WPS4334

Policy Research Working Paper 4334

The Economic Impact of Climate Change on Kenyan Crop Agriculture:

A Ricardian Approach

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August 2007

Policy Research Working Paper 4334

Abstract

This paper measures the economic impact of climate on crops in Kenya. The analysis is based on cross-sectional climate, hydrological, soil, and household level data for a sample of 816 households, and uses a seasonal Ricardian model.

Estimated marginal impacts of climate variables suggest that global warming is harmful for agricultural productivity and that changes in temperature are much more important than changes in precipitation. This result is confirmed by the predicted impact of various climate change scenarios on agriculture. The results further confirm that the temperature component of global warming is much more important than precipitation.

The authors analyze farmers' perceptions of climate variations and their adaptation to these, and also constraints on adaptation mechanisms. The results suggest that farmers in Kenya are aware of short-term climate change, that most of them have noticed an increase in temperatures, and that some have taken adaptive measures.

This paper—a product of the Sustainable Rural and Urban Development Division, Development Economics Research Group Department—is part of a larger effort in the department to mainstream economic research on climate change. Policy Research Working Papers are also posted on the Web at http://econ.worldbank.org. The author may be contacted at jmariara@mail.uonbi.ac.ke.

THE ECONOMIC IMPACT OF CLIMATE CHANGE ON KENYAN CROP AGRICULTURE: A RICARDIAN APPROACH[1]

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[1] An earlier version of this Working Paper was published as CEEPA Discussion Paper number 12.

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SUMMARY

This paper measures the economic impact of climate on crops in Kenya. We use cross-sectional data on climate, hydrological, soil and household level data for a sample of 816 households. To collect the requisite household data, we adopted the common questionnaire used by all countries in the regional GEF/World Bank project. The countries involved in the project adopted the same survey design in terms of sampling and used the same questionnaire designed jointly by the School of Forestry and Environmental Studies of Yale University and the Centre for Environmental Economics and Policy in Africa (CEEPA), University of Pretoria. Climate satellite data were provided by the US Department of Defense and we used data from the Africa Rainfall and Temperature Evaluation System (ARTES). The monthly means were estimated from approximately 14 years of data (1988–2003) to reflect long-term climate change normals (Basist et al. 1998, 2001). The hydrological data were obtained from the International Water Management Institute and the University of Colorado. The runoff and flow data estimates were based on monthly values from 1961–1990 time series data. The final values were estimated using hydrological models for Africa (Strzepek & McCluskey 2006). Soil data were obtained from the Food and Agricultural Organization (FAO 2003).

Since we did not discover any important impact of dry and wet condition climate variables on revenue, we settled for a seasonal Ricardian model. Our results show that climate affects agricultural productivity. Increased winter temperatures are associated with higher crop revenue, but increased summer temperatures have a negative impact. Increased precipitation is positively correlated with net crop yield. The results further show that there is a non-linear relationship between temperature and revenue on the one hand and between precipitation and revenue on the other. Further, our results suggest a hill-shaped relationship between mean flow and net crop revenue. Andosols, irrigation and household size are positively correlated with revenue, but livestock ownership, farm size and wage rates are inversely correlated with crop revenue.

Estimated marginal impacts of climate variables suggest that global warming is harmful for agricultural productivity and that changes in temperature are much more important than changes in precipitation. This result is confirmed by the predicted impact of various climate change scenarios on agriculture. For prediction purposes, we use two Global Circulation Models: the Canadian Climate Model (CCC) and the Geophysical Fluid Dynamics Laboratory (GFDL) model, which predict 3.5°C and 4°C changes in temperature by the year 2030 respectively. The models both predict a 20% change in precipitation over the same period. The prediction results confirm that global warming will have a substantial impact on net crop revenue, and that the impact will be more pronounced in medium and low potential zones than in high potential zones. Based on the CCC model, we predict a 1% (US$3.54 per hectare) gain in high potential zones but a 21.5% (US$54 per hectare) loss in medium and low potential zones. The GFDL model predicts a loss of US$32 per hectare in high potential zones compared to losses of US$178 in medium and low potential zones by the year 2030. The results further confirm that the temperature component of global warming is much more important than precipitation.

We analyze farmers' perceptions of climate variations and their adaptation to these, and also constraints on adaptation mechanisms. The results suggest that farmers in Kenya are aware of short-term climate change, that most of them have noticed an increase in temperatures, and that some have taken adaptive measures. The analysis also shows differences in perceptions and adaptations between farmers in medium/low potential zones and those in high potential zones. Diversification (changes in crop mix) is the most common adaptation measure,

particularly in high potential zones, while water conservation, irrigation and shading/sheltering of crops are the main adaptation measures in drier regions. The analysis shows, however, that credit constraints, poverty and lack of information hinder households from taking the most important adaptive measures, such as water management.

The key policy lesson from this study is that global warming will have adverse effects on agriculture in Kenya. Given the difficulties of averting global warming, adaptation to climate change is essential to counter the expected impacts of long-term climate change. We argue that the government must play a critical role in encouraging adaptations to climate change if farmers are to counter the expected impact of global warming. Critical interventions would be monitoring climate change and disseminating information to farmers through agricultural extension, to encourage both short- and long-term adaptations. Improved management and conservation of available water resources, water harvesting and recycling of waste water could generate more water for irrigation, which is especially important in the arid and semi-arid areas. This would help to lessen the expected repercussions of global warming. Policies for credit provision and improved household welfare are also a priority for both short- and long-term adaptation measures.

One limitation of this study is that it is based on general crop agriculture and does not model the impact of climate change on individual crops and livestock, which would be important for assessing the full impact of climate change on arid and semi-arid areas. The study also does not model the impact of adaptations that farmers make to counter the repercussions of climate change. We recommend future research in these areas. Future research that uses panel//time series data may also be expected to provide better estimates of the impact of climate change on Kenyan agriculture.

1. Introduction

Agriculture continues to be the leading sector in the Kenyan economy in terms of its contribution to real GDP. It contributed 36.6% of GDP in the period 1964–74, 33.2% in 1974–79, 29.8% in 1980–89, 26.5% in 1990–95 and 24.5% in 1996–2000. During the same periods the manufacturing sector recorded a growing contribution to GDP of 10%, 11.8%, 12.8%, 13.6% and 13.3%. Between 1993 and 1998, however, the contribution of agriculture to GDP stagnated at 25% while that of manufacturing declined from 13.8% to 13.3%. In spite of the decline in the agricultural sector's contribution to GDP, it remains one of the most important sectors driving economic growth. Agriculture is, however, the largest contributor to employment despite fluctuations in the percentage share. A large proportion of the labor force (82%) is based in rural areas, while small-scale agriculture absorbs the largest share of new additions to the labor force (Republic of Kenya 1997). The agricultural sector accounts for about 70% of export earnings, with food and beverages constituting over half of the total export earnings. Agriculture is also responsible for providing food security for both the rural and urban populations. However, rapidly expanding population, rapid urbanization and the shortage of high potential arable land cause occasional imbalances between the national demand for food and its supply.

The performance of the agricultural sector is determined by crop production, which depends on a large number of factors. Most important is the country's endowment of soils and climate resources. Kenya lies between latitudes 5° N and 5° S and between longitudes 34° E and 42°E. It is bordered by Tanzania to the south, Uganda to the west, Ethiopia to the north, Sudan to the northwest, Somalia to the east and the Indian Ocean to the southeast. The country has climate and ecological extremes, with altitude varying from sea level to over 5000m in the highlands. The mean annual rainfall ranges from less than 250mm in the arid and semi-arid areas to 2000mm in high potential areas. Kenya has a total area of 580,367 square kilometers, of which only 12% is considered high potential for farming or intensive livestock production. A further 5.5%, which is classified as medium potential, mainly supports livestock, especially sheep and goats. Only 60% of this high and medium potential land is devoted to crops (maize, coffee, tea, horticultural crops, etc.) and the rest is used for grazing and forests. Most of the high potential land is found within the highland areas of the Rift Valley, Central, Eastern Nyanza and Western Provinces. The other 82% of the total land (parts of the Eastern, North Eastern and Coast Provinces) in Kenya is classified as arid and semi-arid and is largely used for extensive livestock production (ranching and pastoralism), as well as being the habitat for wildlife both in and outside national parks and game reserves. It is estimated that the arid and semi-arid areas support about 25% of the nation's human population and slightly over 50% of its livestock. Because of differences in soil, climate and hydrological factors, agricultural productivity and incomes are highest in the high and medium potential zones and lowest in the arid and semi-arid areas. In addition to climate, soil and hydrological factors, productivity in the high and medium potential zones is also driven by better farming practices and access to credit and technologies, which enable farmers to invest in measures to mitigate the adverse impacts of climate change on crop production. The lack of alternative income earning opportunities means that spatial differences in poverty are closely related to and vary with agricultural potential in the country (Republic of Kenya 1999).

The declining agricultural productivity in Kenya is worrisome and a real challenge for a government with a population of approximately 30 million to feed. Worse still is the expected adverse impact of global warming on agriculture in the future. Global circulation models predict that global warming will lead to increased temperatures of about 4°C and cause variability of rainfall by up to 20% in Kenya by the year 2030. From these predictions, the two extreme climate events that may adversely affect the agricultural sector are drought (crop water stress leading to declining yields) and flooding (resulting in waterlogging) in both the arid and semi-arid areas and the high potential areas.[3] However, even with the predicted climate change scenarios, unpredicted climate events such as high frequency of flooding similar to that observed during the 1997–98 El Nino rains may still occur, particularly in vulnerable areas. The overall adverse weather events that may occur because of the projected climate change could have severe socio-economic impacts such as food, water and energy shortages, shortage of other essential basic commodities, and long-term food insecurity.

