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A Ricardian Analysis of the Distribution of Climate Change Impacts on Agriculture across Agro-Ecological Zones in Africa

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Abstract This paper examines the distribution of climate change impacts across the sixteen Agro-Ecological Zones (AEZs) of Africa. We combine net revenue from livestock and

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crops and regress total net revenue on a set of climate, soil, and socio-economic variables with and without country fixed effects. Although African crop net revenue is very sensitive to climate change, combined livestock and crop net revenue is more climate resilient. With the hot and dry CCC climate scenario, average damage estimates reach 27% by 2100, but with the mild and wet PCM scenario, African farmers will benefit. The analysis of AEZs implies that the effects of climate change will be quite different across Africa. For example, currently productive areas such as dry/moist savannah are more vulnerable to climate change while currently less productive agricultural zones such as humid forest or sub-humid AEZs become more productive in the future.

Keywords Climate change · Economic impacts · Agriculture · Africa · AEZ

1 Introduction

The most recent report of the Intergovernmental Panel on Climate Change provides strong evidence of a warming world (Intergovernmental Panel on Climate Change (IPCC) 2007a). Although there are many calls for international action, reducing greenhouse gases is costly. The international community needs to carefully weigh the costs and benefits of any program of action (Nordhaus 2007). One of the major concerns about climate change is food security, especially for people living in the low latitudes.

Previous global climate studies have predicted that climate change would have serious impacts on agriculture in developing countries (Pearce et al. 1996; Tol 2002; Mendelsohn et al. 2006). Early empirical studies using crop simulation models suggested that agriculture in developing countries was highly vulnerable to warming (Rosenzweig and Parry 1994; Reilly et al. 1996). Subsequent economic research using Ricardian models (Mendelsohn et al. 1994) also suggests that developing country crops are vulnerable (Kurukulasuriya et al. 2006; Seo and Mendelsohn 2008a).

These earlier studies provide useful measures of the impacts at a continental or national scale. However, there remains a question of how best to measure the impacts across the landscape. This study takes advantage of Agro-Ecological Zones (AEZs) to predict how impacts will be dispersed across the African landscape. The differential effects of climate change on farms in various agro-ecological zones have not yet been quantified. Specifically, we examine how climate change might affect farm net revenue in different AEZs. Not only does this research provide insights into how climate affects farmers facing different conditions, but it will also help extrapolate climate change results from the existing sample to the continent from which they are drawn.

This study combines the AEZs data with the farm economic data from a recently completed GEF/World Bank study of African agriculture (Dinar et al. 2008). The AEZs data are compiled by the Food and Agriculture Organization of the United Nations using information about climate, altitude, and soils (FAO 1978). The GEF/World Bank study measured crop choice, livestock choice, yields, gross revenues, and net revenues of thousands of farmers (households) in 11 African countries (Dinar et al. 2008). Both the countries and the farm households were sampled across the various climates of Africa.

In addition to studying AEZs, this study makes another important contribution. Past studies have focused on crops alone. The crop studies generally have concluded that the net revenue from African crops will likely fall with warming (IPCC 2007b; Kurukulasuriya et al. 2006; Kurukulasuriya and Mendelsohn 2008). However, the net revenue from African livestock, in many circumstances, was predicted to increase (Seo and Mendelsohn 2008b,c).

This paper combines crop and livestock net revenue into total farm net revenue. The analysis simultaneously considers impacts on both crop and livestock.

In the next section, we briefly discuss the basic underlying theory of a Ricardian analysis. The third section describes the data. Empirical results are shown in the fourth section. We then use the estimated Ricardian model coefficients to predict climate change impacts by 2100 for two different climate scenarios. The paper concludes with a discussion of the results and policy implications.

2 Theory

Farmers in different AEZs employ different farm practices. Depending on the AEZ they are situated in, they will choose a specific farm type, irrigation, crop species, and livestock species that fit that AEZ. As some AEZs are better suited for agriculture while others are not, the average net revenues from these AEZs will differ.

In the Ricardian technique (Mendelsohn et al. 1994), adaptations are implicit and endogenous. The Ricardian technique assumes that each farmer maximizes net revenue subject to the exogenous conditions of the farm, which include climate. Net revenue is defined broadly to include own consumption as well as sold or traded products. The technique assumes each farmer chooses a mix of agricultural activities and inputs that provide the highest net revenue. The resulting net revenue across all farmers is therefore a function of just the exogenous variables:

$$\pi = f(P, C, W, S, H), \tag{1}$$

where π is net revenue per hectare, P is a vector of input and output prices, C is a vector of climate variables and their squared terms, W is available water for irrigation, S is a vector of soil characteristics, and H is a vector of household characteristics. The Ricardian model estimates Eq. 1 econometrically by specifying a quadratic function of climate variables along with other control variables. By grouping the various variables, the reduced form equation for net revenue becomes

$$\pi = C\beta + S\gamma + W\varphi + H\lambda + P\alpha + u \tag{2}$$

where u is an error term which is identically and independently Normal distributed. The remaining symbols are coefficients to be estimated. Because this analysis is applied across multiple countries, it is quite possible that there are variables at the national level such as agricultural policies, trade policies, property rights, and interest rates that are not taken into account in the analysis. We consequently also explore a country fixed effects model that controls for these missing variables with country dummies.

$$\pi = C\beta + S\gamma + W\varphi + H\lambda + P\alpha + L\eta + u \tag{3}$$

where L is a set of country dummies.

We expect that the net revenue of farming varies by AEZs. Certainly, desert areas are less suitable for farming except near oases. Lowland semi-arid areas may also not be a good place for crops (Kurukulasuriya et al. 2006). High land moist forests may not serve as a good place for animal husbandry (Seo and Mendelsohn 2008b). These underlying productivity differences will lead to varying profits across climate, soil, and altitude and thus across AEZs. For example, we anticipate that the marginal climate effects for temperature and precipitation will vary by AEZ. The marginal net revenue effect of an increase in temperature (T) in AEZ

i is calculated:

$$\left[\frac{\mathrm{d}\pi}{\mathrm{d}T}\right]_{\mathrm{AEZ}\,i} = \frac{\mathrm{d}\pi}{\mathrm{d}T}(T = \bar{T}_{\mathrm{AEZ}\,i}) = b_T + 2 \cdot b_{T^2} \cdot \bar{T}_{\mathrm{AEZ}\,i} \tag{4}$$

where b_T, b_{T^2} are parameter estimates of the linear and the quadratic term of T. Note that the parameters are not a function of each AEZ. Climate change has a different effect on each AEZ because the marginal impacts depend on the climate of the AEZ.

In order to measure the welfare value (ΔW) of a change from one climate (C_{A}) to another climate (C_{B}), we subtract the net revenue before the change from the net revenue after the change for each farm household. The welfare change is the difference between the two climates. If the value is negative (positive), profits declined (increased), then the climate change has caused damage (benefit):

$$\Delta W = \pi(C_{\mathrm{B}}) - \pi(C_{\mathrm{A}}) \tag{5}$$

Because the Ricardian function is estimated across space at one moment of time, the level of prices as a function of aggregate output is constant. The model cannot capture how prices would change if global quantities of output changed. With international trade, this bias is not expected to be large (Mendelsohn and Nordhaus 1996). However, if price changes were to occur, they would offset changes in quantity, leading to a smaller change in net revenues. The omission of prices in the Ricardian method may lead the method to overestimate the actual damages. Note also that the welfare measure being considered above is a comparative equilibrium analysis. The Ricardian method is not intended to be a dynamic measurement of transition costs.

