows a similar trend that crop diversification is more pronounced among small and medium scale farmers. Crop diversification is more pronounced in lowlands and among the small farms in all AEZs (Fig. 2A (a-c) in online supplementary material).

Previous research shows that Kenya experienced relatively constant average temperatures of about 20.8 °C from 2000 to 2010 with the highest temperatures in the lowlands (Ochieng et al. 2017). Rainfall first increased across the AEZs then declined sharply between 2008 and 2009 due to a prolonged drought (Rok 2012; Ochieng et al. 2017). This adversely affected agricultural livelihoods in general, farm household food security, and wildlife particularly in the lowlands. Bradshaw et al. (2004) argue that given the changing climatic conditions particularly the increase in extreme climate events, farmers may be forced to revisit their diversified production to minimize production and market risks for a mix of crops with minimal yield and price covariance (Bradshaw et al. 2004; Makate et al. 2016). However, the benefits of crop diversification may be outweighed by the limitations, such as high start-up costs and limited economies of scale.

4.2 Factors influencing adoption of crop diversification as a strategy to mitigate climatic variability and change

The results of the econometric estimation of Eqs. 4 and 5 are shown in Table 2. Most of the empirical results are consistent with the descriptive analysis presented above. The estimated coefficients of the variables of interest are comparable in magnitude, have the expected signs, and are statistically significant in both the RE and CRE models. For brevity, we only present RE models here. CRE model estimates are presented in Table 3A in the online supplementary material.

In the lowlands, crop diversity had a significant negative relationship with long-term rainfall and annual rainfall but a positive one with temperature. This implies that as rainfall increased, farmers in the lowlands opted to specialize more and vice versa. However, farm productivity is low (Ochieng et al. 2017) and households largely depend on the market for food because farm production is constrained by extreme weather shocks, pests, and diseases (FEWSNET 2011).

Table 2 Effect of climatic variability and change on crop diversification: random effects model

Dependent variable: crop diversification index	(1) Pooled	(2) Lowlands	(3) Midlands	(4) Highlands
Mean rainfall	− 0.0001***	− 0.0003*	− 0.0001*	0.0001
	(0.000)	(0.000)	(0.000)	(0.000)
Mean temperatures	− 0.0036	− 0.0514	− 0.0039	− 0.0135
	(0.004)	(0.034)	(0.007)	(0.011)
Long-term rainfall (31 years)	− 0.0000	− 0.0071***	− 0.0002*	− 0.0002
	(0.000)	(0.001)	(0.000)	(0.001)
Long-term temperature (31 years)	0.0044	0.0247***	0.0023	0.0637***
	(0.003)	(0.007)	(0.007)	(0.017)
Age of the head (years)	− 0.0004	0.0014	− 0.0005*	− 0.0001
	(0.000)	(0.001)	(0.000)	(0.001)
Sex of the head (1 = male)	0.0026	0.0210	0.0037	− 0.0233
	(0.008)	(0.029)	(0.009)	(0.021)
Years of education of head	− 0.0005	0.0020	0.0000	− 0.0006
	(0.001)	(0.003)	(0.001)	(0.002)
Household size	0.0008	− 0.0006	− 0.0000	0.0051*
	(0.001)	(0.003)	(0.001)	(0.003)
Land owned (acres)	− 0.0007**	0.0004	− 0.0022***	0.0000
	(0.000)	(0.001)	(0.001)	(0.001)
Amount of fertilizers(kg/acre)	− 0.0001***	− 0.0011**	− 0.0000***	− 0.0006***
	(0.000)	(0.000)	(0.000)	(0.000)
Access to off-farm income sources (1 = yes)	0.0118**	− 0.0006	0.0181***	0.0054
	(0.006)	(0.025)	(0.006)	(0.012)
Distance to input seller (km)	− 0.0003	0.0023**	− 0.0014**	0.0037**
	(0.000)	(0.001)	(0.001)	(0.002)
Distance to motorable road (km)	− 0.0017	− 0.0015	0.0026	0.0005
	(0.002)	(0.004)	(0.002)	(0.004)
Household income (Ksh/AE)	− 0.0132***	0.0219**	− 0.0221***	− 0.0015
	(0.003)	(0.011)	(0.003)	(0.008)
Midlands[a]	0.0089			
	(0.019)			
Highlands	− 0.1515***			
	(0.024)			
Year 2004[b]	0.0631***	0.1733***	0.0468***	0.0515***
	(0.006)	(0.033)	(0.007)	(0.020)
Year 2007	0.0504***	0.1798***	0.0505***	− 0.0111
	(0.007)	(0.030)	(0.008)	(0.018)
Year 2010	0.0205***	0.1852***	0.0140*	− 0.0381**
	(0.007)	(0.042)	(0.007)	(0.018)
Constant	0.9099***	1.5870**	1.0630***	− 0.2714
	(0.069)	(0.770)	(0.065)	(0.245)
Wald χ^2	601.31***	108.30***	226.07***	116.62***
Observations	4924	457	3426	1041

