Will African Agriculture Survive Climate Change?

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Measurement of the likely magnitude of the economic impact of climate change on African agriculture has been a challenge. Using data from a survey of more than 9,000 farmers across 11 African countries, a cross-sectional approach estimates how farm net revenues are affected by climate change compared with current mean temperature. Revenues fall with warming for dryland crops (temperature elasticity of –1.9) and livestock (–5.4), whereas revenues rise for irrigated crops (elasticity of 0.5), which are located in relatively cool parts of Africa and are buffered by irrigation from the effects of warming. At first, warming has little net aggregate effect as the gains for irrigated crops offset the losses for dryland crops and livestock. Warming, however, will likely reduce dryland farm income immediately. The final effects will also depend on changes in precipitation, because revenues from all farm types increase with precipitation. Because irrigated farms are less sensitive to climate, where water is available, irrigation is a practical adaptation to climate change in Africa.

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The increasing concern about climate change has led to a rapidly growing body of research on the impacts of climate on the economy. Quantitative estimates of climate impacts have improved dramatically over the last decade (Pearce and others 1996; McCarthy and others 2001; Tol 2002; Mendelsohn and Williams 2004). Sub-Saharan Africa is predicted to be particularly hard hit by global warming because it already experiences high temperatures and low (and highly variable) precipitation, the economies are highly dependent on agriculture, and adoption of modern technology is low.

Despite the estimated magnitude of the potential impacts on Africa, there have been relatively few economic studies (Kurukulasuriya and Rosenthal 2003). Most of the quantitative projections are interpolations from empirical studies done elsewhere (Tol 2002; Mendelsohn and Williams 2004). A limited number of agronomic studies on Africa have confirmed that warming would have large effects on selected crops (Rosenzweig and Parry 1994), but these studies reflect only a small share of Africa's crops, they fail to capture how farmers might respond to warming, and they do not quantify overall economic impacts. The economic impact on the livestock sector in Africa has gone largely unstudied (Kurukulasuriya and Rosenthal 2003).

This study uses farm-level data collected across diverse climate zones in 11 African countries to explore how the current climate already affects African farmers, specifically net farm revenues. Total net farm revenue is defined as the sum of incomes from three main farm activities: dryland crops, irrigated crops, and livestock. Irrigated crops rely on at least some irrigated water (from surface flows or ground water). Dryland crops rely only on rainfall that falls on the farm. Livestock in Africa largely depend on grazing on natural lands or pasture.

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This information is used to estimate the impacts of changing temperature and precipitation on the net revenues of African farmers using the Ricardian method (Mendelsohn, Nordhaus, and Shaw 1994). Net revenues are regressed on climate, soils, and other control variables. Separate regressions are estimated for the three main farm activities to shed light on the climate response of each of these components of farm income. The amount of land that was planted could be accurately measured for the crop regressions used to estimate net revenue per hectare. Since most African farmers rely on common land for livestock grazing, it was not possible to determine how much land was used. The livestock regressions are consequently based on revenue per farm. Although these analyses are therefore different, total farm income is still the sum of the incomes from these three sources.

I. METHODOLOGY

This study uses a Ricardian approach to measure the determinants of farm net revenues, including climate, through an econometric analysis of cross-sectional data (Mendelsohn, Nordhaus, and Shaw 1994). The approach has been applied to study the relationship between net revenues from crops and climate, including other key variables in selected countries in low latitudes (Kumar and Parikh 2001; Mendelsohn, Sanghi, and Dinar 2001; Molua 2002; Deressa, Hassan, and Poonyth 2005; Gbetibouo and Hassan 2005; Seo, Mendelsohn, and Munasinghe 2005; Kurukulasuriya and Ajwad 2006), but this study is the first application of the method to many countries across a continent (Africa). It is also the first Ricardian study to examine net revenues from livestock.

David Ricardo (1815) was the first to observe that land rents reflects the net revenue value of farmland. Farmland net revenue (R) reflects the net productivity and costs of individual crops and livestock:

$$R = \sum P_i Q_i(\boldsymbol{X}, \boldsymbol{F}, H, \boldsymbol{Z}, \boldsymbol{G}) - \sum \boldsymbol{P}_x \boldsymbol{X} \tag{1}$$

where P_i is the market price of crop i, Q_i is output of crop i, $\boldsymbol{X}$ is a vector of purchased inputs (other than land), $\boldsymbol{F}$ is a vector of climate variables, H is water flow, $\boldsymbol{Z}$ is a vector of soil variables, $\boldsymbol{G}$ is a vector of economic variables, and $\boldsymbol{P}_x$ is a vector of input prices. The farmer is assumed to choose inputs ($\boldsymbol{X}$) to maximize net revenues given the characteristics of the farm and market prices.

Each farmer is assumed to choose inputs and outputs to maximize their net revenue subject to the climate and soils of each farm, in addition to other key economic variables. The observed net revenue function is therefore the locus of maximum profits given the set of exogenous climate, soil, and economic conditions. The Ricardian model is a reduced form hedonic price model of that locus of profits. Net revenue is defined as gross revenue minus the cost of transport, storage, hired labor (valued at the market wage rate), light farm tools (files, axes, machetes), heavy machinery (tractors, plows, threshers), fertilizer, pesticides, and postharvest losses. Household labor costs are not included because the shadow wage rate that workers apply to their own time cannot be measured. This is a common problem in the development literature (Bardhan and Udry 1999). The effects of different soil types are controlled for and tested in this analysis. Water flow is also included because it is particularly important for irrigation (Mendelsohn and Dinar 2003).

In the data set used in this analysis, farmers growing crops either use irrigation or do not. Many farmers, however, combine growing crops with raising livestock. A few farmers just raise livestock. Across Africa, farmers use a combination of irrigated crops, dryland crops, and livestock. The analysis examines each of these revenue sources separately, estimating a separate Ricardian model for livestock, dryland crops, and irrigated crops. This is done, first, because each revenue source is thought to respond to climate differently and second, because information was not available about the amount of land that livestock used, and therefore revenue per hectare models for cropland cannot be used for livestock. Following Schlenker, Hanemann, and Fischer (2005), whether a farm grows dryland crops, grows irrigated crops, or raises livestock is assumed to be exogenous. Future studies will relax this assumption and predict how even the type of farm may be influenced by climate.

