Managing forests, livestock, and crops under global warming: a micro-econometric analysis of land use changes in Africa*

S. Niggol Seo[†]

This paper examines potential land use changes in Africa under climate change by building an integrated model of crop management, animal husbandry, and forestry. Using micro-level decisions from around 9000 household surveys in 11 countries, we analyze the choice of land types across the landscape with a multinomial discrete choice model. The choices and future adaptation measures are analyzed as a mosaic based on the typology of Agro-Ecological Zones. The results indicate that if climate becomes hotter and drier, Africa will adapt by increasing a joint production of crops and animals, especially in the lowland savannahs. On the other hand, if climate becomes wetter, it will switch more to forests, either with crops or with both crops and livestock, especially in the mid and high elevation humid zones. Forestry will play a significant role in adaptation when a substantial increase in precipitation makes animal husbandry an unattractive alternative.

Key words: Africa, climate change, forestry, land use, livestock.

1. Introduction

As scientific evidence becomes stronger, global communities are increasingly concerned about the potential effects of global warming on future economic activities and natural systems around the globe (IPCC 2007; Nordhaus 2008). Although researchers do not agree on the magnitude of the total impacts, they often concur that it will lead to a substantial realignment of regional economic activities and ecosystems across the world. For example, agriculture in the Southern Plains of the United States will be hit hardest by climate change (Adams *et al*. 1990, 1999; Mendelsohn *et al*. 1994; Schlenker *et al*. 2005; Deschenes and Greenstone 2007). Forests in the South and Pacific Northwest are the most vulnerable as the current forest types are not optimally suited for a change in climate (Joyce *et al*. 1995; Sohngen and Mendelsohn 1998). African cropland farmers in dry zones will be highly vulnerable to climate change (Kurukulasuriya *et al*. 2006; Seo 2009). Animal husbandry will substitute crops when climate becomes hotter and drier in the savannahs of

† S. Niggol Seo (email: niggol.seo@aya.yale.edu) is a Senior Fellow in Agricultural and Resource Economics at the University of Sydney, Sydney, NSW 2006, Australia.

Africa (Seo and Mendelsohn 2008). Overall, global warming will change the way people utilize their land as it would alter productivities of these individual sectors.

Past studies cited above indicate potential land use changes in the coming centuries because of climate change. However, they only provide a partial analysis of what would occur because they did not model land use changes from one sector to another explicitly. Moreover, most studies were focused on a single sector, either crops or animal husbandry or forestry. Any change in an individual sector, however, would alter relative profitabilities among them which would spur the changes in allocation of land resources (von Thunen 1826; Hartwick and Olewiler 1986). An exception is Seo (2009) which built a joint model of crops and animal husbandry in Africa. This paper attempts to provide a whole picture of land use changes in Africa by setting up a joint model of crops, animal husbandry, and forestry. Particularly, we add the forest component to the existing climate change adaptation literature. We examine land use types with or without forests, either with crops and/or livestock. In Africa, land used for either crops, livestock, or forests account for most of the land area in the continent (UNEP 2008). The changes in the use of land for these systems because of climate change are likely to be most conspicuous in Africa, a low-latitude underdeveloped continent with rich natural ecosystems (Boko *et al*. 2007). We model the choice of these systems explicitly with a multinomial discrete choice model using around 9000 household surveys collected in 11 countries across Africa (McFadden 1981).

We utilize the typology of Agro-Ecological Zones compiled by the Food and Agriculture Organization (FAO) which classifies the African continent by the suitability for crop production (FAO 1978). The AEZ definition of the FAO classifies the continent into sixteen zones: semi-arid, arid savannah, moist savannah, sub-humid, humid forest zones, and deserts, which are further divided by elevation into lowland, mid elevation, and high elevation. The household surveys on which this paper relies include at least some households from each of the AEZs. We extrapolate land use choice decisions across the Agro-Ecological Zones to the whole of Africa from the sampled farms. A major focus of the paper will be the examination of when and where forests are important adaptation measures under different climate scenarios.

This paper provides evidence on how anthropogenic systems utilizing nature such as crop management, animal husbandry, and forestry would react to the natural climate which is expected to be disequilibrated by centuries of industrial emissions. As land use decisions are made by humans, it is difficult to research this issue solely on the basis of scientific experiments. That is, the topic of this paper calls for a behavioural approach. We analyze observed behavioural responses of about 9000 actual households with a micro-econometric model. We will show which of these systems will become more productive in the future under various climate scenarios constructed by climate scientists. The paper will illustrate how the distribution of these systems across Africa will shift by the end of this century. Based on the empirical

results, we will weigh various development policy efforts in Africa, i.e. whether a specific development program which is heavily invested now is, on the contrary, bound to fail because of climate change.

This paper proceeds as follows. The next section describes a multinomial discrete choice model of the household decision to invest in one of the four major land types. The following section will describe the household survey data collected throughout Africa along with climate, soils, water availability, spatial information, and the AEZ data. Estimation results are presented in the fourth section. Future land use choices are simulated in the succeeding section by altering climate conditions from the baseline projection. The paper concludes with summary and policy discussions.

2. Theory: a geographically scaled microeconometric analysis of adapting portfolios

Africa consists of diverse ecosystems in which forest and wooded zones cover 22 per cent, arable land covers 20 per cent, and arid/semi-arid zones cover 54 per cent (UNEP 2008). Accordingly, anthropogenic activities vary substantially depending upon the existing ecosystem in the area. Therefore, a study focused on crops is likely to underestimate the activities in arid/semi-arid zones which tend to prefer animals (Seo *et al.* 2009). Similarly, a study focused on crops and animals would misrepresent activities in forest and wooded zones which depend on forest products or forest incomes (Vedeld *et al.* 2007). The present paper aims to build a joint model of crops, animal husbandry, and forestry to capture diverse ecological zones and economic activities across the continent.[1]

We study changes in land use among crops, animal husbandry, and forestry by making use of actual choices made at the household level. We rely on 9000 household surveys collected from eleven countries across Africa as part of the World Bank project (Dinar *et al.* 2008). We assume one chooses to use his or her land for a specific purpose when it earns him the highest profit among alternatives. To account for the household that consumes its own products instead of selling them at the markets and that uses family labour instead of hiring labour, we assume that the household values its own consumption and own labour at market prices. Poor road and transportation in the African context are controlled in this paper by travel times to major markets (World Bank 2009). We analyze four most frequently chosen land types in Africa: crops-only, crops-livestock, crops-trees, and crops-livestock-trees. These land types account for almost all of the households in the survey.

