A developing country perspective
Series title: FAO Economic and Social Development Papers - 145
2000
ISBN: 925104470B
X8044/E

Two essays on climate change and agriculture

1. INTRODUCTION

This paper explores the alternative methodologies that have been developed to measure the impact of climate change on agriculture. There is a long causal link starting with economic activity, and moving to greenhouse gas emissions, concentrations of greenhouse gases, radiative forcing, climate change, market and non-market impacts, and finally to economic damages. Agriculture has several parts to play in this drama. First, agriculture has an important role in the carbon cycle. Agriculture has been associated with global land clearance that has led to substantial carbon emissions. Agriculture also affects the storage of carbon in the soils. Second, some agricultural practices have led to the direct release of greenhouse gases, specifically methane and nitrogen emissions. Third, agriculture is affected by climate change and so is an important part of impacts.

Although uncertainty pervades in each step of the logic from economic activity to final climate change damages, more is now understood about the entire process. Climate scientists, for example, now feel more confident that the scientific evidence supports the assertion that climate change is likely to occur (IPCC, 1996). In order to understand how much to spend on mitigation and in order to prepare to adapt, it is critical to understand what would happen if climate does in fact change. This paper examines the methods that have been used to explore agricultural impacts. The paper focuses on the application of these methods to understanding what will happen to agriculture in developing countries.

The primary tool that has been used to study climate change impacts is integrated assessment. The integrated assessment model combines the insights of many disciplines in order to follow the causal chain of events from the initial insult to the environment (greenhouse gas emissions) to the final outcomes (damages to society). Section 2 briefly develops an outline of an integrated assessment model so that readers can follow the logic of the model. However, rather than developing a complete model of all impacts to society, this paper will limit itself strictly to agricultural impacts and specifically focus on impacts to developing countries. Thus, the paper will develop only the portion of a fully integrated assessment model that relates to agriculture. For more information about global warming integrated assessment models, see Dowlatabadi and Morgan (1993); Hope *et al*. (1993); Manne *et al*. (1995); Nordhaus (1991, 1994); and Peck and Teisberg (1992).

The key link for agriculture in the integrated assessment model is the climate sensitivity of agriculture. Climate sensitivity measures how agriculture will be affected if climate changes by a certain amount. This part of the paper borrows heavily from Dinar and Mendelsohn (1999). Three methods have been developed in the literature to measure this climate sensitivity: cross-sectional models, agronomic-economic models, and an agro-ecological zone (AEZ) model developed by FAO. Section 3 reviews the cross-sectional models, Section 4 provides a summary of the agronomic models and Section 5 covers the agro-ecological zone model. The strengths and weaknesses of each method are assessed. We answer three critical questions. First, how does each method link climate and outcomes? Second, how is adaptation modelled? Third, how is adoption captured?

Adaptation, in this paper, concerns how farmers adjust to changing temperature, precipitation, and carbon dioxide levels. Adoption concerns how quickly farmers take advantage of new technologies. Adaptation is a direct response to global warming whereas adoption is an ongoing modernization process largely independent of global warming. In order to understand how climate will affect agriculture in developing countries, it is critical to address adoption. The bulk of climate change is not expected for many decades. The agriculture sector that will be most affected is therefore one that exists far into the future. Adoption is critical because it will determine whether this future sector is a modern capital-intensive industry or similar to the production processes currently in place in most developing countries.

In Section 6, we review the results from all three models and assess the climate sensitivity of agriculture in developing countries. We then return in Section 7 to the integrated assessment model in order to obtain quantitative results. Because near term changes are expected to be small, the range of effects is reasonably narrow at first. However, as decades go by, the magnitude of greenhouse gases increases, the expected climate change increases, and the range of impacts broadens. This produces a relatively wide range of possible global average temperatures by 2100 of from 1 to 3.5C (IPCC, 1996). In this paper, we illustrate these impacts using results from the UIUC11 GCM model (Schlesinger and Verbitsky, 1996). This climate model involves a complex ocean-atmosphere model. The results have been translated to provide country-specific estimates of future temperature and precipitation (Schlesinger and Andronova, 1995). We rely on a climate model because climate experts do not expect climate change to be uniform across the globe. All the climate models suggest that climate change will be more exaggerated near the poles and more subdued in lower latitudes.