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

$$R = \beta_0 + \beta_1 \boldsymbol{F} + \beta_2 \boldsymbol{F}^2 + \beta_3 \boldsymbol{Z} + \beta_4 \boldsymbol{G} + \beta_5 \log(H) + \mu \tag{2}$$

where μ is an error term. Both a linear and a quadratic term for climate, $\boldsymbol{F}$ (temperature and precipitation) are introduced. This quadratic functional form for climate captures the expected nonlinear shape of the relationship between net revenues and climate (Mendelsohn, Norhaus, and Shaw 1994; Mendelsohn, Sanghi, and Dinar 2001; Mendelsohn and Dinar 2003). Based on agronomic research and previously reported cross-sectional analyses, farm net revenues are expected to have a concave (hill-shaped) relationship with temperature. For each crop, there is a known average temperature that is best for crop production, but this relationship is not necessarily concave for each season. Less is known about livestock, but in general, livestock appear to be chosen to match certain climate zones (McCarthy and others 2001). So there is every reason to believe that the quadratic form of the climate variables is suitable for livestock as well. Water flow is introduced in a log form because the benefits from flow diminish as flow increases.

Past Ricardian studies have suggested that crops respond to seasonal variation in climate (Mendelsohn, Norhaus, and Shaw 1994; Mendelsohn, Sanghi, and Dinar 2001; Mendelsohn and Dinar 2003). Climate data for consecutive months are highly correlated and perform poorly in Ricardian models. In a tropical climate, even the seasons are highly correlated as there is not as much variation from one season to the next compared with temperate climate regions. Nonetheless, there was a desire to capture as much of the seasonal effects as possible. Seasons were defined as follows: winter (in the

Southern Hemisphere) is defined as May, June, and July, spring as August through October, summer as November through January, and fall as February through April. The seasons in the Northern Hemisphere are defined in the same way for the appropriate months. These seasonal definitions provide the best fit with the crop farm data, and they reflect the mid-point for key rainy seasons in Africa. All three Ricardian models use the same definition of climate.

An alternative way to measure climate is to use growing degree days (Ritchie and NeSmith 1991). Growing degree days are the sum of degrees above a specified cutoff temperature across a growing season for a particular crop. If climates are stable, growing degree days can measure land value accurately (Schlenker, Hanemann, and Fischer 2006). However, the technique was originally developed to be crop specific, and it was tied to the sowing and harvest dates of individual crops. It becomes a very vague and biased concept when applied across crops and regions with different and changing lengths of growing seasons, because, among other things, it does not capture seasonal effects or account for the impact of cold days.

The marginal impact of a single climate variable, f_j, on crop or livestock net revenue evaluated at the mean of that variable is:

$$E[\partial R/\partial f_j] = \beta_{1,j} + 2\beta_{2,j}E[f_j]. \tag{3}$$

Because flow is expressed in logarithmic terms, the marginal impact of flow, $\boldsymbol{H}$, on net revenue is

$$E[\partial R/\partial H] = \beta_5/H. \tag{4}$$

These marginal effects can be evaluated at any level of climate or flow, but the focus is on showing effects at mean climate levels for Africa. Note that the linear formulation of the model assumes that these marginal effects [equations (3) and (4)] are independent of future technological change. However, it is possible that future technological change could make crops (or other farming activity) more susceptible to temperature or precipitation changes—or less so.

The marginal change in rent is the marginal welfare effect of the change in the exogenous variable. However, with nonmarginal changes in exogenous variables, underlying prices may change. The Ricardian price schedule will overestimate welfare effects in this case because the price changes will mitigate some of the effects (Cline 1996; Adams 1999; Darwin 1999). For globally traded goods such as agricultural crops and livestock products, price changes are not likely to be a problem as local gains and losses in production are expected to offset each other for a small net change in global output (Reilly, Hohmann, and Kane 1994; Mendelsohn and Nordhaus 1999). However, a dramatic reduction in the productivity of African agriculture could affect African wage rates. For example, if productivity in a district fell substantially, local wages might fall—or if productivity rose, wages might also rise. To capture this effect, a more complete analysis would have to model local African labor markets as well as land productivity.

The strength of the Ricardian method is that it captures the adaptation responses of farmers. The use of net revenues in the analysis reflects the benefits and costs of implicit adaptation strategies. Specifically, the analysis incorporates the substitution of different inputs and the introduction of alternative activities that each farmer has adopted in light of the existing climate. For example, the model reflects the costs of seeds, equipment, and hired labor that a farmer might pay in response to climate and the revenue that the farmer consequently earns. Farmers adapt by changing their crops, their sowing methods, their timing, and their inputs. Farms also adapt by changing their types of livestock and number of animals. All of these changes increase net revenues under the new climate conditions. Consequently, accounting for adaptation leads to much lower predicted overall damage from climate change. This is true even if all the adaptations being considered are practices currently being used in Africa.

The Ricardian method is a cross-sectional approach. It assumes that cross-sectional comparisons provide useful insights into long-term intertemporal changes. The Ricardian method does account for adaptation costs that would be associated with comparing one equilibrium state with another. However, cross-sectional analysis does not account for dynamic transition costs that might occur as farms move between two states. For example, the Ricardian model does not capture the costs of learning by doing or of decommissioning capital prematurely (Kaiser, Riha, Wilkes, Rossiter, and others 1993; Kaiser, Riha, Wilkes, and Sampath 1993; Quiggin and Horowitz 1999; Kelly, Kolstad, and Mitchell 2005). Furthermore, innovations in modern agriculture, which have been adopted in other low-latitude regions, have spread slowly in Africa, suggesting that transition costs must be examined carefully in Africa (Evenson and Gollin 2003).

The Ricardian approach has a number of other limitations. For example, the approach does not measure the effect of variables that do not vary across space. Specifically, the effect of different levels of carbon dioxide is not captured as carbon dioxide levels do not vary systematically across Africa. Controlled experiments and crop simulation modeling are required to learn about the likely positive effect of carbon fertilization. It may also be possible that some aspects of future climates do not resemble anything in the present. For example, if there is some type of extreme event in the future that does not occur in the present, the analysis will not be able to evaluate its effect. Finally, the Ricardian results can be distorted by local agricultural policies. If some countries subsidize farm inputs or regulate certain crops, they influence farmers' choices, and the empirical results will reflect these distortions. If the distortion is explicitly modeled, it can be controlled for. But if it is not carefully modeled, the climate variables may be biased. If future decision makers eliminate these subsidies or introduce new ones, the predictions from the empirical results may no longer hold.

II. DATA AND EMPIRICAL SPECIFICATIONS

The study relied on long-term average climate (normals). These long-term data for districts in Africa were gathered from two sources. Satellite data on temperature was measured by a Special Sensor Microwave Imager (SSMI) on U.S. Department of Defence satellites (Basist and others 2001) for 1988–2003. The SSMI detects microwaves through clouds and estimates surface temperature (Basist and others 1998; Weng and Grody 1998). The satellites conduct daily overpasses at 6 a.m. and 6 p.m. across the globe. The precipitation data come from the Africa Rainfall and Temperature Evaluation System (World Bank 2003) created by the Climate Prediction Centre of the U.S. National Oceanic and Atmospheric Administration. It is based on ground station measurements of precipitation for 1977–2000. Thus, the temperature and precipitation data cover slightly different periods. This discrepancy might be a problem for measuring variance or higher moments of the climate distribution, but it should not affect the use of the mean of the distribution.