Against this background of limited arable land, predicted adverse climate conditions and declining agricultural productivity, the biggest challenge facing the Kenyan government is to intensify food crop production so that output can keep pace with rapid population growth without a large increase in land devoted to food crops, especially maize and milk. Currently, agricultural intensification is based on a combination of inputs such as fertilizers and pesticides, plant breeding technology, irrigation and improved agricultural practices such as multiple cropping. However, productivity continues to be undermined by unpredictable weather and climate conditions and declining soil fertility. While there is a growing body of literature on the effect of soils on agricultural productivity in Kenya, there is a dearth of literature on the effect of climate. In addition, adaptive mechanisms farmers use to circumvent the welfare impact of climate change have not been studied in Kenya. This paper addresses these research gaps. It uses the Ricardian approach to analyze the impact of climate on crop productivity in Kenya. It also simulates the impact of long-term climate change on agriculture. Understanding this impact is crucial for future agricultural policies and interventions in Kenya, particularly interventions to mitigate potential adverse impacts of climate change, which would have important implications for future food security and the overall growth of the sector. Such growth would in turn trickle down to the rest of the economy, increasing employment and incomes in agriculture and related sectors and boosting overall economic growth.

Objectives of the study

The general objective of this paper is to analyze the effect of long-term climate change on Kenyan agriculture and to identify the adaptation options of agro-ecological systems. The specific objectives are:

i. To assess farmers' awareness of climate change and to investigate the various adaptation measures they employ to counter adverse effects of climate change.

ii. To carry out an economic analysis of the effect of climate on agricultural production under baseline climate conditions.

iii. To simulate the expected effect of various long-term climate change scenarios on future agricultural productivity.

[3] Water resources in the country are most vulnerable in the arid and semi-arid areas of the country where drought and floods are expected to become more severe, while the ground water resources in the coastal regions (currently strained) will be most vulnerable in the future.

iv. To use the research findings to recommend appropriate interventions for mitigating the potential impact of climate change in the future.

The rest of the paper is organized as follows. Section 2 analyzes the relationship between climate and agriculture in Kenya; Section 3 discusses the study site and data; Section 4 reviews the literature; Sections 5 and 6 present the methods and research findings respectively; and Section 7 concludes.

2. Climate and agriculture in Kenya

Agro-climate zones and farming systems

Climate, vegetation and land use potential have been used to assess land suitability for different uses. The major elements of climate that affect herbage growth are the intensity and duration of rainfall, the relationship between annual rainfall and potential evapotranspiration and the year-to-year variation in rainfall. Kenya is divided into seven agro-climate zones using a moisture index based on annual rainfall expressed as a percentage of potential evaporation (Sombroek et al. 1982). Areas with an index greater than 50% have high potential for cropping and are designated zones I, II and III (Table 1). These zones account for 12% of Kenya's land area. The semi-humid to arid regions (zones IV, V, VI and VII) have indexes of less than 50% and a mean annual rainfall of less than 1100 mm. These zones are generally referred to as the Kenyan range-lands and account for about 80% of the land area. The seven agro-climate zones are each subdivided according to mean annual temperature to identify areas suitable for growing each of Kenya's major food and cash crops. Most of the high potential areas are located above an altitude of 1200m and have mean annual temperatures of below 18°C. These areas are mainly suitable for livestock farming (mostly cattle and sheep), cash crops (coffee, tea and pyrethrum) and key food crops (maize, beans and wheat). The medium potential zones favor farming systems similar to the high potential areas, but temperatures are higher and productivity lower. In these zones barley, cotton, cassava, coconut and cashew nuts are also cultivated. Ninety percent of the arid and semi-arid areas lies below 1260m and mean annual temperatures range from 22°C to 40°C. These areas are less suited for arable agriculture but support sorghum, millet, livestock and wildlife.

Drainage basins

Kenya is endowed with a large potential of water resources: groundwater, river flows, lakes and oceans. The surface water resources are contained within five main drainage basins whose hydrological characteristics are related to moisture availability, rainfall and climate (Table 2). Except for the water resources in the oceans and lakes, rainfall is a major water resource in Kenya and sustains most of the water resources in the country. Rainfall is the main cause of variability in the water balance over space and time, and changes in precipitation have significant implications for hydrology and water resources. The frequency of floods and droughts is affected by changes in the year-to-year variability in precipitation and also by changes in short-term rainfall properties (such as storm rainfall intensity).

Rainfall and temperature

The country receives a bimodal type of rainfall where the 'long rains' fall between March and May and the 'short rains' between October and December. The intensity and spread of the rainfall in each region determines the effectiveness of the rainfall. The average annual rainfall ranges from 250mm to 2500mm; the average potential evaporation ranges from less than 1200mm to 2500mm; and the average annual temperature ranges from less than 10℃ to 30℃. A relatively wet belt extends along the Indian Ocean Coast and another wet area covers western Kenya just east of Lake Victoria. All the mountain ranges have high rainfall while dry tongues are found in the valleys and basins. The annual rainfall generally follows a strong seasonal pattern, with variations being strongest in the dry lowlands of the north and east, but weakest in the humid highlands of the Central and Rift Valley areas.

Mean temperatures in Kenya are closely related to ground elevation. The highest temperatures are recorded in the arid regions of the North Eastern Province along the Somalia coast and to the west of Lake Turkana where the night minimum may be as high as 29℃ during the rainy seasons. Coldest areas are the tops of the mountains where night frost occurs above 10,000 feet and permanent snow or ice cover the area above 16,000 feet (Mt Kenya). Annual temperature variations are generally small (less than 5℃) throughout the country.

Soils and topography

Kenya is a country with varying climate, vegetation, topography and underlying parent rock. Climate is the most important factor influencing soil formation and affects soil type directly through its weathering effects and indirectly as a result of its influence on vegetation. In most parts of Kenya, soils are deficient in nitrogen, phosphorous and occasionally potassium. In dry areas, the soils have low organic matter mainly because rainfall is low, variable, unreliable and poorly distributed. To understand the distribution of soil in Kenya, the country can be divided into three broad regions: humid, sub-humid and arid. The humid regions (highlands) are areas with an altitude of over 1500m which receive an annual rainfall of over 1000 mm, and include the highlands east and west of the Rift Valley and the Rift Valley floor. They have volcanic rocks and the soils are mainly loamy. Other humid areas with an altitude less than 1500m (humid lowlands) have sandy soils which are well drained and are of loamy, sandy clay texture (e.g. along the Kenyan coast). Other areas of the highlands have fertile loam soils, while alluvial soils (silts) are found along river valleys. Sand dunes and mangrove swamps are found along the coast. The soils covered by mangrove swamps are deep, grey, saline and poorly drained.

The sub-humid regions (the Lake Region and western Kenya) receive slightly less rainfall than the humid areas. They have volcanic and basement rocks and soils are red clay and generally productive. These regions lie between 1000m and 2000m above sea level and rainfall is up to 1000 mm per year. Dark red clays, sandy loams and alluvial deposits of eroded material from the uplands are common along the flood plains of big rivers in these regions. Peat swampy soils and black cotton soils dominate the lowlands. The semi-arid regions (northern and northeastern Kenya) receive on average 300–500 mm of rainfall per year and their soils are shallow and generally infertile, but variable. These soils have developed mainly from sedimentary rocks. Fertile volcanic soils, black cotton soils, dark red soils, lava soils and alluvial soils are scattered across the region depending on the distribution of rainfall, altitude and parent rock type.

3. Study site and the data

3.1 Sampling and data collection

The main data for this study were based on a sample of 816 households in Kenya. The data were collected from six out of eight provinces in Kenya between June and August 2004. Two provinces were excluded from the sample, Nairobi because of urbanization, and North Eastern because of aridity and because of inaccessibility of households and other field logistics. From the eight provinces, 38 out of 46 districts were selected for the field survey.[4] The districts chosen captured variability in a wide range of agro-climatic conditions (rainfall, temperatures and soils), market characteristics (market accessibility, infrastructure, etc.) and agricultural diversity, among other factors. Each district was then divided into agro-ecological zones and samples of three different farm types/sizes: large, medium and small chosen from each ecological zone. Detailed information from the Ministry of Agriculture and from the *Farm Management Handbook* (Jaetzold & Schmidt 1982) was used to help identify agro-ecological zones and farm types. The sampling procedure was purposely designed to target at least four households from each agro-ecological zone, comprising at least one household from each farm type. The fourth household in each of the agro-climatic zones would be of any of the three farm types depending on the frequency of the farm types in the district and zone chosen.

Our sample included both crop and livestock farming households, including a number of group ranches and commercial farms. On commercial farms, farm managers were interviewed in the place of absentee farm owners, and group leaders were interviewed on ranches. The limitation of doing this is that there was scant information on household characteristics for these questionnaires. The distribution of the sample across provinces and districts and agro-ecological zones is presented in Table 3. We omitted the tropical alpine zone which is found on the top of the mountains but sampled all other zones in the chosen districts using the criteria discussed earlier. The final sample of households selected and interviewed are listed in the last two columns of Table 3 (see also Table 4). In some districts, only small farmers could be interviewed depending on the scale of production prevailing in the district. The distribution of households by farm type in the final sample of households interviewed is shown in Table 4.

The research instrument

The Kenyan climate and agriculture project adopted the survey design for sampling used by all the countries in the regional GEF/World Bank project. It also used the same questionnaire, which was designed jointly by the School of Forestry and Environmental Studies of Yale University and the Centre for Environmental Economics and Policy in Africa (CEEPA), University of Pretoria. The questionnaire details the socio-economic characteristics of the

[4] Before 1996, Kenya had 46 districts but these were subsequently subdivided to make a total of the current 72 districts. The sampling frame was based on the old district classification, in order to make the data compatible with data on long-term climate variables.

sampled households and their economic activities. The questionnaire also included a module for perceptions and adaptations of households to climate change.