3 Description of Data

The FAO has developed a typology of AEZs as a mechanism to classify the growing potential of land (FAO 1978). The AEZs are defined using the length of the growing season. The growing season, in turn, is defined as the period where precipitation and stored soil moisture is greater than half of the evapotranspiration. The longer the growing season, the more crops can be planted (or in multiple seasons) and the higher are the yields (Fischer and van Velthuizen 1996; Voortman et al. 1999). FAO has classified land throughout Africa using this AEZ concept. Our study will use these FAO defined AEZ classifications.

The economic data for this study was collected by national teams (Dinar et al. 2008). The data was collected for each plot within a household and household level data was constructed from the plot level data. In each country, districts were chosen to get a wide representation of farms across climate conditions in that country. The districts were not representative of the distribution of farms in each country as there are more farms in more productive locations. In each chosen district, a survey was conducted of randomly selected farms. The sampling was clustered in villages to reduce sampling cost. A total of 9,597 surveys were administered across the 11 countries in the study. However, the data from Zimbabwe had to be dropped because of difficulties to accurately conduct the sampling and interviewing due to political turmoil during the data collection period. Further cleaning brought the number of observations down to 8,509. The number of surveys varied from country to country.

We rely on satellites for temperature data and ground stations for precipitation (Mendelsohn et al. 2007). The temperature data come from polar orbiting satellites operated by the US Department of Defense (Basist et al. 1998). The precipitation data come from the Africa Rainfall and Temperature Evaluation System (ARTES) (World Bank 2003). This dataset, created by the National Oceanic and Atmospheric Association's Climate Prediction Center, has interpolated precipitation between ground stations.

We explore alternative measures of seasonal climate including a two season and a four season model. However, the two season model provides more reliable estimates (the four season model is presented in the Appendix). The two seasons include winter and summer. In the southern hemisphere, summer is defined as the average of November–January and winter is the average of May–July. These seasonal definitions provide the best fit. The seasons in the northern hemisphere were adjusted to the opposite months of the year.

Soil data was obtained from FAO (2003). The FAO data provides information about the major and minor soils in each location as well as slope and texture. Data concerning the hydrology was obtained from the results of an analysis of climate change impacts on African hydrology (Strzepek and McCluskey 2006). Using a hydrological model for Africa, the authors calculated flow for each district in the surveyed countries. Data on elevation at the centroid of each district was obtained from the United States Geological Survey (USGS 2004). The USGS data is derived from a global digital elevation model with a horizontal grid spacing of 30 arc seconds (approximately one kilometer).

4 Empirical Results

FAO has identified sixteen AEZs in Africa. Table 1 shows the classification of AEZs and several descriptive statistics. The AEZs are classified by high, mid, and low elevation. Within each elevation, they are further broken down into five categories by the length of growing period: dry savannah, humid forest, moist savannah, semi-arid, and sub-humid. The other

Table 1 Average values by AEZ

AEZ	Description of AEZ	Observations	Annual mean net revenue (USD/ha)	Std. Dev. net revenue	Annual mean temperature (°C)	Annual mean precipitation (mm/mo)
1	Desert	879	2,211	4,277	18.8	11.7
2	High elevation dry savanna	115	392	749	20.4	61.0
3	High elevation humid forest	928	442	661	18.0	91.6
4	High elevation moist savannah	353	8,247	128,987	18.7	74.2
5	High elevation semi-arid	70	542	947	20.0	48.5
6	High elevation sub-humid	781	3,753	86,680	18.0	85.5
7	Lowland dry savannah	2,745	1,427	46,525	25.9	48.5
8	Lowland humid forest	1,215	794	919	20.4	113.3
9	Lowland moist savannah	2,085	1,766	53,210	24.1	68.6
10	Lowland semi-arid	674	635	2,735	26.7	34.2
11	Lowland sub-humid	1,273	773	5,668	22.3	89.9
12	Mid-elevation dry savannah	874	4,030	82,910	20.4	63.9
13	Mid-elevation humid forest	971	741	1,479	18.2	117.0
14	Mid-elevation moist savannah	1,958	2,312	55,620	19.7	73.6
15	Mid-elevation semi-arid	107	1,612	9,075	20.3	50.2
16	Mid-elevation sub-humid	1,016	3,910	76,580	19.0	94.4

remaining zone is desert. Farmers earn higher profits in high elevation moist savannah and sub humid zones and mid elevation dry savannah and sub humid zones. Farmers earn lower profits in high elevation dry savannah, humid forest, and semi arid zones, the lowland semi-arid zone, and in the desert zone.

Figure 1 shows the distribution of the sixteen agro-ecological zones across the continent. The Sahara desert occupies a vast land area in the north. There are also desert zones in the eastern edge and southern edge of the continent. Just beneath the Sahara in West Africa is a lowland semi-arid zone, followed by a lowland dry savannah, a lowland moist savannah, and a lowland sub-humid zone. The lowland humid forest then stretches from Cameroon across Central Africa. Eastern Africa is composed of some desert, lowland dry savannah, and some high elevation humid forest and dry savannah located around Mount Kilimanjaro and the highlands of Kenya. Southern Africa consists of lowland or mid elevation moist savannah, and lowland or mid elevation dry savannah.

Farms in different agro-ecological zones clearly face different conditions for farming. Hence, we expect that farms in favorable ecological zones for agriculture earn higher profits while farms in unfavorable zones earn much less per hectare. In order to examine the climate sensitivity of farms in each AEZ, we examine the variation of farm profits across different climate zones.

Since it is not clear whether Eqs. 2 or 3 is the best specification, we estimate both the OLS and fixed effect model in Table 2. The dependent variable is net revenue from both crops and livestock divided by the hectares of cropland.[1] As many farmers in Africa consume their own produce, we value own consumption at the market values of each product (Kurukulasuriya et al. 2006; Seo and Mendelsohn 2008b,c). In addition, farmers use their own family labor at no pay. There is no observed wage rate for household labor and so it is not included as a cost. Net revenue thus includes returns to land and household labor. Household farms that rely mainly on their own labor may appear to have higher net revenue per hectare in comparison to commercial farms that rely on hired labor.

The estimated coefficients of the two regressions show that the response of net revenue to summer temperature is concave while the response to winter temperature is convex. Responses to summer and winter precipitation depend upon whether or not country fixed effects are included in the model. With the OLS model, precipitation is convex and with the country fixed effects model, precipitation is concave with respect to net revenue. Summer climate interaction terms are generally negative and significant whereas winter climate interaction effects are positive but insignificant. Water flow and electricity coefficients are positive and strongly significant when country fixed effects are not included, but become insignificant when country fixed effects are introduced. Most of the significant soil coefficients are negative. The country coefficients in the fixed effects model are positive for Egypt and Cameroon but negative for Niger, Burkina Faso, and Senegal. The OLS and fixed effects models have similar adjusted R-squared, F-statistics, and Durbin Watson statistics, which indicate that the empirical specifications are highly significant and not distorted by strong covariance among the observations.