The 11 countries in this study were selected across the diverse climate zones of Africa (figure 1) and precipitation of each country in the sample. Although Africa is generally hot and dry, there is a great deal of variation across the continent (figure 2). Egypt and South Africa are much cooler than the rest of the countries in the sample. Similarly, relative to the other countries in the sample, Cameroon is very wet, followed by Kenya, Zambia, Ghana, and Ethiopia; the other countries, especially Egypt, are drier.

Within each country, districts, were selected to capture representative farms across diverse agroclimatic conditions. Between 30 and 50 districts were sampled in each country. In each district, surveys were conducted in 2002–04 of randomly selected farms (seven countries were surveyed in the 2002–03 season and four countries were added in 2003–04). Sampling was clustered in villages to reduce the cost of administering the survey. A total of 9,597 surveys were administered. The final number of surveys with usable information on crop production was 9,064. Of these, 7,238 farms had dryland crops, 1,221 had irrigated crops, and 5,062 had livestock. Many farms had both crops and livestock. The total number of farm surveys per country varied from 222 in South Africa to 1,288 in Burkina Faso.

Median net revenues per farm from dryland crops, irrigated crops, and livestock are presented in figure 3 by country. The relative importance of dryland crops and irrigated crops varies considerably. For example, Egypt is entirely dependent on irrigated crops because the climate is too dry to support crops without irrigation. In contrast, most farms in East Africa and the Sahel have very little irrigated crops. Livestock net revenue varies widely across countries, but it is particularly important in relatively dry countries.

Data on hydrology were obtained from a continental scale hydrological model of Africa (IWMI and University of Colorado 2003). Using climate data and local typography, the model estimated the potential monthly long-term stream flow for each district. Potential water flows were used because water can be withdrawn from many places along a watershed. Water flow measures the

FIGURE 1. Map of Study Countries

amount of water coming from other districts and is an important complement to the water generated in each district from precipitation. Water flow is particularly important in Africa, where water is generally scarce. For example, the Nile delta would be completely unsuitable for farming without the water from the Nile River.

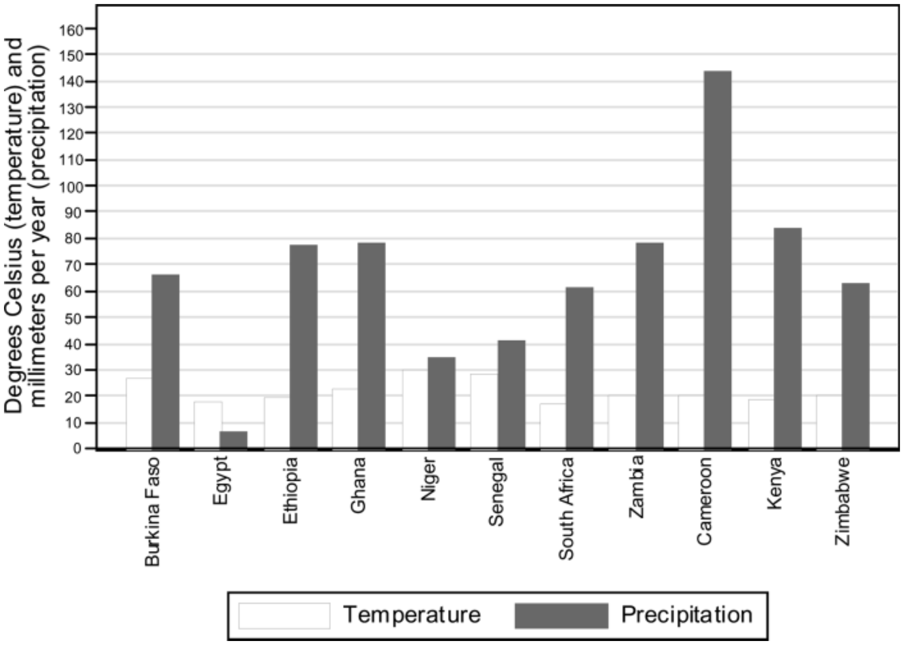
Data on the composition, coarseness, and slope of the major soils in each district were obtained from the Food and Agriculture Organization (FAO 2003).

III. RESULTS

The analysis explores three principle hypotheses. First, African net farm revenues are sensitive to climate. Second, irrigated and dryland crops have different responses to climate (Mendelsohn and Dinar 2003; Schlenker, Hanemann, and Fischer 2005). Third, crops and livestock have different climate response functions.

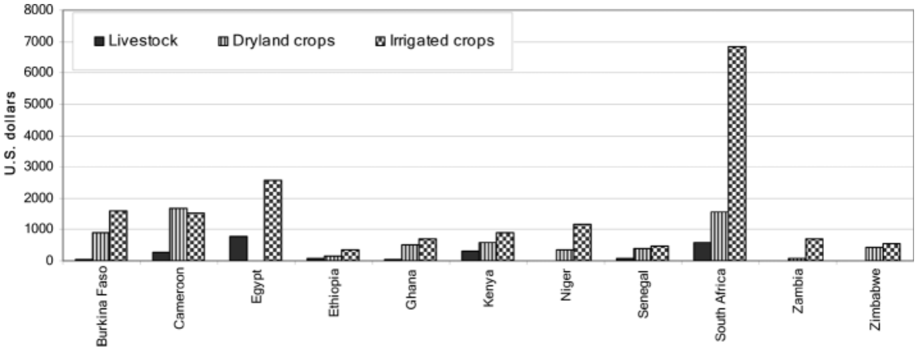
These hypotheses are tested by estimating three regressions. The net revenues per hectare for dryland crops and irrigated crops and the net revenue per farm for livestock are regressed on climate and other control variables (table 1).

FIGURE 2. Mean Annual Temperature (1988–2003 average) and Precipitation (1977–2000 average) by Country



Source: Authors' analysis based on data from Basist and others (2001) and World Bank (2003).

FIGURE 3. Median Net Revenue Per Farm from Dryland Crops, Irrigated Crops, and Livestock (2005 U.S. dollars)



Source: Surveys conducted by the authors in 2002–04.

