Decision Making under Climate Risks: An Analysis of Sub-Saharan Farmers' Adaptation Behaviors

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ABSTRACT

This paper examines decision making under climate risks using farmers' decisions in sub-Saharan Africa, where climate risks are very high. Two risk measures are obtained from the Climate Research Unit's high-resolution climatology, diurnal temperature range (DTR) and coefficient of variation in precipitation (CVP), which are both averages of 30-yr climate data. Farm surveys of around 7600 households were matched cell by cell with the climate risk data. This paper finds that climate risks are indeed highest in the lowland arid zones in the Sahel. A spatial logit analysis shows that farmers in sub-Saharan Africa have adapted their agricultural systems to varying degrees of the CVP and the DTR. In the long term, if the CVP were to increase by 30%, an integrated system would increase by 7.0%. On the other hand, the two specialized systems fall: a crops-only system falls by 5.3% and a livestock-only system falls by 1.7%. When the DTR increases, farmers adapt by switching to a specialized livestock system. Under increased climate risks, this paper finds that farmers in the lowland savannahs and arid zones in the Sahel, where climate risks are high at present, will adapt by switching to an integrated system. Studies of climate risks, therefore, must account for behavioral responses of the individuals. These results can be utilized to help African farmers to adapt to increasing climate risks.

1. Introduction

As the earth is getting warmer, the science of climate change and future climate projections are gaining acceptance increasingly across global communities (Hansen et al. 2006; Solomon et al. 2007; Keeling et al. 2009). For many concerned people, a rapid increase in atmospheric concentration of carbon dioxide recorded at the Mauna Loa observatory and elsewhere poses a great threat to the future of human civilizations, including disruptions in the oceans and a runaway temperature increase (Broecker 1997; Mann et al. 1999; Meyer and Kump 2008). Increasingly, climate scientists warn the world of the possibilities of increased risks associated with global warming, such as more frequent extreme weather events, more destructive hurricanes, and disruptions in rainfall patterns in major farming areas (Easterling et al. 2000; Houghton et al. 2001; Tebaldi et al. 2007; UNFCCC 2009; Knutson et al. 2010; Hansen et al. 2012). Economic studies are also increasingly concerned about increased climate risks and severe consequences of such changes including catastrophe (Weitzman 2009; Nordhaus 2011). Because of global warming, hurricanes may become more frequent and intense, causing more severe economic damages (Nordhaus 2010). Some argue that increases in extreme temperature events will severely harm agriculture if climate thresholds for major staple crops are crossed (Schlenker and Roberts 2009). However, these studies focus on the impacts of increased risks but do not tell the possibilities and constraints of adapting to such increases in climate risks in a similar fashion as people cope with shifts in climate normals (Seo 2010a,b, 2011).

There are a large number of available experimental studies which have studied the impacts of climate change on an array of major crops. These studies employ either open-top chamber experiments such as Soybean Crop Growth Simulation Model (SOYGRO); Crop Environmental Resource Systhesis (CERES)-Maize; CERES-Wheat; or Free-Air CO_2 Enrichments (FACE), which are more expensive but realistic (Adams et al. 1990; Tubiello and Ewert 2002; Ainsworth and Long 2005). Both the crop simulation models and the FACE experiments indicate that CO_2 doubling increases crop yields, but temperature and precipitation effects can have additional

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impacts (Easterling et al. 2007). However, these experimental studies are intended to examine the impacts of mean temperature increase or CO_2 concentration increase in the atmosphere on crop yields. Therefore, they are nearly not capable of capturing the impacts of climate variability that occur for a long period of time (Porter and Semenov 2005). This paper can fill this critical gap in the literature by relying on behavioral observations of farmers.

Risk, small or large, is a fact of life. People always make decisions under uncertainty and in consideration of risks. Economists have delved into decision making under risks when financial returns are concerned (Markowitz 1952; Tobin 1958; Arrow 1971; Kahneman and Tversky 1979). Agricultural economists have studied farm management decisions under various risks, including weather risks (Zilberman 1998). Climate risk is a new type of risk to the humanity that lies ahead in the coming decades; therefore, a rigorous study is not available (Reilly et al. 1996; Easterling et al. 2007). This paper inquires into whether increasing climate risks would pose great threats to the human society as previous studies and prevalent concerns in the climate community have indicated (Solomon et al. 2007). Of particular concern is whether farmers have coping strategies to climate risks in an attempt to reduce damages. Empirical analyses will be conducted focusing on the most vulnerable human activities under climate change: that is, farming in the low-latitude poor countries. In particular, we examine agricultural activities performed in sub-Saharan Africa, where climate risks are considered to be high, especially in the Sahel (Hulme et al. 2001; Shanahan et al. 2009).

We obtain two indicators of climate risks from the Climate Research Unit (CRU) high-resolution average climatology: the coefficient of variation in precipitation (CVP) and the diurnal temperature range (DTR) (New et al. 2002). The DTR captures an increase in temperature range between daily minimum temperature and daily maximum temperature, which is provided as monthly average (Easterling et al. 2000; Houghton et al. 2001; Tebaldi et al. 2007). The CVP captures an increase in precipitation variability and is a key variable of agricultural risks in Africa and elsewhere (Udry 1995; Kazianga and Udry 2006; Zilberman 1998). Both measures are averages from the 30-yr climate observations and are therefore not a measure for an individual weather shock. The climate risk data are combined with the World Bank household surveys of around 7600 farms from nine sub-Saharan countries that recorded detailed farming decisions (Dinar et al. 2008).

This paper examines the variation of farming activities across different zones of climate risks. We examine whether farmers adapt to highly variable climate in a certain way to reduce the damage from the natural shocks. In particular, this paper explains adoption of agricultural systems as a climate risk management behavior. Based on the climate literature, three distinct agricultural systems are examined: a specialized crop system, a specialized livestock system, and an integrated system (Seo 2010a,b). Differing risk characteristics across the 16 agroecological zones (AEZs) in Africa and divergent farming activities given the AEZs are analyzed (FAO 2005). Adaptation strategies in the Sahel region, a high climate risk zone in Africa, are analyzed in detail (Hulme et al. 2001).

This paper proceeds as follows: In the next section, a theory on an individual farmer's adoption of agricultural systems faced with differing degrees of climate risks is described. Section 3 explains various datasets and their sources used for this study. The ensuing sections discuss empirical results and climate risk simulations for the future. The paper is concluded with a summary and discussion of policy implications.

2. Theory

Climate risks that affect agriculture occur in the form of both temperature and precipitation variability (Reilly et al. 1996; Zilberman 1998). For example, rainfall fluctuations are known to affect agricultural productions, especially in low-latitude African countries. A particularly high rainfall period, which can stretch several years, followed by a particularly low rainfall period can result in low crop yields (Kazianga and Udry 2006). Farmers employ various farm practices and tools to cope with natural risks, including climate risks (Udry 1995; Bardhan and Udry 1999).

