WPS4717

Policy Research Working Paper 4717

How Will Climate Change Shift Agro-Ecological Zones and Impact African Agriculture?

Pradeep Kurukulasuriya
Robert Mendelsohn

The World Bank
Development Research Group
Sustainable Rural and Urban Development Team
September 2008

Policy Research Working Paper 4717

Abstract

The study develops a new method to measure the impacts of climate change on agriculture called the Agro-Ecological Zone (AEZ) Model. A multinomial logit is estimated to predict the probability of each AEZ in each district. The average percentage of cropland and average crop net revenue are calculated for each AEZ. Then an estimate of the amount of cropland in Africa and where it is located is provided. Using current conditions, the model calculates baseline values of cropland and crop net revenue, and estimates the future impact of climate change using two scenarios—harsh and mild. Total cropland does not change much across the two climate scenarios. However, the predicted change in African crop revenue ranges from a loss of 14 percent in the mild climate scenario to 30 percent in the harsher climate scenario. The analysis reveals that the greatest harm from climate change is that it will shift farms from high to low productive AEZs. The approach not only identifies the aggregate impacts, but also indicates where the impacts occur across Africa. The central region of Africa is hurt the most, especially in the harsher climate scenario. The Agro-Ecological Zone Model is a promising new method for valuing the long-term impacts of climate change on agriculture.

This paper—a product of the Sustainable Rural and Urban Development Team, Development Research Group—is part of a larger effort in the department to mainstream research on climate change. Policy Research Working Papers are also posted on the Web at http://econ.worldbank.org. The authors may be contacted at Pradeep.Kurukulasuriya@undp.org and Robert.mendelsohn@yale.edu.

Produced by the Research Support Team

How Will Climate Change Shift Agro-Ecological Zones and Impact African Agriculture?[1]

Pradeep Kurukulasuriya and Robert Mendelsohn[2]

---

[1] This project was funded by the KCP/World Bank.

[2] Pradeep Kurukulasuriya, Energy and Environment Group, Bureau of Development Policy, United Nations Development Programme, New York; phone 212-906 6843; email: pradeep.kurukulasuriya@undp.org; Robert Mendelsohn, School of Forestry and Environmental Studies, Yale University; 230 Prospect St. , New Haven, CT06511; phone 203-432-5128; and a consultant to World Bank, email robert.mendelsohn@yale.edu;

1. Introduction

The growing evidence from the Intergovernmental Panel on Climate Change (IPCC) that climate will change as greenhouse gases accumulate (IPCC 2007) has added urgency to the need to understand the consequences of warming. Initial studies of climate change, using a variety of methods, identified Africa as one of the most vulnerable locations on the planet to climate change because it is already hot and dry, a large fraction of the economy is tied to agriculture, and the farming methods are relatively primitive (Pearce et al. 1996; Tol 2002; Mendelsohn and Williams 2004). The livelihoods and welfare of hundreds of millions of Africans depend on how climate change will affect African agriculture.

There have been predominantly two different methods used to measure the economic impact of climate change on African agriculture: the crop simulation approach and the Ricardian approach. The crop simulation approach uses the direct effect of climate change on individual crops (see Rosenzweig and Parry 1994; Parry et al. 2004). These studies reveal that the yields of the major grains grown in Africa would fall precipitously with warming. The Ricardian approach measures the relationship between net revenues from crops and climate using cross sectional evidence (Kurukulasuriya et al. 2006; Kurukulasuriya and Mendelsohn 2008). These studies also find that hot and dry climate scenarios would reduce crop net revenues in Africa. The Ricardian studies, however, generally estimate smaller damages than the crop simulation models. One explanation for this difference is the handling of adaptation. The Ricardian model captures endogenous adaptation, measures that farmers actually take to adjust to climate change. This adaptation is efficient (it makes the farmer better off). In contrast, the crop simulation studies examine only exogenous measures arbitrarily added by the researcher that are not necessarily efficient responses to climate change.

This paper relies on an entirely different approach to measure climate impacts. The study uses AgroEcological Zones (AEZs) as the cornerstone of the analysis. FAO established AEZs as a method of measuring crop productivity (FAO 1978). The zones were intended to capture the length of the growing season taking into account soil moisture. Although longer growing seasons are not always better, the AEZ system does do a good job of dividing a heterogeneous landscape into a set of homogeneous zones. Other factors that determine productivity such as status of soils, drainage, and crop type are reflected in the AEZ classification. In this analysis, we rely on the FAO classification of every district in Africa using this AEZ methodology[3] (FAO 2003). More recent work by FAO in this area includes the Land Use Systems of the World[4] and Globcover[5] initiatives.

---

[3] FAO and IIASA applied the AEZ methodology for the whole world (Fischer et al. 2002), not only for Africa.

[4] This data is developed in the framework of the LADA project (Land degradation Assessment in Drylands) by the Land Tenure and Management Unit of the Food and Agriculture Organization of the United Nations and is copyright of FAO/UNEP GEF.

[5] GlobCover is an European Space Agency led initiative in partnership with JRC, EEA, FAO, UNEP, GOFC-GOLD and IGBP. The GlobCover project has developed a service capable of delivering global

We begin the analysis by calculating the current average net revenue per hectare and the average fraction of cropland from total land in each AEZ. These values simply reflect current cropland and crop net revenues earned by farms in each AEZ. Seo et al (2008) reveal that farms in some AEZs, such as high-elevation moist savannah and mid-elevation sub-humid forest, are more valuable than farms in other AEZs, such as lowland semi-arid, lowland sub-humid, and mid-elevation dry savannah. The climate conditions in these high valued AEZs are more temperate and conducive to rainfed cropland. We then use a multinomial logit model to determine the probability (a value between 0 and 1) of each AEZ in each district across all of Africa given its climate, soils and elevation. Using current climate, this econometric model predicts the current distributions of different AEZs. Combining this information with the average crop net revenue per hectare and fraction of cropland for each AEZ, the expected cropland and crop income in each district in Africa today is estimated.

We then use this econometric model to examine the likely implications of climate change. Climate change will change the probability of each AEZ in each district. The changing probabilities imply that the AEZs will shift across the geography. For example, with warming, land will shift from temperate AEZs to more tropical AEZs or with drying, to more arid AEZs. We assume that future farms in a particular AEZ will have the same performance as current farms in that AEZ. As more land leaves one AEZ and shifts to another, expected cropland and crop income will change. We use this model to examine the impact of two very different climate scenarios for 2100. We rely on data from the Parallel Climate Model (PCM) (Washington et al. 2000) and the Canadian Climate Centre (CCC) (Boer et al. 2000) to examine the effects of two different climate predictions for 2100. These predictions were chosen because they span the range of likely outcomes predicted by the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC 2007). The PCM model predicts mild temperature increases of about 2°C and marginal gains in precipitation during summer and winter months. The CCC model predicts warming of over 5°C with drier summers and wetter winters (see Table 4).

The next section of the paper reviews the methodology and data in detail. The third section describes the results. The final section of the paper summarizes the results and briefly discusses the policy implications.