TABLE 1. Ordinary Least Squares Regression of African Net Farm Revenues

Variable	(1) Dryland crop (per hectare)	(2) Irrigated crop (per hectare)	(3) Livestock (per farm)
Temperature winter	−68 (1.11)	181 (1.06)	−8,643** (2.65)
Temperature winter squared	2.5 (1.61)	−3.2 (0.62)	191** (2.55)
Temperature spring	−28 (0.28)	−180 (0.85)	6,772** (2.45)
Temperature spring squared	−1.0 (0.46)	0.8 (0.15)	−136** (2.37)
Temperature summer	125 (1.77)	1,277*** (4.06)	−2,904** (2.24)
Temperature summer squared	−1.4 (1.02)	−20.2*** (3.67)	58** (2.40)
Temperature fall	−58 (0.85)	−1,517** (3.32)	4,679** (2.97)
Temperature fall squared	0.4 (0.25)	28.7** (3.38)	−95.9** (3.00)
Precipitation winter	−4.6*** (3.37)	11.8 (1.54)	−3.7 (0.15)
Precipitation winter squared	0.03*** (4.00)	−0.05 (1.00)	−0.18 (0.95)
Precipitation spring	4.7*** (3.78)	−12.2 (1.62)	35.2 (1.76)
Precipitation spring squared	−0.01** (2.56)	−0.10** (2.24)	−0.32** (2.66)
Precipitation summer	3.6*** (4.71)	27.9*** (4.86)	34.9** (2.49)
Precipitation summer squared	−0.01*** (3.90)	−0.10*** (4.54)	−0.17** (2.51)
Precipitation fall	−2.1** (2.99)	25.5*** (4.27)	−23.5** (2.37)
Precipitation fall squared	0.01*** (5.47)	0.08*** (4.67)	0.11** (2.69)
Flow	−8.2 (2.39)	10.2** (2.57)	−134.4** (3.11)
Elevation	−0.13*** (5.29)	0.08 (0.47)	0.65** (3.20)
Log household size	23.0 (1.80)	109 (1.61)	−244 (1.31)
Household electricity	95.0*** (5.00)	467** (3.93)	1,236*** (3.49)
Eutric gleysols coarse soils	−403*** (4.15)	−1,570** (3.03)	
Lithosols steep soils	−234*** (5.14)	−1,130*** (3.45)	
Orthic luvosols medium soils	−1,950*** (4.02)		−52,000** (3.17)
Chromic vertisol fine soils	−661** (2.92)	−2,105** (3.01)	
Chromic luvisol fine soils	−227*** (5.88)		−8,240*** (3.35)
Cambic arenosols soils	1,720** (3.05)		
Luvic arenosols soils	−272*** (4.04)		
Calcic yermosols medium soils	−536** (2.69)		
Gleyic luvisols soils	−134** (2.78)		
Rhodic ferralsols steep soils		5,450 (1.66)	814,000** (3.20)
Chromic luvisols medium soils		−6,040** (2.58)	−54,600** (2.91)
Dystric nitosols soil		7,110*** (4.41)	
Eutric cambisols fine soils			−1,710,000*** (3.35)
Calcic cambisols coarse soils			3,120** (2.72)
Vertic cambisols fine soils			913 (2.25)
Orthic ferralsols fine soils			−7,330** (3.23)
Rhodic ferralsols fine soils			−5,620** (2.94)
Lithosols medium steep soils			−2,490,000** (3.26)
Ferric luvisols fine soils			627** (2.61)
Gleyic luvisols medium soils			868 (2.28)
Chromic vertisols soils			895 (2.54)
Eutric planasols fine steep soils			1,018,000*** (3.34)
Constant	665 (1.05)	2,150 (0.85)	−8,057 (1.76)
Number of observations	7,246	1,253	4,759
F-statistic	35.2	45.5	4.8
R-squared	0.16	0.25	0.22

**Significant at the 5 percent level.

***Significant at the 1 percent level.

Note: Numbers in parentheses are robust *t*-statistics.

Source: Authors' analysis based on data described in the text.

Revenue per hectare could not be examined for livestock because most African farmers graze their animals on communal land. Property rights on communal lands are complicated, and reliable measures of the amount of land used are not available. The marginal effect of climate on each source of revenue is examined, and climate elasticities are computed for temperature and precipitation as the percentage change in net revenue for a percentage change in temperature or precipitation.

The overall regressions in table 1 are significant at the 1 percent level, and the *R*-squared values are 0.16 for dryland crop, 0.25 for irrigated crop, and 0.22 for livestock models. Irrigated farms have higher average net revenue per hectare than dryland farms and respond differently to the independent variables. For example, the net revenue of irrigation rises with water flow, as expected. The soil types that affected dryland crop, irrigated crop, and livestock revenues often differ. The soil types that affect both dryland and irrigated crop revenue have a larger impact on irrigated land. Elevation has a strong positive effect on livestock revenue, a strong negative impact on dryland crop revenue, and no effect on irrigated crop revenue. Animals can adapt to high altitudes, but the large diurnal cycles associated with high altitudes are harmful to crops. Farms with more people in the household earn more crop revenue but less livestock revenue. This result implies that growing crops is more labor-intensive than tending animals. Finally, farms with electricity had higher revenue across all farm types, especially irrigated crops. Electricity and the technology associated with it may be the source of this higher value. It is also possible that farms with electricity are close to major markets (cities) and that this contributes to higher values.

The most important comparison across crops and livestock concerns the climate coefficients. Many of these coefficients are not significant because the climate variables are highly correlated with each other. Unlike temperate climates, tropical climates do not vary greatly from season to season. The four-season specification was maintained, however, to keep the study comparable with studies done in other countries. The coefficients vary across the regressions, but they are hard to interpret individually. However, the second-order terms provide a sense of what shape the response functions are taking. A negative coefficient on a squared term implies a concave shape and a positive coefficient implies a convex shape. The expectation is that the second order temperature coefficients would be negative, especially if higher temperatures were catastrophic. However, the results do not support that hypothesis. Because the observed range of precipitation is well below the maximum desired amount, the second order precipitation coefficients could have any sign. Many of these second order precipitation coefficients in table 1 turn out to be positive, suggesting that net revenue rises rapidly with precipitation.

Calculating seasonal marginal effects reveals that higher temperatures in the spring and fall are harmful and higher temperatures in the summer and winter are beneficial. These results mirror findings from the United States, except that they are delayed by one season (Mendelsohn, Nordhaus, and Shaw 1994; Mendelsohn and Nordhaus 1999). In Africa crops are planted during the summer monsoons rather than the spring. The warmer temperatures in summer reflect the benefits of a longer growing season. The warmer temperatures in the winter help the crops to ripen. The warmer temperatures in the fall are harmful because this is when temperatures peak. The warmer temperatures in the spring are harmful because they encourage pests.

The marginal impacts of a change in annual temperature and precipitation are also evaluated at the respective sample mean. This calculation of annual effects adds a constant temperature and precipitation increment to each season. Note that the sample mean climate for dryland, irrigated land, and livestock are quite different. Irrigated land is located in drier (average annual precipitation of 33 millimeters a year) and cooler areas of the sample (average annual temperature 19° Celsius), livestock in drier (66 millimeters a year) and warmer areas (22° Celsius), and dryland crops in the warmer (22° Celsius) and wetter (72 millimeters a year) areas. Many farms in the sample that have crops also have livestock.