Notes: Standard errors in parentheses. ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$. [a] Lowlands is base AEZ [b] base year is 2000

A more interesting story emerges regarding the effect of long-term temperature. Previous studies found that temperature changes had higher negative impacts on crop yields than changes in rainfall (Kabubo-Mariara and Karanja 2007; Ochieng et al. 2016). High temperature was positively associated with increased crop diversification in lowlands and highlands. Farmers adapted by increasing the number of crops grown to reduce the consequences of possible crop failure due to droughts. Highlands usually have better climate and fertile soils than lowlands therefore, farmers are expected to adopt crop diversification strategy in hotter climate. In such harsh climatic conditions, farmers seek alternative crops that would be more yielding, profitable, and reliable. Hence, crop diversification provides an opportunity to diversify crop income and food availability to smoothen household consumption throughout the year. Crop diversification was chosen over specialization in warmer climate scenarios regardless of the historical climatic patterns as also observed by Seo (2010). Frequent occurrences of climate extremes in Kenya have led to the introduction of mitigation programs such as weather index-based crop insurance schemes to indemnity farmers in case of losses. One such program was dubbed “Kilimo Salama” and implemented in collaboration with insurance companies. However, studies showed that it had limited success among small-scale farmers in Kenya due to several challenges such as lack of awareness of the insurance products, complexity and poor design of the insurance schemes, higher premiums, and basis risk, which lead to low uptake of crop insurance (FSD 2013; Kirimi et al. 2016).

The decision to diversify crop production was also influenced by farmer and farm characteristics. Farmer characteristics included access to off-farm incomes and annual household incomes whereas farm characteristics included farm size and input (fertilizer) use per acre. Results show that increased farm sizes were negatively associated with increased crop diversification in the midlands but not in the lowlands and highlands. This is plausible given that the average midland farms were smaller than in the lowlands and highlands (see Table 1 and Fig. 2B in online supplementary material). Midland farmers were likely to specialize with increased farm sizes. This finding is consistent with those of previous studies in Kenya and other developing countries that farm households specialize as farms grow larger and diversify into off-farm employment activities (Kimenju and Tschirley 2008; Kasem and Thapa 2011; Hitayezu et al. 2016). This could be explained by the fact that large farms often demand more management skills, inputs, and finance whereas resource-constrained farm households are unable to produce multiple crops. Households may opt to grow cash crops such as tea and coffee, particularly in the highlands where households have large farms. In contrast, some previous studies show that crop diversification increased with increased farm sizes particularly in arid and semi-arid areas where farmers are more vulnerable to drought risks (Ashfaq et al. 2008; McCord et al. 2015; Makate et al. 2016).

The average farm size per household declined from 6.1 acres in 2000 to 5.2 acres by 2010. The decline also varied by AEZs (Fig. 2B in the online supplementary material). Between 2000 and 2010, average farm size declined from 5.7 to 4.7 acres in the lowlands, 4.7 to 4.1 in the midlands, and 10.6 to 9.2 acres in the highlands. While our results are consistent with the general expectations, it is noteworthy that most land use policies support specialization for larger farms to benefit from modern farming technologies to facilitate economies of scale. This may not be appropriate for resource-constrained farmers with large farms who may not be motivated to diversify production because of high investment costs and difficulty to achieve economies of scale (Bradshaw et al. 2004). Hence, we argue that it is necessary to define an optimal level of diversification that is consistent with declining land sizes while also considering the well-known advantages of specialization. The dwindling arable farmlands present a dilemma on whether to adopt land sharing, sparing strategies or crop diversification to increase food production (Fischer et al. 2008). In the end, crop diversification in small-scale farming will be more a matter of destiny than choice.

On fertilizer use, we found a negative association between crop diversification and increased fertilizer use. That is, ceteris paribus, crop diversification reduced with increased quantities of fertilizer used in all the AEZs (Acharya et al. 2011). This is contrary to findings from a previous study in Africa that reported a positive association (Sichoongwe et al. 2014). Farmers used less fertilizer per acre as their farms became more diversified. This is partly explained by inadequate financial capacities to purchase inputs. Besides, most small-scale farmers deliberately reduce fertilizer application particularly in nitrogen-fixing legume-cereal intercropping systems. This could mean that crop diversification is often taken up by households with limited investment in complementary inputs (e.g., inorganic fertilizers) required to increase crop yields. Previous findings show that farmers reduce the amount of inorganic fertilizer used when they anticipate depressed rainfall (Fufa and Hassan 2006). Fertilizer use is also influenced by general availability in the markets. The distance from homesteads to the input markets (sellers) was positively associated with crop diversification in the lowlands and highlands but negatively associated in the midlands. This means that lowland and highland farmers who resided far away from input sources diversified crop production without investing in improved inputs such as seeds, inorganic fertilizers, and crop chemicals. Midland farmers opted to specialize as physical access to input markets reduced. This may be closely associated with diversification into more off-farm activities as explained in the following discussion. Nonetheless, this finding is indeterminate as farmers may respond to such situations differently.