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[1] Forestry here refers to the households in the sample that have trees. They can either sell timber or non-timber forest products. According to the 51 case studies from developing countries by Vedeld and his co-authors, forest income accounts for 22 per cent of the total household income. Forest incomes are earned from wild foods, fuel wood, fodder, timber, grass/thatch, wild medicine, gold panning and others (Vedeld *et al.* 2007).

Let the profit from land type j by a household i in a specific Agro-Ecological Zone w be written in the following form:

$$\pi_{jiw} = V(Z_{jiw}) + \varepsilon_{jiw} \quad \text{where} \quad j = 1,...,4. \tag{1}$$

where Z is a vector of exogenous variables that affect the profitability of any of the four land use types. For example, Z includes climate, soils, water availability, market access variables, and household characteristics such as education, gender, and age. The profit function is composed of two components: the observable component V and an error term ε that captures errors because of measurements, mis-specification, and omitted variables. The error term is not known to the researchers, but may be known to a decision-maker, which is assumed up to a cumulative distribution function.

The decision of a household which is located in a given AEZ, w, is to choose a land type j from the available choices that yields the highest net revenue given the external factors:

$$\arg\max_{j}\{\pi_{1iw}^{*}, \pi_{2iw}^{*}, ..., \pi_{Jiw}^{*}\} \tag{2}$$

She will choose land type j over other alternatives if:

$$\pi_{jiw}^{*} > \pi_{kiw}^{*} \text{ for } \forall k \neq j. \text{ [or if } \varepsilon_{kiw} - \varepsilon_{jiw} < V(Z_{jiw}) - V(Z_{kiw}) \quad \text{for} \quad k \neq j] \tag{3}$$

The probability P_{jiw} for land type j to be chosen is then

$$P_{jiw} = \Pr[\varepsilon_{kiw} - \varepsilon_{jiw} < V_{jiw} - V_{kiw}]\forall k \neq j \quad \text{where} \quad V_{jiw} = V(Z_{jiw}) \tag{4}$$

Assuming that ε_{jiw} follows an identical and independent Type I Extreme Value distribution and V can be written linearly in the parameters, this probability can be calculated by successively integrating Equation (4), which leads to the following simple form (McFadden 1981):

$$P_{jiw} = \frac{e^{Z_{jiw}\gamma_j}}{\sum_{k=1}^{J} e^{Z_{kiw}\gamma_k}} \tag{5}$$

A log-likelihood function is constructed from Equation (5) and the parameters are estimated by Maximum Likelihood method. Note that this model assumes Independence from Irrelevant Alternatives (IIA). That is, the relative probability of choosing alternatives is independent of other alternatives (Train 2003). If the choice set remains the same for all households, this is not a strong assumption. However, if the choice set varies across households or new choices are introduced in the future, the IIA assumption can be violated.

Using the estimated parameters in Equation (5), we calculate the probability that each land type is chosen in each AEZ, given the exogenous variables in that AEZ. Because these variables (climate, soils, elevation) differ by AEZ, it is expected that land uses will differ across the sixteen AEZs. For example,

in a dry savannah, we expect that households are more likely to choose to have livestock because of a favourable climate condition to livestock management while they prefer forest products in humid forest zones. Differentiating Equation (5) with respect to a climate variable, z_l, yields the marginal effect on the choice probability due to a change in the climate variable:

$$\frac{\partial P_{jiw}}{\partial z_l} = P_{jiw} \cdot \gamma_{lj} - \sum_{k=1}^{J} P_{kiw} \cdot \gamma_{lk} \tag{6}$$

Note that the marginal impact of each climate variable on the choice probability of each land type depends upon the climate and other independent variables which vary by AEZ. It therefore follows that households in different AEZs will react differently to climate change even though the parameters of the model are not specific to an AEZ. The same holds for climate change of a larger scale in the long term.

3. Description of data

This study combines seven distinct datasets from different sources: household surveys by the World Bank, Agro-Ecological Zones of the FAO, soil data of the FAO, water availability data by the University of Colorado hydrology team, African spatial dataset of the World Bank, climate data by the US Ministry of Defense satellites and the World Bank, and climate scenarios by Atmospheric Oceanic General Circulation Models (AOGCMs). We describe each dataset below except for the climate scenarios which are reserved for the simulation section of the paper.

Household surveys were collected from eleven countries across Africa as part of the World Bank project on climate change (Dinar *et al.* 2008). South Africa, Zimbabwe and Zambia were sampled from the South, Kenya and Ethiopia from the East, Senegal, Niger, Burkina Faso, and Ghana from the West, Cameroon from the Central Africa, and Egypt from the North. In each country, districts were selected to represent a broad range of climate in that country. In each selected district, surveys were conducted of randomly selected farms.

Climate data were obtained from both satellite measurements and ground weather station measurements (Mendelsohn *et al.* 2007). Temperature data came from a set of polar orbiting satellites operated by the US Department of Defense. These satellites are equipped with sensors that measure surface temperature by detecting microwaves that pass through clouds. However, these satellites do not measure precipitation directly. Hence, we use precipitation data of the Africa Rainfall and Temperature Evaluation System (ARTES) of the World Bank (World Bank 2003). This data set, created by the National Oceanic and Atmospheric Association's Climate Prediction Center, interpolates weather variables across Africa based on ground station measurements of precipitation.

