The Impact of Climate Change on Agriculture in Developing Countries

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ABSTRACT *The largest known economic impact of climate change is upon agriculture because of the size and sensitivity of the sector. Warming causes the greatest harm to agriculture in developing countries primarily because many farms in the low latitudes already endure climates that are too hot. This paper reviews several studies that measure the size of the impact of warming on farms in developing countries. Even though adaptation will blunt some of the worst predicted outcomes, warming is expected to cause large damages to agriculture in developing countries over the next century.*

Introduction

There is increasing evidence that greenhouse gases have already begun to warm the planet (Intergovernmental Panel on Climate Change (IPCC), 2007). If nothing is done to curb emissions, the stock of greenhouse gases is expected to grow substantially over the next century largely from burning fossil fuels but also from land use change (IPCC, 2007). This in turn will cause future climates to warm and will likely cause changes in precipitation patterns (IPCC, 2007). Although there are many impacts expected from global climate change, one of the largest impacts is expected to be on agriculture (Nordhaus, 1991; Pearce, 1996; Cline, 2007). Quantifying these impacts provides important insights into how much to spend on mitigation. Understanding the impacts of climate change will also help direct where, when, and how adaptation should proceed.

There are many economic studies that have measured climate impacts on US agriculture. Mathematical programming has been used to capture crop switching in response to changing yields (Adams *et al.*, 1990, 1999). The Ricardian method has been used to measure climate impacts using cross-sectional evidence (Mendelsohn *et al.*, 1994, 1996; Mendelsohn & Dinar, 2003; Schlenker *et al.*, 2005). Time series analysis has been used to measure weather effects (Deschenes & Greenstone, 2007). The Schlenker study finds that warming in this century is likely to be highly damaging to US agriculture but the rest of the literature does not.

Agronomists have long warned that farms in developing countries are often more sensitive to warming than US farms (Rosenzweig & Parry, 1994; Reilly *et al.*, 1996). Using crop

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simulation models, these studies revealed that the yields of grains in many developing countries would fall with warming. Economists have also worried that agriculture in many developing countries would be more sensitive to climate than in the US (Pearce, 1996; Tol, 2002; Mendelsohn *et al.*, 2006). Developing countries are more dependent on farming (a sensitive sector), many are located in places that are already too hot or dry and poor farmers are less able to adapt. Further, US results suggested that farms in the southern warmer regions of the US were more vulnerable than farms in the northern regions (Mendelsohn *et al.*, 1994). Farms even closer to the equator were likely to be even more at risk.

Although predictions of large climate impacts to developing country agriculture have been long standing, there have been few economic studies that actually measured climate impacts in these countries. A handful of studies were conducted using existing Agricultural Census data from India and Brazil (Mendelsohn & Dinar, 1999; Kumar & Parikh, 2001; Mendelsohn *et al.*, 2001). The main hurdle to measuring impacts in developing countries was the absence of existing data on farm performance. Existing data were often available only at the country level or in very select places. The next section of this paper reviews the first few studies done in Brazil and India, two countries with very good existing data.

The third section of the paper deals with a more recent wave of studies that have been done with economic data collected precisely to study climate change. Surveys were conducted in Africa and South America in order to obtain individual farm data across a wide range of climate zones. These continental scale studies have confirmed earlier concerns that agriculture in developing countries could well be the largest single damage from climate change.

All of the economic studies on developing countries in this paper rely on the Ricardian method. With the Ricardian method, land values or net revenues are regressed on climate, soils, geographic variables and economic variables that are independent of the farmer (not choices). The approach is a cross-sectional analysis. The method captures the locus of net revenues across each climate. It presumes that farmers adjust their inputs, outputs and farming practices to best take advantage of where the farm is located, including the climate. The Ricardian model is a comparative static analysis. It reflects all the adjustments that farmers and ecosystems have made in response to climate. It is a measure of the long-term consequences of climate change. It is not a dynamic analysis and so it does not measure the transition costs of moving from one climate to another.

One of the important advantages of the Ricardian method is that it takes into account efficient adaptation. Efficient adaptation implies that farmers will make adjustments if it makes them better off. Many early agronomic studies assumed that farmers would continue farming as they always have. This assumption has been labelled the ‘dumb farmer’ approach because the farmer does not make adjustments that are in his own interest. Ignoring adaptation leads to ‘potential impacts’ that always overestimate damages, sometimes dramatically. Including efficient adaptation is important because it provides an unbiased assessment of what will actually happen.