Warmer temperatures have very different marginal effects on dryland crops and irrigated crops. Dryland crop revenue falls an average of $27 per hectare per 1° Celsius increase in temperature, whereas irrigated crop revenue increases an average of $30 per hectare per 1° Celsius (table 2). Temperature has a muted effect on irrigated crops, partially because irrigation buffers the crops from rainfall shortages and partially because irrigated crops are currently planted in relatively cool locations in Africa. The change in revenue per hectare is multiplied by the mean number of hectares of each type (9 hectares of dryland and 101 hectares of

TABLE 2. Marginal Climate Impacts on Net Farm Revenue Per Hectare: Ordinary Least Squares (OLS) and Country Fixed Effects (Dollars Per Hectare)

Marginal impact	Dryland crop	Irrigated crop	Livestock
OLS			
Temperature	−27*** (−37, −16)	30 (−20, 80)	−379 (−775, 17)
Precipitation	1.6*** (0.6, 2.8)	3.0 (−8.8, 14.8)	19.8*** (0.29, 39.5)
Fixed effect			
Temperature	−10 (−21, 0.7)	72*** (19, 125)	−293 (−696, 110)
Precipitation	1.5*** (0.2, 2.8)	−0.9 (−13.6, 11.8)	−5.2 (−20.3, 9.9)

**Significant at the 5 percent level.

***Significant at the 1 percent level.

Note: Values are calculated at the mean climate of the sample using OLS coefficients from table 1 and fixed effects coefficients from table S.5 in the supplemental appendix (available at http://wber.oxfordjournals.org). Numbers in parentheses are 95 percent confidence intervals. Estimates for livestock are at the farm level.

Source: Authors' analysis based on data described in the text.

irrigated crops per farm) to show the change in average revenue per farm: a decline of $239 on dryland farms and an increase of $3,005 on irrigated farms. Livestock net revenue falls by an average of $379 per farm per 1° Celsius. Weighting each effect by the frequency of each type of farm suggests that the mean annual impact of a 1° Celsius increase in temperature is a negligible and insignificant increase in net revenue across African farms. The initial increase in revenue from irrigated land offsets the decline in revenue for dryland and livestock.

The marginal effects of precipitation on net revenues also vary across revenue sources. The marginal effect of precipitation is $1.66 per hectare per 1 millimeter increase in precipitation per month on dryland crops and $2.98 on irrigated crops. However, on a farm basis the marginal effect of precipitation is $15 per millimeter per month on dryland crops and $302 on irrigated crops (table 3). By comparison, the marginal effect of precipitation on livestock net revenue per farm is $15 per millimeter per month. Weighting these values by the frequency of each farm type suggests that a 1 millimeter per month increase in precipitation leads to an expected aggregate increase in net revenue of $67 per farm.

Temperature and precipitation elasticities are also calculated (table 4). The temperature elasticity is –1.9 for dryland crops and 0.5 for irrigated crops, which, as noted are buffered from higher temperatures both by their cooler locations and the moderating effect of irrigation. The temperature elasticity for livestock is –5.4, meaning that livestock is more sensitive to temperature than crops are. Although many livestock can survive in hot locations, the most profitable livestock (beef) are limited to cool regions (South Africa and the Mediterranean). Warmer temperatures would drive these profitable beef cattle out of Africa.

TABLE 3. Marginal Climate Impacts on Net Farm Revenue Per Farm: Ordinary Least Squares (OLS) and Country Fixed Effects (Dollars Per Farm)

Marginal impact	Dryland crop	Irrigated crop	Livestock
OLS			
Temperature	−239*** (–335, –142)	3005 (–2040, 8048)	−379 (–775, 17)
Precipitation	15*** (5.1, 25)	301.3 (–896.6, 1499.3)	19.9** (0.3, 39.5)
Fixed effect			
Temperature	−93 (–192, 7)	7262*** (1940, 12584)	−292 (–695, 110)
Precipitation	13*** (2, 25)	−93 (–1374, 1187)	−5 (–20.3, 9.9)

**Significant at the 5 percent level.

***Significant at the 1 percent level.

Note: Values are calculated at the mean climate of the sample using OLS coefficients from table 1 and fixed effects coefficients from table S.5 in the supplemental appendix (available at http://wber.oxfordjournals.org) for the median size farm of each type. Numbers in parentheses are 95 percent confidence intervals.

Source: Authors' analysis based on data described in the text.

TABLE 4. Comparison of Climate Elasticities: Ordinary Least Squares (OLS) and Country Fixed Effects

Elasticity	Dryland crop	Irrigated crop	Livestock
OLS			
Temperature	−1.9*** (−2.7, −1.1)	0.5 (−0.3, 1.2)	−5.4 (−11.1, 0.3)
Precipitation	0.4*** (0.1, 0.6)	0.1 (−0.2, 0.4)	0.8** (0.0, 1.7)
Fixed effect			
Temperature	−0.7 (−1.5, 0.1)	1.1*** (0.3, 2.0)	−4.2 (−10.0, 1.6)
Precipitation	0.3*** (0.1, 0.6)	−0.02 (−0.4, 0.3)	−0.2 (−0.9, 0.4)

**Significant at the 5 percent level.

***Significant at the 1 percent level.

Note: Values are calculated at the mean climate and mean net revenue of the sample using OLS coefficients from table 1 and fixed effects coefficients from table S.5 in the supplemental appendix (available at http://wber.oxfordjournals.org) for each farm type. Numbers in parentheses are 95 percent confidence intervals.

Source: Authors' analysis based on data described in the text.

Precipitation elasticities are much smaller than temperature elasticities. The precipitation elasticity is 0.1 for irrigated crops, 0.4 for dryland crops, and 0.8 for livestock. Although many agronomic models focus on precipitation, these empirical results suggest that crops and livestock are more sensitive to temperature than to precipitation.

Warming may affect water flow as well. Flow has a significant effect on all three sources of farm income (see table 1). Higher flow increases the net revenue per hectare of irrigated land (the elasticity of net revenue with respect to water flow is 0.2 for irrigated land). However, flow is also likely to have a large effect on the amount of land available for irrigation. Reduced flow would limit the amount of farmland that could be converted from dryland to irrigated cropland. Flow has a negative effect on dryland and livestock net revenue even though dryland crops and to a large extent livestock do not use irrigation. In areas with good flow, farmers may use their best land for irrigation, leaving relatively poor lands for livestock and dryland crops.