Comparing the two models, it is evident that the country dummy variables are significant. They are clearly explaining some of the variation in net revenue. However, they are also capturing the differences in climate from country to country. The fixed effects model must estimate climate impacts relying solely on within country climate variation. It is not clear

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[1] In Africa, it was difficult to get the amount of pasture that each farm owns for livestock since most of them rely on public land to raise livestock. We divided net revenue per farm by the amount of cropland.

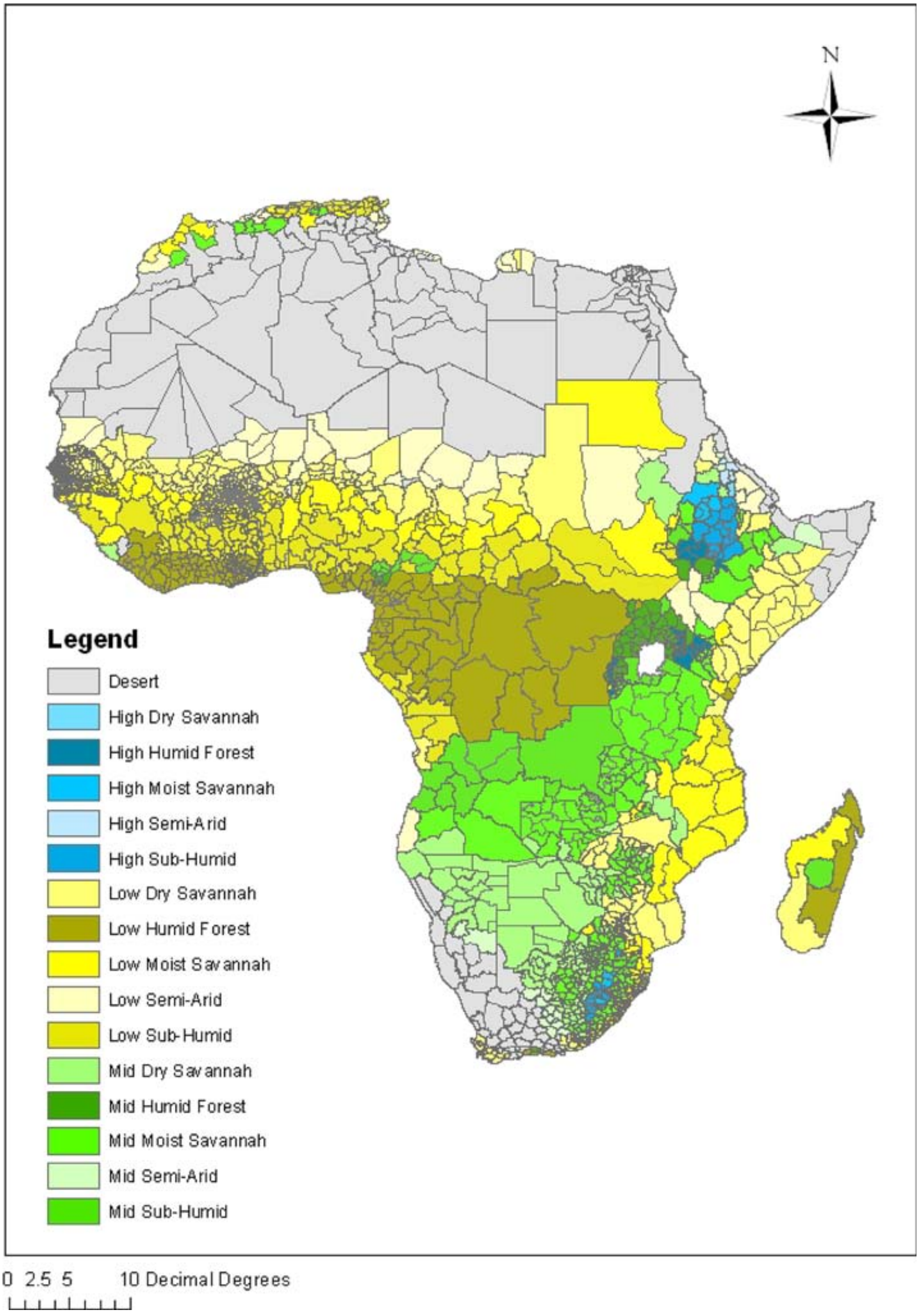

Fig. 1 Agro-Ecological Zones in Africa

Table 2 Ricardian regressions on net revenue (USD/ha)

Var	OLS		Country fixed effects	
	Coef.	*t*	Coef.	*t*
Intercept	570.9	0.55	−904.0	−0.76
T summer	256.8	3.31	264.3	2.55
T summer 2	−3.55	−2.47	−3.17	−1.73
T winter	−282.8	−4.74	−228.9	−3.05
T winter 2	4.22	2.50	3.82	2.09
P summer	1.83	0.40	17.05	3.44
P summer 2	0.02	3.01	−0.02	−2.21
P winter	−9.78	−1.54	−1.49	−0.22
P winter 2	0.00	−0.20	0.03	1.58
T sum ∗ P sum	−0.27	−1.75	−0.60	−3.34
T win ∗ P win	0.66	1.99	−0.01	−0.02
Water flow	23.70	4.11	9.15	1.50
Head farm	−177.9	−1.43	−87.7	−0.70
Soil Ferralsols	539.6	0.32	1217.1	0.72
Soil Luvisols C1	−1505.3	−3.74	−244.9	−0.57
Soil Luvisols C2	−5506.3	−2.21	−3876.5	−1.55
Soil Luvisols O	−3680.5	−2.56	−3160.3	−2.18
Soil Vertisols	−2409.3	−3.24	−1714.0	−2.28
Electricity	492.5	7.61	76.95	0.99
Burkina Faso			−180.59	−0.91
Egypt			1296.8	3.47
Ethiopia			−136.0	−1.02
Ghana			51.6	0.35
Niger			−551.5	−2.36
Senegal			−507.4	−2.33
South Africa			−116.6	−0.35
Zambia			−540.8	−3.15
Cameroon			948.6	6.12
R^2		0.10		0.12
F-stat		51.83		41.78
DW stat		1.89		1.96
N		8,509		8,509

Note: Dependent variable includes both crop and livestock net revenue

which of these two models is the best one to use for assessing policy interventions, so we include them both.