Subsequent analyses of adaptation reveal that farmers in Africa and South America make very many important adaptations in response to climate. They choose whether to grow crops or livestock (Mendelsohn & Seo, 2007; Seo & Mendelsohn, 2008e). They choose whether to irrigate (Mendelsohn & Seo, 2007; Kurukulasuriya & Mendelsohn, 2008c). They alter their crop mix (Kurukulasuriya & Mendelsohn, 2008b; Seo & Mendelsohn, 2008d). They alter which species of livestock to raise (Seo & Mendelsohn, 2007, 2008a,b; Seo *et al.*, forthcoming). So although the Ricardian method did not specify how farmers adjusted to climate change, subsequent research has specified and quantified the adaptations farmers actually make.

The Ricardian method makes a number of other assumptions. Because the method is a cross-sectional analysis, the method assumes that prices remain constant. The Ricardian method consequently overestimates welfare changes (both gains and losses). Several authors are concerned that the Ricardian method does not account for the farming method, especially whether or not irrigation is used (Cline, 1996; Schlenker *et al.*, 2005). One of the problems of including irrigation is that it is a choice by farmers and a choice that is sensitive to climate (Kurukulasuriya & Mendelsohn, 2008c). Several Ricardian analyses have explicitly distinguished between irrigated and rain-fed land in order to address this concern (Kurukulasuriya & Mendelsohn, 2008a,c; Seo & Mendelsohn, 2008c; Wang *et al.*, 2008). The studies measure a different climate response from rain-fed versus irrigated cropland, but it is not clear that a model that includes all farms is consequently biased. Finally, like all empirical studies, there remains the possibility that the functional form of the model could be improved or that there are important missing variables in the regressions.

Studies with Aggregate Data

Empirical economic studies of agriculture in developing countries were rare because of the absence of suitable data. Existing economic data in many countries simply was not reliable. For example, current estimates of the amount of cropland in Africa vary by a factor of two (Lotsch, 2006).

The first economic studies of climate change focused on Brazil and India precisely because both of these countries kept good agricultural records (Mendelsohn & Dinar, 1999; Kumar & Parikh, 2001; Mendelsohn *et al.*, 2001). Using the Ricardian method developed by Mendelsohn *et al.* (1994), these studies examined the average net revenue (India) and land value (Brazil) in each district or *municipio*, respectively. Net revenue measured in rupees per hectare per year was used in India was used because land values were not available there. In general, land values are easier to analyse because they reflect the long term productivity of the land. Net revenues capture the annual productivity and can be influenced by many factors that are peculiar to a given year such as the weather. In the India study, only net revenue per hectare was available and so that was used as the dependent variable. In Brazil, both net revenue and land value were available and both were tested. However, the land value data led to more consistent and significant results. One must be careful in comparing land values to net revenues to remember that land values are the present value of all future net revenue. In general, land values are about 20 times larger than annual net revenue. The coefficients on a regression with land value are consequently expected to be about 20 times larger than a similar regression using net revenues.

The Ricardian studies in Brazil and India revealed that agriculture in both countries would be sensitive to even modest warming. Because the Ricardian method takes adaptation into account, these first analyses suggested that there would be residual harm in these countries even with adaptation. Even marginal increases in temperature would result in reductions in average net revenue and land value. The analyses also revealed, however, that not every farm in these countries would be affected the same. The wet eastern region of India would mildly benefit from warming whereas the dry western region of India would suffer large damages. The southeastern region of Brazil would benefit whereas the Amazonian and northeastern region of Brazil would be hurt.

One interesting technical question posed by studying agriculture in developing countries is that existing climate can be hard to measure. Although weather stations take accurate recordings of weather over time (climate), the stations are often widely dispersed and concentrated in cities. Farms, because they are located in rural settings, can be quite distant from the closest weather station. The Ricardian studies consequently relied on two sources of climate data. Temperature was measured using satellites. The advantage of satellites is that they can take direct measurements of the entire earth, especially of temperature. One of the disadvantages of satellites is that they cannot measure everything of importance, especially precipitation. In order to obtain precipitation measures, it was necessary to interpolate between weather stations. This combination was found to provide the most reliable climate (Mendelsohn *et al.*, 2007a).