2. Methodology

The AEZ analysis presented in this paper is a comparative static analysis. It is intended to measure the long-run consequences of AEZs shifting over space from one equilibrium to another. As a long-run equilibrium analysis, it captures adaptation. It reflects the fact that farmers have adapted to the AEZ to which they are accustomed. This long-run approach also captures secondary effects such as changes in insects or other pests that may go along

---

composite and land cover maps using as input observations from the 300m MERIS sensor on board the ENVISAT satellite mission.

with being in a specific AEZ. The approach, however, is not a dynamic analysis. It does not capture transition costs that farmers may have as they adapt to a new AEZ.

As mentioned in the introduction, the FAO has assigned an AEZ to each district based on numerous characteristics of that district (FAO 2003). We now develop an econometric model that predicts how AEZs are assigned so that we can determine how climate change would alter the distribution of AEZs. We begin by estimating a model that explains the current distribution of AEZs. We employ a multinomial logit model to estimate the probability (P_{nj}) of each AEZ$_j$ in each district n given its characteristics, thereby quantifying the relationship between AEZs and climate, soils and elevation[6].

$$P_{nj} = \frac{e^{Z_{nj}\gamma_j + C_{nj}B_j}}{\sum_{k=1}^{J} e^{Z_{nk}\gamma_k + C_{nk}B_k}} \qquad (3)$$

where γ_j and β_j are vectors of estimated coefficients, Z_{nj} is a vector of soil and elevation characteristics, and C_j is a vector of climate coefficients. Interaction terms between temperature and precipitation were tried but dropped because they did not significantly improve the explanatory power of the model. Interactions between elevation and climate were included because elevation is an important component of AEZ classifications and the interaction terms are significant.

In order to make comparisons between the distributions of AEZs with current versus future climate, we must first predict a baseline distribution. The baseline is the predicted probability of each AEZ in each district given the baseline climate, C_0. Although the original data is discrete (each district is assigned a single AEZ), we predict the probability of each AEZ in each district for the baseline given current climate.

The baseline amount of cropland in each district n is equal to the amount of land in the district times the sum of the cropland fractions across all the AEZs weighted by their baseline probability in that district:

$$CR_n (C_0) = L_n * \sum F_j * P_{nj}(C_0) \qquad (4)$$

The baseline crop income in each district n is the amount of land in that district times the sum of the revenue per hectare of cropland in each AEZ times the cropland fraction in each AEZ weighted by the probability of each AEZ:

$$R_n (C_0) = L_n * \sum R_j * F_j * P_{nj}(C_0) \qquad (5)$$

We then use a future climate scenario, C_1, to determine how the probabilities of AEZs will change as climate changes. New probabilities for each AEZ in each district are calculated

---

[6] This is a commonly utilized statistical approach for modeling categorical response variables that take on more than two values. In this case, the categorical variable reflects the type of AEZ in a district the choice set is 14 types, as explained below.

with the new climate. Using the fraction of cropland and the net revenue per hectare of each AEZ, we then calculate new amounts of cropland and net revenue for each district.

$$CR_n\,(C_1) = L_n *\sum F_j * P_{nj}(C_1) \qquad (6)$$

and

$$R_n\,(C_1) = L_n *\sum R_j * F_j * P_{nj}(C_1) \qquad (7)$$

The difference between equations (6) and (4) reflects the change in cropland for each district and the difference between (7) and (5) reflects the change in crop revenue in each district. These results are then aggregated to different scales, namely country, region, and continent.

To test the above empirical framework, we make use of information on 16 AEZs identified and complied by the FAO for Africa (FAO 2003). Two of these AEZs, high elevation semi-arid and mid-elevation semi-arid, occur in only two small locations in Africa and so were dropped from the analysis. Two additional AEZs were combined into a single category because they are similar and again there are not many observations: high sub-humid forest and mid-elevation sub-humid forest. The analysis consequently evaluates 13 distinct AEZs across Africa as listed in Table 1. As can be seen in Table 1, one third of Africa is desert. Lowland dry savannah and lowland humid forest make up another third of Africa. The remaining third is broken into the ten remaining AEZ types.

We obtain cropland estimates across Africa from Lotsch (2007). These estimates are based on remote sensing-based land cover maps measured by the Moderate Imaging Spectroradiometer on the National Aeronautics and Space Administration (NASA) satellites. From this data, land was categorized into discrete uses (e.g. croplands, cropland mosaic, forest, shrublands etc.) at the scale of 1km^2. There are 197 land cover categories for the African continent in this data set. The information on agricultural land use was then compiled by the International Food Policy Research Institute (Wood, Sebastian, and Scherr 2000) and checked against national statistics. Additional estimates of cropland in Africa by the Oak Ridge National Laboratory (Dobson et al. 2000) and by the University of Wisconsin (Ramankutty and Foley 1998) yield similar results.

Using GIS methods, we overlay the cropland and AEZ data sets and calculate the average fraction of cropland in each AEZ *j*.

$$F_j=CR_j/L_j \qquad (1)$$

where CR_j is the amount of cropland in AEZ *j* and L_j is the amount of land in AEZ *j*.
For each AEZ, we assume that the amount of cropland changes proportionally with the amount of land in that AEZ. That is, the fraction of cropland remains constant for each AEZ. Land simply moves from being in one AEZ to another as climate changes.

The frequency of cropland reflects the suitability of conditions for rainfed agriculture. Table 1 reveals that mid and high elevation humid and subhumid forests have the highest fraction of cropland followed by mid elevation moist savannah. The AEZs with the lowest fraction of cropland are the deserts and lowland semi-arid areas. Cropland in these areas is largely irrigated and depends on the availability of water.

We obtained economic data on crop net revenue from a sample of over 10,000 farmers collected in 11 countries (Burkina Faso, Cameroon, Egypt, Ethiopia, Ghana, Kenya, Niger, Senegal, South Africa, Zambia, and Zimbabwe) (Dinar et al 2008). For each farm, we were able to identify the AEZ for the district. We then calculated the average net revenue per hectare of cropland, $R_{,}$, for each AEZ *j* (see Table 1).

$$R_j=TR_j/CR_j \qquad (2)$$

where TR_j is the total farm revenue generated in AEZ *j*.

An estimate of the expected crop revenue per hectare of land in each AEZ is calculated by multiplying the average net revenue per hectare by the fraction of cropland in that particular AEZ. As shown in Table 1, the two AEZs that produce the most net revenue per hectare of land are high-elevation moist savannah and high-mid elevation sub-humid forest. The lowest valued AEZs are lowland semi-arid, lowland sub-humid forest, and high-elevation dry savannah. Note that the net revenue per hectare of cropland in the desert is very high because it is irrigated.

Data on climate was gathered from two sources. We relied on temperature data from polar orbiting satellites operated by the Department of Defense (Basist et al. 1998). The precipitation data comes from interpolations between weather stations made by the National Oceanic and Atmospheric Association's Climate Prediction Center- Africa Rainfall and Temperature Evaluation System (ARTES) (World Bank 2003).

We have combined monthly climate data into winter and summer seasonal averages (Kurukulasuriya and Mendelsohn 2008). In the southern hemisphere, we define the average of November, December and January as summer and May, June and July is winter. The northern hemisphere seasons are the opposite. It is apparent that each AEZ has different climate characteristics. Table 2 shows the average climate variables for each AEZ in Africa. Lowland semiarid and lowland dry savannah AEZs are relatively hot. Deserts have average temperatures for Africa but they are dry. Mid and high elevation AEZs are cooler.