Alternative specifications were also attempted but found less successful. We estimated a model without climate interaction terms but the coefficients on the interaction terms are statistically significant. We also estimated a model that included all four seasons of the year (see Appendix). In this case, the seasonal climate coefficients mostly become insignificant.[2]

Because climate is introduced in a quadratic form, it is difficult to interpret the impact of climate directly from the climate coefficients. Table 3 calculates the marginal change in net revenue from a marginal change in temperature and precipitation for the models in Table 2. These marginal effects are calculated at the mean climate of each Agro-Ecological Zone. Higher temperatures are harmful. Net revenues fall as temperatures rise in every AEZ for both models. The largest negative impact is on high elevation dry savannah. The OLS model also predicts a large negative impact on high elevation semi-arid areas. Although both models predict temperature is harmful, they do not agree about the magnitude of the effect. The fixed effect model generally predicts smaller negative impacts from warming. However, this difference between the models is not consistent. The fixed effect model predicts larger harmful impacts in more humid places whereas the OLS model predicts larger harmful impacts in dryer places.

Despite the fact that Africa is relatively dry, the two models do not agree that increased rainfall is beneficial. The OLS model implies more rain is generally beneficial, whereas the fixed effect model implies that rainfall is generally harmful. The OLS model predicts increased rainfall will be beneficial in all the AEZs except the desert. This odd result for the desert may have to do with the fact that desert agriculture depends strictly on irrigation. The fixed effect model predicts rainfall to be harmful for Africa but especially for high dry savannah and all lowland areas except humid forests. The fact that these results do not make sense is a serious deficiency of the fixed effect model.

5 Climate Predictions

The previous analysis suggests that temperature and precipitation currently have different effects on the net revenues in each AEZ. In this section, we explore the impacts future climate change scenarios may have on each AEZ. We use the estimated coefficients from the OLS and fixed effects models to predict long term impacts. However, we do not adjust earnings for other important factors that will change over the century such as capital investments, technological change, and changes in prices. So it is important to remember that these predictions are just indications of the effect of climate change, not predictions of what may actually occur.

We use the country specific predictions of two climate models for 2100: CCC (Canadian Climate Centre) (Boer et al. 2000) and PCM (Parallel Climate Model) (Washington 2000). We use the A2 emission scenarios from the SRES report (IPCC 2000). These two scenarios reflect the range of outcomes predicted in the most recent Intergovernmental Panel on Climate Change report (IPCC 2007a). In each climate scenario, we add the predicted change in temperature from the climate model to the baseline temperature for each season in each district. For precipitation, we multiply the predicted percentage change in precipitation from the climate models by the baseline precipitation for each season in each district. Table 4 presents the continental mean temperature and rainfall results. The PCM scenario is relatively mild and wet and the CCC scenario is significantly hot and dry. The PCM predicts a 2°C annual increase and CCC a 6.5°C annual increase in temperature. The PCM predicts a 10% increase

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[2] There was a concern whether Egypt is an outlier because Egypt is the only country north of the Sahara desert. We explored a model that estimated separate climate coefficients for Egypt (see Appendix). Climate coefficients for Egypt were slightly different from the rest of the continent. This was also the case for Cameroon, South Africa, and West Africa.

Table 3 Marginal effects and elasticities by AEZ

AEZ	Marginal effects		Elasticities	
	T	P	*T*	P
(a) OLS model				
Africa	−39.20	2.02	−0.06	0.01
Desert	−87.57	−5.87	−0.08	0.00
High elevation dry savanna	−40.28	2.95	−2.41	0.53
High elevation humid forest	0.58	3.36	0.00	0.14
High elevation moist savannah	−20.32	2.84	−0.06	0.03
High elevation semi-arid	−37.48	1.41	−1.59	0.14
High elevation sub-humid	−29.22	3.46	−0.14	0.08
Lowland dry savannah	−47.08	2.10	−0.38	0.03
Lowland humid forest	−11.73	5.09	−0.19	0.46
Lowland moist savannah	−33.62	3.08	−0.22	0.06
Lowland semi-arid	−53.19	0.85	−0.11	0.00
Lowland sub-humid	−24.95	4.77	−0.50	0.38
Mid-elevation dry savannah	−25.90	1.36	−0.05	0.01
Mid-elevation humid forest	−6.29	4.61	−0.04	0.19
Mid-elevation moist savannah	−19.24	1.69	−0.09	0.03
Mid-elevation semi-arid	−49.27	0.89	−0.02	0.00
Mid-elevation sub-humid	−17.66	4.10	−0.09	0.10
(b) Country fixed effects model				
Africa	−23.96	−0.89	−0.04	−0.004
Desert	−30.00	1.10	−0.03	0.001
High elevation dry savanna	−19.45	−0.46	−1.16	−0.083
High elevation humid forest	−14.32	3.93	−0.12	0.172
High elevation moist savannah	−16.01	2.15	−0.05	0.026
High elevation semi-arid	−7.58	0.56	−0.32	0.058
High elevation sub-humid	−29.84	1.66	−0.15	0.038
Lowland dry savannah	−13.07	−3.95	−0.11	−0.054
Lowland humid forest	−33.01	1.08	−0.54	0.097
Lowland moist savannah	−21.47	−1.96	−0.14	−0.036
Lowland semi-arid	−10.65	−3.78	−0.02	−0.010
Lowland sub-humid	−27.35	−0.80	−0.55	−0.065
Mid-elevation dry savannah	−15.24	1.63	−0.03	0.011
Mid-elevation humid forest	−34.17	2.93	−0.22	0.123
Mid-elevation moist savannah	−22.73	2.60	−0.11	0.047
Mid-elevation semi-arid	−19.60	−0.05	−0.01	0.000
Mid-elevation sub-humid	−27.38	1.77	−0.14	0.045

and, CCC a 15% decrease in annual mean rainfall. The predicted changes in each country varied slightly from these means depending on the climate scenario.

We calculate the baseline net revenue for each model by multiplying the climate coefficients times the current climate for each farm. Because the climate coefficients are not the

Table 4 Climate scenarios

	Current	Change in 2100		Current	Change in 2100
Summer temperature (°C)	25.7		Summer rainfall (mm/mo)	149.8	
CCC		+6.0	CCC		−33.7
PCM		+2.2	PCM		−4.7
Winter temperature (°C)	22.4		Winter rainfall (mm/mo)	12.8	
CCC		+7.3	CCC		+3.5
PCM		+3.1	PCM		+21.6

same in the OLS and fixed effect models, the baseline values are different. The fixed effects model predicts higher baseline net revenues than the fixed effect model in desert, high elevation dry savannah and humid forest, mid elevation humid forest, semi arid and sub-humid forest, and low elevation semi arid, sub-humid forest, and humid forest. In contrast, the OLS model predicts higher baseline net revenues in low elevation dry savannah, mid elevation dry savannah, and mid elevation moist savannah.

Future net revenues are calculated by multiplying the climate coefficients by future climate. Climate change impacts are measured as the differences between net revenues in 2100 and net revenues in the baseline. The OLS results are shown in Table 5. Both marginal changes and percentage changes are presented for Africa for each AEZ. African farmers currently earn on average $630 per year for a hectare of land. The OLS model predicts that the PCM scenario leads to a 12% increase in net revenue and the CCC scenario leads to a 27% reduction in net revenue for Africa at large. The fixed effects model predicts similar but more positive results. The fixed effects model predicts that net revenue will rise by 19% with the PCM scenario and will fall by only 2% with the CCC scenario.