Another topic that was investigated in these studies was whether farms were more responsive to climate normals or climate variance. The climate normal is the mean weather over a 30 year period. The climate variance is the interannual variation around that mean over that same period. Studies that have examined both normals and variance have found that both measures are important (Mendelsohn *et al.*, 1996, 2007b). Increased interannual variance in spring and summers reduce land value. Increased interannual variance in the winter, however, increases land value. Whereas farmers can adapt to observed changes in winter weather by planting different crops and changing the timing of the following growing season, there are fewer adjustments that can be made during the growing season to the weather that unfolds.

Impact Studies with Individual Farm Data

The absence of local economic data is a severe limitation to conducting climate studies in most developing countries. One way to overcome this limitation is to collect data on individual farms across a wide range of climate zones. This section describes a new wave of research that is based on samples of farms collected precisely to study climate change. The sampling was designed to examine countries in different climate zones and to select farms within each country across a wide range of climate zones. The survey instrument was designed to measure annual net revenue in places without land markets and land values when possible. The instrument collected information about the choices that farmers made: which crops to plant, which livestock to raise and which inputs to purchase. Data was collected about inputs, outputs and prices (see Dinar, *et al.*, 2008 for a copy of the survey instrument). This information was combined to estimate gross revenues and costs. Net revenues were calculated by subtracting costs from gross revenues. Information from other sources was collected on climate, soils and other control variables and then merged with the economic data.

The first set of impact studies with individual farm data was undertaken in Africa. The GEF and World Bank financed a study of 11 African countries (Burkina Faso, Cameroon, Egypt, Ethiopia, Ghana, Kenya, Niger, Senegal, South Africa, Zambia and Zimbabwe). A survey instrument was designed and tested for Africa. Teams from each country collected data using this instrument across a wide range of African climate zones. Over 10000 farmers were interviewed about their livestock and crop incomes, costs and farming choices. The economic data was matched with climate data from satellites and weather stations. Soils data was collected from FAO (2003).

A Ricardian analysis was undertaken to measure the impact of climate on current net revenues (Kurukulasuriya *et al.*, 2006; Kurukulasuriya & Mendelsohn, 2008a). In many places in Africa, land markets were not sufficiently formed to provide land values. Three regressions are displayed in Table 1. The first regression shows the relationship between net revenues and climate and soils for all farms. The second regression looks at only dryland farming. The third regression looks at only irrigated farms. All three regressions reveal that both temperature and precipitation play a role in determining net revenue per hectare. All four seasons are important and the impacts of each season are different. The climate effects are nonlinear. The climate coefficients are not the same in each regression. Climate has a different impact on dryland versus irrigated farms. Other variables that are important include the flow of water into the district, the size of the farm, the elevation, availability of electricity and several soil types.

In order to compare results across countries, local currency values were all converted to USD using currency exchange rates. Examining the marginal impact of warming, Table 2, a one degree (C) increase in temperature would reduce average net revenue per hectare by −$28 (or −6%). Looking at just dryland farmers, the marginal temperature effect is −$27 (−8%). Finally, looking at irrigated farms, the marginal temperature effect is +$35 (+3%). Warming is harmful to rain-fed farming but actually beneficial to irrigated farms. The marginal effect of a 1 cm/mo increase in precipitation is to increase farm net revenue by +$33 (+7%) on average. Net revenues on rain-fed farms increase by +$27 (+8%) and on irrigated farms they increase by +$38 (+3%). Rain-fed and irrigated farms both benefit (lose) if rainfall increases (falls).

In addition to studying crops, the African study also examined the net revenue from livestock (Seo & Mendelsohn, 2008a). The amount of land used for livestock is difficult to measure because most farmers graze their animals on common land. Instead of analysing net revenue per hectare, the livestock analysis examines net revenue per farm. This decision is broken down into two choices. First, the farmer must decide how many animals of each type to own. This is a stocking question. The stock is calculated by multiplying the number of animals times the average market price for each species. Note that the farmer does not control the price per animal. The stocking question depends on the net revenue per unit animal. This ratio is the annual net revenue per dollar of stock owned. The more productive is the stock, the higher is this ratio and the more stock the farmer is going to want to own. In order to estimate this model, a two-stage regression is estimated. The value of livestock owned is first regressed on climate and other site characteristics. The fraction of grassland in the district (an ecosystem measure) identifies the choice. In the second regression, income per animal is regressed on climate and a few control variables. The model also distinguishes between small and large farms. Size, in this case, was determined by the value of livestock owned. Climate variables were interacted with a dummy variable for small and large farms in order to estimate their individual climate sensitivity.