Soil data came from the FAO digital soil map of the world CD-ROM (FAO 2003).The FAO data provide information about major and minor soils in each location as well as slope and texture. Data concerning the hydrology were obtained from the University of Colorado (Strzepek and McCluskey 2006). Using a hydrological model for Africa, seasonal flows and runoffs were calculated for each district in the surveyed countries.

To explain the difference in land uses across divergent external soil and climate conditions, we use a typology of Agro-Ecological Zones (AEZs) developed by the FAO as a mechanism to classify the crop potential of the land (FAO 1978). The AEZ dataset determines the agro-ecological type of land in Africa (such as desert, forest, and savannahs) based on the growing length of the season using climate, soils, and elevation. The AEZs were expected to be helpful predictors of the productivity of land for crops (Fischer and van Velthuizen 1996). Africa is classified into sixteen AEZs, which will be discussed in detail in the next section.

Finally, data on spatial characteristics of the farms were obtained from the World Bank's spatial dataset, Africa Infrastructure Country Diagnostic (AICD; World Bank 2009). The dataset contains spatial characteristics of a given identity such as distance to a nearest city and distance to a major port. This information is calculated based on the information from various previous studies by the World Bank.

4. Empirical results

Varied agro-ecosystems across Africa can be seen from the Agro-Ecological Zones defined by the FAO in Figure 1. It shows dominant ecosystems across all the districts in Africa. The Sahara desert occupies a vast land area in the North. There are also desert zones in the eastern and southern edges of the continent. Just beneath the Sahara in West Africa is the lowland semi-arid zone, followed by lowland dry savannah, lowland moist savannah, and the lowland sub-humid zone. The lowland humid forest then stretches from Cameroon across Central Africa. Below the humid forest zone is mid elevation dry and moist savannahs. Eastern Africa is composed of desert, lowland dry savannah, and high elevation humid forest, and high elevation dry savannah which are located around Mount Kilimanjaro and part of Kenya. Eastern coasts are lowlands in which the landscape is dry and mostly savannahs. Southern Africa consists of lowland or mid elevation moist savannah and dry savannah.

As each AEZ is endowed with unique agro-ecological resources, we expect preferred land use types to differ across the AEZs. We summarize, in Table 1, the sample distribution of the four land uses defined in the theory section across the sixteen AEZs. As expected, in lowland dry and moist savannahs, the most dominant land use is crops-livestock. Crops-livestock is chosen most frequently in dry and moist savannahs, semi-arid, sub-humid zones in mid elevation. In high elevation, dry zones are favourite areas for crops-livestock. In
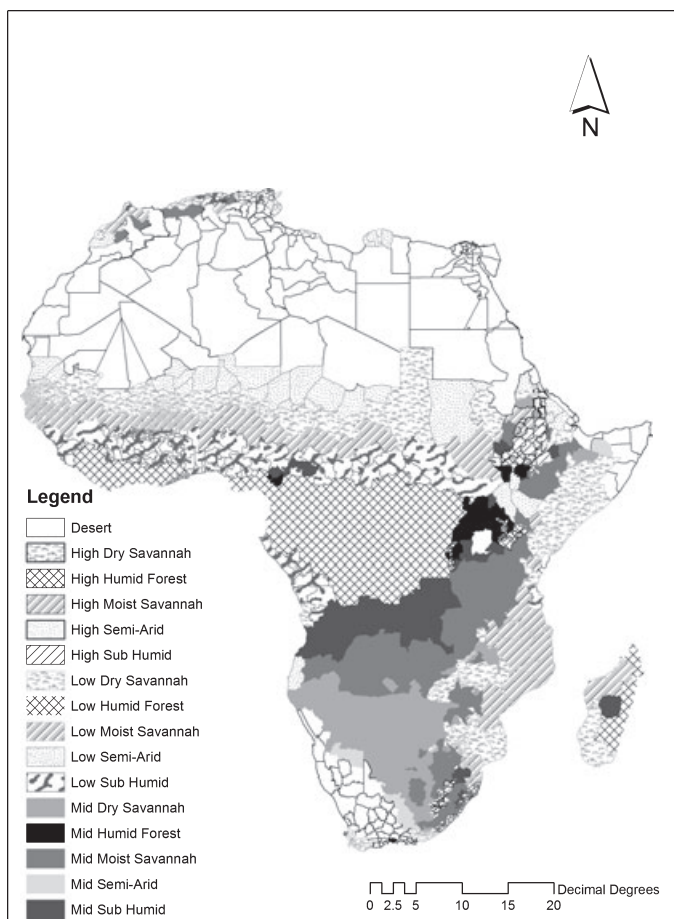
Figure 1   Agro-ecological zones of Africa.

lowland humid forest, the most dominant land use is crops-trees. Trees are chosen, either crops-trees or crops-livestock-trees, most frequently in lowland, mid elevation, and high elevation humid forests. Crops-only are chosen most often in lowland semi-arid zones and deserts. The table also shows annual mean temperatures and precipitations for each AEZ. Temperature is highest in lowland semi-arid and dry savannahs. Precipitation is highest in humid forests regardless of elevation. Precipitation is as low as 11 mm/month in the deserts.