3.2 Data description

Climate data

In addition to the household data, the study also makes use of climate data (temperatures, soil wetness indices and precipitation). Satellite data were provided by the US Department of Defense. The data values were derived from a set of polar orbiting satellites that are equipped with sensors to detect microwaves through clouds and estimate surface temperature and surface wetness (Basist et al. 1998, 2001; Weng & Grody 1998). The other set of climate data were obtained 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, is based on ground station measurements of precipitation and minimum and maximum temperature. The data were constructed from a base with data for each month of the survey year and for morning and evening. The monthly means were estimated from approximately 14 years of data (1988–2003) to reflect long-term climate change.

To save space in Tables 5 and 6, we present only the estimated mean annual and seasonal values for all climate variables. Table 5 summarizes the ARTES temperature and precipitation data. The long-term mean annual ARTES temperature is estimated at about 22℃, the long rains temperature at 21℃ and the short rains at 22℃, showing that there are no major variations in seasonal temperatures in Kenya (because the country is located across the equator). The three-month seasonal values show the lowest mean temperature as about 20℃ (winter, June–August) and the highest as about 23℃ (summer, March–May). The variations across provinces (results not presented), show Coast Province as having the highest temperatures among the selected provinces, with an annual mean of 25℃. The lowest temperature observed for this province is for winter at 24℃. Central Province has the lowest temperatures, with an annual mean of 20℃, and the lowest long rain mean temperature, 18℃.

The ARTES precipitation data in Table 5 show the mean annual precipitation for the whole country as 85mm, with a standard deviation of 19mm. The long rains mean (at 91mm) is significantly higher than the short rains mean (81mm).[5] This implies that there are significant seasonal variations in mean precipitation in Kenya. This variation is also observed across provinces, with Nyanza and Western Province recording the highest long-term mean precipitation values (112mm for Nyanza and 110mm for Western Province, but the long rains reach a high of 129mm and 136mm for the two provinces respectively). Coast Province is observed to have the lowest precipitation (an annual mean of 65mm, with long rains at 76mm and short rains at 51mm). In the empirical analysis, we find that defining winter as June–August and fall as December–February gives us the climate model that best fits the data.

[5] Though long rains fall between March and May and short rains between October and December, there is the extended cropping season. Long rain crops planted in early March are harvested in August. Farms are then prepared and planted in September and the crops harvested in February.

Table 6 presents satellite temperatures and moisture indices. The long-term mean annual and seasonal satellite temperatures for Kenya are estimated at 19°C, with Coast Province reporting the highest mean of 25°C. In contrast to the ARTES temperatures where Central Province had the lowest mean values, here Nyanza and Western Provinces report the lowest mean temperatures at about 17°C. The moisture index is unit-less but low values indicate dry conditions and higher values moist ones. An index of less than 2 indicates very dry conditions, 2–4 vegetated areas such as forests and woodlands, and 5–8 croplands. Values greater than 8 suggest conditions ranging from abundant water to permanently inundated lands. The estimates for moisture indices are quite modest. The country's annual and seasonal averages are about 3 implying that, on average, Kenya does not have enough moisture for crop farming. Most provinces report a mean of about 2. The lowest are observed for Eastern and Central Provinces. It is surprising that Coast Province seems to have more moisture than these two provinces, given that it has the highest temperatures. Western Province has a mean of about 4, while Nyanza has the highest at about 6. The reason for the very low estimates for moisture is not clear, given that temperature estimates are within reasonable range. According to the classification in Table 6, only Nyanza would seem suitable for crop farming, yet the actual situation is that this province has more wetlands than any other province.

In the empirical analysis, we tested the impact of climate using the ARTES precipitation and satellite temperature data. The latter is preferred to the ARTES temperatures because the ARTES dataset is based on province level estimates, while the satellite data is based on district level ones and is therefore more reliable as it allows for more variability. However, the satellite moisture index has some temperature component embedded in it. It is therefore not very reliable for predicting the impact of precipitation on agriculture. We therefore rely on the ARTES precipitation estimates.

Hydrological data

The other datasets used in this study were obtained from the IWMI (International Water Management Institute) and the University of Colorado and include estimates of runoff and flow data based on monthly values from 1961–1990 time series. The final values were estimated using hydrological models for Africa (STRZEPEK & MCCLUSKEY 2006). The original data was made available to us in mean monthly values and long-term variance for each of the sampled districts. The mean runoff for the country is estimated at about 39mm, with a high standard deviation of 25mm, implying that there is high variability in the mean runoff across the six provinces. The highest estimate is for Nyanza Province at 73mm, followed by Western Province at 63mm; the lowest estimates are for Coast and Eastern Provinces, at only 12mm. Provinces with very high runoff estimates also have the highest estimates for surface flow. For instance, Nyanza Province has an estimated mean flow of about 452,000m^3, compared to a national estimate of 301,000m^3. Central and Western Provinces follow with 397,000 m^3 and 373,000 m^3 respectively. Rift Valley Province has the lowest at 186,000 m^3.

Soil data

Soil data were obtained from the Food and Agricultural Organization (FAO 2003). Kenya has at least 28 different types of soil but we focused only on the key types in the six sampled provinces, which can be divided into 8 main groups, as shown in Table 7. The sample statistics for soils presented in the last column of Table 7show the percentage of district area covered by each soil type. As with other variables, endowment of soil resources differs from one province to another. The means show that about 50% of the sampled provinces in Kenya are covered by nitosols and ferralsols. All other soils cover relatively small proportions. Nitosols are well-structured soils which vary from deep to very deep and are well drained. These soils are concentrated in the more arable districts. Central Province has 34% of its total land covered by nitosols, Eastern Province has 23%, Nyanza and Rift Valley Provinces each 31%, while Western Province has the highest coverage at 38%. Ferralsols are strongly weathered and leached soils with a low chemical fertility. They are mostly found in Nyanza and Western Provinces where they cover 50% and 57% respectively. Other important soils include luvisols, mostly found in Coast Province (68%) and Eastern Province (23%), andosols (covering 22% of Central Province) and lithosols (covering 20% of Rift Valley Province).

Household level data

Here the key variables of interest for the Ricardian analysis include net crop revenue, wage rates and a few other household variables. We define net revenue as gross revenue less all total variable costs, costs of hired labor, farm tools, machinery, fertilizers and pesticides. Costs of household labor are not netted due to difficulties of accurate measurement. Instead we introduce household wage rates for adults and children as independent variables in the net revenue regression. Other household variables used are summarized in Table 8. Other than for precipitation, farm size, household male wage rates and irrigation, there are no significant differences in the means of variables in medium/low and high potential zones. For the full sample, further analysis suggests that there is little variation across provinces/zones in the mean number of family laborers for both children and adults. On average, each household uses four adult workers, two of each gender and two children, one of each gender. The data across provinces further shows that about 70% of all household heads have farming as their main occupation and about 20% have farming as their secondary occupation. This implies that on average about 90% of all Kenyans are engaged in farming, which is consistent with countrywide statistics on the percentage of the population relying on agriculture.

4. Literature review

4.1 Introduction

There are four ways in which climate affects agriculture (Kurukulasuriya & Rosenthal 2003):

(i) Changes in temperature and precipitation directly affect crop production and can even alter the distribution of agro-ecological zones.

(ii) Increased CO_2 is expected to have a positive effect on agricultural production due to greater water use efficiency and higher rates of plant photosynthesis.

(iii) Runoff or water availability is critical in determining the impact of climate change on crop production, especially in Africa.

(iv) Agricultural losses can result from climate variability and the increased frequency of changes in temperatures and precipitation (including droughts and floods).

A large body of literature has developed to analyze these effects, both in developed and in developing countries, although the impact of climate change on agriculture became of interest only in the 1990s. The interest was spurred by the expectation that accumulation of CO_2 and other greenhouse gases will lead to global warming and other significant climate changes. Although there are a large number of studies on the effects of climate change in general, and global warming in particular, on agriculture in developed countries, there is a paucity of such studies in developing countries, especially in Africa. However, there is growing interest in studying these effects and making regional comparisons. This section presents a brief review of literature both for developed and developing countries.

Two main methods have been used in the literature to study the impact of climate change on agriculture. The traditional approach is a production function method which relies on empirical or experimental production functions to predict environmental change (Mendelsohn et al. 1994). To overcome the main weakness of this approach[6] most studies employ a method that corrects for the bias in the production function technique by using the economic data on the value of land to analyze the impact of climate on agriculture. This new method, referred to as the Ricardian approach, has, however, been criticized for not fully controlling for the impact of important variables that could also explain the variation in farm incomes; for assuming that prices are constant and adjustment costless; and for possibly yielding biased results when land within locations is heterogeneous and land owners behave optimally (Mendelsohn et al. 1994; Kurukulasuriya & Rosenthal 2003). Timmins (2003) also argues that while the Ricardian method is extremely practical for predicting the consequences of global warming with limited data, it may yield biased results when land use decisions depend on the climate attributes being valued and when land has unobserved attributes that differ with the use to which it is put. The authors argue that using an instrumentation strategy would correct for this bias. Sections 4.2 and 4.3 briefly review some relevant studies that use Ricardian and production function approaches.