Soil data were obtained from the FAO (FAO 2003); providing information on the major and minor soils in each location as well as slope and texture. Predicted natural water flows in each district were predicted from a hydrological model for Africa (Strzepek and McCluskey 2006). Data on elevation at the centroid of each district was obtained from the United States Geological Survey (2004). The USGS data is derived from a global digital elevation model with a horizontal grid spacing of 30 arc seconds (approximately one kilometer).

3. Results

The estimated multinomial regressions are reported in Table 3. The omitted AEZ is the desert. The coefficients for the climate, soils, and elevation variables are shown for a weighted and unweighted regression. The weighted regression weights districts by the square root of area. Precipitation and temperature clearly play a significant role in determining the probability of AEZs. In the unweighted regressions, there is a significant temperature effect in every AEZ except mid and high elevation humid forest and lowland dry savannah. In the weighted regressions, there is no temperature effect in these same three AEZs as well as in mid-elevation dry and moist savannah. In the unweighted regressions, there is a significant precipitation effect in every regression. In the weighted regressions, precipitation is significant in all but high elevation humid forest, mid elevation moist savannah, mid elevation sub-humid forest, and lowland dry savannah. Despite the fact that many AEZs are labeled by elevation, elevation is not always significant. Elevation is not significant in identifying many mid-elevation AEZs or in the lowland dry savannah and lowland semi-arid AEZs. The interaction terms between elevation and climate capture a subtle effect across some AEZs. Elevation and summer temperature often have a negative and significant interactive effect. Controlling for elevation and climate, places that are both higher and hotter during the summer are relatively more likely to be desert. Several lowland AEZs have a positive interaction effect between precipitation and elevation. Controlling for climate and elevation, places that are both higher and wetter are more likely to be lowland savannah or humid forest AEZs. Finally, although we examined the explanatory power of detailed soil data, no soil variables were jointly significant, and consequently soils were dropped from the model.

The estimated models in Table 3 correlate strongly with the present AEZ distribution. The overall fit of the unweighted model is high as measured by the pseudo-R squared 0.62 and the log likelihood function value of -1611. Similarly, the weighted model has a log likelihood value of -1138.3 with a pseudo-R squared of 0.70. These estimates suggest that both models do a good job of capturing the distribution of AEZs currently observed.

Figure 1 compares the observed distribution of AEZs relative to the predicted distribution given current climate and the weighted model. Both maps are similar. However, observed high humid forests in Central Africa are predicted to be low to mid elevation humid forests and some observed lowland dry savannahs in southwest Africa are predicted to be moist savannahs. Except for these differences, the predicted AEZs look like the observed AEZs.

We now predict how future climate scenarios might affect the distribution of AEZs, the amount of cropland, and cropland net revenues in Africa. For exposition purposes we use two 2100 scenarios, although the analysis could just as easily have been replicated for any other time-frame. The actual predicted climate changes in each country vary. We used the predicted absolute change in temperature and percentage change in precipitation from the 2000-2010 decade to the 2090-2100 decade from each climate model. District changes in temperature are calculated by adding the predicted country temperature changes to current temperature. Precipitation changes are calculated by multiplying predicted changes in precipitation by current rainfall values.

Using the district level changes for each climate scenario, we then predict how AEZs will change in each district using the weighted regression in Table 3. The total amount of land in Africa remains the same, but the amount of land in each AEZ shifts. As shown in Figure 2, there are three large land changes in the PCM scenario: a reduction of 195 million hectares of lowland humid forest, a reduction of 94 million ha of desert, and an increase of 217 million hectares of lowland sub-humid forest. There are much larger land shifts across AEZs in the CCC scenario. The model predicts a loss of 451 million ha of lowland humid forest, a loss of 335 million ha of desert, a gain of 390 million ha of lowland sub-humid forest, and a gain of 356 million ha of medium elevation sub-humid forest.

We map the AEZ changes across the landscape in Figure 3. By comparing the original predicted values in Figure 1b with the distribution of AEZs in Figure 3a, and Figure 3b, one can see how AEZs have changed in the PCM and CCC scenarios. There are large changes in AEZs between the baseline and the PCM maps in North, South, and East Africa. In particular, high elevation humid forests increase in Eastern Africa and mid-elevation moist savannahs increase in southern Africa. In the CCC scenario, one can see changes in East, Central, West and South Africa. The most notable change in the CCC scenario is the increase in all elevations of sub-humid forests and the reduction of lowland humid forests and deserts. The fact that the model predicts deserts in the southern Sahara shrink may seem counterintuitive but the African deserts are not too hot, they are simply too dry. According to the GCM predictions, there is enough increase in rainfall in these desert regions to change their status. Whether this translates into a change in crop production is a more complicated issue since desert crops depend on surface flows. Although future studies could analyze how surface flows change with warming, this analysis does not predict potential changes in surface flows.

The changes in the area of each AEZ have implications for the amount of cropland as shown in Table 5. The percent of cropland in each AEZ is assumed to remain constant so that as the size of an AEZ changes, cropland changes. Although the sizes of the AEZs change considerably, the effect on cropland is offsetting, so that the net changes in cropland for Africa are small in both scenarios. In the PCM scenario, the large decrease of 47 million ha of cropland in lowland humid forest is partially offset by the increases in cropland in high elevation humid forest and all elevation sub-humid forest, lowland moist savannah, and mid elevation dry savannah. The net effect in the PCM scenario is a loss of 27 million hectares (5%) of cropland. With the CCC scenario, the cropland in lowland humid forest is almost completely lost but it is offset by increases in cropland in lowland dry savannah and sub-humid forests at all elevations. The net impact is a gain of 20 million hectares or 4%.

With the PCM scenario, in addition to the 5% loss of cropland, there is a slight shift to lower valued cropland as shown in Table 6. With the PCM scenario, there is a $36 billion loss of annual crop revenue from lowland humid forests and another $10 billion loss from deserts. This is partially offset by small gains in several other AEZs. The net effect of the PCM scenario is a $39 billion loss per year, which amounts to 14% of net crop revenue. Although the CCC scenario predicts a slight gain in cropland area, it predicts a large loss in crop revenues as land shifts into lower valued AEZs. The CCC scenario leads to gains in net revenue from lowland dry savannahs and especially mid to high elevation sub-humid forests but these gains are overwhelmed by losses in deserts and especially lowland humid forests. The net impact is a crop revenue loss of $84 billion per year or 30%.

The aggregate effects are broken down by region in Table 7. Each of the regions is affected differently by each climate scenario. The largest losses are suffered by Central Africa (28% and 80% losses under the PCM and CCC scenario, respectively), which accounts for half of the net damages in each scenario. East Africa (11-12% losses) and North Africa (4-7% losses) are affected the least. Losses in Southern Africa increase from 12% under the PCM scenario to 17% under the CCC scenario.

The change in net revenues across the landscape can be seen in Figures 4a and 4b. Figure 4a captures the changes in net crop revenue in each district with the PCM scenario. There are damages in Western, Central and Southern Africa whereas there are benefits along a narrow band from East to West Africa where rainfall is expected to increase. Figure 4b depicts the CCC scenario. Although there are some small patches of gains in North and South Africa, most of the continent is harmed by this scenario. The net revenues losses across large swaths of land in West and Central Africa are greater than 90 percent.