These relatively positive results for Africa contrast sharply with earlier more pessimistic predictions for Africa (Kurukulasuriya et al. 2006; Kurukulasuriya and Mendelsohn 2008). However, the earlier studies examined only crop net revenue. Studies on the livestock sector suggested there would be offsetting gains (Seo and Mendelsohn 2008b,c). The analysis in this paper, by combining both cropland and livestock net revenues, reveals a more moderate picture.

With the OLS model, the PCM scenario is beneficial in all AEZs but the desert. The CCC scenario is especially harmful in dry and moist savannah and high humid forests. However, the CCC scenario is expected to be slightly beneficial to lowland humid and sub-humid forest. With the fixed effects model, the only AEZ not predicted to gain under the PCM scenario is again the desert. The CCC scenario is expected to be harmful to high elevation moist savannah, humid forest, and sub-humid forest, and mid dry savannah, and humid forest. However, the CCC scenario is especially harmful to mid moist savannah.

In Figs. 2 and 3, we map the spatial distribution of the predicted impact from each of the climate scenarios. The figures reflect the percentage change in net revenue per hectare of land in 2100 due to climate change. Five quintiles of the percentage loss of farm net revenues are drawn for each climate scenario. Under the CCC scenario, lowland AEZs in general gain from climate change. Desert areas, mid elevation AEZs, and high elevation AEZs are predicted to lose by a large percentage. Predictions from the PCM scenario are quite different. All places would gain except for the deserts. However, the largest benefits from climate change would fall on the mid elevation AEZs and highlands.

Table 5 Climate change impacts by AEZs and climate scenarios in 2100

AEZ	Scenario	OLS			Fixed effects		
		Base line	Change	% Change	Base line	Change	% Change
Africa		616			628		
	CCC		−169	−27		−15	−2
	PCM		71	12		+121	+19
Desert		2,360			2,632		
	CCC		−500	−21		−161	−6
	PCM		−371	−16		−177	−7
High elevation dry savanna		256			320		
	CCC		−128	−50		15	5
	PCM		180	70		15	5
High elevation humid forest		341			378		
	CCC		−32	−9		−33	−9
	PCM		421	123		510	135
High elevation moist savannah		272			271		
	CCC		−111	−41		−41	−15
	PCM		253	93		150	55
High elevation semi-arid		362			371		
	CCC		−106	−29		11	3
	PCM		205	57		40	11
High elevation sub-humid		371			374		
	CCC		−171	−46		−76	−20
	PCM		266	72		470	126
Lowland dry savannah		314			234		
	CCC		−184	−59		43	18
	PCM		53	17		99	42
Lowland humid forest		711			885		
	CCC		68	10		58	7
	PCM		182	26		327	37
Lowland moist savannah		271			261		
	CCC		−169	−62		9	3
	PCM		56	21		93	36
Lowland semi-arid		600			650		
	CCC		−196	−33		52	8
	PCM		109	18		215	33
Lowland sub-humid		401			552		
	CCC		26	6		50	9
	PCM		165	41		206	37
Mid-elevation dry savannah		421			244		
	CCC		−164	−39		−39	−16
	PCM		332	79		269	110

Table 5 continued

AEZ	Scenario	OLS			Fixed effects		
		Base line	Change	% Change	Base line	Change	% Change
Mid-elevation humid forest		533			669		
	CCC		−86	−16		−63	−9
	PCM		286	54		515	77
Mid-elevation moist savannah		478			225		
	CCC		−221	−46		−96	−43
	PCM		276	58		260	116
Mid-elevation semi-arid		324			357		
	CCC		−110	−34		30	8
	PCM		228	70		44	12
Mid-elevation sub-humid		432			496		
	CCC		−116	−27		−25	−5
	PCM		319	74%		571	115%

6 Conclusion and Policy Implications

This paper examines the role that climate plays in different AEZs in Africa. The paper relies on a cross-sectional analysis to assess the climate sensitivity of farms in each AEZ. The paper differs from previous studies in two important ways. It provides an analysis of total net revenue from both crops and livestock. Second, based on the AEZ classification, the analysis extrapolates impacts across the African landscape.

The paper compares Ricardian regressions with and without country dummies: OLS and fixed effect models. Both models reveal that climate variables are important determinants of farm net revenues in Africa. Summer and winter temperature and precipitation are all significant. A small increase in temperature would harm agricultural net revenues in Africa. The OLS model predicts that increased rainfall would increase net revenues whereas the fixed effect model predicts that increasing rainfall is harmful, but the rainfall effects vary by AEZs.

The estimated coefficients from both models were then used to predict climate change impacts for 2100 across a range of climate scenarios. The OLS model predicts that the PCM scenario leads to a 12% increase in net revenue, but the CCC scenario leads to a 27% reduction in net revenue for Africa at large. The fixed effects model predicts that net revenue will rise by 19% with the PCM scenario, but will fall by 2% with the CCC scenario.

The results suggest that African agriculture is more resilient to climate change than what earlier studies suggested (Rosenzweig and Parry 1994; Reilly et al. 1996; Kurukulasuriya et al. 2006). We believe that this is because earlier studies examined only the impacts to crops whereas this study examines the impact on the combined net revenue of crops and livestock. There is evidence that some livestock are heat tolerant and that farmers will switch to these species in hotter places and thus reduce their climate vulnerability (Seo and Mendelsohn 2008b,c).

The results, however, are not uniform across all of Africa. The PCM scenario is not beneficial in the desert. Farmers in high elevation humid and sub-humid forests, mid elevation and low elevation savannahs, and low elevation semiarid areas will especially benefit. The