   The summary statistics in Table 1 describe, at the AEZ level, the choices African households have made in coping with natural conditions they are faced with. With the help of micro-econometric methods, we can further explore actual decisions by the households themselves, not the district level averages. As explained in the theory section, we assume that an individual chooses to use its land for a specific purpose when the expected income from that use is larger than those from other uses. We explain the household choices by a set of climate variables after controlling soil conditions, water

S.N. Seo

Table 1 Africa's land use by agro-ecological zone

AEZ	Crops only (%)	Crops + livestock (%)	Crops + trees (%)	Crops + livestock + trees (%)	Annual mean temperature (°C)	Annual mean precipitation (mm/month)
Desert	46	51	1	2	18.8	11.7
High elevation dry savannah	34	66			20.4	61.0
High elevation humid forest	27	40	16	17	18.0	91.6
High elevation moist savannah	42	52	3	3	18.7	74.2
High elevation semi-arid	34	66			20.0	48.5
High elevation sub-humid	28	49	11	12	18.0	85.5
Lowland dry savannah	44	51	2	3	25.9	48.5
Lowland humid forest	31	22	40	17	20.4	113.3
Lowland moist savannah	30	60	4	6	24.1	68.6
Lowland semi-arid	50	46	2	2	26.7	34.2
Lowland sub-humid	30	49	13	11	22.3	89.9
Mid-elevation dry savannah	40	54	3	4	20.4	63.9
Mid-elevation humid forest	27	35	20	18	18.2	117.0
Mid-elevation moist savannah	42	46	6	6	19.7	73.6
Mid-elevation semi-arid	30	70			20.3	50.2
Mid-elevation sub-humid	23	45	14	17	19.0	94.4

availability, market conditions, household characteristics, spatial access variables, and policy factors.

In Table 2, we show the Multinomial Logit choice analysis of the four land use types: crops only, crops-livestock, crops-trees, and crops-livestock-trees. The table reports three sets of parameters setting the crops-livestock-trees as the base case. Climate variables are highly significant. The model includes summer and winter temperatures in quadratic forms to reflect non-linear responses. To distinguish the Sahel climate and the higher agricultural risks in the region, the regression uses climate and West Africa interaction variables. Precipitation variables are specified in the same manner. Climate variables as well as West African interaction terms are highly significant.

Among the significant covariates is water availability at the district. Larger water flow increases the choices of crops-only and crops-livestock. Larger runoff increases the likelihood of crops-only land type. The results indicate

Table 2   Multinomial Logit model of land use choice

	Crops only		Crops + livestock		Crops + trees	
	Est.	P	Est.	P	Est.	P
Intercept	−9.0717	0.02	−5.5113	0.16	−17.514	0.00
Summer temperature	0.8405	0.03	0.6755	0.08	1.0295	0.07
Summer temperature sq	−0.00327	0.72	−0.00185	0.84	−0.0159	0.25
Summer precipitation	0.0151	0.00	0.0199	<0.0001	0.0154	0.01
Summer precipitation sq	−0.00008	<0.0001	−0.00009	<0.0001	−0.00004	0.03
Winter temperature	−0.1469	0.65	−0.2521	0.43	0.5148	0.23
Winter temperature sq	−0.012	0.16	−0.00715	0.40	−0.0198	0.08
Winter precipitation	0.0209	0.01	0.0125	0.13	0.023	0.04
Winter precipitation sq	−0.00012	0.01	−0.00008	0.07	−0.00008	0.16
Sum temp* WestAf	0.1891	0.00	2.2485	<0.0001	−2.6736	0.00
Sum temp sq* WestAf	−0.00948	0.00	−0.0451	<0.0001	0.0479	0.01
Sum prec* WestAf	−0.0735	0.03	−0.095	0.00	0.000095	1.00
Sum prec sq* WestAf	0.000413	0.01	0.000524	0.00	−0.00001	0.95
Win temp* WestAf	−0.684	0.00	−2.929	<0.0001	2.566	0.01
Win temp sq* WestAf	0.0413	<0.0001	0.086	<0.0001	−0.0411	0.08
Win prec* WestAf	−0.0134	0.54	−0.00391	0.86	0.00536	0.84
Win prec sq* WestAf	0.000187	0.45	0.000119	0.64	−0.00001	0.97
Water flow	0.6361	<0.0001	0.5617	<0.0001	0.2284	0.08
Run off	0.0117	0.01	0.00268	0.56	−0.00282	0.56
Arenasols	−1.2655	0.20	−2.4612	0.01	0.00233	1.00
Ferralsols	2.4892	0.00	2.1669	0.01	−1.9215	0.17
Luvisols	−1.3117	0.00	−1.4193	0.00	−0.8251	0.09
Elevation	0.000655	0.00	0.000485	0.01	0.000642	0.00
Distance to port	0.0234	0.04	0.0299	0.01	−0.0701	<0.0001
Extension visits	−0.00825	0.01	−0.00485	0.07	−0.00159	0.66
Education years	−0.0195	0.11	−0.0307	0.01	−0.00874	0.53
Age of head	−0.0189	<0.0001	−0.0159	0.00	−0.0114	0.03

*P value for LR statistic <0.0001.

the importance of water availability at the ground for the success of crops in addition to rainfall.

Soil conditions and geography play important roles. When soil is Ferralsols, a family is more likely to choose crops-livestock. When the dominant soil is Luvisols or Arenosols, it is less likely to choose this land type. Soil Ferralsols increases the use of crops-only while soil Luvisols decreases it. High elevation increases the three land types against the all-inclusive land type, i.e. the land type that has crops, livestock, and trees together.

Accessibility to a major market is tested by the distance to the nearest major port. As the distance increases, land use for crops-trees declines against crops-livestock-trees land use while those for crops-only or crops-livestock increase again against the all inclusive land type. Distance to the nearest city was also tested but not significant, and was therefore dropped out of the regression.

Household characteristics are tested using years of schooling, age of the head of the household, and the number of visits by extension service. An older farmer tends to decrease the choices of the three land types against the all-inclusive land use. This may reflect higher risk aversion by an old person

to specialize in a certain product. A more educated household head is less likely to have crops-livestock combination. This may just reflect that the average years of schooling is only 4 years in the sample. When the household has more visits by extension service, it is less likely to specialize in crops probably because livestock farms need to rely on this service more heavily.

Using the estimated parameters in Table 2, the probability of each land type to be chosen by each household is calculated. The current probability distributions of these four land types across Africa are drawn in Figure 2 by extrapolating estimated results by AEZs. The crops-only land use is chosen frequently in the desert zones and mid/high elevation regions. The crops-animals, on the other hand, is chosen widely across the lowlands in West Africa and East African coasts when it is not too wet. The crops-trees is dominantly chosen in humid forested zones in Central Africa. The crops-trees-animals land type is chosen more often in Central Africa. The figures clearly show that the favoured use of land varies across the continent as existing climate condition varies.