4. Discussion

This paper develops an alternative method to evaluate climate change impacts. A model is estimated that captures how temperature, precipitation, and elevation cause land to be in one AEZ or another. Climate change is assumed to cause land to shift across AEZs according to this econometric model. For example, warming will cause land to shift from temperate towards tropical AEZs. The suitability of land for cropland and the net revenue per hectare of cropland is measured using the AEZ classifications of land. If warming causes districts to shift from high to low productive uses, it will cause damages. Similarly, if warming causes districts to shift from low to high productive AEZs, it will cause benefits.

The cooler temperatures of mid to high elevations are conducive to higher fractions of cropland in Africa. The dry desert and lowland semi-arid AEZs have the least amount of cropland. The most valuable cropland (highest crop net revenue per hectare of cropland) in Africa is in the Egyptian desert. All of this land is along the Nile, has ample water, and is irrigated. However, most of the rest of Africa depends on rainfed agriculture. In Sub-Saharan Africa, the most valuable cropland is in humid forests where there is plenty of rainfall. Combining the fraction of land in cropland and the net revenue per ha of cropland, reveals that the most valuable AEZs (highest net revenue per ha of land) are high elevation moist savannah and mid and high elevation subhumid forests. These AEZs are both relatively cool and wet. The lowest valued AEZs are the high elevation dry savannah, lowland semi-arid, and lowland subhumid forests which are AEZs that depend on rainfed farming but are too hot or too dry for cropland.

The econometric analysis linking AEZs to climate and elevation is convincing. Current seasonal temperatures and rainfall play important roles in determining the AEZ classification of a district. The multinomial regression is significant and effective at linking climate and the distribution of AEZs across Africa.

The climate scenario analysis suggests that the impact of climate change on Africa varies a great deal across scenarios and across the landscape. The results suggest that warming will be harmful to African agriculture not because it will reduce cropland but rather because it will reduce the value of cropland. That is, land will shift from high value to low value AEZs. The mild PCM scenario predicts a 5% reduction in cropland but a 14% reduction in crop net revenue. The CCC scenario predicts a 4% increase in cropland but a 30% reduction in crop net revenue. The impacts are not uniform across the landscape. According to the model, Central Africa will have the largest reduction in crop net revenue in all scenarios. Pockets of land in North and South Africa, by contrast, are predicted to benefit.

The extrapolation to future climate scenarios must, however, be viewed with caution. There may be key missing variables in the econometric analysis, many variables are measured with error, and economic conditions will change over time. The link between climate change and surface water flows has not been made in this analysis. Nonetheless, it is interesting to see that this AEZ analysis yields similar predictions to other methods of measuring climate impacts on agriculture.

The paper demonstrates that the AEZ concept first introduced by the FAO can successfully break down a complex landscape into a set of homogenous zones. Within each zone, farmers face similar conditions and earn similar net revenues. We estimate the productivity of a landscape simply by measuring how the size of each of these zones might change with climate change. The approach in this paper measures the long run change in productivity across the landscape. The econometric model predicting the current distribution of zones provides validity to the approach as it explains between 60 to 70 percent of the variation one observes across the landscape. Further, the method produces estimates of how crop net revenue will change over time that are consistent with other research methods (Kurukulasuriya et al. 2006; 2008). The changing AEZ model provides a new tool for understanding how climate change will impact agriculture in the future.

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. Applied Meteorology **37**: 888–911.

Boer, G., Flato, G., & Ramsden, D. 2000. "A Transient Climate Change Simulation with Greenhouse Gas and Aerosol Forcing: Projected Climate for the 21st Century" Climate Dynamics **16**: 427–450.

Dinar, A., R. Hassan, R. Mendelsohn, and J. Benhin. 2008. Climate Change and Agriculture in Africa: Impact Assessment and Adaptation Strategies, London: EarthScan.

Dobson, J. E., Bright, E. A., Coleman, P. R., Durfee, R. C., & Worley, B. A. 2000. "LandScan: A global population database for estimating populations at risk" Photogrammetric Engineering & Remote Sensing **66**: 849-857.

European Space Agency (ESA). 2008. Ionia Globcover, *http://ionia1.esrin.esa.int/index.asp*

Fischer, G., van Velthuizen, H., Shah, M., and Nachtergaele, F. 2002. Global Agro-Ecological Assessment for Agriculture in the 21st Century: Methodology and Results (Research Report RR-02-02). Laxenburg, Austria: International Institute for Applied Systems Analysis (IIASA) and Food and Agriculture Organization (FAO) of the United Nations (UN). *http://www.iiasa.ac.at/Research/LUC/GAEZ/index.htm*

Food and Agriculture Organization (FAO). 1978. "Report on Agro-Ecological Zones; Volume 1: Methodology and Results for Africa" Rome, Italy.

Food and Agriculture Organization (FAO). 2003. "The Digital Soil Map of the World: Version 3.6" Rome, Italy.

Food and Agriculture Organization (FAO). 2008 "Land Use Systems of the World", *http://lprlada.fao.org/lada/index.php?option=com_content&task=blogsection&id=4&Itemid=158*

Food and Agriculture Organization (FAO). 2008. Agro-maps Data Sources, Land and Water Division, FAO. Rome. *http://www.fao.org/ag/agl/agll/agromaps/datasource.jsp*

Intergovernmental Panel on Climate Change (IPCC). 2007. "The Physical Science Basis" Fourth Assessment Report, Cambridge University Press, Cambridge, UK.

Kurukulasuriya, P. and R. Mendelsohn. 2008. "A Ricardian Analysis of The Impact of Climate Change on African Cropland" African Journal Agriculture and Resource Economics **2**: 1-23.

Kurukulasuriya, P., R. Mendelsohn, R. Hassan, J. Benhin, M. Diop, H. M. Eid, K.Y. Fosu, G. Gbetibouo, S. Jain, , A. Mahamadou, S. El-Marsafawy, S. Ouda, M. Ouedraogo, I. Sène, N. Seo, D. Maddison and A. Dinar. 2006. "Will African

Agriculture Survive Climate Change?" World Bank Economic Review **20**: 367-388.

Lotsch A, 2006. "Sensitivity of cropping patterns in Africa to transient climate change" CEEPA Discussion Paper No. 14, University of Pretoria, Pretoria, South Africa.

Mendelsohn, R. and L. Williams. 2004. "Comparing Forecasts of the Global Impacts of Climate Change" Mitigation and Adaptation Strategies for Global Change **9**: 315-333.

Parry, M.L., C. Rosenzweig, A. Iglesias, M. Livermore and G. Fischer. 2004: Effects of climate change on global food production under SRES emissions and socio-economic scenarios. Global Environmental Change **14:** 53-67.

Pearce, D. et al. 1996. "The Social Costs of Climate Change: Greenhouse Damage and Benefits of Control" in Climate Change 1995: Economic and Social Dimensions of Climate Change, J. Bruce, H. Lee, E. Haites. Eds. Cambridge Univ. Press, Cambridge, UK, pp.179-224.