Climate risks are not the same as weather risks on which past studies of African agriculture have concentrated (Udry 1995; Kazianga and Udry 2006). A village may suffer from occasional weather shocks such as droughts or floods, but it can still be a low climate risk zone if such occurrences are not frequent in the long term. A high climate risk zone is where such weather shocks are more frequent from a long-term perspective: for example, a 30-yr time period.

A long-term variability of rainfall can be captured by CVP measured from many decades of observations: that is, for the 30-yr period from 1961 to 1990, based on more than 26 000 weather station data around the world (New et al. 2002). The CVP is a measure of rainfall dispersion that does not depend on the unit of measurement and can be defined as follows with R_{kj} being monthly precipitation in month j and year k ($K = 30$) and $\overline{R}_j$ being 30-yr average rainfall for month j:

$$\mathrm{CVP}_j = \sigma_j / \overline{R}_j \quad \text{where} \quad \sigma_j = \sqrt{\sum_{k=1}^{K} (R_{kj} - \overline{R}_j)^2 / (K-1)}. \tag{1}$$

Another major concern is that climate change will lead to more frequent occurrences of extremely hot days and cold days and/or more variable temperature (Houghton et al. 2001; Tebaldi et al. 2007). This implies an increase in the range between maximum temperature and minimum temperature, altering growing periods for crops (Easterling et al. 2000; FAO 2005; Schlenker and Roberts 2009). The temperature range can be measured by the DTR.[1] Average monthly DTRs for the 30-yr period mentioned above have been measured by the CRU dataset (New et al. 2002). Let $T_{\max}$ be daily maximum temperature, $T_{\min}$ be daily minimum temperature, j be day, m be month, and k be year. Then, the DTR for month m is defined as follows:

$$\mathrm{DTR}_m = \frac{\sum_{k=1}^{K} \sum_{j=1}^{J} (T_{k,m,j,\max} - T_{k,m,j,\min})}{JK} \quad \text{where} \quad J = 30\,\text{days}, \quad K = 30\,\text{yr}. \tag{2}$$

Given climate uncertainties and soil conditions for the long term, a farmer decides whether to specialize in crops or livestock or to diversify into both crops and livestock (Seo 2010a,b). She or he would choose an agricultural system that earns a higher expected return than other systems. The farmer's decision is also affected by market and socioeconomic conditions such as access to a major city or a major port. Finally, family characteristics such as the number of family members, electricity provision, age, gender, and education level will play an important part.

More formally, a farmer's (n) decision is to choose an agricultural system (j) that yields the highest expected profit, which is defined as follows:

$$\mathbf{E}(\pi_{nj}) = f(\mathbf{E}_n, \mathbf{G}_n, \mathbf{W}_n, \mathbf{M}_n, \mathbf{H}_n) \quad \text{where} \quad \mathbf{E}_n = [\mathrm{CVP}_n, \mathrm{DTR}_n], \tag{3}$$

where **E** denotes climate risks, **G** soils and topography, **W** hydrology, **M** market and social conditions, and **H** household characteristics. In the above equation, CVP and DTR are the measures of climate variability. The term $\mathbf{G}_n$ is a vector of the percentages of dominant soil types in the district to which the farm n belongs provided by the Food and Agriculture Organization (FAO; FAO 2003). The term $\mathbf{W}_n$ is a vector of hydrological variables such as water flow and runoff (Strzepek and McCluskey 2006). The term $\mathbf{M}_n$ includes such variables as country dummies and market access such as travel times to a major port and a city provided by the World Bank spatial data team (World Bank 2009). The term $\mathbf{H}_n$ is directly collected from the reports by the farm households (Dinar et al. 2008).

Note that the expected profit captures the fluctuations of farm profits year by year. That is, it is the net present value of the stream of profits expected in the future on the farming land. This expectation is formed by decades of past experience of farming on the land given climate and geographical conditions. Therefore, the decision to adopt a system is not motivated by annual weather conditions but rather on the long-term climate of the region (Udry 1995; Kazianga and Udry 2006). The expected return will also include household consumption of produced goods and family labor hours used for agriculture as many farms in Africa consume their products and depend on family labors (Bardhan and Udry 1999).

To estimate the choice model of the agricultural systems, let the expected profit be expressed as the sum of the observable component and the unobservable component. If the observable component can be written linearly of the parameters and the error term is assumed, after spatial resampling, to follow an independent and identical Gumbel distribution, the probability to choose system j can be written simply as a logit after successive integrations of the density functions (McFadden 1974; Case 1992; Seo 2011),

$$P_{nj} = \frac{\exp(\mathbf{X}_n \beta_j)}{\sum_{j=1}^{J} \exp(\mathbf{X}_n \beta_j)} \quad \text{where} \quad \mathbf{X}_n = [\mathbf{E}_n, \mathbf{G}_n, \mathbf{W}_n, \mathbf{M}_n, \mathbf{H}_n] \tag{4}$$

A log-likelihood function can be formed from the probabilities as follows and the parameters are estimated using the maximum likelihood method,

$$\mathrm{LL} = \sum_{n=1}^{N} \sum_{j=1}^{J} D_{nj} \ln P_{nj}, \tag{5}$$

where D_{nj} is a dummy variable denoting that the farm n chose agricultural system j. This choice information is obtained from the household surveys (Dinar et al. 2008).

The impacts of increases in CVP and/or DTR can be measured by the difference in the estimated probabilities

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[1] An increase in DTR implies that the increase in maximum temperature is larger than the increase in minimum temperature if the latter also increases as some authors observed (Easterling et al. 2000).

before and after such changes. If the difference is negative (positive), it implies that the system will decline (expand) because of an increased climate risk. If the farmer decides to increase (or decrease) a certain system in response to increased climate risks, it can be viewed as behavioral adjustments of the farmer to cope with the risks. Uncertainties surrounding the estimates can be measured by confidence intervals constructed from a large number of bootstrap samples (Efron 1979; Andrews and Buchinsky 2000).

3. Description of data

The new data this paper introduces are climate risk indicators. We obtained the high-resolution climate data from the CRU average climatology, which provides the two climate risk measures for each gridded cell of the globe at the scale of 10 arcminutes (New et al. 2002). The dataset provides monthly CVP constructed from more than 26 000 weather station observations across the globe measured for the 30-yr period from 1961 to 1990.[2] It also provides monthly DTR estimates for the same time period. Using the ArcView program, climate risk indicators are matched with the household surveys using the cell that each household belongs to.