As it is difficult to see climate sensitivities of different land uses directly from Table 2, marginal effects from the changes in climate variables are calculated in Table 3. The table shows estimated choice probabilities of the four land types across the AEZs. Crops-only is chosen most frequently in lowland semi-arid, lowland dry savannah, and deserts. Crops-animals is chosen most often in high elevation dry savannah and semi-arid zones, mid elevation semi-arid, and lowland moist savannah zones. Crops-trees is chosen most often in humid forest zones regardless of elevation. Crops-trees-animals is chosen most often in high elevation humid forest, lowland humid forest, and mid elevation sub-humid zones.

The table also shows how these current choices will change if the climate were to be disturbed by a small amount. If temperature increases by 1°C, crops-only will increase except in wet zones, crops-livestock will decrease except in lowland wet zones, crops-trees will increase with an exception of lowland sub-humid AEZ, and crops-livestock-trees will increase except for lowland humid forest. If precipitation increases by 1 mm/month, crops-only will decrease except for deserts and lowland dry zones, crops-livestock will decline except in highland semi-arid, lowland moist savannah, lowland sub-humid, and mid elevation semi-arid zones, crops-trees will increase without exceptions, and crops-trees-animals will increase except in semi-arid zones regardless of elevation, lowland sub-humid, and lowland dry savannah zones.

5. Climate simulations

The analyses in the previous section make it clear that the current land allocation across the landscape depends significantly on climate factors. Consequently, any change in climate will prompt changes in future land use. We analyze in this section how anticipated climate changes would affect land use decisions in the future. By controlling other factors that might affect land use
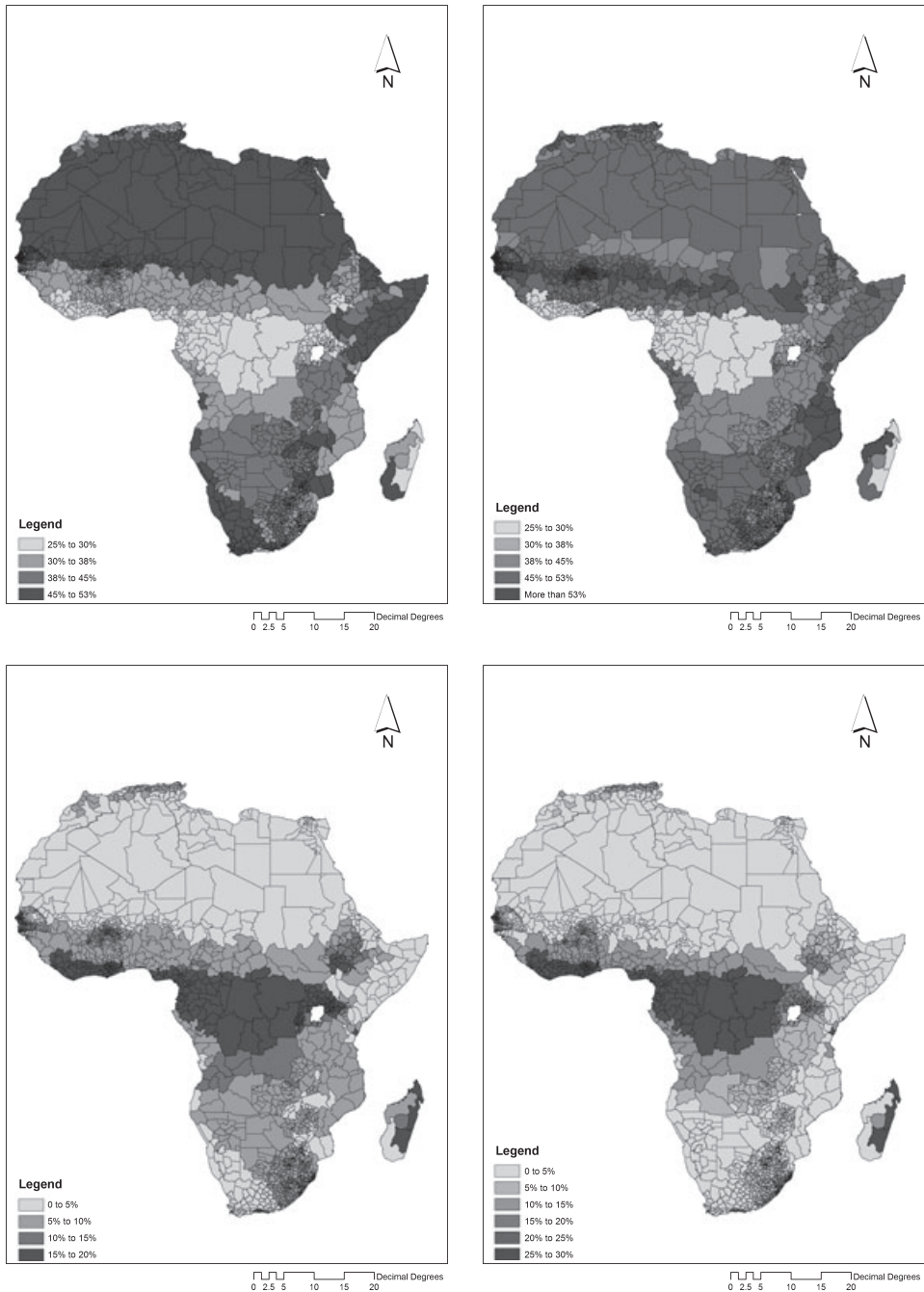
Figure 2 Probabilities to choose crops-only, crops-livestock, crops-trees, crops-livestock-trees (Clockwise from top left).

decisions, we single out the sole effects of climate. Needless to say, future decisions will crucially rely on other factors than climate such as population, technology, international trade, and policy factors.