Ramankutty, N. & Foley, J. A. 1998. "Characterizing patterns of global land use: an analysis of global croplands data" Global Ecology & Biogeography **12**: 667-685.

Reilly, J. et al. 1996. "Agriculture in a changing climate: Impacts and adaptations", in R. Watson, M. Zinyowera, R. Moss and D.Dokken (eds.), Climate Change 1995: Impacts, Adaptations, and Mitigation of Climate Change: Scientific-Technical Analyses, Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK.

Rosenzweig, C. and M. Parry. 1994. "Potential Impact of Climate Change on World Food Supply" Nature **367**: 133-38.

Seo, N., Mendelsohn, R., Dinar, A., Kurukulasuriya, P., Hassan, R. 2008. A Ricardian Analysis of the Distribution of Climate Change Impacts on Agriculture across Agro-Ecological Zones in Africa, *Environmental and Resource Economics* (forthcoming)

Strzepek, K. and A. McClusky. 2006. "District level hydro-climatic time series and scenario analyses to assess the impacts of climate change on regional water resources and agriculture in Africa" CEEPA Discussion Paper #13, University of Pretoria, Pretoria, South Africa.

Tol, R. 2002. "Estimates of the damage costs of climate change. Part 1: benchmark estimates". Environmental and Resource Economics **21**: 47-73

Washington,W., Weatherly, J., Meehl, G., Semtner, A., Bettge, T., Craig, A., Strand, W., Arblaster, J., Wayland, V., James, R., & Zhang, Y. 2000. "Parallel Climate Model (PCM): control and transient scenarios" Climate Dynamics **16**: 755–774.

Wood, S., Sebastian, K., & Scherr, S. 2000, "Pilot Analysis of Global Ecosystems: Agrosystems" World Resources Institute and International Food Policy Research Institute, Washington D.C.

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

Table 1: Average Fraction of Cropland and Net Revenue per Hectare by AEZ

AEZ	Cropland/Land (%)	Crop Net Revenue per Hectare of Cropland (USD/ha)	Crop Net Revenue Per Hectare of Land (USD/ha)	Land Share of AEZ in Africa (%)
Desert	7%	1497	155	33%
High elevation dry savannah	10%	192	39	1%
High elevation humid forest	36%	310	159	3%
High elevation moist savannah	24%	190	1979	1%
Lowland dry savannah	25%	249	357	18%
Lowland humid forest	20%	735	158	15%
Lowland moist Savannah	22%	315	389	9%
Lowland semi-arid	5%	212	32	0%
Lowland sub-humid forest	10%	340	77	9%
Mid-elevation dry savannah	21%	320	846	5%
Mid-elevation humid forest	47%	573	348	1%
Mid-elevation moist savannah	33%	219	763	3%
High and Mid-elevation sub-humid forest	40%	221	1564	2%

Table 2: Annual Temperature and Precipitation by AEZ

AEZ	Annual Temperature ˚C	Annual Precipitation (cm/mo)
Desert	20.42	2.06
High elevation dry savannah	16.84	4.72
High elevation humid forest	17.84	8.08
High elevation moist savannah	15.86	6.49
Lowland dry savannah	25.80	3.98
Lowland humid forest	19.91	9.42
Lowland moist Savannah	23.94	5.61
Lowland semi-arid	25.66	1.69
Lowland sub-humid forest	20.49	7.17
Mid-elevation dry savannah	17.52	4.78
Mid-elevation humid forest	17.39	8.97
Mid-elevation moist savannah	16.45	7.10
High and Mid-elevation sub-humid forest	15.91	7.18

Table 3: Multinomial Regression of Probability of AEZ

(a) High Elevation AEZs

	High elevation dry savanna		**High elevation humid forest**		**High elevation moist savannah**	
	Unweighted	Weighted	Unweighted	Weighted	Unweighted	Weighted
Temp - winter	-0.54	0.01	2.94	-0.13	-1.14	-2.12*
	(0.47)	(0.01)	(0.96)	(0.03)	(1.81)	(2.00)
Temp - winter sq	0.01	-0.01	-0.04	0.05	0.05*	0.08*
	(0.27)	(0.11)	(0.63)	(0.63)	(2.95)	(3.19)
Temp - summer	5.68*	8.97*	0.61	2.65	4.18	1.66
	(2.12)	(2.23)	(0.22)	(0.67)	(1.66)	(1.01)
Temp - summer sq	-0.1	-0.17	-0.02	-0.07	-0.09	-0.04
	(1.75)	(1.80)	(0.37)	(0.96)	(1.66)	(1.21)
Precip - winter	4.66	11.55*	0.61	0.61	0.75	1.94*
	(1.69)	(3.32)	(1.64)	(1.08)	(1.53)	(2.70)
Precip - winter sq	-0.66	-1.54*	-0.05*	-0.04	-0.02	-0.04
	(1.55)	(2.45)	(2.58)	(1.25)	(0.83)	(1.23)
Precip - summer	2.18*	2.61*	0.99*	0.89	1.14*	1.09*
	(2.54)	(3.30)	(3.65)	(1.53)	(3.70)	(2.13)
Precip - summer sq	-0.09*	-0.14*	-0.03*	0.00	-0.05*	0.02
	(2.87)	(2.23)	(3.31)	(0.06)	(4.41)	(0.52)
Elevation	2.95*	3.48*	3.24*	3.77*	2.93*	3.13*
	(2.81)	(2.98)	(4.19)	(2.85)	(3.50)	(3.03)
Flow	-0.70	-0.42	-0.43	-1.91	-0.29	-0.56
	(0.46)	(0.22)	(1.16)	(1.74)	(0.67)	(1.74)
Elevation x Temp - winter	0.05	0.05	0.04	0.07	0.03	0.02
	(1.79)	(0.90)	(0.67)	(0.70)	(1.34)	(0.56)
Elevation x Temp - summer	-0.12*	-0.13*	-0.16*	-0.21	-0.13*	-0.10
	(2.72)	(2.29)	(2.40)	(1.86)	(2.87)	(1.82)
Elevation x Precip - winter	-0.04	-0.22	0.06*	0.04	0.01	-0.06
	(0.30)	(1.77)	(2.37)	(0.78)	(0.28)	(1.12)
Elevation x Precip - summer	-0.02	0.01	-0.01	-0.02	0.01	0
	(0.51)	(0.15)	(0.61)	(0.84)	(0.76)	(0.17)
Constant	-93.30*	-147.57*	-58.01*	-51.63	-57.05*	-30.2
	(2.93)	(3.08)	(2.32)	(1.41)	(2.03)	(1.55)