4.2 Ricardian approach studies

Mendelsohn et al. (1994) use the Ricardian technique to estimate the value of climate in US agriculture using cross-sectional data for about 3000 counties in the US. Their results show that climate has complicated effects on agriculture, which can be highly non-linear and vary by season. Specifically they find that increased temperatures are likely to reduce average farm values, but increased precipitation to improve them. Their results further show that a scenario of increasing temperatures by an average 5°C and precipitation by a corresponding 8% average leads to a loss in land value from warming to an annual neighborhood damage of 4–5%. However, the same policy change scenario results in a 1% gain when using the crop-revenue approach. A number of studies that employ the Ricardian approach have supported findings by Mendelsohn et al. (1994) of an adverse impact of climate change on agriculture.

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[6] The traditional approach has been argued to have a bias in that it overestimates the damage climate change causes to agriculture (Mendelsohn et al. 1994). It is also criticized because price effects cannot satisfactorily be included in domestic level models.

Mendelsohn et al. (2003) use the same approach to analyze the relationship between climate and rural income based on country data for two US states and municipos from Brazil. The results suggest that favorable climate increases agriculture net revenues and thus per capita incomes. They conclude that climate is an important determinant of household welfare and therefore that providing new technology and capital may be an ineffective strategy for increasing rural incomes in hostile climate regions.

Mendelsohn et al. (2000) explore climate change impacts on African agriculture using the IPCC (Intergovernmental Panel on Climate Change) forecast of future CO_2 levels in the atmosphere by 2100. Because of the lack of African studies that calibrate climate sensitivity, the authors rely on studies of climate sensitivity for the US. Their results show that the most pessimistic forecast implies that African countries may lose 47% of their agricultural revenue because of global warming, while a cross-sectional forecast suggests losses of only 6% of agricultural GDP. With the expected fall in the contribution of agriculture to GDP over time, the authors conclude that the damage from climate change to African agriculture may be expected to range from 0.13% to 2% of GDP by 2100. They further argue that every region in Africa will experience some negative climate change impacts. They caution that their findings may be quite optimistic given that they are based on US climate response functions, and they call for African countries to estimate the climate effects and to understand adaptation options for Africa.

Seo et al. (2005) employ the Ricardian approach to measure the impact of climate change on Sri Lankan agriculture, focusing on four major crops. The authors find that global warming is expected to be harmful to Sri Lanka but increases in rainfall will be beneficial. They also find that with warming the already dry regions are expected to lose large proportions of their current agriculture, but the cooler regions are predicted to remain the same or increase their output. They conclude that climate change damages could be extensive in tropical developing countries but will depend on actual climate scenarios.

Tol (2002) assesses the impacts of climate change on agriculture, forestry and other aspects of human welfare using GCM (Global Circulation Model) based scenarios of climate change. This study is based on a number of countries. The results show that a 1℃ increase in the global mean surface air temperature would have a positive impact on the OECD, China and Middle East countries but a negative effect on others. The author further argues that the distributional aspects of climate change and the uncertainty about the impacts can be extremely large.

Kumar et al. (1998) use farm level data to examine and the agricultural impacts and adaptation options of climate change in India. They find that adverse climate change would lead to huge loses in agricultural revenues, even if farmers were to adapt their farming practices to climate change. Molua (2002), in an analysis of the impact of climate on agriculture in Cameroon, finds that increased precipitation is beneficial for crop production and that farm level adaptations are associated with increased farm returns. Etsia et al. (2002) find that a combination of increasing CO_2, temperature and rainfall is likely to have adverse effects on agricultural production in Tunisia. These results support findings by Rosenzweig and Parry (1994) who find that increased CO_2 and temperatures reduce rice production in India.

Deressa et al. (2005), use the Ricardian model to analyze the impact of climate on South African sugarcane production, using time series data for both irrigated and dry land farming. The authors show that climate change has significant non-linear impacts on net revenue with higher sensitivity to future increases in temperature than precipitation. Further, they find that doubling CO_2, which leads to rises in temperatures by 2°C and precipitation by 7%, would have a negative impact on sugarcane production. They also find that irrigation in sugarcane production does not provide an effective option for reducing climate change damages in South Africa. Gbetibouo and Hassan (2005) also use the Ricardian approach to analyze the economic impact of climate change on major South African field crops. They find that crops are quite sensitive to marginal changes in temperature compared to changes in precipitation. Contrary to findings by Deressa et al. (2005), they argue that irrigation would be an effective adaptation measure for limiting the harmful effects of climate change, and that the impact of climate change is agro-ecological zone specific and therefore that location is important in dealing with climate change issues.

4.3 Production function approach studies

Turpie et al. (2002) analyze the economic impact of climate change in South Africa. Their study addresses impacts on natural, agricultural, man-made and human capital. They use the production function approach to measure the natural capital lost from global warming. They predict the impact of climate change on rangelands will be positive, with the fertilization impact of CO_2 outweighing the negative effects of reduced precipitation. However, they find the impact of climate change on maize production will be negative both 'with' and 'without' CO_2 fertilization. They found estimates of impact of climate change for other crops were not reliable.

Other studies that use the production function approach argue that climate change may have beneficial effects on agriculture, especially in more arable lands, but adverse effects on more arid zones (for example Downing 1992). The positive impact of CO_2 fertilization effects and rising temperatures may however be determined by the adaptation measures adopted by farmers. Studies that support this argument include Inglesis and Minguez (1997), Mohamed et al. (2002) and Schulze et al. (1993). Inglesis and Minguez (1997) report that with a combination of different adaptation strategies in Spain, farmers not only derived higher crop yields with increased temperatures but also used water and land more efficiently. Mohamed et al. (2002) argue that climate change factors are significant determinants of millet productivity in Niger and predict a huge fall in crop productivity by 2025 as a result of global warming. Downing (1992) argues that potential food production in Kenya will increased if increased temperatures are accompanied by high rainfall, while marginal zones will be adversely affected by decreased rainfall. Fischer and Velthuizen (1996) (as cited by Kurukulasuriya & Rosenthal 2003) note that food productivity in Kenya may well increase with higher levels of atmospheric CO_2 and climate change induced increases in temperatures accompanied by some increases in precipitation, as predicted by several GCMs. These arguments are also supported by Makadho (1996), who argues that maize production in Zimbabwe is expected to fall as a result of increased temperatures that shorten the crop growth period. Downing (1992) also shows that shifts in agro-climate potential would affect national food production and land use in Zimbabwe.

Schulze et al. (1993) in a study of South Africa, Lesotho and Swaziland find climate change to be associated with potential increases in maize production, though they argue that it is likely to have little effect in marginal areas where yields are already low. Sivakumar (1992) in a study for Niger argues that climate has significant implications for agriculture because farmers tend to change their farming patterns with climate change and this is likely to have adverse environmental consequences. Onyeji and Fischer (1994) in a study for Egypt find that adverse climate change will lead to a decline in agricultural production and in GDP. However, they argue that large instruments in adaptation are required to make significant gains in avoiding the adverse impacts of climate change on the economy. Yates and Strzepek (1998) argue that global warming is likely to have adverse consequences for the Egyptian economy. Benson and Clay (1998) in a study involving a number of African countries argue that developing countries in Africa may be less prone to climate change shocks than industrial countries.

4.4 Overview of the literature

The above review of the literature shows that in spite of the weaknesses of the production function approach, the findings of studies based on it concur in some ways with those of studies using the Ricardian approach. Nevertheless, most of the production function approach studies seem to argue more strongly that climate change may be expected to have positive impacts on agriculture, while most Ricardian studies predict a negative impact. In addition, the production function studies show that farmers can overcome the adverse impact of global warming by implementing adaptation measures as the climate changes.

5. Methodology

Most studies of the impact of climate change on agriculture employ the Ricardian analysis (see for instance Mendelsohn et al. 1994) while traditional studies have used the production function approach (for example Rosenzweig & Iglesias 1994). As noted in the literature review, it has been criticized for having an inherent bias and tending to overestimate the damage climate change causes to farming because of failing to take into account the enormous variety of substitutions, adaptations and old and new activities that may displace obsolete activities as climate changes. The Ricardian approach is based on the observation by David Ricardo (1772–1823) that land rents reflect the net productivity of farmland and it examines the impact of climate and other variables on land values and farm revenues. This approach has been found attractive because it corrects the bias in the production function approach by using economic data on the value of land. By directly measuring farm prices or revenues, the Ricardian approach accounts for the direct effects of climate on the yields of different crops as well as the indirect substitution of different inputs, the introduction of different activities and other potential adaptations to different climates (Mendelsohn et al. 1994). It is also attractive because it includes not only the direct effect of climate on productivity but also the adaptation response by farmers to local climate.

The Ricardian approach is a cross-sectional model applied to agricultural production. It takes into account how variations in climate change affect net revenue or land value. Following Mendelsohn et al. (1994), the approach involves specifying a net productivity function of the form:

$$R = \Sigma P_i Q_i (X, F, Z, G) - \Sigma P_x X \qquad (1)$$

where R is net revenue per hectare, P_i is the market price of crop i, Q_i is output of crop i, X is a vector of purchased inputs (other than land), F is a vector of climate variables, Z is a set of soil variables, G is a set of economic variables such as market access and P_x is a vector of input prices. The farmer is assumed to choose X to maximize net revenues given the characteristics of the farm and market prices. The Ricardian model is a reduced form model that examines how a set of exogenous variables F, Z, and G affect farm value.

The standard Ricardian model relies on a quadratic formulation of climate:

$$R = B_0 + B_1F + B_2 F^2 + B_3 Z + B_4 G + u \quad (2)$$

where u is an error term, and F and F^2 capture levels and quadratic terms for temperature and precipitation. The introduction of quadratic terms for temperature and precipitation reflect the non-linear shape of the response function between net revenues and climate. From the available literature, we expect that farm revenues will have a concave relationship with temperature. When the quadratic term is positive, the net revenue function is U-shaped, but when the quadratic term is negative, the function is hill-shaped. For each crop there is a known temperature where that crop grows best across the seasons, though the optimal temperature varies by crop (Mendelsohn et al. 1994). From equation (2), we can derive the mean marginal impact of a climate variable on farm revenue as well as the mean marginal impact of runoff and flow on farm revenue.