A country fixed effect analysis was also conducted, with a dummy variable introduced for each country. A country fixed effect model removes unmeasurable differences between countries due to omitted variables. Again, many of the individual climate coefficients are insignificant (detailed results are presented in table S.5 in the supplemental appendix, available at http://wber.oxfordjournals.org). This is partly because country fixed effects remove some of the intercountry climate variation that was part of the sample design. However, the country dummy variable may also be picking up hidden factors that vary by country. In the livestock regression the only significant country dummy variable is for South Africa. This could be due to the large profitable beef cattle farms in South Africa or to the climate that supports such farms. In the regression for irrigated crops, the only significant country dummy variable is for Kenya, which has lower than average returns per hectare. It is not clear why irrigated farms would be less profitable in Kenya than in other countries. For the dryland crop revenue regression, Cameroon has above average returns per hectare, and Ethiopia, Kenya, and Zambia have below average returns. The pattern of the dryland country coefficients may reflect the benefits of ample water in Cameroon and little water in East Africa, or they may reflect a set of hidden factors.

Tables 2 and 3 present the marginal results of the country fixed effects model along with the ordinary least squares (OLS) results already discussed. The marginal effect of temperature on dryland crops is –$95 per hectare, which is a much larger loss than the OLS regression predicts. The marginal effect of temperature on irrigated crops is positive but also much larger than the OLS regression predicts. Only the livestock results are not significantly different. The introduction of country fixed effects also changes the marginal effect, increasing the benefits to dryland farmers but eliminating the effects on irrigated crops and livestock. In comparing the OLS with the fixed effects results, part of the more harmful effect of higher temperatures on dryland crops, the more beneficial effect of temperature on irrigated crops, and the more beneficial effect of higher precipitation on livestock may be due to unmeasured country level variables. When the fixed effects are introduced, these effects are moderated.

Another concern in this analysis is that Egypt is a unique case because of its dependence on the Nile River. Farmers along the Nile can irrigate and produce two seasons of crops, leading to significantly higher earnings per hectare. Because Egypt is cooler and drier than most of the sample, this could bias the climate results. Dropping Egypt has no effect on the dryland analysis, because there are no dryland observations for Egypt, but a large impact on irrigation, because a great deal of the irrigated sample comes from Egypt (table S.4 in the supplemental appendix).

Of the 1,253 observations of irrigation in the original analysis, only 531 are left when the observations for Egypt are dropped. Many of the coefficients in the new regression for irrigated crops are consequently insignificant (for example, water flow, elevation, and all the temperature coefficients). The precipitation coefficients remain significant, however. And although many observations remain in the livestock regression, many of the coefficients become insignificant except for the precipitation coefficients. Thus the observations for Egypt have a strong impact on the results for livestock and irrigated crops.

To interpret how dropping the observations for Egypt has affected the climate results, we compared the marginal effects of the climate coefficients in table 5. Dropping Egypt makes the marginal impact of warmer temperatures on irrigated land harmful, but the change in impact is not statistically significant. Without Egypt, the marginal impact of precipitation on livestock increases, but the change is also not significant. However, the marginal effect of

TABLE 5. Comparison of Marginal Impacts of Climate on Net Farm Revenue Per Farm with and Without Egypt (Dollars Per Farm)

	Irrigated crop		Livestock	
	Egypt included	Egypt omitted	Egypt included	Egypt omitted
Marginal impact of temperature	3005 (–2040, 8048)	–3247 (–10769, 4276)	–379 (–775, 17.2)	–642** (–1,196, –89)
Marginal impact of precipitation	301.3 (–896.6, 1499.3)	–1502*** (–2459, –545.6)	19.9** (0.3, 39)	7.1 (–10.4, 24.5)

**Significant at the 5 percent level.

***Significant at the 1 percent level.

Note: Effects are calculated at the mean climate of the sample using table 1 coefficients including Egypt and table S.4 coefficients in the supplemental appendix (available at http://wber.oxfordjournals.org) excluding Egypt. The mean farm size (in hectares) is assumed. Numbers in parentheses are 95% confidence intervals.

Source: Authors' analysis based on data described in the text.

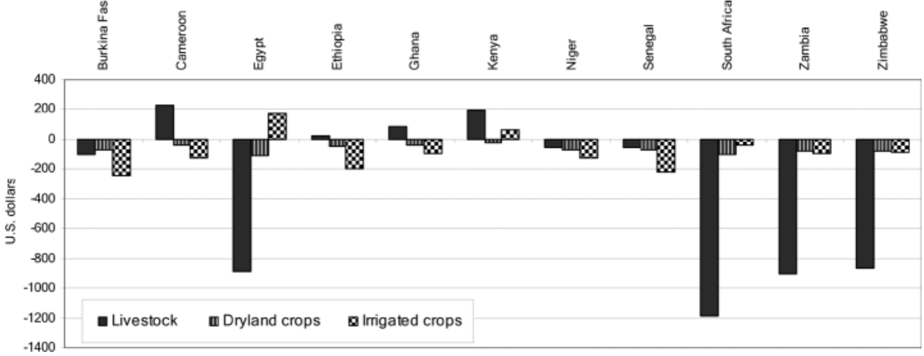
precipitation on irrigated land changes from \$301 to -\$1502 per farm, which is a significant change (the precipitation elasticity changes from +0.1 to –0.4). In Sub-Saharan Africa increased precipitation reduces the net revenues of irrigated farms. Irrigation is a better investment in drier locations. The data for Egypt, despite the country's low precipitation and high productivity, were hiding this effect.

The marginal impact of temperature and precipitation on each country is also calculated (figures 4 and 5). This calculation differs from the previous analysis in that it uses the mean temperature and mean rainfall values for each country. The analysis reveals that the impacts of climate change differ across countries. Cooler countries such as Egypt, South Africa, Zambia, and Zimbabwe are likely to suffer livestock losses from warmer temperatures because of the loss of beef cattle (figure 4). Irrigated crops in currently hot regions such as Ethiopia and West Africa will suffer with warming, whereas irrigated crops in the Nile Delta and Kenyan highlands will gain. However, some effects are fairly universal. Dryland crops in all countries throughout Africa will be damaged by any warming. Figure 5 suggests that the marginal impact of precipitation is mostly beneficial, compared with that of warming, and that livestock and irrigated farms will mostly benefit from rising precipitation and lose from declining precipitation.

IV. CONCLUSION AND POLICY IMPLICATIONS

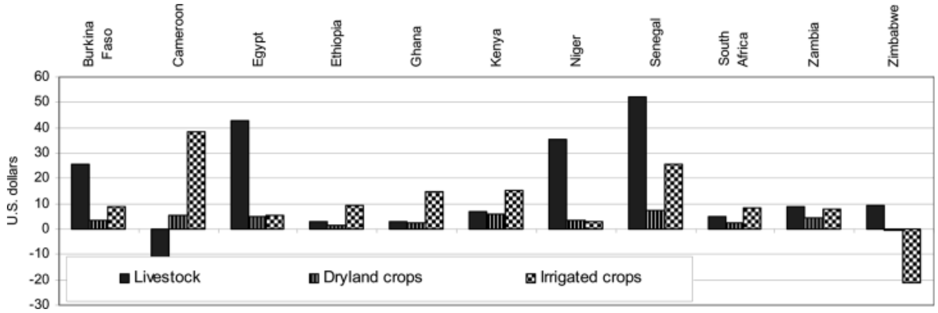
This study examined the net revenues of farmers in 11 African countries and provided quantitative confirmation of what scientists have long suspected. Although African dryland farmers have adapted to local conditions, net revenues would fall with more warming or drying. Dryland crop and livestock farmers are especially vulnerable, with temperature elasticities of –1.9 and –5.4, respectively. Irrigated cropland benefits slightly from marginal warming because irrigation

FIGURE 4. Marginal Impact of Temperature by Country



Source: Authors' analysis based on data described in the text.