Regarding off-farm incomes, we found that farmer's access to off-farm income sources was positively associated with crop diversification particularly in the midlands (Table 2). Usually, households with the highest off-farm earnings tend to invest more in agriculture (Mathenge et al. 2015) while those with least earnings from off-farm activities diversify production as a risk management strategy (Meert et al. 2005). Exposure to low rainfall in the midlands reduces both on-farm and off-farm incomes given the interconnectedness between agriculture and non-agricultural activities in the rural agrarian economy, so that off-farm sectors suffer in years of poor weather (Wineman et al. 2017). Further, common off-farm activities alone hardly yield adequate incomes to sustain household needs. The off-farm activities included petty trade such as part time shoe shining, selling second-hand clothes, or selling fish among other activities. The majority of lowland and midland farmers had off-farm incomes (79% and 76%, respectively) and this is explained by the relatively lower agricultural commercialization potential in those areas than in the more commercialized agricultural areas of the highlands where about 47% of farm households had off-farm income sources (Table 1). Further, findings show that households with higher net incomes per adult equivalent were less likely to diversify crop production. Instead, they specialized by focusing on a few food crops that generated higher returns and guarantee their food and nutrition security. This shows that low-income households often face constraints that limit their off-farm employment opportunities.

5 Conclusion and policy implications

Small-scale farmers are diversifying their crop production as a risk management strategy to counter adversities of climatic variability and change to enhance crop production and productivity. This paper examined (1) trends in crop diversification between 2000 and 2010 in Kenya; (2) how climatic variability and change and farm and farmer characteristics influence crop diversification; and (3) the contexts in which crop diversification is more beneficial to small-scale farmers through a disaggregated analysis by agroecological zones (AEZs).

We found that climatic variability and change significantly influenced farmers' decision to diversify crop production. Increased rainfall and temperature had differential effects on crop diversification across AEZs. Increased temperature was positively associated with increased crop diversification in lowlands, while increased rainfall was negatively associated with increased diversification in lowlands and midlands. Farmers in lowlands, which experience warmer climate with frequent prolonged dry spells, are more likely to diversify crop production as a livelihood strategy while also reducing improved inputs (e.g., inorganic fertilizer) use due to production uncertainties under rain-fed production systems.

Overall, the findings show a trend in increased crop diversification in warmer climate, even as arable land continues to dwindle over time. Hence, farmers need to adopt crop diversification alongside other farm management practices and take up crop insurance to increase resilience to climatic variability and change. The results show that farmers are constrained in terms of declining farm sizes, limited access to farm inputs such as inorganic fertilizers, and inadequate income to invest in intensive agriculture. A diversified crop production system is likely to persist among small-scale farmers who are more vulnerable to climatic variability and change. We argue that the decision to adopt should not be solely guided by climatic and farmer-level conditions but also by other farm and market factors.

Crop diversification is not a one-size-fits-all strategy and may work in some AEZs but not in others. Under the prevailing climatic conditions, crop diversification is beneficial in the semi-arid lowlands where it gives maximum benefits. In the advent of more frequent extreme weather events, greater uncertainties in rain-fed production systems and the declining arable farm sizes, crop diversification will remain a relevant risk-reducing strategy not only in the semi-arid lowlands but in other AEZs. The strategy should not crowd-out specialization, particularly among resource-endowed farmers who have the capacity to invest and maximize benefits of specialized cropping systems. The central agricultural policy issue is price and income stabilization and what crop diversification can contribute to increased farm incomes when markets are well-functioning and prices and demand for crops are high.

Crop diversification remains a relevant risk management strategy particularly in the smallholder farm sector of developing countries. Nonetheless, its adoption should be consistent with the existing country-specific land use policies and known benefits of a specified crop portfolio. This can also be influenced by other farm or non-farm factors. One important agricultural policy response to mitigate farm-level risks is crop insurance, which may significantly influence farm production decisions. Further research is needed to understand the interactions between crop diversification and other strategies such as crop insurance among others geared towards reducing price and yield risks.

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Compliance with ethical standards

Disclaimer The views expressed in this study are those of the authors only.

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