The CRU data are also matched, based on the survey locations, with the AEZ classification of Africa obtained from the FAO CD-ROM on global agroecological zones (FAO 2005). As shown in Fig. 1, Africa is classified into five agroecological zones and deserts based on the suitability of the land for agricultural production using the length of growing period. The five AEZs are semiarid, dry savannah, moist savannah, subhumid, and humid zones. The five AEZs are further divided by elevations into lowlands (<900 m), middle elevations, and high elevations (>1700 m). The high-elevation AEZs are only present in the vicinity of Mount Kilimanjaro. In Fig. 1, the lowland AEZs are drawn as a box while the mid-elevation AEZs are drawn as a box with a point in the center. For each of the 16 AEZs, we calculate the CVPs and DTRs. This information is then used to identify high climate risk zones (i.e., high CVP zones or high DTR zones), such as the Sahelian region, in which climate variability has been very high during the past century (Hulme et al. 2001).

Household surveys came from the Global Environmental Facility (GEF)/World Bank project on climate change and agricultural production in Africa (Dinar et al. 2008). The locations of household surveys are marked as solid dots in Fig. 1, which show the samples were drawn from all the 16 AEZs. The surveys were drawn from Burkina Faso, Niger, Senegal, and Ghana from western Africa; Cameroon from central Africa; Kenya and Ethiopia from eastern Africa; Zambia, Zimbabwe, and South Africa from southern Africa; and Egypt from northern Africa. The household surveys, conducted in the time period of 2002–04, collected details of crop cultivation activities and livestock management activities during the farming period from July 2002 to June 2003. Farmers were asked about whether they own livestock or not, and agricultural systems were defined based on the answers. Surveys were collected from the 11 countries, stated above, across Africa, from which we dropped the Zimbabwe data because of political turmoil at the time of surveys and the extremely poor data quality. Excluding Egypt, we concentrate on the nine sub-Saharan African countries for the analysis of climate risks.[3]

Spatial and market access data were obtained from the newly constructed World Bank spatial dataset, called the African Information and Country Diagnostics (AICD) (World Bank 2009). The travel times (in hours) from a district centroid to a nearest port and a nearest city were calculated by a spatial data analysis team at the World Bank.

Soil data came from the FAO digital soil map of the world CD-ROM (FAO 2003). The data report the distributions of 116 dominant soil types (and 26 greater soil groups) across the world at the gridcell resolution of ½° latitude and ½° longitude and also as a vector file. Elevation at the centroid of each district was obtained from the United States Geological Survey at the 30-arcsecond resolution (USGS 2004).

Hydrology data were obtained from the University of Colorado hydrology model. It measured seasonal water flows and runoffs for each district in cubic meters per second in Africa (Strzepek and McCluskey 2006).

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[2] The primary sources for the CRU data were national meteorological agencies and archive centers and the World Meteorological Organization (WMO) climatological normals (WMO 1996). The authors note that several countries in Africa (e.g., Zaire and Angola) provided few or no 1961–90 normals; in these cases data were extracted from several published sources. Although there are data density/quality issues in Africa, the data point maps presented in the CRU paper indicate that weather stations are located across all countries sampled in this paper and fairly dense.

[3] Although the overall qualities of the household data reported by the farmers can be questioned, we believe that the two primary household data we rely on are of high quality. Household characteristics such as age, education, and gender were by and large accurately reported because these questions were put up front in the questionnaire and are simple questions. The same is true of the agricultural systems. Farmers were asked to report yes/no on whether the farm owns livestock.

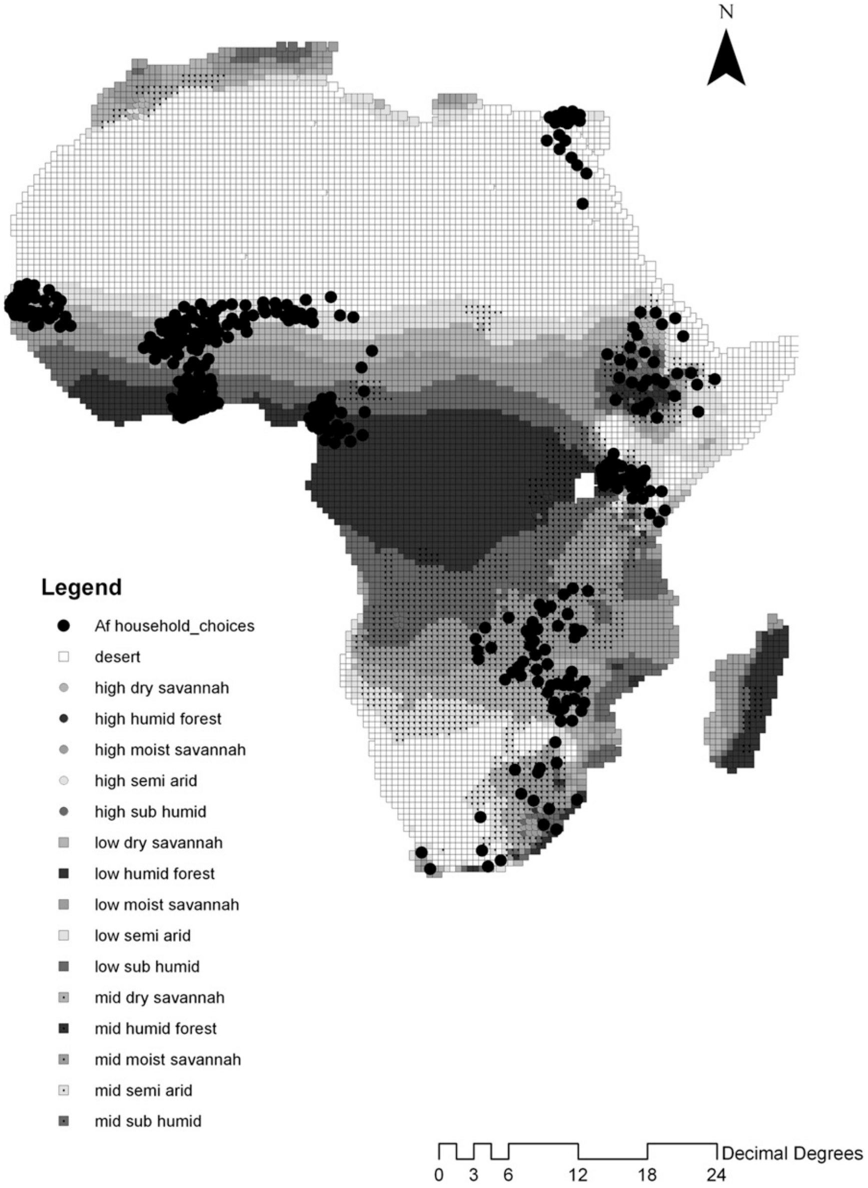

FIG. 1. Agroecological zones and the locations of household surveys. The AEZ data are extracted by the present author from the FAO (2005). The lowlands are marked by a box while mid-elevation AEZs are marked by a box with a point in the center. The high-elevation AEZs are only present in the vicinity of Mount Kilimanjaro.