Table 3 Marginal effects of climate on land use by agro-ecological zone

	Desert (%)	High elevation dry savannah (%)	High elevation humid forest (%)	High elevation moist savannah (%)	High elevation semi-arid (%)	High elevation sub-humid (%)	Lowland dry savannah (%)	Lowland humid forest (%)
Crops	51.20	32.60	29.20	35.20	32.90	33.00	46.00	28.80
ΔT	3.80	2.40	-1.50	1.20	2.80	0.60	3.10	0.40
ΔP	0.01	-0.03	-0.12	-0.03	-0.02	-0.09	0.02	-0.15
Cr + lvs	45.70	59.50	38.10	48.80	60.30	45.60	49.20	26.60
ΔT	-5.40	-6.80	-8.70	-8.00	-6.70	-8.40	-4.10	0.20
ΔP	-0.01	0.00	-0.14	-0.04	0.03	-0.13	-0.04	-0.02
Cr + trees	2.00	3.50	15.20	7.10	2.90	10.00	2.20	27.20
ΔT	1.00	1.80	5.60	3.50	1.80	4.10	0.20	0.30
ΔP	0.01	0.03	0.19	0.08	0.01	0.15	0.02	0.13
Cr + lvs + trees	1.20	4.40	17.50	9.00	3.90	11.50	2.50	17.40
ΔT	0.60	2.60	4.60	3.30	2.10	3.70	0.80	-0.90
ΔP	-0.01	0.00	0.07	0.00	-0.02	0.07	0.00	0.05

	Lowland moist savannah (%)	Lowland semi-arid (%)	Lowland sub-humid (%)	Mid-elevation dry savannah (%)	Mid-elevation humid forest (%)	Mid-elevation moist savannah (%)	Mid-elevation semi-arid (%)	Mid-elevation sub-humid (%)
Crops	31.90	52.70	30.30	42.50	29.70	41.70	35.40	31.40
ΔT	1.90	2.90	-0.10	2.40	-2.10	2.60	3.00	-0.40
ΔP	-0.07	0.04	-0.11	-0.02	-0.22	-0.04	-0.02	-0.12
Cr + lvs	57.90	43.40	50.00	47.70	33.60	44.80	58.20	42.00
ΔT	-3.80	-4.70	0.40	-6.60	-8.00	-6.60	-6.60	-8.10
ΔP	0.03	-0.04	0.07	0.00	-0.21	-0.05	0.02	-0.18
Cr + trees	4.50	1.30	11.10	4.20	19.40	6.30	2.90	12.90
ΔT	0.70	0.30	-0.30	1.70	5.90	1.90	1.50	4.30
ΔP	0.03	0.01	0.06	0.03	0.28	0.06	0.02	0.19
Cr + lvs + trees	5.70	2.70	8.70	5.60	17.30	7.10	3.60	13.70
ΔT	1.20	1.50	0.00	2.40	4.20	2.20	2.10	4.30
ΔP	0.01	-0.01	-0.02	-0.01	0.15	0.03	-0.01	0.11

To simulate the effects of climate, a range of climate outcomes is explored that are consistent with the most recent scientific report (IPCC 2007). Two distinctly different future climate predictions for 2060, half a century from now, are examined: The CCC (Canadian Climate Centre) scenario (Boer *et al.* 2000) and the PCM (Parallel Climate Model) scenario (Washington *et al.* 2000). In each scenario, expected changes at the grid cell level were summed with population weights to predict climate changes by country. Then, the consequences of these country level climate change scenarios for 2060 on land use choices are examined.

To obtain district level climate predictions for each scenario, predicted changes in temperature from the climate models were added to the baseline temperature of each season in each district. For precipitation, predicted percentage changes in precipitation from the two climate models were multiplied to the baseline precipitation of each season in each district. Table 4 summarizes the African mean temperatures and precipitations predicted by the two scenarios. By 2060, the PCM predicts an average increase of 1.3°C increase while the CCC predicts an average increase of 2.7°C increase in annual mean temperature. The PCM predicts an average 10 per cent increase in annual mean rainfall in Africa but the CCC predicts an average 10 per cent decrease. So, the PCM scenario predicts a mild and wet future whereas the CCC scenario a hot and dry future in Africa.

The impacts of each climate scenario were measured by the differences in the probabilities to choose each land type before and after climate change. Table 5 reports the simulation results by Agro-Ecological Zones. Under a hot and dry future as the CCC scenario foresees, it is quite noticeable that crops-livestock system increases by large percentages in the lowland zones and deserts in Africa (Seo and Mendelsohn 2008). A hotter drier condition turns the landscape into savannahs which are more suitable for livestock grazing than crops (Sankaran *et al.* 2005; Nin *et al.* 2007). By contrast, crops-only and crops-trees land types decline in the same zones, consistently with the previous literature on crop vulnerabilities (Reilly *et al.* 1996). On the other hand, in high elevations, crops-only and crops-trees land types increase, albeit slightly. In high and mid elevations, when the area is dry, crops-livestock and crops-livestock-trees land types increase. In mid elevation humid zones, crops-trees decline substantially (See Figure 3).