As mentioned in the literature review, the Ricardian analysis has, however, been criticized on several accounts. Firstly, it does not measure transition costs, where a farmer changes from one crop to another suddenly, yet transition costs are clearly very important in sectors where there is extensive capital that cannot easily be changed. Secondly, it cannot measure the effect of variables that do not vary across space. Thirdly, it fails in that the change in climate that can be observed across space may not resemble the change that will happen over time. Fourthly, it generally assumes prices to be constant, which introduces bias in the analysis, overestimating benefits and underestimating damages. Fifthly, it explicitly includes irrigation, and lastly it reflects current agricultural policies (Kurukulasuriya & Mendelsohn 2006).

6. Research findings

6.1 Results of Ricardian analysis

Our empirical implementation of the Ricardian model was based on equation 2 in the methodology section. We carried out an analysis for net crop revenue per acre as the dependent variable, focusing on the impact of seasonal climate factors. Though the relationship between seasonal climate variables can be quite complex, we expected that farm revenues would have a concave relationship with temperature (Kurukulasuriya & Mendelsohn 2006). Annual climate and wet/dry condition factors were found to be insignificant determinants of crop revenue. In addition to the climate variables, we also modeled the impact of hydrological, soil and household specific factors.

Estimation issues

As is typical of most cross-sectional regressions, four econometric issues were likely to affect the robustness of our results: (i) endogeneity of explanatory variables, (ii) heteroscedasticity in the error terms, (iii) multicollinearity among explanatory variables and (iv) the impact of outliers. The problem of endogeneity of explanatory variables would be solved using an instrumental variable (IV) estimator. However, this requires that there are valid instrumental variables that are highly correlated with the explanatory variables concerned with but not directly related to revenue. Lacking appropriate instruments, we resorted to the next best alternative: estimating a reduced form net revenue model rather than a structural model.

Heteroscedasticity in the error terms does not pose a serious problem for obtaining consistent estimates as it only causes a bias in the estimates of standard errors for which we corrected using White's general method (see Greene 1997). However more serious problems are posed by multicollinearity and the influence of outliers. We controlled for multicollinearity by dropping the most troublesome variables. In the first place, monthly climate variables are highly correlated and were all dropped from the analysis. Other seasonal (three-month average) climate variables were dropped sequentially as we ran the regressions. We note, however, that multicollinearity is normally an issue of extent rather than absence and so it cannot be completely eliminated. The idea is to reduce the degree of multicollinearity. We therefore retained only those variables which seem to have a tolerable degree of multicollinearity. For outliers, we omitted a total of 116 households believed to be outliers for various reasons (see footnote 6).

Discussion of results

The Ricardian analysis results are presented in Table 9, which displays three model results. The second column presents model results with climate variables only, the third column introduces hydrological and soil factors and the fourth column introduces household characteristics. For climate variables, we present results for summer and winter temperatures only because fall and spring are collinear with summer and winter temperatures. For precipitation, we retain fall and summer precipitation for the same reason. The results are robust across the three models. High summer temperatures are harmful to crop production while high winter temperatures are beneficial. This is because summer (March–May) is the planting period followed by formative crop growth, while winter (June–August) is the period for ripening and maturing of crops. High summer temperatures would therefore slow down or destroy crop growth, while higher winter temperatures are crucial for ripening and harvesting. In the Kenyan highlands, winters can be quite chilly and excessively low winter temperatures have been associated with crop damage from frost. The negative coefficient for the quadratic term suggests, however, that excess winter temperatures would be harmful for crop productivity. Summer temperatures exhibit a U-shaped relationship with net crop revenue and winter temperatures a hill-shaped one. Both fall and summer precipitation are, however, positively correlated with net crop revenue and exhibit a hill-shaped relationship with it. The results further show that climate exhibits a non-linear relationship with net revenue, which is consistent with the available literature (Mendelsohn et al. 1994, 2003, Kurukulasuriya & Mendelsohn 2006). The Chow test results show that the overall models are significant at the 1% level of significance, but the R^2 shows that the models explain only between 3 and 13% of the total variation in net revenue.[7]

Introducing flow and hydrological variables reduces the F statistic marginally from 3.73 to 3.27. However the R-squared increases by almost 100%. The results imply a hill-shaped relationship between mean flow and net revenue, and both coefficients are statistically different from zero at the 10% level. All soils except andosols turned out to be insignificant and reduce the significance of other variables considerably and we therefore dropped all other soils. The results indicate that andosols have a positive and significant impact on net crop revenue, which conforms to a priori expectations because andosols are quite fertile and thus suited for crop production.

Finally we tested the impact of some selected household level variables. Introduction of these variables raises the F statistic from 3.27 to 5.30, while the R squared doubles. Most of the household level variables have a significant impact on crop revenue. Livestock ownership dummy, farm size and wage rates are inversely correlated with crop revenue. Farm size exhibits a U-shaped relationship with crop revenue, implying that large farm size may be associated with higher productivity. Main and secondary occupation of household head, religion of household head and average number of years of education of the household members are positively correlated with net crop revenue. Household size, introduced as a proxy for household labor (or remotely population density) has a positive and significant impact on net crop revenue

Livestock ownership dummy has a negative and significant impact on net revenue. This implies competition rather than complementarity between farming and livestock keeping. We did not discover any significant effect of education on crop productivity but the sign of the coefficient implies that education is associated with higher crop revenue. Irrigation has a large positive impact on crop revenue, implying the importance of adaptations to counter the impact of climate change.

6.2 Marginal impacts and elasticities

In this subsection, we estimate the marginal impacts of climate on crop agriculture (Table 10). The results are based on the regression results in the second and fourth columns of Table 9. The marginal impacts for winter temperatures are positive, but summer temperatures have larger negative impacts on net crop revenue. Using the climate only model, crop revenue is inelastic (-0.55) with respect to changes in temperature. The seasonal marginal impacts with respect to summer temperature are statistically significant and thus different from zero, but the impacts for winter are insignificant. Using the model with all variables, the elasticity of

[7] The results presented here omit households we suspected to be outliers, 92 in all. Most of the outlying households reported zero or very low revenues, or very high revenues or very high costs, making net revenues negative. We also excluded five households that reported very high crop land (group ranches). When these variables are included in the regression models, most variables are insignificant but they do not affect the signs of the coefficients. Their impact on the overall explanatory power of the model is also minimal. Median regressions which control for outliers are robust with Ordinary Least Squares (OLS) and so we present and discuss the latter.

crop revenue with respect to changes in temperature falls drastically in absolute terms (from 0.55 to 0.071). These results show that high temperatures are harmful for productivity (elasticity is negative), confirming that global warming is likely to have devastating effects on agriculture unless farmers take adaptation measures to counter the impact of climate change (Kurukulasuriya & Mendelsohn 2006).

The marginal impacts of precipitation are more modest than for temperatures, but the elasticities are higher. The last row of Table 10 shows that crop revenue is highly elastic with respect to changes in precipitation, and that increased precipitation increases productivity. The elasticity of revenue with respect to precipitation in the all variable model is larger (3.25) than in the first model. A 1% increase in rainfall would lead to a 3.25% increase in net crop revenue, though a similar change in temperature would lead to only a 0.07% fall in revenue.

6.3 Predicting impact of global warming on Kenyan agriculture

Results from the Ricardian analysis show that climate has important effects on agriculture in Kenya. In this subsection, we use the regression results for Model 3 to project the impact of global warming on Kenyan agriculture. To simulate the impact of different climate scenarios, two General Circulation Models (GCMs) were used, namely the Canadian Climate Model (CCC) and the Geophysical Fluid Dynamics Laboratory model (GFDL). These models have been found to give reasonable climate forecasts for Kenya. The CCC and GFDL models predict an average increase in temperature of 3.5℃ and 4℃ respectively with the doubling of CO_2 by the year 2030. For rainfall, evidence from Kenya shows that there have been very large geographical disparities in the trend patterns. Estimates show that there has been a tendency for annual rainfall to decrease in the arid and semi-arid areas and increase over Lake Victoria and the coastal and neighboring regions. This implies that some regions may gain from global warming while others may be adversely affected. Both models predict, however, that on average, Kenya will experience a 20% decrease in rainfall by the year 2030.

Using the regression results in the fourth column of Table 9, we simulated the expected impact of climate change on net crop revenue, using the CCC and GFDL models. We added the predicted change in temperature to the benchmark values, and then evaluated the impact on the baseline net crop revenue. We also adjusted benchmark precipitation by the predicted percentage to get the new precipitation levels. For the CCC model, we simulated the impact of an increase in temperature of 3.5℃ combined with a 20% decrease in rainfall and took a similar scenario for the GFDL model but with a 4℃ change in temperature. We applied the scenarios separately for medium and low potential zones on the one hand and high potential zones on the other, and then for the country as a whole.[8] This was because it is expected that the effects of climate change on agriculture will not be uniform across continents or even within a country. Some regions may gain while others may experience losses (Gbetibouo & Hassan 2005; Deressa et al. 2005; Seo et al. 2005).