Table 3 (Cont): Mid-Elevation AEZs

	Mid-elevation dry savannah		**Mid-elevation humid forest**		**Mid-elevation moist savannah**		**Mid-elevation sub-humid forest**	
	Unweighted	Weighted	Unweighted	Weighted	Unweighted	Weighted	Unweighted	Weighted
Temp - winter	1.11*	0.34	-0.44	2.28	1.74*	1.00	-0.97	-2.07*
	(1.98)	(0.49)	(0.07)	(0.52)	(2.46)	(0.98)	(1.58)	(2.16)
Temp - winter sq	-0.04*	-0.02	0.06	0.04	-0.04*	-0.01	0.04*	0.08*
	(2.58)	(1.30)	(0.41)	(0.41)	(2.13)	(0.27)	(2.51)	(3.07)
Temp - summer	0.53	1.90	4.06	-0.79	4.96*	3.93	1.13	1.43
	(0.48)	(1.38)	(0.44)	(0.11)	(2.24)	(1.18)	(0.88)	(0.94)
Temp - summer sq	-0.01	-0.03	-0.16	-0.09	-0.12*	-0.1	-0.02	-0.03
	(0.43)	(1.01)	(0.72)	(0.53)	(2.58)	(1.40)	(0.90)	(0.91)
Precip - winter	-0.22	-0.14	2.17*	3.26*	0.21	-0.18	1.03	2.01
	(0.48)	(0.22)	(2.10)	(2.77)	(0.59)	(0.41)	(1.72)	(1.83)
Precip - winter sq	-0.01	0.01	-0.11*	-0.13*	-0.01	0.02	-0.12*	-0.13
	(0.43)	(0.23)	(2.20)	(2.32)	(0.53)	(0.77)	(2.51)	(1.53)
Precip - summer	1.17*	1.28*	1.16*	1.02	0.59*	0.37	0.67*	0.73
	(3.90)	(2.19)	(2.15)	(1.71)	(2.40)	(0.71)	(2.49)	(1.44)
Precip - summer sq	-0.08*	-0.05	-0.04*	-0.01	-0.03*	0.00	-0.02*	0.00
	(6.05)	(1.76)	(2.72)	(0.28)	(3.11)	(0.13)	(2.61)	(0.03)
Elevation	0.77	1.83	1.16	1.63	2.03*	2.02	2.56*	3.27*
	(1.10)	(1.93)	(0.82)	(1.12)	(2.45)	(1.88)	(3.70)	(3.30)
Flow	0.31*	0.08	-0.37	-0.90*	-0.11	-0.46*	-0.29	-0.55
	(2.01)	(0.45)	(0.98)	(2.44)	(0.60)	(2.27)	(0.59)	(1.84)
Elevation x Temp - winter	0.00	0.02	0.04	-0.10	-0.02	-0.05	0.03	0.03
	(0.07)	(0.54)	(0.25)	(1.24)	(1.02)	(1.55)	(1.60)	(0.81)
Elevation x Temp - summer	-0.02	-0.06	-0.05	0.08	-0.07	-0.05	-0.11*	-0.12*
	(0.68)	(1.26)	(0.30)	(0.72)	(1.51)	(0.92)	(3.10)	(2.29)
Elevation x Precip - winter	0.06*	0.04	0.01	-0.06	0.04	0.04	0.04	-0.01
	(2.04)	(0.72)	(0.12)	(0.89)	(1.60)	(1.14)	(1.12)	(-0.20)

Elevation x Precip - summer	0.03	0.00	0.01	-0.01	0.02	0.04	0.00	-0.01
	(1.46)	(0.06)	(0.31)	(0.33)	(1.33)	(1.47)	-(0.18)	(-0.35)
Constant	-23.62	-41.12*	-45.82	-32.67	-72.46*	-56.84	-22.18	-27.29
	(1.62)	(2.36)	(0.81)	(0.63)	(2.91)	(1.59)	(1.37)	(-1.38)

Table 3 (Cont) Low Elevation AEZs

	Lowland dry savannah		**Lowland humid forest**		**Lowland moist Savannah**	
	Unweighted	Weighted	Unweighted	Weighted	Unweighted	Weighted
Temp - winter	-0.70*	-1.05*	-1.35*	-2.99*	-1.89*	-2.69*
	(2.75)	(2.78)	(2.35)	(2.94)	(6.08)	(4.93)
Temp - winter sq	0.03*	0.04*	0.05*	0.11*	0.05*	0.08*
	(4.00)	(4.70)	(2.99)	(3.61)	(5.82)	(5.83)
Temp - summer	0.43	-0.17	10.72*	8.40*	5.34*	6.97*
	(1.12)	(0.28)	(3.81)	(3.00)	(8.90)	(7.82)
Temp - summer sq	-0.01	0.00	-0.27*	-0.22*	-0.09*	-0.13*
	(1.29)	(0.30)	(4.14)	(3.57)	(8.86)	(8.67)
Precip - winter	0.31	-0.02	0.27	0.26	-0.22	-0.13
	(1.40)	(0.09)	(1.04)	(0.74)	(0.86)	(0.38)
Precip - winter sq	-0.01	0.01	-0.01	0.00	0.02	0.02
	(1.28)	(0.43)	(0.92)	(0.11)	(1.17)	(0.99)
Precip - summer	0.81*	0.33	1.48*	1.46*	1.61*	1.68*
	(6.15)	(0.82)	(7.76)	(2.87)	(10.14)	(3.73)
Precip - summer sq	-0.04*	-0.01	-0.04*	-0.02	-0.05*	-0.04
	(5.97)	(0.46)	(6.88)	(0.58)	(6.52)	(1.32)
Elevation	-0.08	-0.66	1.92*	1.66	3.00*	3.23*
	(0.22)	(1.30)	(2.28)	(1.50)	(6.23)	(4.17)
Flow	-0.05	-0.35*	-0.22*	-0.78*	-0.71*	-0.70*
	(0.57)	(2.45)	(2.05)	(3.62)	(3.19)	(3.25)
Elevation x Temp - winter	0.02	0.00	0.07*	0.07*	0.08*	0.06*
	(1.75)	(0.09)	(3.34)	(2.34)	(5.40)	(2.05)
Elevation x Temp - summer	-0.04*	-0.01	-0.17*	-0.16*	-0.20*	-0.21*
	(1.94)	(0.23)	(3.79)	(2.62)	(8.21)	(4.52)
Elevation x Precip - winter	0.06*	0.06	0.07*	0.05	0.07*	0.06
	(3.65)	(1.88)	(3.51)	(1.40)	(3.65)	(1.76)
Elevation x Precip - summer	0.05*	0.06*	0.00	-0.01	-0.02	-0.01
	(3.83)	(2.91)	(0.31)	(0.35)	(1.25)	(0.53)
Constant	-2.94	11.94	-103.15*	-66.37*	-61.54*	-74.36*
	(0.61)	(1.48)	(3.59)	(2.33)	(7.89)	(6.69)