Table 4 AOGCM climate scenarios

	Current	Half a century later, 2060
Temperature (°C)		
CCC	18.1	20.8 ($+2.7$)
PCM	18.1	19.5 ($+1.3$)
Rainfall (mm/month)		
CCC	119	107 (-9.5%)
PCM	119	133 ($+11.9\%$)

Table 5 Impacts of climate scenarios on land use change by agro-ecological zone

		Desert (%)	High elevation dry savannah (%)	High elevation humid forest (%)	High elevation moist savannah (%)	High elevation semi-arid (%)	High elevation sub-humid (%)	Lowland dry savannah (%)	Lowland humid forest (%)
Crops	CCC	-6.50	0.20	2.90	2.40	0.70	4.40	-17.70	-6.10
	PCM	-1.20	9.00	-19.00	-0.50	9.10	-9.20	5.50	-4.10
Cr + lvs	CCC	6.00	0.10	-0.50	-1.40	-1.30	-0.80	18.10	23.40
	PCM	-6.00	-9.40	-25.20	-14.40	-11.10	-19.20	-8.80	-0.10
Cr + trees	CCC	-0.10	-1.60	0.80	0.00	-0.60	-1.30	-1.20	-17.80
	PCM	5.20	2.10	16.00	11.20	3.40	14.40	0.10	-1.30
Cr + lvs + trees	CCC	0.50	1.40	-3.20	-1.00	1.20	-2.20	0.80	0.50
	PCM	2.10	-1.80	28.20	3.70	-1.50	14.00	3.20	5.50

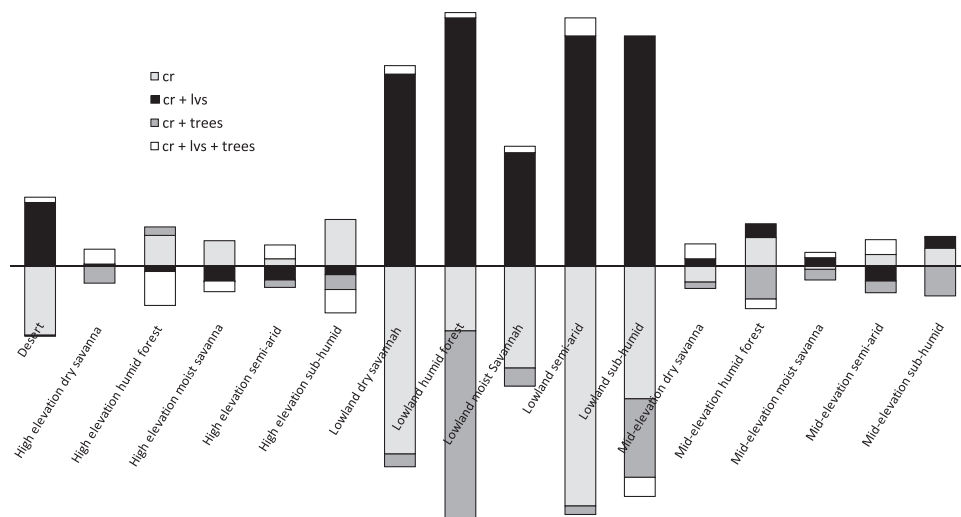|		Lowland moist savannah (%)	Lowland semi-arid (%)	Lowland sub-humid (%)	Mid-elevation dry savannah (%)	Mid-elevation humid forest (%)	Mid-elevation moist savannah (%)	Mid-elevation semi-arid (%)	Mid-elevation sub-humid (%)
Crops	CCC	-9.60	-22.60	-12.50	-1.50	2.70	-0.30	1.10	1.70
	PCM	1.60	4.10	-3.60	-2.80	-21.20	-2.80	7.30	-12.90
Cr + lvs	CCC	10.70	21.70	21.70	0.70	1.30	0.80	-1.40	1.10
	PCM	-7.90	-14.10	-1.90	-9.40	-24.10	-8.10	-8.60	-19.60
Cr + trees	CCC	-1.80	-0.70	-7.40	-0.60	-3.10	-1.00	-1.20	-2.80
	PCM	-0.90	1.00	-0.40	4.40	17.70	2.70	2.50	11.50
Cr + lvs + trees	CCC	0.60	1.70	-1.70	1.50	-0.90	0.50	1.50	0.10
	PCM	7.30	8.90	5.80	7.90	27.70	8.20	-1.20	21.00

Figure 3 Land use changes by agro-ecological zone under the CCC 2060. Note: Bars refer to the changes in selection probabilities. For reference, the bar of 'Cr + lvs' in the desert refers to the 6 per cent increase in the choice of this land use. Cr, crops; lvs, livestock.

With a different climate scenario which foresees a milder and wetter future, land uses would be quite different by 2060. Under the PCM scenario, mid to high elevation humid zones will be affected most from climate change. In these zones, crops-trees and crops-livestock-trees increase by large percentages while crops-only and crops-livestock land types decline by large percentages. In the lowland dry zones, crops-only and crops-livestock-trees increase while crops-livestock declines. In the lowland wet zones, crops-livestock-trees increases while crops-only and crops-livestock decline (See Figure 4). Animal husbandry in Africa is highly vulnerable to livestock diseases which become prevalent in a hot and wet condition (Ford and Katondo 1977; University of Georgia 2007).

6. Conclusions and policy implications

This paper examines potential land use changes in Africa due to climate change with a micro-econometric analysis of cross-sectional household surveys. Particularly, we examine the potentials of forestry and animal husbandry in the continent as an adaptation measure to climate change by building a joint model of crops, animal husbandry, and forestry. We analyze micro-level choice decisions observed in around 9000 household surveys collected from 11 countries across all sub-regions of Africa. Four dominant land types are analyzed: crops-only, crops-livestock, crops-trees, and crops-livestock-trees. Current and future choice probabilities are estimated and extrapolated to the entire continent using the classification of Agro-Ecological Zones by the FAO.
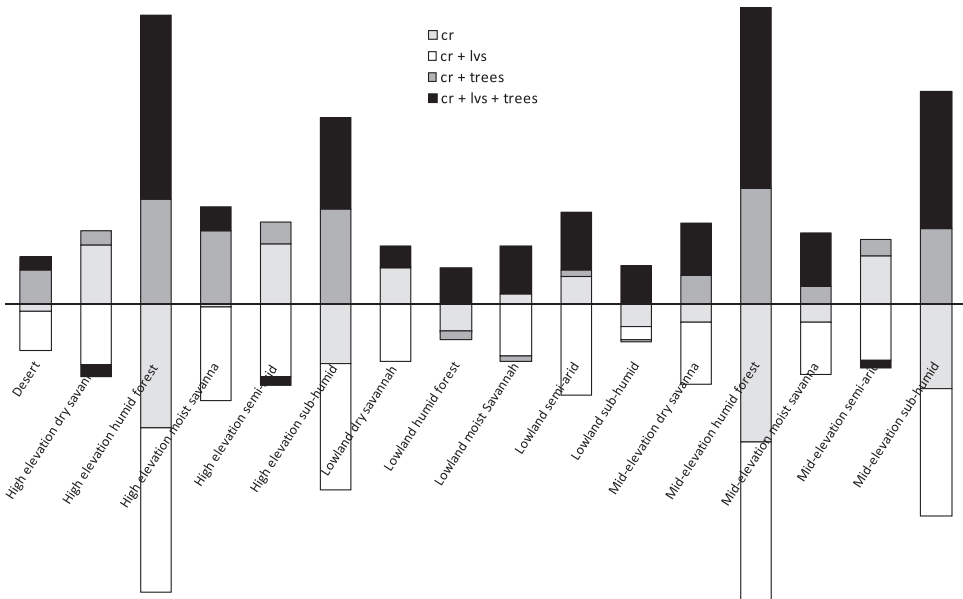
Figure 4 Land use changes by agro-ecological zone under the PCM 2060. Note: Bars refer to the changes in selection probabilities. For reference, the bar of 'Cr + trees' in the desert refers to the 5.2 per cent increase in the choice of this land use. Cr, crops; lvs, livestock.