4. Empirical results

Agricultural production in sub-Saharan Africa takes one of the following forms: a specialized crop system, a specialized livestock system, and an integrated system (Seo 2011). Major crops are known to be vulnerable to temperature increase, rainfall changes, and carbon dioxide increase (Reilly et al. 1996; Gitay et al. 2001; Tubiello and Ewert 2002). Livestock are vulnerable because of direct impacts of heat (Hahn 1999; Mader 2003) or indirect impacts through vegetation changes, livestock diseases, and livestock feed changes (Ford and Katondo 1977; Baker et al. 1993; Parsons et al. 2001; Sankaran et al. 2005; Fischlin et al. 2007; United States Animal Health Association 2008). About two-thirds of farmers in Africa own some livestock (Seo and Mendelsohn 2008). Most frequently raised livestock species are beef cattle (raised for meat), dairy cattle, sheep, goats, camel, and chickens, and livestock products such as beef, milk, cheese, eggs, and wool are important part of the

TABLE 1. Climate risks across agroecological zones.

AEZs	No. of observations	CVP (%) Mean	CVP (%) Std dev	DTR (°C) Mean	DTR (°C) Std dev
Desert	193	144.76	51.77	13.18	1.64
High-elevation dry savanna	75	97.59	14.98	14.00	0.49
High-elevation humid forest	224	69.13	14.07	13.78	0.87
High-elevation moist savannah	135	90.19	15.12	13.76	0.49
High-elevation semiarid	20	99.78	0.00	13.73	0.00
High-elevation subhumid	153	77.95	16.76	13.37	0.70
Lowland dry savannah	1395	198.36	34.54	12.73	1.05
Lowland humid forest	1061	71.33	12.49	8.59	1.19
Lowland moist savannah	826	148.11	34.00	11.80	1.03
Lowland semiarid	1272	226.25	21.69	13.03	0.91
Lowland subhumid	299	84.27	13.96	10.24	1.17
Mid-elevation dry savannah	195	145.77	41.78	14.54	1.13
Mid-elevation humid forest	291	68.55	13.27	12.37	2.36
Mid-elevation moist savannah	1086	185.49	41.28	13.43	1.04
Mid-elevation semiarid	27	156.55	33.06	12.47	0.59
Mid-elevation subhumid	381	89.95	29.71	12.87	1.28

livelihood in Africa (Nin et al. 2007; Seo and Mendelsohn 2008). The value of livestock holdings may account for half of agricultural values in sub-Saharan African farms but vary seasonally and by subregions (Udry 1995; Seo 2010a). In the United States, livestock accounts for 52% of the sale value of agricultural products in 2007 (USDA 2007).

Two indicators of climate risks across the 16 AEZs are summarized in Table 1 by agroecological zone. It shows the means and standard deviations of CVP and DTR. The table reveals that climate risks are indeed higher in the Sahel. That is, the CVP is the largest in the lowland dry savannah and lowland semiarid zones. The lowest CVP zones are humid forests and subhumid zones, regardless of elevation. The variation in CVP across Africa is very large, ranging from 69% to 226%. The DTR, on the other hand, is higher in high elevations. Also, the DTR is higher in dry zones than in wet zones. The DTR ranges from 8.6° to 14.5°C. These summary statistics are consistent with the African climate modeling, which showed that the Sahelian climate has a high yearly and decadal variability (Hulme et al. 2001; Shanahan et al. 2009).

The means and standard deviations of the climate risk indicators across agricultural systems are summarized in Table 2. The DTR is higher in livestock systems, especially in the specialized livestock. The CVP is larger in the mixed system than the specialized systems by 16%. The results in Tables 1 and 2 signal that livestock and integrated systems may be more resilient to climate risks, even though crop systems are highly vulnerable to increased risks.

A flow diagram of the factors that affect farmers' choices of agricultural systems is drawn in Fig. 2. A farmer is located at the center circle and makes adaptation decisions. There are six outer circles that affect the decisions: climate risks, soils and topography, hydrology, market access, country-specific factors, and household characteristics. The AEZs are defined by the first three factors. As climate change scenarios are realized, the farmer's decisions are adjusted to adapt.

The descriptive statistics in Tables 1 and 2 give the initial evidence that agricultural systems are chosen by the farmers after carefully considering climate risks. To explain the observed choices by climate risk factors, both a standard multinomial logit and a spatial logit model [defined in Eqs. (4) and (5) in section 2] of the three agricultural systems are run in Table 3. A standard multinomial logit model is shown on the left columns of the table. Explanatory variables are climate risks, soils, hydrology, market access, household characteristics, and country dummies. Against the base case of the

TABLE 2. Climate risks across agricultural systems.

Variables	Crops only Mean	Crops only Std dev	Integrated Mean	Integrated Std dev	Livestock only Mean	Livestock only Std dev
CVP (%)	141.78	68.94	158.06	63.81	142.94	51.41
DTR (degrees)	11.87	2.23	12.43	1.81	12.73	1.87
No. of farms	2880		4309		444	

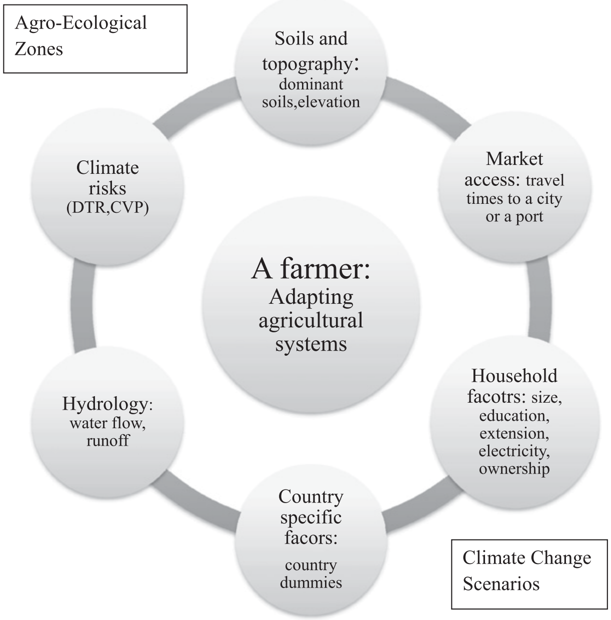

FIG. 2. A flow diagram of the factors that affect farmer choices.

specialized livestock system, the parameter estimates for the crops-only system and for the integrated system are shown. To account for nonlinearities, the DTR and CVP are entered as quadratic forms. The model is highly significant according to the likelihood ratio statistic.