Table 3 (Cont) Low Elevation AEZs

	Lowland semi-arid		Lowland sub-humid	
	Unweighted	Weighted	Unweighted	Weighted
Temp - winter	-1.79	-2.22*	-3.15*	-4.48*
	(1.45)	(1.96)	(7.68)	(6.95)
Temp - winter sq	0.04	0.06*	0.09*	0.14*
	(1.41)	(2.10)	(8.60)	(8.33)
Temp - summer	6.70	7.05	6.22*	9.77*
	(1.74)	(1.38)	(6.14)	(7.31)
Temp - summer sq	-0.10	-0.11	-0.13*	-0.21*
	(1.65)	(1.31)	(6.48)	(8.02)
Precip - winter	5.04*	6.11*	0.53*	0.88*
	(2.07)	(2.33)	(2.01)	(2.18)
Precip - winter sq	-0.50	-0.62*	-0.01	-0.01
	(1.77)	(2.56)	(0.94)	(0.56)
Precip - summer	11.25*	11.50*	1.80*	1.77*
	(2.31)	(2.61)	(9.51)	(3.56)
Precip - summer sq	-2.49*	-2.60*	-0.05*	-0.03
	(2.02)	(2.78)	(7.75)	(0.98)
Elevation	-3.30	-4.99	2.79*	3.89*
	(0.40)	(0.94)	(4.39)	(4.50)
Flow	1.50*	1.76*	-1.02*	-1.61*
	(2.40)	(1.96)	(3.72)	(4.15)
Elevation x Temp - winter	-0.07	-0.22	0.07*	0.08*
	(0.52)	(1.00)	(3.96)	(3.11)
Elevation x Temp - summer	0.14	0.27	-0.19*	-0.25*
	(0.48)	(0.96)	(5.61)	(5.49)
Elevation x Precip - winter	-0.35	-0.39	0.00	-0.05
	(0.46)	(0.88)	(0.16)	(1.11)
Elevation x Precip - summer	-0.01	0.13	-0.01	-0.02
	(0.02)	(0.33)	(0.32)	(0.59)
Constant	-109.32*	-112.04	-56.79*	-88.41*
	(1.96)	(1.46)	(4.89)	(5.59)
Wald chi2 (168)	5351		2206	
Pseudo R2	0.62		0.70	
Log likelihood	-1611		-1138	

Values in parenthesis are t-statistics. * significant at 5% There are 2026 observations in the regressions.

Table 4: Climate Scenarios in 2100

Change	Baseline	PCM	CCC
Summer Temperature (C°)	24.8	+1.9	+5.4
Winter Temperature (C°)	18.7	+1.8	+5.8
Summer Precipitation (%)	88.8 mm/mo	+2% +1.8mm	-17% -15.1 mm
Winter Precipitation (%)	22.7 mm/mo	+7% +1.6mm	+21% +4.8 mm

Table 5 Total Cropland by Climate Scenario for each AEZ (million ha)

AEZ	Current	PCM	CCC
Desert	70.6	63.9	46.8
High elevation dry savannah	1.8	3.1	4.9
High elevation humid forest	28.3	33.6	17.8
High elevation moist savannah	9.7	8.0	7.6,
Lowland dry savannah	133.0	140.0	179.0
Lowland humid forest	113.0	64.6	0.5
Lowland moist Savannah	51.1	60.4	61.3
Lowland semi-arid	1.2	2.5	2.8
Lowland sub-humid	14.3	25.1	33.7
Mid-elevation dry savannah	16.6	16.4	8.5
Mid-elevation humid forest	8.1	1.2	0.0
Mid-elevation moist savannah	39.8	32.3	2.8
Mid-elevation sub-humid	26.8	36.2	169.0
TOTAL	**514.3**	**487**	**534**
% Change		**(-5.3%)**	**(+3.8%)**

Table 6 Change in Total Annual Crop Net Revenue by AEZ (million USD/year)

	Current	PCM	CCC
Desert	105,688	-10,000	-35,600
High elevation dry savannah	346	+253	+589
High elevation humid forest	8,773	+1,630	-3,260
High elevation moist savannah	1,843	-341	-417
Lowland dry savannah	33,117	+1,660	+11,300
Lowland humid forest	83,055	-35,800	-82,900
Lowland moist Savannah	16,097	+2,910	+3,200
Lowland semi-arid	254	+278	+329
Lowland sub-humid	4,862	+3,690	+6,630
Mid-elevation dry savannah	5,312	-78	-2,600
Mid-elevation humid forest	4,641	-3,960	-4,660
Mid-elevation moist savannah	8,716	-1,640	-8,110
High and Mid-elevation sub-humid	5,923	+2,080	+31,500
TOTAL	**278,627**	**-39,318**	**-83,999**
% Change		**(-14.1%)**	**(-30.1%)**

Table 7: Change in Annual Crop Revenue by Region (Billion USD/yr)

AEZ	PCM	CCC
North Africa	-3.7 (-4%)	-5.9 (-7%)
West Africa	-9.2 (-17%)	-17.4 (-32%)
Central Africa	-17.5 (-28%)	-49.2 (-79%)
East Africa	-3.1 (-11%)	-3.2 (-12%)
Southern Africa	-5.9 (-12%)	-8.4 (-17%)
Total	**-39.4** **(-14%)**	**-84.0** **(-30%)**

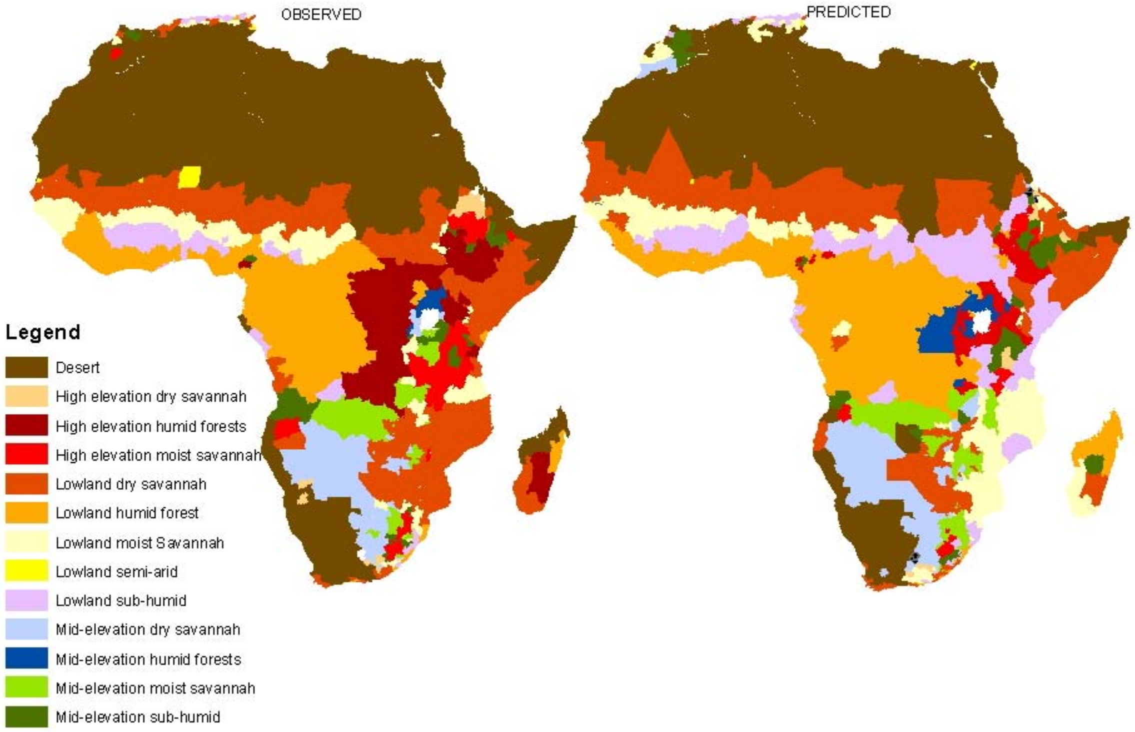
Appendix A

Table A-1: Change in Annual Crop Revenue by Country (USD Billions/year)