The results indicate that the dominant land uses at present differ a great deal by the external Agro-Ecological Zone. The crops-only land use is chosen most frequently in lowland dry zones and deserts, and mid elevation dry and moist savannahs. The land use for crops-livestock is found most often in high elevation dry zones, mid elevation dry and moist zones, and lowland dry zones and moist zones. Crops-trees land type is favoured in humid forest zones regardless of elevation. All inclusive land use of crops-livestock-trees is practised most frequently in high elevation humid forest, lowland humid forest, and mid elevation humid zones.

Land use decisions are found to be strongly climate sensitive after controlling covariates, signaling the changes in the near future because of climate change. A small temperature increase by 1°C is predicted to increase crops-only land type except in wet zones, decrease crops-livestock land type except in lowland wet zones, increase crops-trees type with an exception of lowland sub-humid AEZ, and increase crops-livestock-trees land type except for lowland humid forest. A small precipitation increase by 1 mm/month is predicted to decrease crops-only type except for deserts and lowland dry zones, decrease crops-livestock except in highland semi-arid, lowland moist savannah, lowland sub-humid, and mid elevation semi-arid zones, increase crops-trees type without exceptions, and increase crops-livestock-trees land type except in semi-arid zones regardless of elevation, lowland sub-humid, and lowland dry savannah zones.

Expected changes in four land uses after half a century are simulated using two AOGCM climate scenarios. A hotter and drier scenario would change

the African landscape to be more animal populated, particularly in the low-lands. Under the CCC scenario, the crops-livestock system will increase by large percentages in the lowland zones and deserts in Africa. In these areas, crops-only and crops-trees land types will decrease. On the other hand, in high elevations, crops-only and crops-trees will increase, but only slightly. The land types of crops-livestock and crops-livestock-trees will increase in high and mid elevations if the area is currently dry. In mid elevation humid zones, crops-trees will decrease substantially. On the other hand, a wetter condition would change the landscape to be more populated by trees, particularly in the mid high elevation wet zones. Under the wetter PCM scenario, individuals are more likely to have some trees in their portfolio while they are less likely to have animals. Mid high elevation humid zones will be affected most from this scenario. In these zones, crops-trees and crops-livestock-trees will increase by large percentages while crops-only and crops-livestock will decrease by large percentages. In the lowland dry zones, crops-only and crops-livestock-trees will increase at the expense of crops-livestock. In the lowland wet zones, crops-livestock-trees will increase at the sacrifice of crops-only and crops-livestock.

The results contain important policy implications that are relevant in the discussions of adaptation to climate change in Africa (Smit and Pilifosova 2001). Land use choices at present across the landscape in Africa are highly sensitive to climate variations. In adapting to climate change, people, both individuals and policy organizations, could learn from the lessons this paper finds in the current distributions of land types. If climate becomes hotter and drier, people should be able to switch from crops-trees to crops-livestock or crops-only. If climate becomes wetter, on the other hand, they should avoid having animals and instead should switch to crops-trees. However, these adaptation responses should consider the existing agro-ecological condition to which an individual farm belongs (Seo *et al.* 2009). That is, the switch to crops-livestock under a hotter drier climate is most effective in the lowlands while the switch to crops-trees under a wetter climate is most effective in mid and high elevation humid zones.

In addition, the findings in the paper shed a new light on the past and future development programs in Africa which have focused heavily on high yielding crop varieties and often have failed (Byerlee and Eicher 1997; World Development Report 2008). As shown in this paper, lowland dry savannahs are not favourable zones for crops, neither are hot and humid forests in Central Africa. Development programs must consider existing climate and soil conditions as well as future climates carefully for them to be successful for crops, but more importantly they should consider diversifying their efforts into livestock and forest incomes. However, there is another layer in this discussion, i.e. future changes in technology that the current analysis does not include. If a certain heat tolerant crop species were to be developed in the near future, crops-only land type as well as a development project focusing on that new crop species might still be competitive even under a warmer climate condition.

Moreover, other factors such as government policies, trade regimes, and democratic governance may prove important in a farmer's adaptation to climate change by altering land uses, but the future changes in these factors are difficult to model at the moment (World Development Report 2008; Anderson and Masters 2009). This paper makes only limited efforts in controlling policy factors by including such variables as travel time to major markets, extension service, and West Africa specific variables. Finally, this paper does not provide an analysis of potential adaptation cost which could be beyond the capacity of subsistent households in sub-Saharan Africa. International policy organizations may need to assist adaptations of these subsistent populations, but should be careful not to induce perverse incentives, i.e. mal-adaptations by such engagements.

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