The results in Table 11 show that with precipitation remaining the same, changes in temperature predicted by the CCC model would result in a 1% (US$3.54 per hectare) gain in high potential zones but a 21.5% (US$54 per hectare) loss in medium and low potential

[8] The definition of zones is based on Table 3. We define high potential zones as including Central Western and Nyanza Provinces (agro-ecological zones I, II and III) and all other provinces in the sample as medium and low potential zones (Zones IV–VII). We combined the latter zones because of the difficulties of accurately separating them into two categories.

zones. The results further suggest that medium and low potential zones will bear the brunt of global warming in Kenya. Using the GFDL model, we estimated losses of up to US$178 per hectare by the year 2030 for these zones compared to losses of only US$32 for high potential zones and US$117 for the whole country. Though these results may sound surprising, they can be interpreted to mean that a small increase in global warming would have immediate adverse effects on already dry areas. This is what is happening to Kenya at present because of prolonged drought in the arid and semi-arid areas, which has already claimed lives of both human beings and livestock, yet the effect is still not pronounced in high potential zones. The results confirm that long-term climate change has important implications for agriculture and support findings in related literature for Africa and beyond (see for instance Gbetibouo & Hassan 2005; Deressa et al. 2005; Turpie 2002; Tol 2002; Mendelsohn et al. 2000, 2003). Mendelsohn et al. (2000, 2003) also argue that every region in Africa is expected to experience negative climate change impact by the year 2100.

Our results further show that medium and low potential zones are likely to suffer more from rising temperatures resulting from global warming than from a fall in precipitation. However, the reverse is the case for high potential zones and this may be because such zones are located in the highlands where temperatures are quite low and so a rise in temperature may have a lower impact than a fall in precipitation. The whole country is also expected to suffer more from decreases in rainfall than from rising temperatures, just as in medium and low potential zones.

6.4 Perceptions of and adaptations to climate change

Economic adaptation has been argued to significantly reduce vulnerability to anticipated future impacts of climate change. Previous studies have shown that the potential contribution of adaptation to reducing the negative impacts of global warming is large. The basic forms of adaptation identified in the literature including micro-level adaptations, market responses, institutional changes and technological developments (Kurukulasuriya & Rosenthal 2003; Reilly 1999; Darwin et al. 1995). In our study, we focused on micro-level adaptations which include farm production adjustments such as diversification and intensification of crop and livestock production, changing land use, irrigation and altering the timing of operations.

Perceptions of and adaptations to short-term climate variations

In this section, we analyze the perceptions and adaptation of farmers to short-term climate variations and also constraints on adaptation mechanisms. In the first instance, we analyze the adaptations to short-term climate variations shown in Table 12. The table presents the main adaptation measures adopted by households, showing that though households practice a range of adaptation measures, the most popular one is crop diversification or mixed cropping, adopted by 37% of all households, and tree planting, adopted by 16%. The results for the first measure support literature which argues that farmers are likely to adopt diversification of crop and livestock varieties, including the replacement of plant types, in order to increase productivity in the face of temperature and moisture stress (Kurukulasuriya & Rosenthal 2003). The relatively low proportion adopting adjustments to livestock management could be explained by land scarcity in more arable areas, which may hinder large scale livestock production. Nevertheless, such a measure is expected to reduce soil erosion and improve moisture and nutrient retention (Kurukulasuriya & Rosenthal 2003).

Most other measures were adopted by between 11% and 14% of all households. Though the percentage of households involved is small, results for irrigation, water and soil conservation support the argument that a range of management practices such as water and soil conservation can help reduce vulnerability by reducing runoff and erosion and promoting nutrient restocking in soils, while other techniques may improve the soil structure and fertility (Kurukulasuriya & Rosenthal 2003). It was reported by 13% of households that they did not do anything to counter the impact of short-term variations in weather. Analysis by agro-ecological potential reveals that the use of mixed cropping, different planting dates and soil conservation techniques are more common in high potential zones, while livestock, irrigation, water conservation and shading/sheltering are more important in medium and low potential zones.

Table 13 shows the constraints on adaptations to climate change. About 60% of all households are hindered from adapting by lack of credit and savings (poverty). This supports findings in the literature that diversification is costly in terms of the income opportunities that farmers forgo (Kurukulasuriya & Rosenthal 2003). Another 19% fail to adopt any measure because of lack of knowledge about appropriate adaptations. The other constraints are reported by a relatively small proportion of households. Only 8% of households reported that there were no barriers to adaptation. Poverty and lack of knowledge seem to be more critical constraints in medium and low potential zones than in high potential zones.

Perceptions of and adaptations to long-term climate variations

Addressing long-term climate change should entail a comprehensive long-term response strategy at the national or local level and requires a dynamic approach (Kurukulasuriya & Rosenthal 2003). However, in the absence of directed policy responses, farmers choose their own adaptation measures depending on their household and farm characteristics. This adaptation could take several forms: changing crop types, such as introduction of drought tolerant varieties, and shifting from crop production to game ranching, among other measures.

Table 14 shows the percentage of households that reported having observed long-term changes in temperatures: 47% of all households noticed long-term increases in mean temperatures, while only 5% noticed decreased temperatures; 18% noticed climate variations but did not indicate the direction of change; and 28% reported that they had not noticed any change. Farmers in high potential zones were more aware of long-term climate change than their counterparts in medium and low potential zones. In Table 15, we present the percentage of households that reported having noticed long-term changes in precipitation: 56% of all households reported that precipitation had decreased over the years, compared to only 5% who reported increased precipitation, while 16% reported that they had not noticed any change. There were no clear patterns in the differences in perceptions of high potential zone farmers and medium and low potential zone farmers, though a higher percentage of the latter (59%) reported having observed shorter rainy seasons.

From Tables 14 and 15, it is clear that farmers in Kenya have perceived increased global warming though a few households are not clear on the direction of change. Next we consider the range of adjustments that the farmers make to counter the impact of long-term temperature and precipitation changes, conditional on perceiving global warming. The results are presented in Tables 16 and 17. The last row of these tables shows that only 60% of all households made any effort to counter long-term temperature changes (40% reported no adaptations), compared to 78% in the case of precipitation. For long-term temperature changes, two main adaptations emerge: crop diversification and shading/sheltering or planting of trees. As in the case of short-term climate change, crop diversification is more common in high potential zones, while shading/sheltering is more common in medium and low potential zones. In the case of crop diversification, farmers in Kenya are known to switch to more adaptive crop varieties such as fast growing and hybrid varieties. This supports the literature which shows that long-term adaptation measures mainly take the form of changing crop types, such as drought tolerant varieties. However, the low percentages adopting this measure could be due to lack of knowledge, skills and finances (Kurukulasuriya & Rosenthal 2003). Shading/sheltering/tree planting is important because in addition to countering climate change it is also a form of soil conservation.

Improved water management is one of the most important long-term adaptation options that countries must pursue. Though few households reported water management measures for long-term changes in temperature, this contrasts with adjustments for long-term precipitation changes, which included increased water conservation, crop diversification and increased use of irrigation. The low overall adoption rates could be attributed to scarcity of resources, including water for irrigation, and lack of knowledge about the importance of these options. Indeed, only about 10% of the overall sample of 816 households reported having used any irrigation at all.

The above analysis shows that farming households in Kenya are aware of both short- and long-term climate change. Further, more than 80% of households have implemented various adaptation mechanisms to counter short-term climate variations, compared to 60% and 78% that have implemented various mechanisms to counter long-term temperature and precipitation changes respectively. Though we did not investigate the role of government in promoting farm level adaptations to climate change, it can play a critical role in encouraging adaptations. For instance, improving knowledge through agricultural extension could encourage both short- and long-term adaptations to climate change. Kurukulasuriya and Rosenthal (2003) argue that there is a clear and distinct role for strengthening extension services in agriculture in vulnerable countries to enhance farmer awareness of potential adaptation response options. Policies that improve household welfare are, however, a priority for both short- and long-term adaptation measures, given that 60% of all households reported that adaptation is constrained by lack of credit and income.

7. Conclusions and implications for policy

This paper explores the impact of climate on crop revenue in Kenya, using primary household level data enriched with secondary climate, hydrological and soil data. We concentrated on a seasonal Ricardian model to assess the impact of climate on net crop revenue per acre. We first assessed the impact of climate on agriculture by estimating models with climate factors only, then tested the impact of hydrological, soil and household variables.

Our results suggest that climate affects agricultural productivity. Increased winter temperatures increase net crop revenue, while high summer temperatures decrease it. Increased precipitation increases net crop revenue. The results further show that there is a non-linear relationship between temperature and crop revenue on the one hand and between precipitation and crop revenue on the other. This finding is consistent with studies on the impact of global warming on agriculture (Mendelsohn et al. 1994, 2003; Kurukulasuriya & Mendelsohn 2006). Another key result is a hill-shaped relationship between mean flow and net crop revenue. Further, we also find that andosols, irrigation and household size are positively correlated with crop revenue, while livestock ownership, farm size and wage rates are inversely correlated with revenue.

Estimated marginal impacts further show that crop revenue is elastic with respect to climate change, but less elastic with respect to temperature than to precipitation. The temperature elasticities suggest that global warming is harmful for agricultural productivity. Though precipitation elasticities are much higher than temperature elasticities, the marginal impacts suggest that the temperature component of global warming may have more serious repercussions than rainfall.

This study further predicts the impact of different climate change scenarios on Kenyan agriculture. We used two GCMs to do so: CCC and GFDL, which predict 3.5°C and 4°C changes in temperature by the year 2030 respectively and a 20% change in precipitation over the same period. The predictions show that long-term changes in temperatures and precipitation will have a substantial impact on net revenue, and that the impact will be more pronounced in medium and low potential zones than in high potential zones. The latter are expected to receive some marginal gains from mild temperature increases, holding precipitation constant.