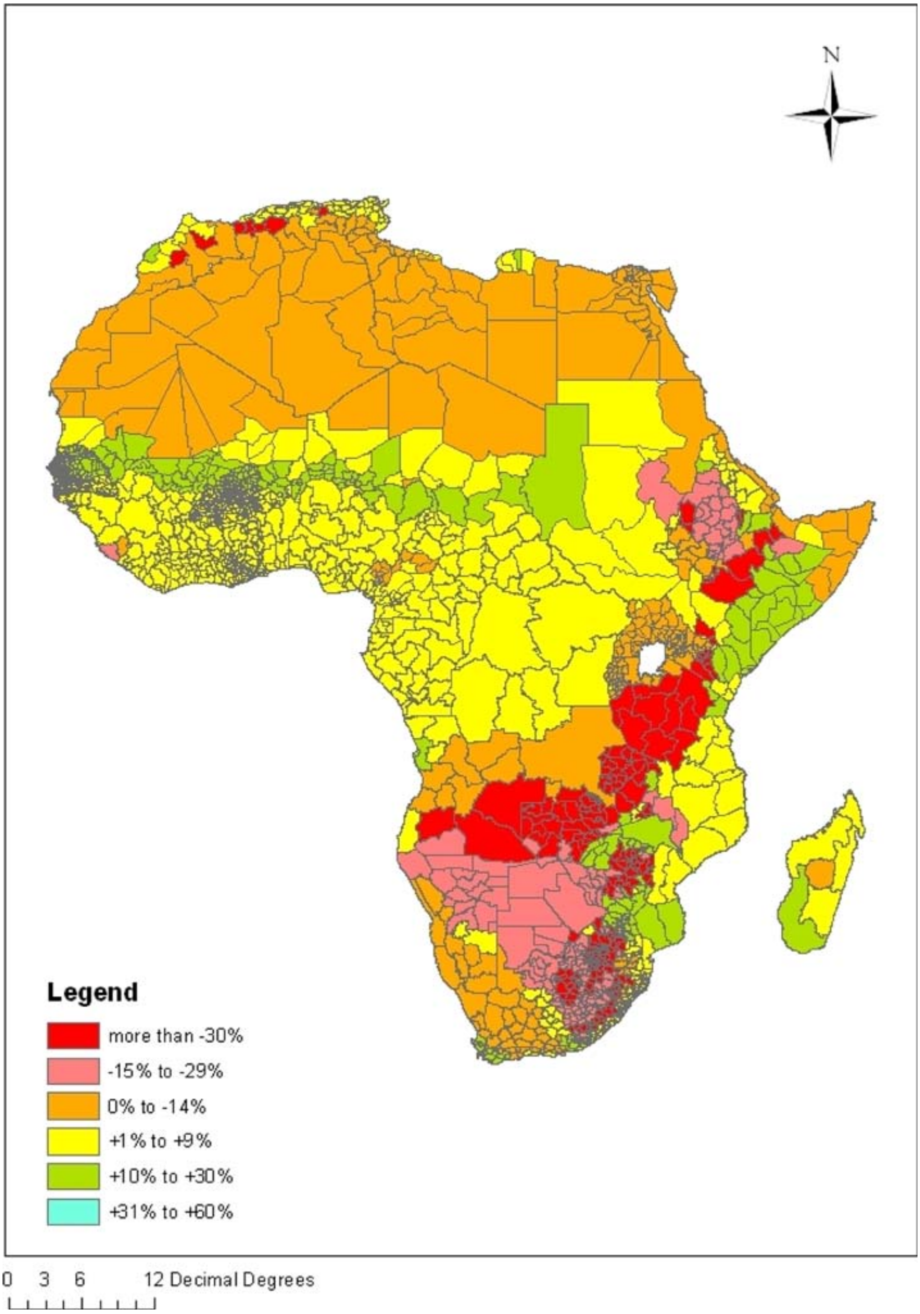

Fig. 2 Percentage change of farm net revenue with CCC 2100 scenario

CCC scenario is expected to be harmful to farmers in high elevation moist savannah, humid forest, and sub-humid forest, and mid elevation dry savannah, and humid forest. The CCC scenario is especially harmful to mid elevation moist savannah.

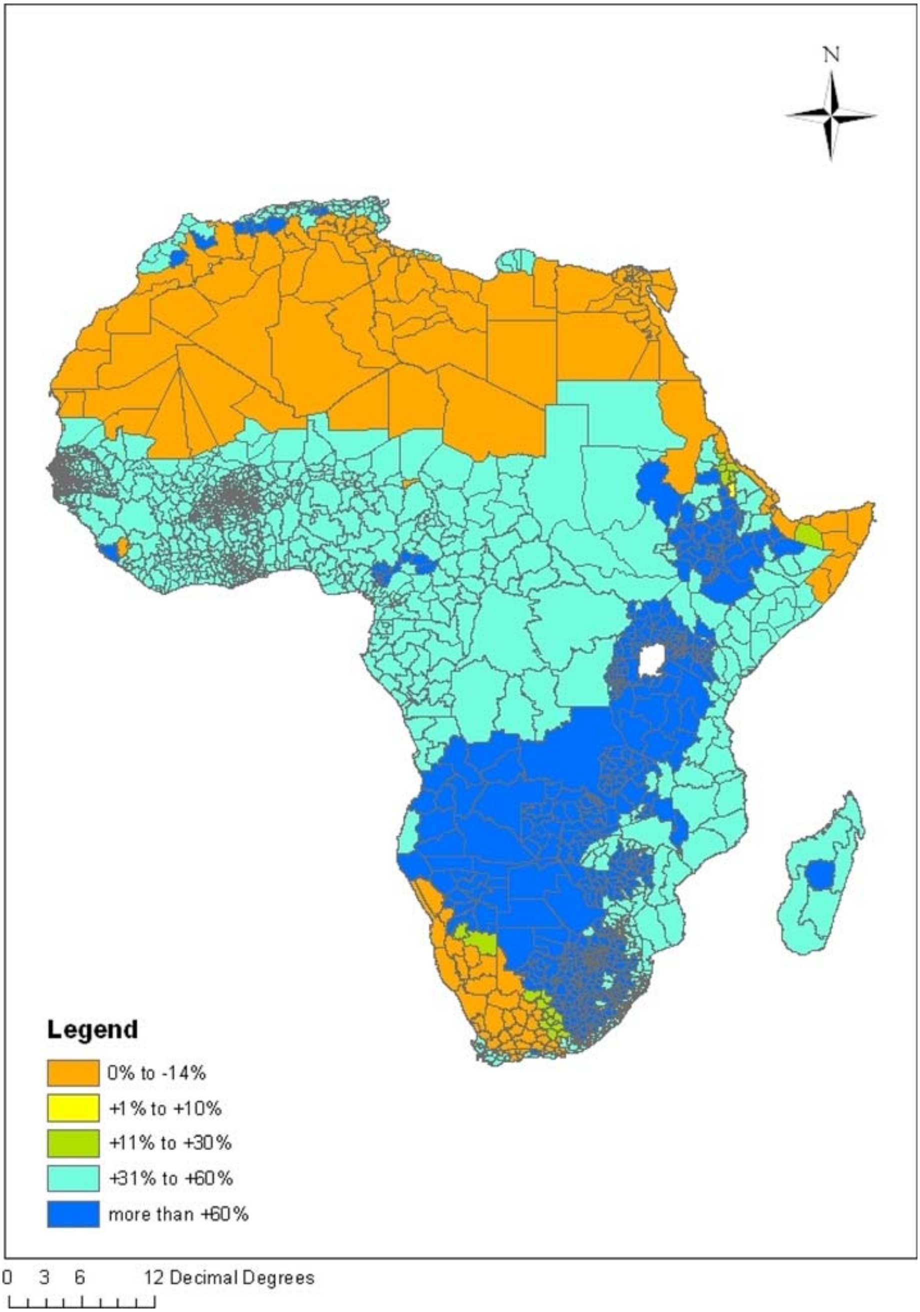

Fig. 3 Percentage change of farm net revenue with PCM 2100 scenario

As policy makers seek to address the vulnerability of developing countries to climate change, they may be tempted to apply interventions across the board, applying the same policy interventions to an entire society facing climate risks. However, this paper suggests that climate change may have very different effects on different farmers in various locations.

Further, their economic and institutional ability to implement adaptation measures may also vary. Farmers facing similar climate situations may be affected differently, depending on other physical and economic/institutional conditions they face. Both physical and economic/institutional conditions may affect the type of adaptation relevant for each location and the ability of the farmers residing in each location to adapt. Therefore, policy makers should consider tools that tailor assistance as needed. Policy makers should look carefully at impact assessments to identify the most attractive adaptation options. They should apply policies across the landscape using a ‘quilt’ rather than a ‘blanket’ approach. The proposed quilt policy approach will allow much more flexibility and will likely lead to much more effective and locally beneficial outcomes.