The results of this two stage model are shown in Table 3. Climate variables are significant determinants of both how many animals farmers own as well as the net revenue per unit stock. The climate coefficients for small and large farms are not the same. The climate response is nonlinear. Smaller households, a lower percentage of Muslims, electricity, higher population densities and grasslands all led to higher stocks. Larger households, a lower percentage of Muslims, higher population densities and grasslands all led to higher income per unit stock. The role of some of these control variables such as the percent of grasslands are easy to interpret—they reflect the productivity of the ecosystem for

Table 1. African regression of crop net revenue of all farms, rain-fed farms, and irrigated farms with regional dummies

Variable	All farms	Rain-fed	Irrigated
Winter temperature	–173.6**	–106.7	–93.5
Winter temperature squared	6.1**	3.9*	4.9
Spring temperature	115.1	–82.8	58.7
Spring temperature squared	–5.0**	–0.3	–4.1
Summer temperature	173.9**	198.6**	827.5**
Summer temperature squared	–1.9	–3.2*	–13.1*
Fall temperature	–98.1	–92.4	–824.2*
Fall temperature squared	1.1	1.5	15.3*
Winter precipitation	–2.9*	–1.9	5.8
Winter precipitation squared	0.0**	0.00	0.00
Spring precipitation	3.5*	3.6**	–10.6
Spring precipitation squared	–0.001	–0.011*	0.091*
Summer precipitation	3.4**	1.9*	21.4**
Summer precipitation squared	–0.012**	–0.005	–0.086**
Fall precipitation	–0.5	–0.6	–14.7**
Fall precipitation squared	0.0055*	0.0053*	0.0586**
Mean Flow	9.4**	–5.4	8.8**
Farm area	–0.1**	–0.3**	–0.0**
Farm area squared	0.0*	0.0**	0.0*
Elevation	0.035	–0.0009	0.229
Log(household size)	22.9	10.1	62.4
Irrigate(1/0)	237.5**		
Electricity (1/0)	66.6**	47.7**	233.2*
Eutric Gleysols—*Coarse, Undulating*	–631**	–287**	–540
Lithosols and Luvisols—*Hilly to Steep*	–387**	–156**	–1147**
Orthic Luvisols—*Medium, Hilly*	–2181**	–1959**	
Chromic Vertisols—*Fine, Undulating*	–1180**	–1006**	–1719**
Chromic Luvisols—*Medium to Fine, Undulating*	–295**	–241**	
Cambic Arenosols	1633**	1726**	
Luvic Arenosols	–482**	–188**	
Chromic Luvisols—*Medium, Steep*	–2153		–6157**
Dystric Nitosols	214		7051**
Gleyic Luvisols	–199**	–154**	
Rhodic Ferralsols—*Fine, Hilly to Steep*	1428**		3212
Calcic Yermosols—*Coarse to Medium, Undulating to Hilly*	1071**	148	
West Africa dummy	136**	208**	–285
North Africa dummy	457**		675*
East Africa dummy	–186**	–154**	–361
Heavy machinery dummy	51.8**	55.5**	–60.8
Animal power dummy	10.4	49.3**	–185.5**
Constant	–388	1081	–549
N	8459	7238	1221
R2	0.4	0.2	0.3
F	63.6	32.4	46.3

Notes: * Significant at 5% level; ** significant at 1% level. From Kurukulasuriya and Mendelsohn, 2008, Table 4.

Table 2. Marginal climate impacts on African crop net revenue

Annual	Africa regression	Irrigated regression	Rain-fed regression
Temperature ($/ha/°C)	–28.5**	+35.0	–26.7**
Precipitation ($/ha/mm/mo)	+32.8**	+38.2	27.0**

Notes: Marginal impacts evaluated at the mean climate of each sample from coefficients in Table 1; ** significant at 1% level.