Our analysis of perceptions and adaptation of farmers to climate change show that farming households in Kenya are aware of both short- and long-term climate change and some have implemented various adaptation mechanisms. The analysis also shows differences between the perceptions and adaptations of medium/low potential zone farmers and their counterparts in high potential zones. Diversification (changing the crop mix) is the most common adaptation measure, particularly in high potential zones, while water conservation, irrigation and shading/sheltering of crops are the main adaptation measures in drier regions.

These results imply that adaptation to climate change in Kenya is important if households are to counter the expected impacts of long-term climate change. The government should therefore play a more critical role in encouraging adaptations. Monitoring of climate change and disseminating information to farmers would be a critical intervention, while knowledge on adaptation measures could encourage both short- and long-term adaptations to climate change. To gather such knowledge requires a multidisciplinary approach involving soil scientists, hydrologists, climate experts and agronomists. Using this knowledge, farmers and local leaders should be sensitized, through extension network, to the implications of climate change, including the vulnerability of crop production and the necessity for adaptation strategies. Management of the scarce water resources in the country could generate more water for irrigation purposes, especially in the drier zones. Given the dwindling and fluctuating water resources in the country, the government needs to embark on recycling of waste water, which can then be used to save on available water. In addition, water harvesting techniques should be introduced to farmers and adoption encouraged, particularly in drier areas, to supplement any available water. In addition, protection, conservation and rehabilitation of water catchment areas and river basins is critical to ensure sustainable water supply. Policies that improve household welfare as well as access to credit are also a priority for both short- and long-term adaptation measures.

The results in this study are based on general crop agriculture for which data were collected on all crops produced by farmers. Given that different crops have different climate requirements, future studies need to be focused on specific crop responses and adaptations, particularly the staple foods which have long-term implications for food security in the country. This paper does not take into account revenue from livestock production, yet most farmers in Kenya combine livestock and crop production for both subsistence and commercial purposes. Our results show that medium and low potential (mostly semi-arid and arid) areas are expected to be much more adversely affected by global warming. However, these areas are best suited for livestock production by both small scale producers (pastoralists) and large scale ones (ranchers). Analysis of the impact of climate change on livestock production would give a better picture of the impact in arid and semi-arid areas. There is also a need for studies to model the impact of climate change with and without the impact of adaptations that farmers make to counter the impact of climate change. Another shortcoming of this study springs from the nature of the household data used. Though there is data on long-term climate change, the full impact would be better assessed with time series data on crop production. Long-term changes in agricultural production may better reflect the impact of long-term climate change than one-time estimates of production.

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Table 1: Characteristics of agro-climate zones and farming systems in Kenya

Zone	*Moisture index (%)*	Climate classification	Average annual rainfall (mm)	Average annual potential evaporation (mm)	Vegetation	Farming system
I	>80	Humid	1100-2700	1200-2000	Moist forest	Dairy, sheep, coffee, tea, maize, sugarcane
II	65-80	Sub-humid	1000-1600	1300-2100	Moist and dry forest	Maize, pyrethrum, wheat, coffee, sugarcane
III	50-65	Semi-humid	800-1400	1450-2200	Dry forest and moist woodland	Wheat, maize, barley coffee, cotton, coconut, cassava
IV	40-50	Semi-humid to semi-arid	600-1100	1550-2200	Dry woodland and bush land	Ranching, cattle sheep, barley, sunflower, maize, cotton, cashew nuts, cassava
V	25-40	Semi-arid	450-900	1650-2300	Bush land	Ranching, livestock, sorghum, millet
VI	15-25	Arid	300-550	1900-2400	Bush land and scrubland	Ranching
VII	<15	Very arid	150-350	2100-2500	Desert scrub	Nomadism and shifting grazing

Source: Sombroek et al. (1982); Jaetzold & Schmidt (1982)

Table 2: Characteristics of the main drainage basins in Kenya

Drainage basin	Area (km^2)	Mean annual rainfall (mm)	Mean annual runoff (mm)	Climate classification
Lake Victoria	49,210	1000	270	Humid to sub-humid
Rift Valley	126,910	600	120	Arid to semi-arid
Athi River	69,930	650	200	Semi-arid
Tana River	132,090	520	170	Semi-humid (headlands), semi-arid to arid
Ewaso Nyiro	204,610	400	80	Arid to semi-arid

Source: Sombroek et al. (1982)

Table 3: Distribution of sample by province, district by agro-ecological zone

Province	District	Type of zones	District sample	Province sample
Central	1.Kiambu	LH1,UH1, UM2, UM3, UM4, UM5	24	112
	2.Kirinyaga	LM4, LM3, UM3, UM2, UM1, LH1	24	
	3.Muranga	UM1, UM2, UM3, UM4, LH1	20	
	4.Nyandarua	UH3, UH2, UH4, LH4	16	
	5.Nyeri	LH1, LH2, LH3,LH4, LH5, UH2, UH3, UM2, UM3	28	
Coast	6.Kilifi	L6, L5, L4, L3	24	83
	7.Kwale,	L6, L5, L4, L3	22	
	8.TaitaTaveta,	LM6, L6, L5, UM3	17	
	9.Tana River	L3, L4, L5, L6	20	
Eastern	10.Embu	LM5, LM4, LM3, UM4, UM3, UM2, UM1, LH1	33	172
	11.Kitui	LM5, LM4, UM4, UM6	25	
	12.Machakos,	LM5, LM4, LM3, UM4, UM6	28	
	13.Makueni	LM5, UM4, L6	20	
	14.Meru Central	UM1, UM2, LH1, UH3	20	
	15.Nyambene (Upper Meru)	UM1, UM2, LH1, UH3, LH4	20	
	16.Nithi (Lower Meru)	LM3, LM4, LM5, LM6, L5, UM1, UM2, UM3	26	
Nyanza	17.Homa Bay	LM3, LM5, LM4, LM2, LM1	17	133
	18.Kisii Central	UM1, LH1, LH2	24	
	19.Kisumu	LM3, LM2, LM4	12	
	20.Migori	UM2-3, UM3-4, LM3, LM2	26	
	21.Nyamira	UM1, LH1, LH2	24	
	22.Siaya	LM1, LM2, LM3, LM4	18	
Rift Valley	23.Baringo	LM6, LM5, LM4, UM5	18	227
	24.Bomet	LH3, LH2, UM3, UM4	18	
	25.E. Marakwet	UH1, UH1-2, UM4, LM5	14	
	26.Kajiado	LM6, LM5, UM5, UM4	23	
	27.Kericho	LH1, LHH2, UM1, UM3, UM2, UH	18	
	28.Laikipia	UM6, UM5, LH5, Lh4	16	
	29.Nakuru	UH, UH3, LH2, UM3, UM4, UM5, UM6	18	
	30.Nandi	UM4, LH3, LH1, UM1, LM2	18	
	31.Narok	UM6, LH3, UM5, UH2	27	
	32.Trans Nzoia	LH4, LH2, LH3, UM2, UM3, UM4	15	
	33.Uasin Gishu	LH3, LH4, UH1, UH2, UM4	27	
	34.West Pokot	LM5, L6, UM4-5	15	
Western	35.Bungoma	LM2, LM3, LH1, UM1, UM3, UM4	24	89
	36.Busia	LM1, LM2, LM3, LM4	23	
	37.Kakamega,	LM1, LM2, UM4	25	
	38.Vihiga	UM1	17	
Total sample			816	816

Source: Authors' construction

Key: UH – upper highlands, LH – lower highlands, UM – upper midland, LM – lower midland

Table 4: Distribution of sample by farm type

Farm type	Frequency	%
Small (0-5 acres or 0-2 Ha)	540	66.18
Medium (5-20 acres or 2-8 Ha)	176	21.57
Large (>20 acres or > 8 Ha)	100	12.25
Total	816	100

Table 5: Sample statistics for ARTES temperatures and precipitation by season

	Temperatures (˚C)		Precipitation (mm/mo)	
Season	Mean	Std dev.	Mean	Std dev.
Fall (December–February)	22.19	1.30	88.80	41.45
Summer (March–May)	22.91	1.27	103.71	31.57
Winter (June–August)	19.89	2.08	62.40	40.82
Spring (September–November)	21.04	1.35	71.89	26.95
Annual average	21.51	1.35	84.53	18.60
Long rains (March–August)	20.85	1.70	90.90	34.97
Short rains (September–February)	22.42	1.20	81.27	23.71

Table 6: Sample statistics for satellite temperatures and wetness indices by season

	Temperatures (˚C)		Moisture index	
Variable	Mean	Std dev.	Mean	Std dev.
Fall (December–February)	19.29	2.67	3.17	1.79
Summer (March–May)	19.07	2.74	2.73	1.86
Winter (June–August)	18.50	2.36	3.29	1.89
Spring (September–November)	19.09	2.66	2.72	1.70
Annual average	18.99	2.58	2.98	1.80
Long rains (March–August)	19.33	2.73	2.95	1.82
Short rains (September–February)	18.65	2.46	3.01	1.79

Table 7: Soil types by characteristics and distribution in study sample

Major soil classification	Texture subsoil	Texture topsoil	Depth	Organic matter component of topsoil	Drainage	Fertility	% of soil type in survey
Ferralsols	Clay	Clay	Variable	Variable	Good	Low	22
Luvisols	Clay	Variable	Variable	Variable	Moderate	Low to moderate	11
Arenosols	Sand	Sand	Variable	Low	Good	Low to very low	1
Nitosols	Clay	Clay	Deep	Moderate to high	Good	Moderate to high	28
Andosols	Clay	Clay	Deep	Moderate to high	Good	High	6
Cambisols	Variable	Variable	Variable	Variable	Moderate to good	Moderate to high	8
Vertisols	Clay	Clay	Variable	Low to moderate	Poor	Moderate to high	3
Planosols	Clay	Variable	Variable	Low to moderate	Poor	Low to moderate	2
Lithosols/ Leptosols	Rock	Variable	Very shallow	Variable	Variable	Variable	8
All other soils	Variable	Variable	Variable	Variable	Variable	Variable	11