Country	PCM	CCC
Angola	-3.6	-4.8
Algeria	-0.3	0.4
Burundi	0.0	-0.1
Benin	-0.3	-0.4
Burkina Faso	0.0	0.4
Botswana	0.0	0.9
Central African Rep.	-4.2	-6.1
Cameroon	-2.4	-5.4
Cote D'Ivoire	-2.2	-2.9
Congo	-1.3	-3.9
Djibouti	-0.1	0.0
Egypt	-0.1	-0.3
Eritrea	0.0	0.1
Ethiopia	-1.4	-0.5
Gabon	-1.7	-2.7
Ghana	-1.1	-1.4
Guinea	-0.5	-0.7
Gabon	0.0	0.0
Guinea Bissau	0.0	0.0
Guinea Equatorial	-0.2	-0.4
Kenya	-0.3	-0.1
Liberia	-1.2	-1.7
Libya	0.1	-0.1
Lesotho	0.0	-0.1
Madagascar	-1.4	-2.8
Mali	-0.5	-1.9
Morocco	-0.3	-0.7
Mozambique	-0.1	0.6
Mauritania	-0.7	-1.5
Malawi	0.0	-0.1
Namibia	0.0	0.8
Nigeria	-2.5	-5.2
Niger	-0.3	-1.6
Rwanda	0.0	0.0
Sudan	-2.6	-3.9
Senegal	0.0	0.0
Sierra Leone	-0.6	-1.1
Somalia	-0.3	-0.1
South Africa	-0.8	-2.1
Swaziland	0.0	0.0
The Chad	-0.1	-1.4
Togo	-0.3	-0.3

Tunisia	0.1	0.2
Tanzania	-0.6	-1.2
Uganda	-0.4	-1.3
Zambia	0.0	-0.6
Zaire	-7.2	-30.1
Zimbabwe	0.0	-0.2

Figure 1: Observed Versus Predicted Distribution of AEZs Given Current Climate



Note: Map of observed AEZs based on data from FAO (2003)

Figure 2: Distribution of Land in Each AEZ by Climate Scenario

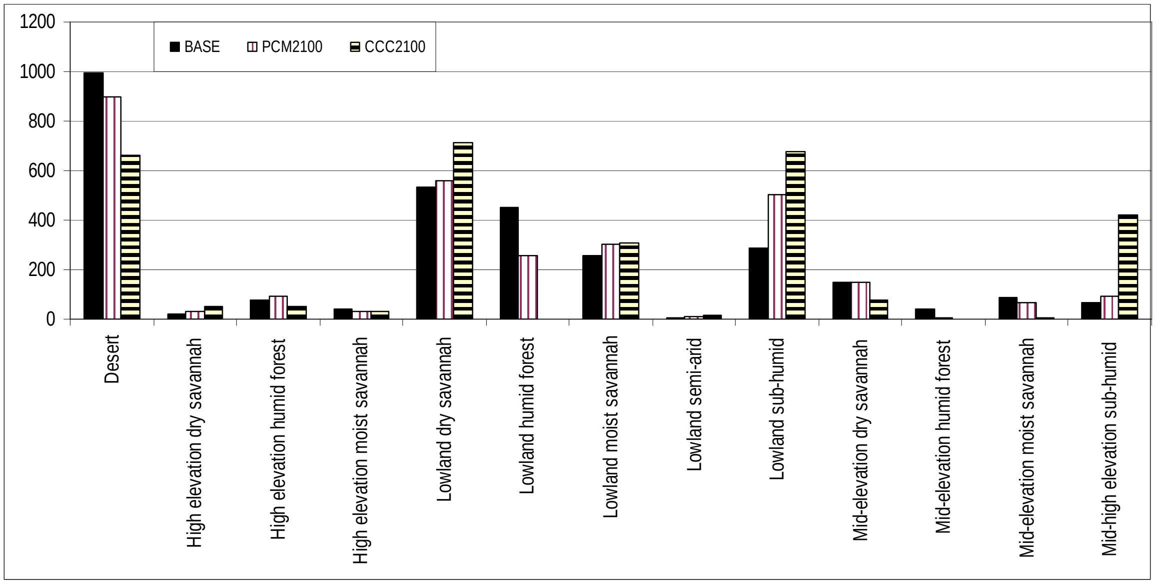


Figure 3: Distribution of AEZs with 2100 PCM and CCC Scenario

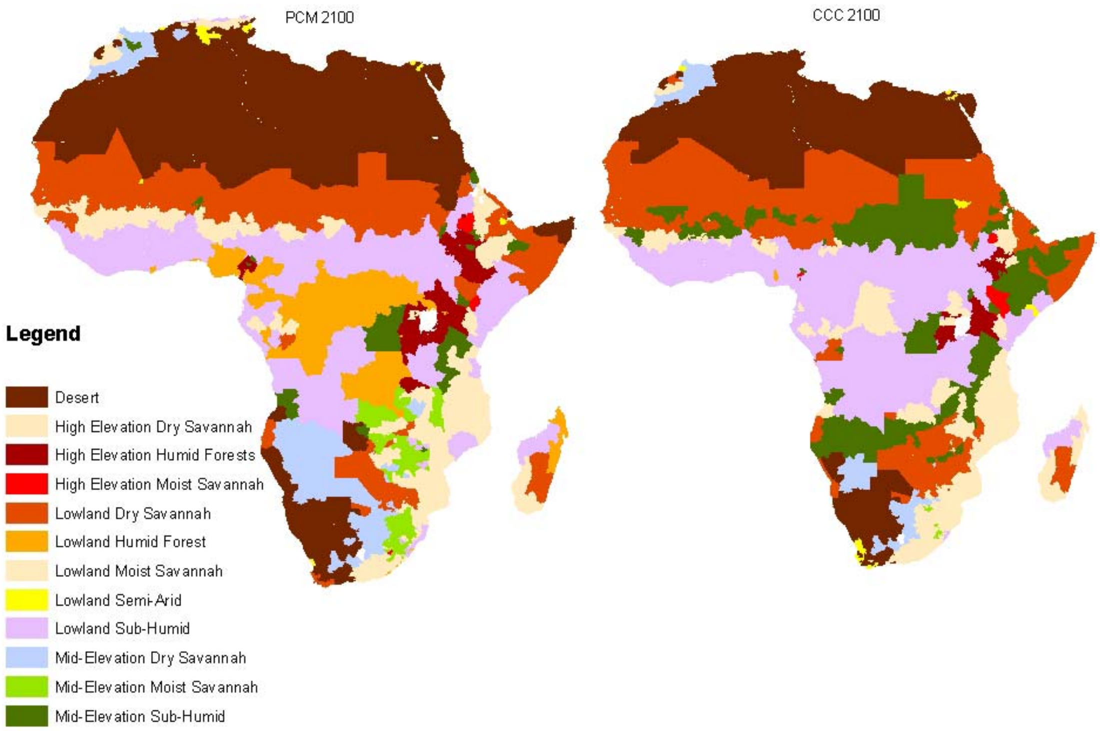


Figure 4: Percentage Change in Income with 2100 PCM and CCC Scenario