We examine three climate scenarios and two climate sensitivities. The climate scenarios involve a 1, 2, and 3.5C average global temperature increase. These scenarios were taken from the IPCC report to capture the likely range of global outcomes (IPCC, 1996). The climate sensitivities involve a relatively pessimistic prediction using agronomic-economic results and a more optimistic prediction from cross sectional results (Mendelsohn and Schlesinger, 1999). We then combine the information about the agricultural sector in 2100, the climate scenario, and the climate sensitivities to provide a range of possible impacts to agriculture in both developed and developing countries.

The agronomic results suggest that developing country farming systems would be vulnerable to climate change because these systems tend to be in warm climates already and they tend to rely on less capital-intensive methods. Agronomic research on carbon fertilization, however, suggests that the increase in carbon dioxide would stimulate the productivity of crops. The cross-sectional studies further suggest that adaptation would mitigate crop losses in developing countries and add to gains in developed countries. The overall result is that global warming is expected to have only a small affect on aggregate global output. Although aggregate output in developing countries may well decline from global warming, this effect most likely will be small. Nonetheless, climate change is likely to exacerbate local problems in low productivity regions.

2. INTEGRATED ASSESSMENT MODEL

Global warming integrated assessment models follow the causal change of events from greenhouse gas emissions to final effects. The models begin with predictions of future greenhouse gas emissions from projections of economic development over the next century. These emissions are then evaluated with a carbon cycle model in order to predict what will happen to carbon dioxide concentrations in the atmosphere. These carbon dioxide concentrations have been observed increasing over the last century. The rising carbon dioxide and other greenhouse gas concentrations are expected to lead to warming as they trap infrared heat near the earth's surface.

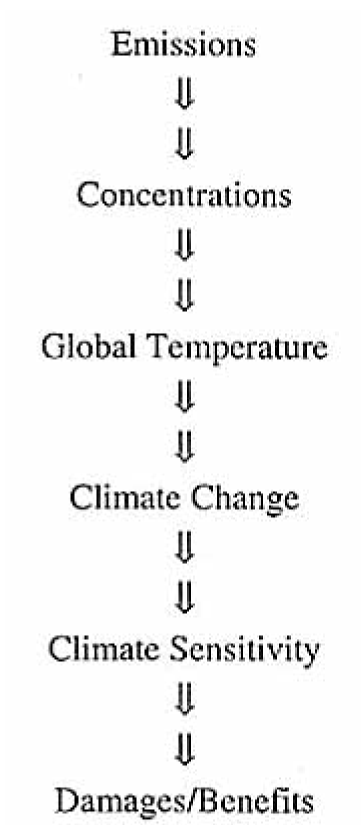
This additional heat, in turn, is expected to increase the amount of water in the atmosphere, another greenhouse gas. The additional water will serve as a positive feedback, leading to even more heat being trapped. Oceans will gradually warm transporting the heat across the planet. This process is expected to take several decades. Climate change will consequently lag behind the increase in greenhouse gas concentration by several decades. As climates change, impacts will gradually become evident. Agriculture is expected to be affected by both temperature and precipitation changing and by carbon dioxide concentrations changing as well. An outline of the model is presented in Figure 1. Although there is a great deal of variation from one model to the next, all the integrated assessment models tend to follow this general form (for example, see Dowlatabadi and Morgan, 1993; Hope *et al*., 1993; Manne *et al*. , 1995; Nordhaus, 1991; 1995; and Peck and Teisberg, 1992).

Current projections indicate that emissions will increase over time for the next 100 years due largely to the burning of fossil fuels. Clearly, this prediction can be adjusted by policy initiatives to shift to alternative low carbon fuels, reduce energy consumption, or remove carbon from the atmosphere. However, if nothing is done, carbon emissions will increase steadily through 2150 (Manne *et al*., 1995). The bulk of greenhouse gas emissions are carbon dioxide but methane, nitrogen oxides, and CFCs also contribute. Figure 2 presents likely emission scenarios for CO_2 over the next century.