Among the climate risk indicators, parameter estimates of the DTRs and CVPs are weakly significant according to the P values. In both types of farms, the parameter estimates for the linear terms of CVP are negative and those for the quadratic terms are positive while the parameter estimates for the linear terms of the DTR are positive and those for the quadratic terms are negative. When spatial logit model is used, the signs are reversed, implying that the impacts of climate risk indicators on the choices are rather linear.

Among the control variables, water flows, runoffs, and geography are significant. A higher runoff increases the odds of a farm to have some crops. A higher level of soils ferralsols, luvisols, or vertisols decreases the odds of a crops-only system, but they are not significant. These soils are not ideal for crop growth because of wet tropical, arid, or rocky conditions (Driessen et al. 2001). At higher altitudes, farmers are less likely to choose a crops-only or an integrated system.

Many market and household variables are significant. When travel time increases from a port, a crops-only system is less frequently chosen. When extension visits are more frequent, it is likely to be farms that have some crops. When the household has more members, it is less likely to be crop farms. Years of schooling, age, electricity, and property ownership are not significant. Against the base case of South Africa, a farmer in Burkina Faso and Senegal is less likely to choose a crops-only system, but a farmer in Zambia is more likely to adopt a crops-only system and a farmer in Ethiopia is more likely to adopt an integrated system.

A spatial logit model is shown on the right columns in Table 4 based on 250 bootstrap runs of spatially resampled data as explained in section 2. The spatial resampling is done at the district level from 352 districts (second administrative division). The bootstrap means are shown in the table. The spatial logit model shows that all the significant variables in the multinomial logit model preserve the same signs with an exception of water flow.

The marginal impacts from climatic shifts are calculated in Table 4 from both logit models. When the diurnal temperature range increases by 1°C, it increases a crops-only system by 0.31% and a livestock-only system slightly, which is offset by the decrease in the mixed system by 0.32%. However, when spatial logit is used, there is a large increase in the livestock-only system to offset the decreases in a crops-only system and an integrated farm.

When the CVP increases by 1%, integrated farming increases by 0.23% at the expense of specialized systems in either crops (by 0.15%) or livestock (0.08%). Under the spatial logit model, the increase in the mixed system is even larger (+0.30%).

This finding tells that a farmer diversifies its portfolio under increased climate risk. That is, if rainfall pattern is more difficult to predict in the region, a farmer diversifies into both crops and livestock to offset the loss of crops in severe drought years and the loss of livestock in heavy rainfall years. Therefore, a crops–livestock diversification can be seen as a risk coping strategy by the farmers.

Based on the parameter estimates of the spatial logit model in Table 3, estimated adoption probabilities are drawn across the entire ranges of DTR and CVP in Figs. 3 and 4 . The box plots in Fig. 3 show means, medians, 95% confidence intervals, and extremes across the DTR. The figure demonstrates a clear pattern. As the DTR increases, a crops-only system falls steadily while an integrated system increases gradually until it is as large as 11°C, after which it has little impacts. The livestock-only system is chosen by a smaller number of farms and the adoption probability shows fluctuations across the DTR with slightly higher probabilities in the high DTR zones.

Across the range of the CVP, as shown in Fig. 4, a similarly clear pattern is evident. Again, an integrated farming increases steadily across the horizontal axis as the CVP increases until it becomes as large as 200%.

TABLE 3. Logit choice models of agricultural systems.

	Multinomial logit				Spatial logit	
	Crops only		Integrated			
	Estimate	*P* value	Estimate	*P* value	Crops only Bootstrap means	Integrated Bootstrap means
Intercept	−1.935	0.541	−1.839	0.560	185.918	185.70
DTR	0.997	0.058	0.8808	0.092	−29.7451	−29.85
DTR^2	−0.0382	0.069	−0.0342	0.101	1.157	1.161
CVP	−0.0089	0.501	−0.0110	0.405	0.820	0.814
CVP^2	0.000 071	0.097	0.000 009 1	0.031	−0.0017	−0.0017
Water flow	−0.1761	0.009	−0.119	0.073	2.367	2.438
Runoff	0.0179	0.010	0.0168	0.014	0.188	0.184
Soil ferralsols	−1.230	0.270	−0.213	0.847	−31.14	−29.52
Soil luvisols	−0.161	0.531	0.0327	0.893	4.969	5.277
Soil vertisols	−0.196	0.792	0.293	0.677	53.340	54.265
Elevation	−0.0014	<0.0001	−0.001 09	<0.0001	−0.0235	−0.0231
Travel time city	−0.0462	0.255	−0.0081	0.839	−0.524	−0.462
Travel time port	−0.0676	0.035	−0.0519	0.099	−0.761	−0.755
Household size	−0.0766	<0.0001	−0.0303	0.019	−0.060	−0.025
Extension visits	0.0295	0.009	0.0292	0.009	1.144	1.145
Years schooling	0.0173	0.396	0.0213	0.290	−0.320	−0.321
Age	0.009 41	0.111	0.0098	0.088	−0.015	−0.0131
Electricity	0.0685	0.797	−0.239	0.367	5.922	5.6082
Private ownership	−0.179	0.362	−0.264	0.164	−8.712	−8.873
Burkina Faso	−3.002	<0.0001	−1.934	0.001	−52.942	−51.281
Niger	0.216	0.792	−0.698	0.388	−2.107	−2.742
Cameroon	0.905	0.217	0.552	0.449	17.107	17.348
Senegal	−3.2002	<0.0001	−2.705	<0.0001	−57.335	−56.59
Ghana	0.399	0.505	0.575	0.334	6.389	6.970
Kenya	1.024	0.086	0.883	0.135	33.331	33.497
Ethiopia	1.687	0.020	1.7909	0.013	54.82	55.298
Zambia	2.816	0.008	1.939	0.066	49.018	48.186
	$N = 7633$; likelihood ratio = 5486.13 ($P < 0.0001$)				$N = 352$; $B = 250$.	

The crops-only system, on the other hand, falls gradually as the CVP becomes ever higher up to around 200%. The adoption probability of the livestock-only system shows a hill shape function in which the peak is located at around 160%.

5. Future climate risks in the Sahelian region

Climate scientists report that the world's climate will be significantly altered by the latter half of this century (Solomon et al. 2007). The Intergovernmental Panel on Climate Change (IPCC) reports as well as several scientists also noted that extreme climate events as well as climate variability will likely increase (Easterling et al. 2000; Tebaldi et al. 2007; Hansen et al. 2012). This section simulates the impacts of increases in climate risks on farmer behaviors based on the estimated parameters in Table 3. We assume that the DTR would increase by 3°C and the CVP would increase by 30% at the end of this century to approximately match the average climate

TABLE 4. The impacts of marginal changes in climate risks.