Table 3. Two equation model of climate impacts on African livestock

	Value of stock of livestock ($/farm)		Net revenue per unit of stock	
Variables	Coefficient	T-stat.	Coefficient	T-stat.
Intercept	12460	1.86	1424	6.72
Temperature × small[1]	–1049	–1.71	–49.9	–2.53
Temperature sq × small[1]	28.2	2.10	0.55	1.28
Precipitation × small[1]	–103	–2.98	–13.41	–12.05
Precipitation sq × small[1]	0.47	2.60	0.07	13.17
Temperature × large[1]	1351	7.15	14.90	2.43
Temperature sq × large[1]	–42.8	–7.21	–0.50	–2.59
Precipitation × large[1]	–7.62	–0.20	–2.67	–2.19
Precipitation sq × large[1]	–0.32	–1.47	0.01	1.07
Log household size	–2240	–4.55	10.57	0.66
Electricity dummy	4960	7.13	219.5	9.72
Population density	126.6	2.77	11.55	7.96
Population density sq	–2.13	–4.21	–0.12	–7.79
% Muslim	–4508	–3.02	–31.75	–0.75
% Grassland	22952	10.58		
R-squared	0.20		0.20	
Observations	4763		4763	

Notes: [1]Climate variables were multiplied by farm size dummy to measure farm size specific climate impacts. From Seo and Mendelsohn, 2008a.

animals. Other control variables are more difficult to interpret. For example, it is not clear whether electricity increases the productivity of animals or whether it is correlated with a missing variable such as proximity to cities that make larger stocks more profitable. Similarly, it is not clear why the percentage of Muslims is significant in these regressions.

In order to interpret the climate coefficients, the marginal impact of climate at the sample mean is calculated in Table 4. Warmer temperatures increase the amount of stock that small farmers own even though the net income per unit stock falls. The productivity of livestock does not increase with warmth, but the productivity of livestock relative to crops increases. Small farms thus find it attractive to switch from crops to livestock depending upon whether they are in cool versus warm places. In contrast, large farms reduce their stock of livestock as temperature increases. The animals that large farms tend to rely upon (beef cattle) are slightly more sensitive to higher temperatures (the net revenue falls slightly more rapidly). More important, though, large livestock farms do not grow crops in cooler places. Large livestock farms do not substitute as readily as small livestock farms

Table 4. Marginal climate effects on African livestock net revenue

Dependent variable	Size	Current value	Marginal temperature impact ($/C°)	Marginal precipitation impact ($/mm)
Value of stock per farm	Small	259	256.8*	–41.0*
Value of stock per farm	Large	7795	–357.9*	–93.0
Net revenue per unit stock	Small	0.371	–0.024*	–0.004*
Net revenue per unit stock	Large	0.394	–0.033*	–0.006*
Expected impact per farm	Small	96	83	–16
Expected impact per farm	Large	3071	–386	–83

Note: Values calculated at mean of sample from Table 3; * significant at 5% level.

either across livestock species or between livestock and crops. Large commercial farms are thus more vulnerable to warming than small household farms. This empirical result was supported by subsequent analyses of adaptation. Large livestock farms in Africa (located predominantly in temperate places) are heavily specialized in high valued but heat intolerant beef cattle (Seo *et al.*, forthcoming). Warming reduces the value of these beef cattle. Small farmers are dispersed across Africa and rely on a wider set of species that may earn less per animal but are more tolerant of the range of climate in Africa (Seo *et al.*, forthcoming).

Both small and large farms reduce stock as precipitation increases but small farms have a larger percentage reduction. The larger response by small farms is because they can more readily substitute into crops in wetter places. They are both subject to reductions in income because ecosystems shift from grasslands to forests and livestock diseases become more prevalent with more rainfall.

Following the successful analysis in Africa, a subsequent study was funded by the World Bank to be undertaken in seven countries in South America. Data were collected by national teams in Argentina, Brazil, Chile, Columbia, Ecuador, Uruguay and Venezuela. The African survey instrument was modified. Questions about individual household characteristics that proved burdensome and not useful were dropped. Additional crops and animals relevant to South America were added. From talking with the team and pretests, it was also clear that land value data could be collected in South America. A total of 2283 farmers were interviewed. The economic information was then matched with climate and soil data.

The Ricardian analysis of land value data in South America is shown in Table 5 (Seo & Mendelsohn, 2008b). Three regressions are shown for all farms, rainfed farms and irrigated farms. The dependent variable in these regressions is the land value of farms and it reflects both crop and livestock earnings. The analysis was not able to distinguish between four climate seasons. Table 5 consequently shows an analysis that includes only summer and winter temperature and precipitation variables. The climate effects are clearly nonlinear and many climate variables are significant. Table 5 not only examines the average impact of climate but it also investigates whether small and commercial (large) farms have the same climate sensitivity. Interaction terms are introduced between climate and a dummy variable for a commercial farm. In the regression of all farms, only the summer precipitation squared interaction term was significant suggesting very little difference between small and large farms. However, in the subsamples, more of the interaction terms