FIGURE 5. Marginal Impact of Precipitation by Country



Source: Authors' analysis based on data described in the text.

mutes climate impacts and because these farms are currently located in relatively cool places in Africa.

With precipitation elasticities of 0.4 for dryland crops and 0.8 for livestock across Africa, net revenues for dryland crops and livestock will increase if precipitation increases with climate change and decrease if precipitation decreases with climate change. Net revenues for irrigated land will follow in the same direction but to a much smaller extent (elasticity of 0.1). Increases in precipitation will have an unambiguously beneficial effect on African farms on average, whereas decreases in precipitation will have a harmful effect. However, country effects and within-country effects can differ.

The revenue effects for dryland crops, irrigated crops, and livestock are assessed independently. When the marginal temperature effects across all three sources of revenue are summed, increases in revenues on irrigated cropland at first offset losses for dryland crops and livestock. As temperatures continue to rise, however, the net effect on African farms becomes steadily more harmful. Total farm revenue decreases as precipitation falls but rises as precipitation increases. Climate scenarios that entail either significant warming or substantial drying will consequently be quite harmful. However, climate scenarios that entail only mild increases in temperature and more rainfall may actually be beneficial. The total impact on African agriculture will depend on the climate scenario.

The analysis reveals that net farm revenue has a quadratic relationship with both temperature and precipitation. The marginal impact of climate change consequently will depend on each farm's initial temperature and precipitation. Farms that are located in hotter and drier areas are at greater risk because they are already in a precarious state for agriculture. Dryland farming throughout Sub-Saharan Africa is vulnerable to warming. Dryland farming in the East, West, and Sahel regions of Africa are especially at risk. In contrast, irrigated crops in places that are relatively cool now, such as the Nile delta and the highlands of Kenya, enjoy marginal gains from warming. Finally, drier locations such as Egypt, Niger, and Senegal get big livestock gains from increased precipitation relative to wetter locations in Africa.

Because Sub-Saharan African economies as a whole depend more heavily on agriculture, total GDP and per capita income is also vulnerable. In contrast, nonagricultural GDP in Northern Africa is more diversified, and so the economies of these countries are less vulnerable to climate change.

This study measures the marginal impact of climate change. It does not predict the future. Simulating likely future climate impacts is a large undertaking. First, one must examine the projections of several climate models to get a sense of the range of plausible climate scenarios. Second, one must project how agriculture is likely to change in the future, both in technology and in land use. For example, the average dryland farmer currently earns $319 a hectare and the average irrigated land farmer earns $1,261 a hectare. The more technologically advanced irrigated farms earn even more. The adoption of technology and capital is very important to the future of agriculture in Africa. Third, one must estimate by how much carbon fertilization is likely to increase crop productivity over time (Reilly and others 1996). These gains will reduce the magnitude of the damages in Africa, although it is not clear by how much.

Will Africa survive climate change? The results of this study suggest that Africa will be hit hard by severe climate change scenarios. Some countries are more vulnerable than others, so it is important to focus on the countries that really need help. In fact, in several scenarios, many African farmers gain whereas others lose from climate change. This study also notes that African farmers already practice some forms of climate adaptation. Policymakers may want to pay special attention to these successful adaptation practices. For example, irrigation water (including related inputs) and livestock are already used in some areas to alleviate climate hardships such as droughts and low levels of precipitation.

One adaptation that has moved very slowly in Africa is technology adoption. Africa lags behind the rest of the world in adopting irrigation, capital, and high-yield varieties (Evenson and Gollin 2003). Some technologies may help farmers adapt to drier or hotter conditions, such as the development of new soybean varieties in Brazil. However, even climate-neutral technical advances will help farmers increase productivity and counterbalance losses from climate change. Through research and outreach, governments could encourage the development and use of varieties with more tolerance for the hot and dry conditions of many of Africa's agroclimatic zones.

The quantitative results, especially the sizable differences between irrigated and dryland agriculture and livestock in Africa, suggest that promoting irrigation could help alleviate the likely effects of climate change in Africa. Where water is available, moving from dryland to irrigated agriculture would increase not only average net revenue per hectare but also the resilience of agriculture to climate change. Governments could make public investments in infrastructure and canals for water storage and conveyance, where appropriate and where the public good nature of these investments prevent adequate private sector investment. Investment in successful irrigation in Sub-Saharan Africa ranges between $3,600 and $5,700 a hectare in 2000 prices (Inocencio and others 2005). This analysis suggests that the difference between dryland and irrigated agriculture runs between $150 and $5,000 a hectare, depending on the country. This range of investment values implies that farmers in some countries could repay irrigation investments within a very reasonable period. Policymakers may want to consider supporting such coping interventions for climate change, where appropriate.

Finally, in addition to encouraging direct adaptations, both local and national governments and international organizations could invest in infrastructure and institutions to ensure a stable environment to enable agriculture to prosper. Such policy interventions may not only achieve the long-term goal of helping vulnerable populations adapt to climate change, but may also increase the likelihood of achieving the more immediate Millennium Development Goals, such as halving hunger, reducing poverty, and improving health.

REFERENCES

Adams, R. M. 1999. "On the Search for the Correct Economic Assessment Method." *Climatic Change* 41(3–4): 363–70.

Bardhan, P., and C. Udry. 1999. *Development Microeconomics*. Oxford: Oxford University Press.

Basist, A., N. C. Grody, T. C. Peterson, and C. N. Williams. 1998. "Using the Special Sensor Microwave/Imager to Monitor Land Surface Temperatures, Wetness, and Snow Cover." *Journal of Applied Meteorology* 37(9): 888–911.

Basist, A., C. N. Williams, N. Grody, T. Ross, and S. Shen. 2001. "Using the Special Sensor Microwave Imager to Monitor Surface Wetness." *Journal of Hydrometeorology* 2(3): 297–308.

Cline, W. R. 1996. "The Impact of Global Warming on Agriculture: Comment." *American Economic Review* 86(5): 1309–11.

Darwin, R. 1999. "The Impact of Global Warming on Agriculture: A Ricardian Analysis: Comment." *American Economic Review* 89(4): 1049–52.

Deressa, T., R. Hassan, and D. Poonyth. 2005. "Measuring the Economic Impact of Climate Change on South Africa's Sugarcane Growing Regions." *Agrekon* 44: 524–42.