Agricultural systems	Scenarios	Means	Lower 95% CL	Upper 95% CL	Bootstrap means from spatial logit
Crops only	Current	38.82%			38.87%
	Δ DTR	0.31%	0.30%	0.32%	−0.67%
	Δ CVP	−0.15%	−0.15%	−0.14%	−0.15%
Integrated	Current	57.89%			57.35%
	Δ DTR	−0.32%	−0.32%	−0.31%	−0.51%
	Δ CVP	0.23%	0.23%	0.23%	0.30%
Livestock only	Current	3.29%			3.78%
	Δ DTR	0.005%	−0.004%	0.014%	1.18%
	Δ CVP	−0.08%	−0.09%	−0.08%	−0.16%

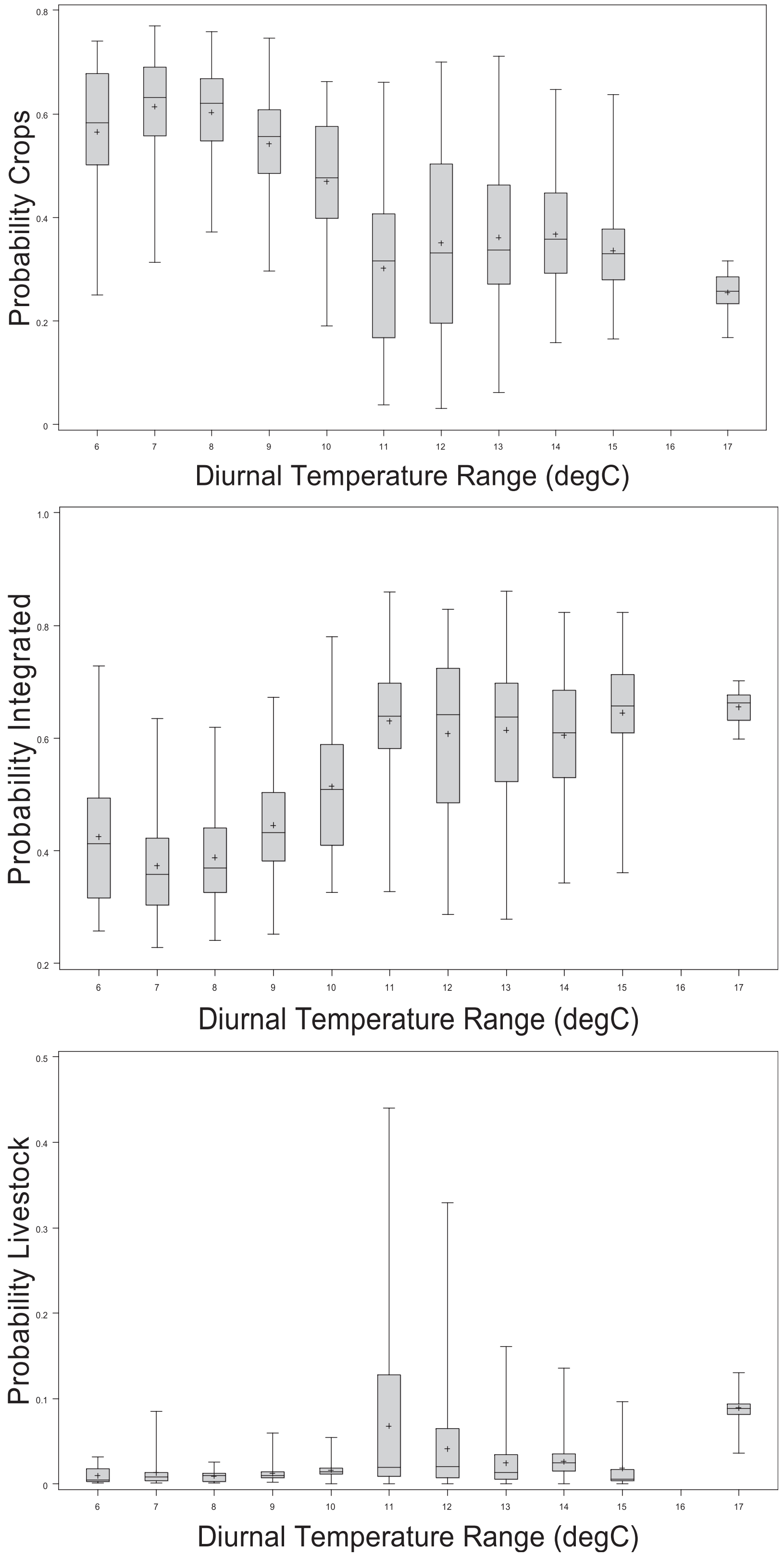

FIG. 3. Adoption probabilities across diurnal temperature range: (top) crops, (middle) integrated, and (bottom) livestock.