Several points can help in prioritizing, sequencing, and packaging interventions. First, even across the AEZs, policies that are designed in different countries should take into account the existing institutions and infrastructure in the country. While this advice may seem obvious, experience in replicating ‘best practices’ across countries and regions suggest that such considerations are not always taken into account.

The facts in Table 1 suggest that there is lot of variation between the AEZs in terms of the population living in them and their net revenue. The analysis in the paper suggests that there is a large range of impacts across AEZs. Policy makers could sequence their interventions such that they address the most vulnerable AEZs first. This analysis does not lead to specific policy recommendations concerning what interventions are needed. However, it is clear that the indicated AEZ vulnerability is valid under many criteria: the population affected, the mean net revenue, and the total impacts.

The results presented in this paper, however, should be read with caution. First, the analysis does not take into account the direct effects of carbon doubling which is believed to be beneficial to crop growth and may indirectly benefit livestock. Second, the study assumes agricultural prices, technology, inputs and capital remain the same for the coming century. Third, it does not take into account transition costs involved in making adaptations (Kelly et al. 2005). Finally, the analysis does not consider changes in policy that might take place that would either facilitate adaptation or make it more difficult.

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Appendix

See Tables 6 and 7.

Table 6 Regression with country interaction terms

Variable	Egypt		Cameroon		South Africa		West Africa	
	Coef.	*t*	Coef.	*t*	Coef.	*t*	Coef.	*t*
Intercept	−1035.3	−0.73	−601.5	−0.48	−459.9	−0.37	2918.5	1.22
T summer	128.7	1.13	243.6	2.25	263.0	2.42	−26.8	−0.13
T summer 2	−1.80	−0.90	−2.93	−1.55	−3.03	−1.59	4.23	1.01
T winter	−53.0	−0.40	−218.7	−2.89	−268.7	−3.28	−339.1	−3.85
T winter 2	1.09	0.36	3.650	1.97	4.48	2.32	7.20	2.51
P summer	11.41	2.19	12.32	1.94	17.88	3.53	21.22	3.09

Table 6 continued

Variable	Egypt		Cameroon		South Africa		West Africa	
	Coef.	*t*	Coef.	*t*	Coef.	*t*	Coef.	*t*
P summer 2	−0.014	−1.81	−0.009	−0.66	−0.020	−2.56	−0.010	−1.22
P winter	3.97	0.58	−0.84	−0.12	−6.06	−0.82	−1.26	−0.17
P winter 2	0.021	1.10	0.023	1.08	0.027	1.41	0.032	1.34
T sum ∗ P sum	−0.379	−2.00	−0.458	−2.3	−0.603	−3.28	−0.925	−3.03
T win ∗ P win	−0.273	−0.77	−0.022	−0.06	0.241	0.61	−0.090	−0.19
T summer ∗ Dummy	2477.8	1.40	−21016.0	−4.13	8260.2	1.42	−70.8	−0.21
T summer 2 ∗ Dummy	−33.5	−1.00	444.1	4.14	−193.0	−1.51	−2.9	−0.49
T winter ∗ Dummy	−3280.9	−4.38	6696.7	1.82	1051.1	0.54	310.3	0.55
T winter 2 ∗ Dummy	124.6	2.38	−193.2	−2.04	−38.8	−0.36	−6.9	−0.58
P summer ∗ Dummy	16174.0	0.71	−162.7	−2.31	92.7	0.47	−36.0	−1.11
P summer 2 ∗ Dummy	−8.735	−0.19	−0.179	−4.04	0.245	0.99	0.063	0.87
P winter ∗ Dummy	−16.5	−0.03	−425.9	−4.01	−200.2	−0.70	1.8	0.03
P winter 2 ∗ Dummy	−9.025	−1.19	0.528	3.39	0.150	0.25	−0.072	−0.46
T sum ∗ P sum ∗ Dummy	−691.0	−0.69	12.21	3.37	−7.64	−0.88	1.2	1.43
T win ∗ P win ∗ Dummy	27.26	0.39	20.55	3.63	10.31	0.41	0.291	0.11
Water flow	1238.1	0.74	1337.9	0.8	5430.5	0.95	880.6	0.52
Head farm	−135.8	−0.32	−207.8	−0.47	−269.5	−0.62	−72.9	−0.16
Soil Ferralsols	−3404.7	−1.36	−3773.9	−1.51	−5770.7	−1.60	−3838.9	−1.53
Soil Luvisols C1	−3168.8	−2.19	−3108.6	−2.15	2037.8	0.46	−3285.7	−2.26
Soil Luvisols C2	−1404.6	−1.84	−1675.0	−2.23	−2009.5	−1.69	−1796.5	−2.37
Soil Luvisols O	5.0	0.70	8.90	1.47	7.9	1.28	10.7	1.75
Soil Vertisols	−93.3	−0.75	−77.7	−0.62	−78.8	−0.63	−90.2	−0.72
Electricity	80.2	1.04	67.9	0.87	78.1	1.01	73.0	0.94
Burkina Faso	−16.7	−0.08	−268.7	−1.27	−199.8	−1.00	−151.4	−0.02
Egypt	−18661.0	−0.76	1255.8	3.24	1195.6	2.96	958.8	2.04
Ethiopia	−76.9	−0.57	−165.0	−1.18	−155.4	−1.15	−179.3	−1.24
Ghana	71.8	0.48	16.5	0.11	37.7	0.25		
Niger	−256.1	−1.06	−628.3	−2.56	−573.5	−2.43		
Senegal	−187.8	−0.82	−561.8	−2.44	−518.4	−2.33		
South Africa	581.3	1.40	−111.5	−0.33	−90003.0	−1.50	−112.0	−0.28
Zambia	−267.2	−1.44	−567.6	−3.15	−566.3	−3.20	−439.9	−2.00
Cameroon	1000.3	6.45	176917.0	3.67	959.5	6.17	1029.3	6.39
R^2		0.12		0.12		0.12		0.12
F-stat		32.58		31.58		31.00		33.66
DW stat		1.95		1.94		1.93		1.93
N		8,509		8,509		8,509		8,509

Note: (1) F-statistic to test the significance of Egypt interaction terms: $F = 6.94$, P-value < 0.0001. (2) F-statistic to test the significance of Cameroon interaction terms: $F = 3.68$, P-value < 0.0001. (3) F-statistic to test the significance of South African interaction terms: $F = 1.07$, P-value $= 0.05$. (4) F-statistic to test the significance of West Africa interaction terms: $F = 2.75$, P-value $= 0.002$. (5) F-statistic to test the significance of all country interaction terms: $F = 13.43$, P-value < 0.0001. (6) Dummy indicates corresponding country dummy in each regression