Table 5. South American Ricardian regressions on farmland value (USD/ha)

	Est.		
Variables	All farms	Rainfed farms	Irrigated farms
Intercept	2878.8*	1114.2	6706.7*
Temp. summer	285.11*	132.08	210.99
Temp. summer squared	–10.31*	–5.30	–6.87
Temp. winter	–153.36*	41.72	–225.39
Temp. winter squared	0.26	–3.98	–2.25
Prec. summer	–4.12	6.74	–26.60*
Prec. summer squared	–0.01	–0.02*	0.02
Prec. winter	–9.38*	–7.34	–24.95*
Prec. winter squared	0.01	0.03*	0.11*
Temp. summer × large	–43.32	216.56*	84.57
Temp. summer squared × large	2.14	–4.79	–5.71
Temp. winter × large	–101.26	–267.71*	–771.08
Temp. winter squared × large	1.30	4.15	29.17*
Prec. summer × large	7.28	2.73	28.70
Prec. summer squared × large	–0.02*	–0.01	–0.14*
Prec. winter × large	–4.8	–5.88	11.27
Prec. winter squared × large	0	–0.03	–0.11
Temp. × prec. summer	0.37*	0.09	1.01
Temp. × prec. winter	0.63*	0.40*	0.40
Temp. × prec. summer × large	0	0.07	0.65
Temp. × prec. winter × large	0.39	0.55	1.68
Soil Cambisols	–3.03	–0.24	–14.33
Soil Ferrasols	12.77*	14.48*	–13.88
Soil Phaeozems	11.74*	22.89*	6.21
Soil Luvisols	27.07*	–1.61	20.82
Soil Arenosols	5.55*	2.70	16.26*
Soil Regosols	10.66*	8.82*	12.18
Soil Vertisols	16.01*	14.35*	9.09
Soil Yermosols	–2.5	0.62	–3.80
Altitude	0.18	0.49*	–0.75*
Electricity dummy	421.4*	214.2	1085.7*
Computer dummy	363.7*	439.4*	73.5
Texture (mixed)	–64.33	–172.61	862.69
Texture (clay)	–361.5*	–474.3*	415.98
Age of the head	–6.13	–0.09	–26.95*
Female dummy	–46.18	10.04	–103.21
Argentine	–1423.9*	–1368.7*	–2198.7*
Chile	–2355.8*	–1601.8*	–3822.0*
Colombia	804.1*	764.0*	2188.2*
Ecuador	–236.5	–460.2	92.0
Uruguay	–2534.0*	–2050.2*	
Venezuela	–40.1	233.3	–726.5
N	2283	1753	530
F-statistic	16.4	14.91	5.88
Adjusted R-squared	0.22	0.28	0.28

Notes: * Significant at 5% level. From Seo and Mendelsohn (2008b).

were significant suggesting it is possible that commercial and small farms have different climate sensitivities.

Table 5 introduces an interaction term between temperature and precipitation. In the full sample, the summer and winter temperature–precipitation interaction coefficients are positive implying that warmer temperatures are more beneficial in wetter places and that more precipitation is more beneficial in warmer places. The temperature–precipitation interaction coefficients in the subsamples were also positive but less significant.

Other control variables that are significant in Table 5 include soils, altitude, electricity, computers and dummy variables for each country. The country dummy variables are intended to control for unmeasured national variables that might explain why land values vary from country to country. They are clearly significant with Columbia and the omitted Brazil having the highest land value per hectare.

In order to interpret the climate coefficients in Table 5, we present the marginal impacts of climate change in Table 6. Warmer temperatures are predicted to be harmful in all three regressions. Small and large farms appear to have similar temperature sensitivity in the regression of all farms. However, small rain-fed and large rain-fed farms and small irrigated and large irrigated farms are not all alike. Small rain-fed farms are less sensitive to warming whereas small irrigated farms are more sensitive.

The regression on all farms suggests that additional precipitation is beneficial. Large farms gain more per hectare than small farms from more rain. With rain-fed farms, however, small farms gain more from more rain than large farms. With irrigated farms, small farms earn much less income with more rain whereas large irrigated farms get large benefits. It is not clear why irrigated farms are so sensitive to rainfall and why small and large farms have such different responses to rain.