* Variable means more than three classes

Source: Jaetzold & Schmidt (1982)

Table 8: Distribution of selected variables by agro-ecological zone

Variable	Medium & low potential		High potential		All zones	
	Mean	Std dev.	Mean	Std dev.	Mean	Std dev.
Net revenue (US$)	339.2	376.9	352.38	317.14	344.60	353.44
Temperature summer	20.2	2.9	17.47	1.46	19.07	2.74
Temperature winter	19.5	2.4	17.12	1.35	18.50	2.36
Precipitation fall	101.1	75.4	57.40	24.68	83.20	63.74
Precipitation summer	97.2	19.3	145.94	24.91	117.18	32.41
Log (mean flow)	5.3	0.3	5.50	0.21	5.40	0.26
Soils (andosols)	0.1	0.1	0.06	0.09	0.06	0.11
Livestock ownership dummy	0.9	0.3	0.89	0.32	0.88	0.32
Primary occupation of household head is farming	0.8	0.4	0.70	0.46	0.73	0.44
Secondary occupation of household head is farming	0.2	0.4	0.23	0.42	0.21	0.41
Household head is Christian	0.9	0.2	0.98	0.14	0.96	0.20
Average years of education of household members	8.5	3.1	8.46	2.78	8.46	2.99
Farm size	8.5	55.8	2.53	2.81	6.02	42.87
Household size	6.8	2.9	6.26	1.88	6.60	2.53
Male wage rates	115.6	52.7	97.29	34.63	108.11	47.02
Child wage rates	57.4	17.6	51.55	13.25	54.98	16.18
Irrigation dummy	0.2	0.4	0.07	0.26	0.14	0.34
Sample size	427		297		724	

Table 9: Ricardian regression estimates of the net crop revenue model

Variable	Model 1[τ]	Model 2[τ]	Model 3[τ]
Temperature summer	-542.02 (-2.44)***	-397.71 (-1.85)**	-479.31 (-2.21)**
Temperature summer squared	11.76 (2.03)**	8.68 (1.58)*	11.03 (1.96)**
Temperature winter	716.22 (2.55)***	567.73 (2.08)**	702.63 (2.64)***
Temperature winter squared	-17.09 (-2.30)**	-13.48 (-1.92)**	-17.44 (-2.51)***
Precipitation fall	13.70 (2.64)***	19.51 (2.98)***	19.79 (2.86)***
Precipitation fall squared	-0.04 (-2.21)**	-0.06 (-2.82)***	-0.07 (-2.68)***
Precipitation summer	82.97 (2.49)***	83.00 (2.38)***	76.29 (2.08)**
Precipitation summer squared	-0.33 (-2.49)***	-0.33 (-2.40)***	-0.31 (-2.11)**
Log (mean flow)		3953.32 (1.86)**	3494.69 (1.64)*
Log (mean flow squared)		-367.62 (-1.88)**	-326.70 (-1.65)*
Soils (andosols)		602.84 (1.62)**	887.29 (2.34)***
Livestock ownership dummy			-120.25 (-2.58)***
Primary occupation of household head is farming			21.22 (0.51)
Secondary occupation of household head is farming			132.46 (2.62)***
Household head is Christian			154.70 (2.26)**
Average years of education of household members			1.17 (0.31)
Farm size			-3.59 (-3.14)***
Farm size squared			0.01 (2.94)***
Household size			9.15 (1.59)*
Male wage rates			-0.81 (-2.10)**
Child wage rates			-2.57 (-2.41)***
Irrigation dummy			136.43 (2.46)***
Constant	-6567 (-2.33)	-17510 (-2.52)	-16194 (-2.16)
Number of observations	724	724	715
F	3.73***	3.27***	5.30***
R-squared	0.0297	0.0558	0.1291

[τ] Model 1 uses only climate variables as regressors, Model 2 introduces hydrological and soil factors, and Model 3 introduces household characteristics.

* significant at 10% level ** significant at 5% level *** significant at 1% level

Table 10: Marginal impacts of climate on net crop revenue (US$/ha)

Marginal impacts	Climate variable model	All variable model
Summer temperature	-94.77**	-59.35
Winter temperature	84.87***	58.35
Overall temperature	-9.90	-1.35
Temperature elasticity	-0.55	-0.07
Fall rainfall	7.11***	8.75***
Summer rainfall	5.95**	4.59
Overall rainfall	13.06***	13.34***
Precipitation elasticity	3.18	3.25

*** significant at 1% level ** significant at 5% level

Table 11: Predicted impacts of different climate scenarios by zone (loss in US$)*

Climate change scenario	Medium & low potential	High potential	All zones
+3.5^{o}C	80.05 (24%)	-3.54 (-1%)	68.45 (20%)
+4.0^{o}C	108.79 (32%)	11.91 (3%)	93.04 (27%)
20% reduction in rainfall	69.54 (21%)	20.14 (6%)	24.39 (7%)
+3.5^{o}C+ 20% reduction in rainfall	149.59 (44%)	16.60 (5%)	92.84 (27%)
+4^{o}C+ 20% reduction in rainfall	178.33 (53%)	32.05 (9%)	117.43 (34%)

*Percentage loss in brackets

Table 12: Adaptations to short-term variations in weather

Variable	All regions	High potential	Med-low potential
Crop diversification / Mixed / Multi-cropping	37% (0.48)	44% (0.50)	33% (0.47)
Different planting dates	13% (0.34)	16% (0.37)	11% (0.31)
Adjustments to livestock management	6% (0.24)	4% (0.19)	7% (0.26)
Increased use of irrigation	14% (0.34)	9% (0.29)	16% (0.37)
Increased water conservation techniques	13% (0.33)	12% (0.32)	13% (0.34)
Soil conservation techniques	11% (0.31)	13% (0.34)	10% (0.30)
Shading and shelter / Tree planting	16% (0.37)	14% (0.34)	18% (0.38)
Other adaptation measures	12% (0.32)	9% (0.29)	13% (0.34)
No adaptation	13% (0.33)	17% (0.38)	10% (0.30)

Table 13: Constraints to short-term adaptations (% of households)

Constraint faced	All regions	High potential	Med-low potential
Lack of information about short-term climate variation	8% (0.27)	7% (0.26)	10% (0.29)
Lack of knowledge of appropriate adaptations	19% (0.39)	16% (0.36)	25% (0.43)
Lack of credit or savings	59% (0.49)	56% (0.50)	64% (0.48)
No access to water	8% (0.27)	12% (0.32)	3% (0.16)
Lack of appropriate Seed	5% (0.21)	4% (0.19)	6% (0.24)
Other constraints	13% (0.33)	12% (0.32)	14% (0.35)
No barriers to adaptation	8% (0.28)	9% (0.28)	8% (0.27)

Table 14: Households (%) observing long-term changes in temperatures

Observed variation	All regions	High potential	Med-low potential
Increased temperature	47% (0.50)	52% (0.50)	43% (0.50)
Decreased temperature	5% (0.22)	5% (0.22)	5% (0.22)
Altered climate range	18% (0.38)	19% (0.39)	17% (0.37)
No change	28% (0.45)	4% (0.20)	2% (0.13)
Don't know	3% (0.16)	4% (0.20)	2% (0.13)

Table 15: Households (%) observing long-term changes in precipitation

Observed variation	All regions	High potential	Med-low potential
Increased precipitation / extended rainy season	5% (0.22)	10% (0.30)	2% (0.14)
Decreased precipitation / shorter rainy season	56% (0.50)	52% (0.50)	59% (0.49)
Change in timing of rains / earlier / later	18% (0.39)	21% (0.41)	17% (0.37)
Change in the frequency of droughts	7% (0.26)	7% (0.25)	7% (0.26)
No change	16% (0.37)	13% (0.34)	19% (0.39)

Table 16: Adaptation to long-term temperature changes (% of households)

Variable	All regions	High potential	Med-low potential
Crop diversification / mixed / multi-cropping	25% (0.43)	38% (0.49)	17% (0.38)
Different planting dates	6% (0.23)	7% (0.25)	5% (0.21)
Adjustments to livestock management	4% (0.19)	4% (0.20)	4% (0.19)
Increased irrigation / groundwater / watering	6% (0.23)	6% (0.24)	5% (0.22)
Increased water conservation techniques	7% (0.25)	6% (0.24)	7% (0.25)
Decreased water conservation techniques	6% (0.24)	10% (0.29)	4% (0.19)
Shading and shelter / tree planting	22% (0.41)	12% (0.32)	28% (0.45)
No adaptation	40% (0.49)	37% (0.48)	41% (0.49)

Table 17: Adaptation to long-term precipitation changes (% of households)

Variable	All regions	High potential	Med-low potential
Crop diversification / mixed / multi-cropping	34% (0.47)	35% (0.48)	34% (0.47)
Different planting dates	15% (0.36)	19% (0.40)	13% (0.33)
Adjustments to livestock management	6% (0.23)	3% (0.16)	7% (0.26)
Increased irrigation / groundwater / watering	16% (0.37)	15% (0.35)	18% (0.38)
Increased water conservation techniques	21% (0.41)	17% (0.37)	23% (0.42)
Decreased water conservation techniques	13% (0.34)	16% (0.37)	12% (0.33)
Shading and shelter / tree planting	9% (0.28)	4% (0.20)	12% (0.32)
No adaptation	22% (0.41)	24% (0.43)	21% (0.41)