Because a large fraction of the emissions stay in the atmosphere for long periods of time, the gases accumulate. At the moment, natural sinks are absorbing some of the carbon being emitted. However, mankind is currently emitting more carbon than natural systems remove. Scientists are confident that the aggregate stock of carbon dioxide in the atmosphere will therefore continue to increase for the next century unless severe mitigation efforts are undertaken. Even if no further emissions occur, the greenhouse gases are expected to stay in the atmosphere for many decades before settling out.

FIGURE 1

Integrated assessment model



These accumulating greenhouse gases allow light to enter but block infrared heat from leaving the planet's surface. This greenhouse effect leads to a slight warming. As the atmosphere warms, evaporation increases, raising the amount of water vapour in the atmosphere. This increase in clouds increases the greenhouse effect. The magnitude of this cloud effect, however, depends upon which clouds are formed, complicating this calculation.

Emissions of sulphur dioxide have been counter-balancing this greenhouse effect in certain regions. It has recently been discovered that sulphur dioxide has been cooling the atmosphere resulting in much cooler temperatures in northern latitudes. Sulphur dioxide, however, has a much shorter resident time in the atmosphere. Consequently, sulphur dioxide has not been accumulating. Future cooling effects from sulphur dioxide will consequently hinge on future emissions. Because sulphur dioxide causes health effects, industrialized countries have been reducing their sulphur emissions in the last two decades. If sulphur dioxide emissions are further controlled in the future, some of this regional cooling will lessen resulting in regional warming.

The increasing concentration of greenhouse gases is predicted to increase average global temperatures gradually. The range of changes in global average temperature predicted by climate scientists over the next century are presented in Figure 3 (IPCC, 1996). There is uncertainty about the full magnitude of the temperature response because scientists do not know the temperature sensitivity of the planet with certainty. Further, the full temperature increase from any specific level of greenhouse gas concentration takes several decades to be realized because of lagged effects from the oceans. Although the atmosphere responds relatively quickly to changes in heat sources, the ocean responds more slowly. The long lags between emissions and climate changes are due largely to the time that it takes to heat the deeper parts of the ocean. The ocean is important because it moves heat from the equator towards the poles. As the deeper parts of the ocean warm, more heat is transferred. Such lags are evident even in seasonal patterns of temperature as the hottest times of the year in high latitudes follow the longest days of the year by 4 to 6 weeks. However, with climate change, one is considering more permanent and therefore deeper ocean changes that can take 30-40 years to reach equilibrium.