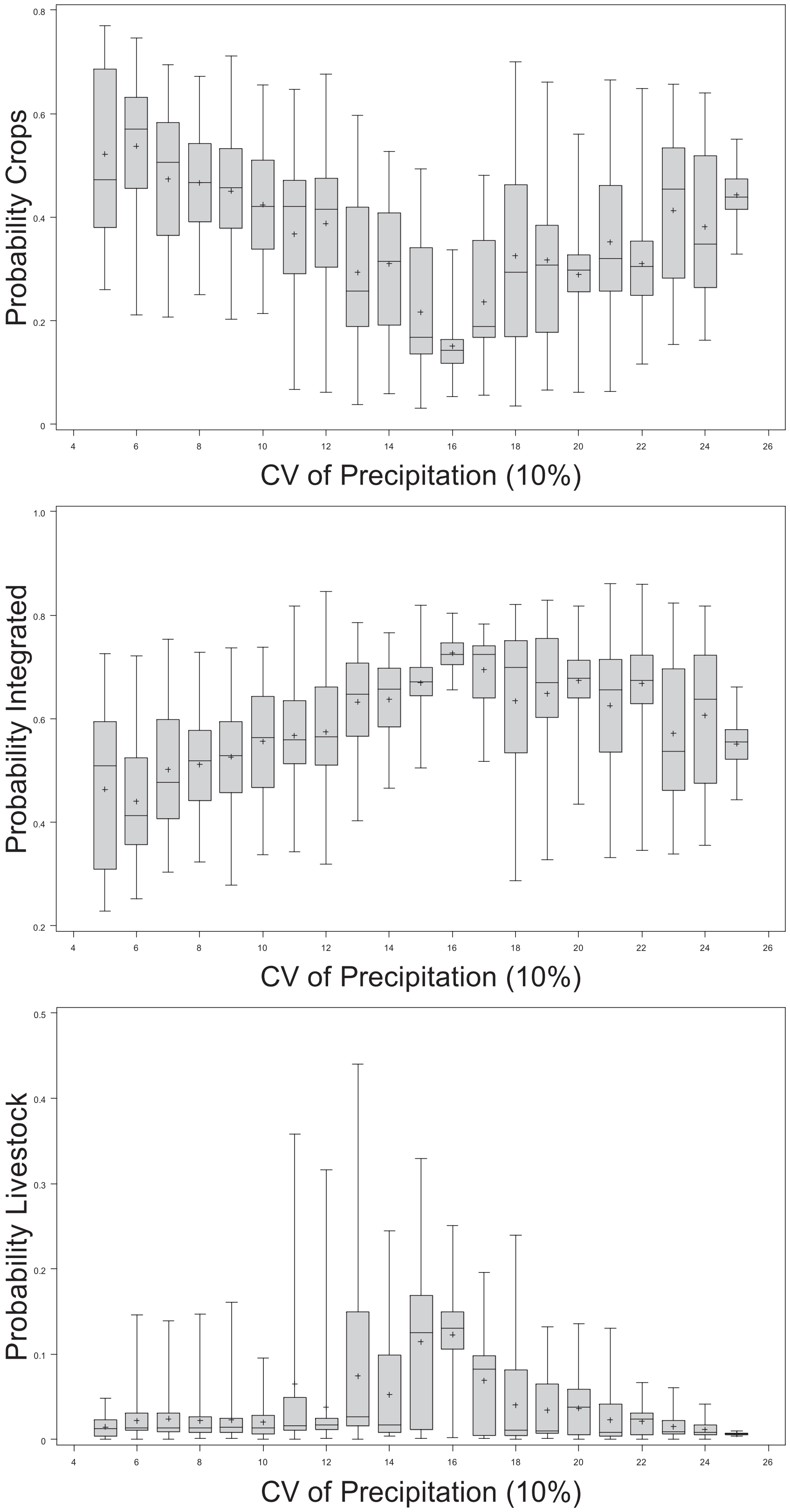

FIG. 4. Adoption probabilities across CV in precipitation: (top) crops, (middle) integrated, and (bottom) livestock.

TABLE 5. The long-term impacts of increased climate risks on agricultural systems.

Agricultural systems	Scenarios	Means	95% lower CL	95% upper CL	Bootstrap means from spatial logit
Crops only	DTR (+3°C) and CVP (+30%)	−4.92%	−5.04%	−4.79%	−7.02%
	DTR (+3°C)	0.19%	0.15%	0.22%	−2.74%
	CVP (+30%)	−5.26%	−5.37%	−5.14%	−5.39%
Integrated	DTR (+3°C) and CVP (+30%)	6.33%	6.19%	6.47%	2.86%
	DTR (+3°C)	−1.00%	−1.03%	−0.98%	−2.70%
	CVP (+30%)	7.00%	6.88%	7.13%	2.73%
Livestock only	DTR (+3°C) and CVP (+30%)	−1.41%	−1.48%	−1.35%	4.16%
	DTR (+3°C)	0.81%	0.78%	0.85%	5.43%
	CVP (+30%)	−1.74%	−1.81%	−1.68%	2.66%

change predictions of the IPCC: that is, around a 3°C increase in average temperature. The following three risk scenarios are examined: a DTR increase by 3°C, a CVP increase by 30%, and simultaneous changes in both indicators.

The simulations single out the sole impact of climate risks by keeping other factors such as technology and population fixed. Therefore, the purpose of this simulation is not to predict the future but to learn from the present farming activities how climate risks would affect farming decisions in the future.

In Table 5, simulation results are presented. When the CVP increases by 30%, integrated farming would increase by 7.0% while a specialized crop farm would decline by 5.3% and a specialized livestock farm would decline by 1.7%. When rainfall variability is increased, so that there are more frequent drought years and heavy rainfall years, farmers adapt by having both crops and livestock. That is, they diversify their portfolios to reduce the loss from precipitation risks in a similar way as a financial investor diversifies her/his portfolio into assets that have negative correlations to an economic shock (Markowitz 1952; Tobin 1958). When the spatial logit model is used, a livestock-only system is also expected to increase.

The responses to the increase in DTR by 3°C are only minor. Farmers switch away from the integrated system (−1.0%) to a livestock-only system (+0.8%) and a crops-only system (+0.2). When the spatial logit model is used, however, expected impacts are more pronounced. A livestock-only system increases as large as 5.4% by decreasing a crops-only system and an integrated system by 2.7% each.

Finally, we are in a position to unravel how the farmers in the Sahelian region, which has the highest climate risks, will adapt to future increases in the CVP and DTR. As shown in Table 1, the CVP is particularly large in the lowland arid zones and in the Sahel. Climate reports warn that further increases in temperature and/or precipitation variability will have harmful consequences on these regions (Houghton et al. 2001; Solomon et al. 2007). In Fig. 5, we draw adoption probabilities of the three agricultural systems across the 16 agroecological zones using the spatial logit model. The figure shows that the distributions of agricultural systems vary across the AEZs. An integrated system is favored in the lowland savannahs and semiarid zones. It is also adopted most often in mid-elevation savannah zones and in the highlands. A crops-only system, on the other hand, is most frequently chosen in the humid forests and subhumid zones in the lowlands.

Assuming simultaneously an increase of the DTR by 3°C and an increase in the CVP by 30%, changes in adoption probabilities are drawn across the AEZs in Fig. 6. Conspicuously, lowland dry savannah zones and semiarid zones switch in droves to an integrated system (i.e., by almost 14%). The increase of an integrated system is also large in the lowland moist savannah zones. In these zones, there can be seen large decreases in the crops-only system. A large number of farms also switch to an integrated system in the mid-elevation moist savannah, dry savannah, and semiarid zones. There is also a large increase of an integrated system in the desert zones. Farmers in high elevations switch to both an integrated system and a livestock-only system, but the expected changes are much smaller. The crops-only system falls across all the agroecological zones in Africa with a few exceptions, indicating a high vulnerability of this system, as shown by previous studies (Reilly et al. 1996; Schlenker and Roberts 2009).

6. Conclusions

This paper provides an analysis of climate risks and adaptation strategies using the observed adoptions of agricultural systems across the varied zones of climate risks based on the detailed household surveys collected from sub-Saharan African farms. This paper finds that the diurnal temperature range (DTR) is higher in livestock systems, especially in the specialized livestock