Table 7 Regression with four seasons

Var	Four seasons	
	Est.	*T*
Intercept	−1242.7	−0.87
T summer	325.8	1.36
T summer 2	−3.84	−0.92
T winter	−344.3	−1.98
T winter 2	7.87	1.75
P summer	22.67	2.95
P summer 2	−0.04	−2.24
P winter	−4.71	−0.54
P winter 2	0.06	2.18
T spring	119.9	0.60
T spring 2	−3.45	−0.80
T fall	−64.4	−0.25
T fall 2	0.78	0.15
P spring	5.46	1.08
P spring 2	−0.02	−0.64
P fall	−4.39	−1.06
P fall 2	0.02	1.23
T sum ∗ P sum	−0.62	−2.92
T win ∗ P win	−0.24	−0.59
Water flow	8.57	1.40
Head farm	−86.9	−0.69
Soil Ferralsols	1175.8	0.70
Soil Luvisols C1	−215.4	−0.49
Soil Luvisols C2	−4331.7	−1.71
Soil Luvisols O	−3290.0	−2.26
Soil Vertisols	−1926.2	−2.47
Electricity	74.91	0.96
Burkina Faso	−180.2	−0.72
Egypt	1479.6	3.29
Ethiopia	−171.8	−0.81
Ghana	23.2	0.13
Niger	−511.0	−1.89
Senegal	−353.5	−1.19
South Africa	−170.6	−0.51
Zambia	−423.3	−2.01
Cameroon	801.0	3.73
R^2		0.12
F-stat		32.37
DW stat		1.93
N		8,509

Evaluated at the mean climate, the marginal temperature effect is −29.3 USD/ha/yr per °C and the marginal precipitation effect is −0.41 USD/ha/yr per mm/mo

References

Basist A, Peterson N, Peterson T, Williams C (1998) Using the Special Sensor Microwave Imager to monitor land surface temperature, wetness, and snow cover. J Appl Meteorol 37:888–911. doi:10.1175/1520-0450(1998)037<0888:UTSSMI>2.0.CO;2

Boer G, Flato G, Ramsden D (2000) A transient climate change simulation with greenhouse gas and aerosol forcing: projected climate for the 21st century. Clim Dyn 16:427–450. doi:10.1007/s003820050338

Dinar A, Hassan R, Mendelsohn R, Benhin J (eds) (2008) Climate change and agriculture in Africa: impact assessment and adaptation strategies. EarthScan, London, p189

FAO (1978) Report on Agro-Ecological Zones; vol 1: methodology and results for africa. Rome

Fischer G, van Velthuizen H (1996) Climate change and global agricultural potential: a case of Kenya. IIASA Working Paper WP-96-071

Food and Agriculture Organization (2003) The Digital Soil Map of the World (DSMW) CD-ROM. Italy, Rome. Available in http://www.fao.org/AG/agl/agll/dsmw.stm. Accessed March 2004

Intergovernmental Panel on Climate Change (IPCC) (2000) Special report on emissions scenarios. Cambridge University Press, Cambridge, UK

Intergovernmental Panel on Climate Change (IPCC) (2007a) The physical science basis. Fourth Assessment Report, Cambridge University Press, Cambridge, UK

Intergovernmental Panel on Climate Change (IPCC) (2007b) Impacts, adaptations, and vulnerability. Fourth Assessment Report, Cambridge University Press, Cambridge, UK

Kelly, DL, Kolstad CD, Mitchell G (2005) Adjustment costs from environmental change J Environ Econ Manag 50: 468–495

Kurukulasuriya P, Mendelsohn R (2008) A Ricardian analysis of the impact of climate change on African cropland. Afr J Agric Resour Econ 2:1–23

Kurukulasuriya P, Mendelsohn R, Hassan R, Benhin J, Diop M, Eid HM, Fosu KY, Gbetibouo G, Jain S, Mahamadou A, El-Marsafawy S, Ouda S, Ouedraogo M, Sène I, Maddision D, Seo N, Dinar A (2006) Will African agriculture survive climate change? World Bank Econ Rev 20:367–388. doi:10.1093/wber/lhl004

Mendelsohn R, Nordhaus W (1996) The impact of global warming on agriculture: reply. Am Econ Rev 86:1312–1315

Mendelsohn R, Nordhaus W, Shaw D (1994) The impact of global warming on agriculture: a Ricardian analysis. Am Econ Rev 84:753–771

Mendelsohn R, Dinar A, Williams L (2006) The distributional impact of climate change on rich and poor countries. Environ Dev Econ 11:1–20. doi:10.1017/S1355770X05002755

Mendelsohn R, Kurukulasuriya P, Basist A, Kogan F, Williams C (2007) Measuring climate change impacts with satellite versus weather station data. Clim Change 81:71–83. doi:10.1007/s10584-006-9139-x

Nordhaus W (2007) To tax or not to tax: alternative approaches to slow global warming. Rev Environ Econ Policy 1:22–44

Pearce D et al (1996) The social costs of climate change: greenhouse damage and benefits of control. In: Bruce J, Lee H, Haites E (eds) Climate change 1995: economic and social dimensions of climate change. Cambridge University Press, Cambridge, UK pp 179–224

Reilly J, Baethgen W, Chege F, van de Geijn S, Erda L, Iglesias A, Kenny G, Patterson D, Rogasik J, Rotter R, Rosenzweig C, Somboek W, Westbrook J (1996) Agriculture in a changing climate: impacts and adaptations. In: Watson R, Zinyowera M, Moss R, Dokken D (eds) Climate change 1995: intergovernmental panel on climate change impacts, adaptations, and mitigation of climate change. Cambridge University Press, Cambridge, UK

Rosenzweig C, Parry M (1994) Potential impact of climate change on world food supply. Nature 367:133–138. doi:10.1038/367133a0

Seo SN, Mendelsohn R (2008a) A Ricardian analysis of the impact of climate change on South American farms. Chil J Agri Res 68:69–79

Seo SN, Mendelsohn R (2008b) Animal husbandry in Africa: climate change impacts and adaptations. Afr J Agric Resour Econ 2:65–82

Seo SN, Mendelsohn R (2008c) Measuring impacts and adaptations to climate change: a structural Ricardian model of African livestock management. Agric Econ 38:151–165

Strzepek K, McCluskey A (2006) District level hydroclimatic time series and scenario analyses to assess the impacts of climate change on regional water resources and agriculture in Africa. CEEPA Discussion Paper No. 13, Centre for Environmental Economics and Policy in Africa, University of Pretoria

Tol R (2002) Estimates of the damage costs of climate change. Part 1: benchmark estimates. Environ Resour Econ 21:47–73. doi:10.1023/A:1014500930521

USGS (United States Geological Survey) (2004) Global 30 arc second elevation data, USGS National Mapping Division, EROS Data Centre. http://edcdaac.usgs.gov/gtopo30/gtopo30.asp

Voortman R, Sonnedfeld B, Langeweld J, Fischer G, Van Veldhuizen H (1999) Climate change and global agricultural potential: a case of Nigeria. Centre for World Food Studies. Vrije Universiteit, Amsterdam

Washington W et al (2000) Parallel climate model (PCM): control and transient scenarios. Clim Dyn 16:755–774

World Bank (2003) Africa Rainfall and Temperature Evaluation System (ARTES). World Bank, Washington DC