Our final analysis examines impacts in China. This analysis is also at the farm level. Farm observations were selected from a survey that had already been conducted in China. Observations were chosen in counties with weather stations. This sampling approach assured an accurate measure of climate for each farm. Data were gathered on the net revenues of each farm as well as many farm characteristics. A total of 8405 farms were gathered. It was not possible to identify whether an individual farm was irrigated or not. In order to examine the difference between rain-fed and irrigated farms, subsamples were selected from villages where over 90% of the farms were one type or the other. This selection process explains why there are only 2750 irrigated farms and 2119 rain-fed farms in the subsamples. The remaining farms come from villages that had a combination of irrigated and rain-fed farms.

Table 6. South American marginal climate impacts on farmland value

	Temperature (USD/°C)		Precipitation (USD/mm/mo)	
Sample	Small	Large	Small	Large
All	–155	–157	+14	+45
Rainfed	–101	–170	+55	+35
Irrigated	–198	–117	–125	+253

Note: Values calculated at the mean of sample using coefficients from Table 5.

The Ricardian regressions for China are shown in Table 7. There is a regression with all farms, just irrigated farms, and just rain-fed farms. The regressions reveal that in at least one equation, all four seasons of temperature and precipitation have a significant effect on net revenues. The impacts are nonlinear. The seasonal coefficients are not alike. The irrigated and rain-fed regressions are clearly quite different.

Several control variables are significant: clay soil, silt soil, whether the farm is on a plain, whether a road is nearby, production association, size of cultivated area and elevation. In the all farm regression, all of the above coefficients are positive except for land area and elevation. The results for the irrigated regression were very similar except that the plain dummy has a negative coefficient. The results for the rain-fed regression were similar except that clay soils were not significant, participating in the production association had a negative effect and elevation had a larger harmful effect.

Table 7. China regression of crop net revenue on climate and other variables

	Net crop revenue (Yuan/ha)		
	All farms	Irrigated	Rain-fed
Spring temp.	1453 (2.18)*	4149 (1.79)	1789 (1.54)
Spring temp. squared	–118.1 (5.88)**	–170.4 (2.18)*	–106.9 (2.97)**
Summer temp.	–1803 (2.01)*	1263 (0.57)	–6200 (4.75)**
Summer temp. squared	48.7 (2.53)*	17.0 (0.35)	125.9 (4.03)**
Fall temp.	119 (0.20)	–5178 (2.55)*	2,678 (2.54)*
Fall temp. squared	–12.1 (0.56)	67.7 (0.93)	–116.1 (2.60)*
Winter temp.	1226 (4.44)**	2064 (3.64)**	911 (1.66)
Winter temp. squared	62.6 (7.34)**	63.9 (2.91)*	67.2 (4.87)**
Spring prec.	–300.6 (8.52)**	–268.3 (2.84)*	–132.3 (1.50)
Spring prec. squared	1.0574 (8.56)**	0.7255 (2.21)*	0.6050 (1.69)
Summer prec.	5.61 (0.39)	151.1 (3.68)**	–76.5 (2.70)*
Summer prec. squared	–0.06078 (1.55)	–0.2414 (2.22)*	0.1322 (1.64)
Fall prec.	–107.4 (2.92)*	–413.8 (3.67)**	–171.6 (2.71)*
Fall prec. squared	0.9442 (5.31)**	2.3112 (3.22)**	1.2763 (4.25)**
Winter prec.	554.4 (8.07)**	668.9 (3.43)**	655.9 (5.33)**
Winter prec. squared	–6.355 (7.96)**	–5.212 (2.42)*	–8.248 (5.27)**
Share of clay soil	4360 (7.26)**	201 (0.14)	–109 (0.08)
Share of silt soil	2080 (3.85)**	2,865 (2.68)**	747 (0.79)
Plain (1 = Yes; 0 = No)	856 (2.57)*	–1459 (1.96)*	1248 (2.11)*
Road (1 = Yes; 0 = No)	2022 (2.96)**	722 (0.55)	3313 (3.66)**
Distance to township government	21.9 (0.77)	83.4 (1.19)	–35.8 (0.93)
Share of irrigation in village	4.6 (1.11)		
If participate production association (1 = Yes; 0 = No)	1,713 (2.50)*	2,940.6 (2.57)*	–2,168.4 (1.27)
Share of labour without education	4.901 (0.71)	24.6 (1.71)	–9.3 (0.90)
Log of cultivated land area per household	–5,189 (29.46)**	–4,942 (13.72)**	–3,934 (14.53)**
Elevation	–1.956 (4.56)**	–0.920 (1.41)	–3.493 (2.46)*
Constant	26,242 (3.28)**	–4,167 (0.19)	70,431 (5.22)**
Observations	8405	2750	2119
Adjusted R-squared	0.21	0.17	0.26
F-test	89.23		

Notes: From Wang, *et al.,* 2008. * implies significance at 5% level and ** significance at 1% level.