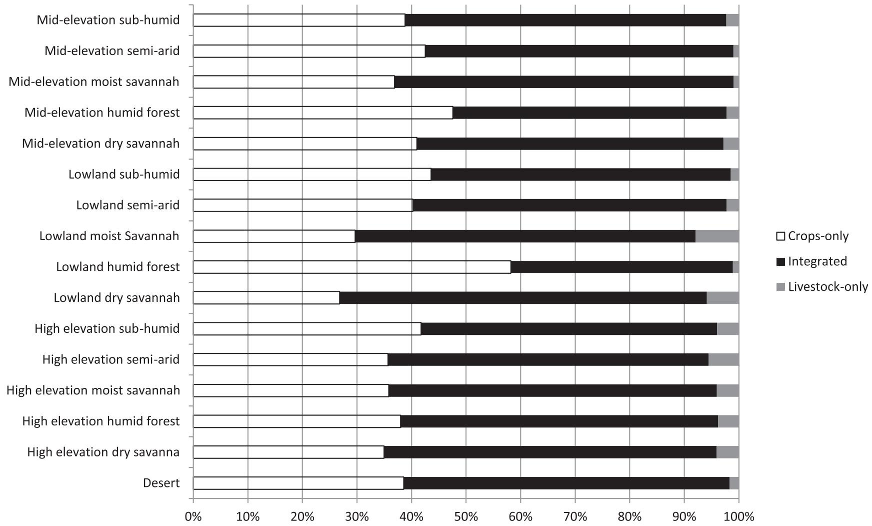

FIG. 5. Adoption probabilities across agroecological zones.

system, while the coefficient of variation in precipitation (CVP) is higher in the mixed system. If the CVP increases by 30%, farmers adapt by switching away from a crops-only system (−5.3%) and a livestock-only system (−1.7%) to an integrated system (+7.0%). When the DTR increases by 3°C, farmers adapt by switching to a livestock-only system. We find that there will be large increases in the integrated farming in the lowland savannas and arid zones of sub-Saharan Africa when climate risks further increase in the future.

In summary, this paper finds that sub-Saharan farmers do manage climate risks by selecting agricultural systems carefully. In comparison with the earlier studies on selected villages in a chosen African country (Udry 1995; Kazianga and Udry 2006), this paper reveals much stronger risk management behaviors by individual farmers to cope with variabilities in climate. Although farmers do not increase or decrease an integrated farming in response to an individual year weather shock, these systems are carefully adopted in consideration of the long-term variability in the climate of the corresponding region. Farmers cannot switch from a specialized crop system to a specialized livestock system year by year to cope with weather fluctuations. Therefore, they often rely on storage of crops to cope with a yearly weather fluctuation (Wright 2011). This behavior is augmented by the fact that banking and insurance are not as well developed across African villages as they are

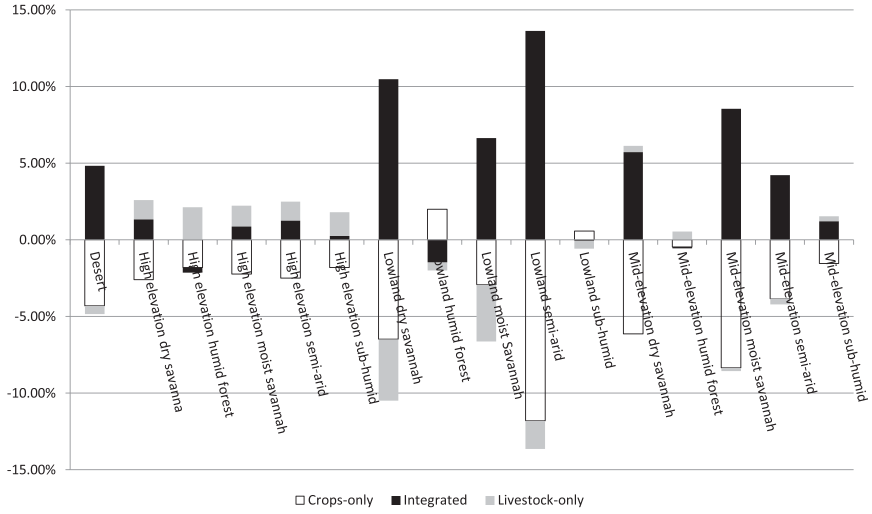

FIG. 6. Long-term impacts of increased DTR (+3°C) and CV (+30%) across agroecological zones.

in modern cities around the world (Shiller 2003). If the region is more variable in climate for the long term, farmers adapt by switching their farming systems.

This finding negates, albeit partially, the recent study that agriculture will be severely harmed because of the impacts of increased climate risks on selected crops (Easterling et al. 2000; Solomon et al. 2007; Schlenker and Roberts 2009). As in other economic behaviors, farmers do manage risks arising from climate risks by diversifying their farm portfolios (Markowitz 1952; Tobin 1958; Zilberman 1998). Farmers are expected to adjust farming activities when growing periods are altered and precipitation variability is changed. A focus on selected crops essentially removes the possibility of adapting to a more resilient agricultural system. The damage due to climate risks will be substantially reduced when such behaviors are well accounted for (Seo 2010a,b).

The results can also be viewed from the standpoint of the climate literature. Previous studies found that African farmers adopt an integrated system more frequently when temperature becomes hotter and drier (Seo 2011). From a climate science perspective, global warming is associated with other changes in climate such as increased precipitation fluctuations and increased extreme temperature events. In the sample used for this study, mean temperature and the CVP has a correlation coefficient close to 0.90. This means temperature increase (i.e., global warming) serves as a sufficient indicator for global warming studies in Africa. Global warming (temperature increase) leads to increased climate risks, which both lead to more frequent adoptions of an integrated system by the farmers.

Several qualifications should be made to the findings in the paper. First of all, the results in this paper may not be applicable if global temperature passes a threshold, if there were to be such a threshold, and becomes much more unpredictable than this paper simulates (Weitzman 2009; Schlenker and Roberts 2009). The same is true if future changes are so large that irreversible capital investments to ward off heat and extremes are required (Hanemann 2000). Second, this analysis is concerned with long-run equilibriums in climate and farming activities. Therefore, what happens in the transition period and cost is not explained by this paper (Kelly et al. 2005). However, adoption of an integrated system is closely related with the transition. That is, this system is likely preferred by the farmers partly because of the high cost of transition from one specialized system to another. To put it differently, the integrated system has a higher option value than the other systems. Third, in the future, more heat-tolerant or moisture-resistant crop varieties may become available, comparable to those from the Green Revolution, and technological advances may make it possible to produce heat-tolerant animal breeds and crop varieties (Evenson and Gollin 2003; Hoffmann 2010). Also, agriculture in Africa may shrink or expand as the sub-Saharan economy develops (Nin et al. 2007). In simulating the impacts in the future, this analysis kept these factors fixed and calculated the changes that arise from climate alterations only. Fourth, increases in climatic variabilities may occur simultaneously with an increase in carbon dioxide concentration in the atmosphere. If the carbon dioxide increase benefits one system more than the other, it can affect adaptation behaviors described in this paper (Ainsworth and Long 2005). Finally, there always remain the issues with regard to the data qualities of the African household surveys (reported directly by farmers) and the spatial resolutions of climate, soils, and geography data. However, the present author believes that these issues are rather marginal in a large-scale study at the continental level, which aims to examine the shifts of choices across the whole African continent, where variations in climate and farm behaviors are very large. Further, climate science and data quality and resolution are improving.

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