Evenson, R., and D. Gollin. 2003. "Assessing the Impact of the Green Revolution, 1960–2000." *Science* 300: 758–62.

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

Gbetibouo, G., and R. Hassan. 2005. "Measuring the Economic Impact of Climate Change on Major South African Field Crops: A Ricardian Approach." *Global and Planetary Change* 47(2–4): 143–52.

Inocencio, A., M. Kikuchi, D. Merrey, M. Tonosaki, A. Maruyama, I. de Jong, H. Sally, and F. Penning de Vries. 2005. "Lessons from Irrigation Investment Experiences: Cost-Reducing and Performance-Enhancing Options for Sub-Saharan Africa." Report 6. International Water Management Institute, Colombo. African Water Investment Strategies. [www.iwmi.cgiar.org/africanwaterinvestment/].

IWMI (International Water Management Institute and University of Colorado). 2003. Hydroclimatic data for the Global Environment Facility/Centre for Environmental Economics and Policy in Africa/World Bank Project "Climate, Water and Agriculture: Impacts and Adaptation of Agro-ecological Systems in Africa." Colombo and Boulder.

Kaiser, H. M., S. J. Riha, D. S. Wilkes, D. G. Rossiter, and R. K. Sampath. 1993. "A Farm-Level Analysis of Economic and Agronomic Impacts of Gradual Warming." *American Journal of Agricultural Economics* 75(2): 387–98.

Kaiser, H., S. Riha, D. Wilkes, and R. Sampath. 1993a. "Adaptation to Global Climate Change at the Farm Level." In H. Kaiser and T. Drennen, eds., *Agricultural Dimensions of Global Climate Change*. Delray Beach, Fl.: St. Lucie Press.

Kelly, D. L., C. D. Kolstad, and G. T. Mitchell. 2005. "Adjustment Costs from Environmental Change." *Journal of Environmental Economics and Management* 50(3): 468–95.

Kumar, K., and J. Parikh. 2001. Indian Agriculture and Climate Sensitivity. *Global Environmental Change* 11(2): 147–52.

Kurukulasuriya, P., and M. Ajwad. 2006. "Application of the Ricardian Technique to Estimate the Impact of Climate Change on Smallholder Farming in Sri Lanka." *Climatic Change*. doi: 10.1007/s10584-005-9021-2.

Kurukulasuriya, P., and S. Rosenthal. 2003a. "Climate Change and Agriculture: A Review of Impacts and Adaptations." Climate Change Series 91. Environment Department Papers, World Bank, Washington, D.C.

McCarthy, J., O. Canziani, N. Leary, D. Dokken, and K. White, eds. 2001. *Climate Change 2001: Impacts, Adaptation, and Vulnerability*. Cambridge: Cambridge University Press.

Mendelsohn, R., and A. Dinar. 2003. "Climate, Water, and Agriculture." *Land Economics* 79(3): 328–41.

Mendelsohn, R., and W. Nordhaus. 1999. "The Impact of Global Warming on Agriculture: A Ricardian Analysis: Reply." *The American Economic Review* 89(4): 1053–55.

Mendelsohn, R., and L. Williams. 2004. "Comparing Forecasts of the Global Impacts of Climate Change." *Mitigation and Adaptation Strategies for Global Change* 9(4): 315–33.

Mendelsohn, R., W. Nordhaus, and D. Shaw. 1994. "The Impact of Global Warming on Agriculture: A Ricardian Analysis." *American Economic Review* 84(4): 753–71.

Mendelsohn, R., A. Sanghi, and A. Dinar. 2001. "The Effect of Development on the Climate Sensitivity of Agriculture." *Environment and Development Economics* 6(1): 85–101.

Molua, E. 2002. "Climate Variability, Vulnerability and Effectiveness of Farm-level Adaptation Options: The Challenges and Implications for Food Security in South-Western Cameroon." *Environment and Development Economics* 7(3): 529–45.

Pearce, D., W. R. Cline, A. N. Achanta, S. Fankhauser, R. K. Pachauri, R. S. J. Tol, and P. Vellinga. 1996. "The Social Costs of Climate Change: Greenhouse Damage and Benefits of Control." In J. Bruce, H. Lee, and E. Haites, eds., *Climate Change 1995: Economic and Social Dimensions of Climate Change*. Cambridge: Cambridge University Press.

Quiggin, J., and J. Horowitz. 1999. "The Impact of Global Warming on Agriculture: A Ricardian Analysis: Comment." *American Economic Review* 89(4): 1044–45.

Reilly, J., N. Hohmann, and S. Kane. 1994. "Climate Change and Agricultural Trade: Who Benefits, Who Loses?" *Global Environmental Change* 4(1): 24–36.

Reilly, J., W. Baethgen, F. E. Chege, S. C. van de Greijn, L. Ferda, A. Iglesias, C. Kenny, D. Patterson, J. Rogasik, R. Rotter, C. Rosenzweig, W. Sombroek, and J. Westbrook. 1996. "Agriculture in a Changing Climate: Impacts and Adaptations." In R. Watson, M. Zinyowera, R. Moss, and D. Dokken, eds., *Climate Change 1995: Intergovernmental Panel on Climate Change Impacts, Adaptations, and Mitigation of Climate Change*. Cambridge: Cambridge University Press.

Ricardo, D. 1815. *An Essay on Profits*. London: John Murray. [www.econlib.org/library].

Ritchie, J. T., and D. NeSmith. 1991. "Temperature and Crop Development." In J. Hanks and J. Ritchie, eds., *Modeling Plant and Soil Systems Agronomy 31*. Madison, Wisc.: American Society of Agronomy.

Rosenzweig, C., and M. Parry. 1994. "Potential Impact of Climate Change on World Food Supply." *Nature* 367(6459): 133–38.

Schlenker, W., M. Hanemann, and A. Fischer. 2005. "Will U.S. Agriculture Really Benefit from Global Warming? Accounting for Irrigation in the Hedonic Approach." *American Economic Review* 95(1): 395–406.

———. 2006. "The Impact of Global Warming on U.S. Agriculture: An Econometric Analysis of Optimal Growing Conditions." *Review of Economics and Statistics* 88(1): 113–25.

Seo, N., R. Mendelsohn, and M. Munasinghe. 2005. "Climate Change and Agriculture in Sri Lanka: A Ricardian Valuation." *Environment and Development Economics* 10(5): 581–96.

Tol, R. 2002. "Estimates of the Damage Costs of Climate Change. Part 1: Benchmark Estimates." *Environmental and Resource Economics* 21: 47–73.

Weng, F., and N. Grody. 1998. "Physical Retrieval of Land Surface Temperature Using the Special Sensor Microwave Imager." *Journal of Geophysical Research* 103(D8): 8839–48.

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