Table 8. Chinese marginal climate impacts on crop net revenue for all farms, irrigated farms and rain-fed farms

	All farm	Irrigated farm	Rain-fed farm
Temperature (USD/ha/°C)	−10 (−0.5%)	+68 (+2.8%)	−95 (−6.4%)
Precipitation (USD/ha/mm/mo)	+15* (+0.7%)	+27** (+1.1%)	+23* (+1.5%)

Notes: Calculated at the mean climate using the coefficients in Table 7. * implies a 5% significance and ** implies a 1% significance.

Examining the marginal effect of temperature in China (Table 8) reveals that warmer temperatures would slightly reduce net revenues in the all farm regression. This small net effect hides two much larger responses in the subsamples. Net revenues would fall substantially in the rain-fed regressions with warmer temperatures. In contrast, warmer temperatures in the irrigated regression were predicted to increase net revenues. It appears that these two opposing effects are offset in the model that includes both types of farms. Precipitation is predicted to be beneficial for all farms in China. The effect is slightly larger for irrigated farms.

Conclusion

This paper describes several new studies that measure the economic impact of climate change on agriculture in developing countries. The studies confirm some earlier hypotheses and prove that other hypotheses were false. The studies generally confirm the hypothesis that tropical and subtropical agriculture in developing countries is more climate sensitive than temperate agriculture. Even marginal warming causes damages in Africa and Latin America to crops. Crops are also sensitive to changes in precipitation. In semi-arid locations, increased rainfall is beneficial. However, in very wet places, increased rainfall can be harmful. If climate scenarios turn out to be relatively hot and dry, they will cause a lot of damage to farms in low latitude countries. However, if climate scenarios turn out to be relatively mild and wet, there will be only modest damages and maybe even beneficial effects. The magnitude of the damage depends greatly on the climate scenario.

Small farmers are not necessarily more vulnerable than large commercial farmers. The livestock study in Africa found that small household incomes would rise with warming whereas commercial incomes would fall. Small livestock farmers have many options to switch crops and livestock that appear to make them less vulnerable than commercial livestock operations that are more specialized. The study in South America found that small farmers are no less sensitive to warming than large farmers. Within developing countries, small farmers may well be less vulnerable than commercial farmers.

Irrigation appears to be a very effective tool to counteract the harmful effects of either warming or drying. The incomes of irrigated farms are generally less vulnerable to warming than rain-fed farms and can even increase with warming. For example, irrigated farms in Africa and China are much less vulnerable to warming than rain-fed farms in those same countries. However, it is important to recognize that irrigation is constrained by the availability of water. If climate change reduces water supplies and increases water demand, water may become scarcer. Farmers may well find that they cannot pay for or obtain the water they would need to irrigate. Farmers may be forced to switch from irrigated to rain-fed acreage. It is very important that analyses of agriculture in regions relying upon or considering irrigation examine watershed management as part of their analysis of the agriculture sector. There have been a few pioneering studies of climate and water but they are still rare (Strzepek *et al.*, 1996; Hurd *et al.*, 1999; Howitt & Pieneer, 2006; Lund *et al.*, 2006).

The analysis in this paper examines the climate sensitivity of current farms. In order to project the impacts of climate in the future, it is necessary to project how agriculture will change over time. It is future farms that will experience future climates. Technical change, increased capital, improved access and possible changes in policy must all be considered. How will climate change affect these future farms?

Finally, it is important to note that the impacts of climate change are not going to be the same for every developing country or even for each region inside a country. The analysis suggests that the impacts will depend greatly on current local climate, how climate locally changes, and other conditions of each place such as market access and soil conditions. Some developing countries with temperate climates may well benefit from warming. Some countries may find they receive needed rains in the future climate scenario. Some countries may well have good substitutes for current activities that keep them from serious harm. Other countries will be much less fortunate. They may suffer large temperature increases, lose needed rain, or be unable to adapt. It is important when addressing programs to assist countries with climate change to take note of what specific problems they are having and what actions would provide the greatest long-term relief.

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