FIGURE 2
Likely carbon emissions, years 2000-2100

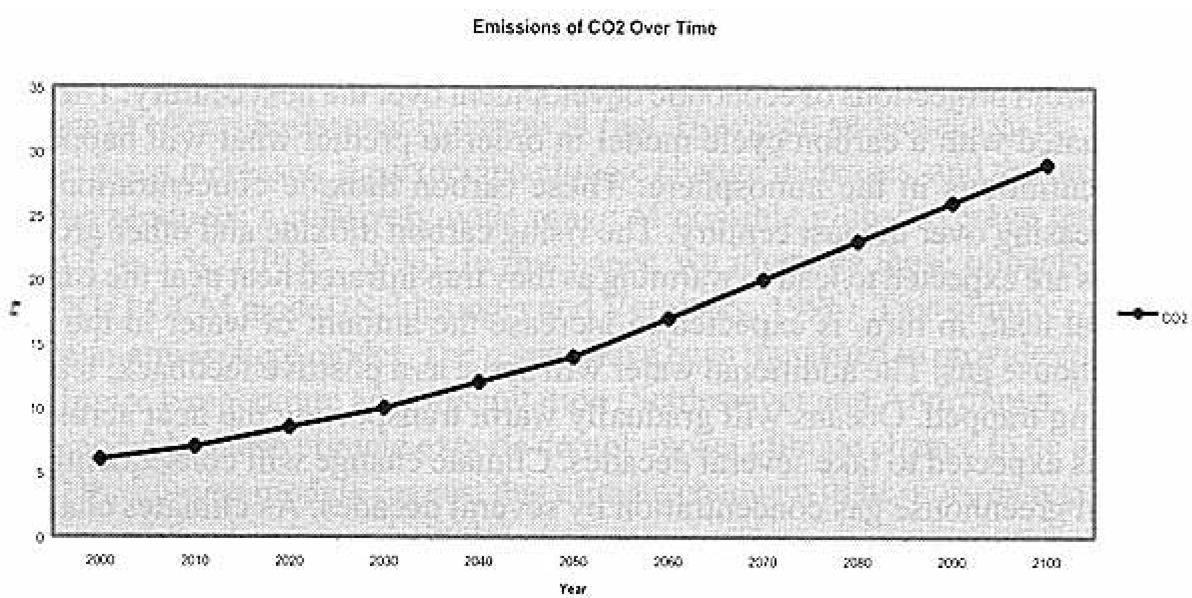
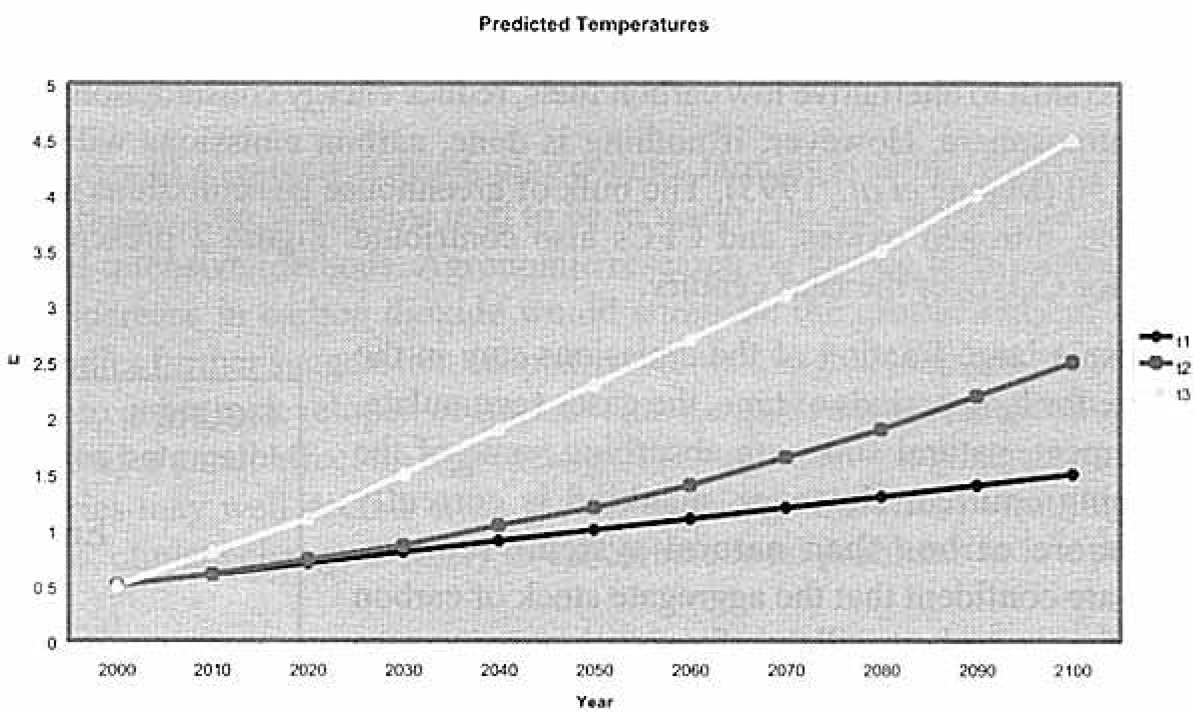


FIGURE 3
Predicted global temperature changes, years 2000-2100



These long lags are important to understand because they separate cause and effect. The consequences of society's actions today (emissions) take many decades to unfold. If society does not trust the predictions of models and instead waits for events to unfold, policy makers will underestimate the consequences of their actions because they take so long to behold. If we judge current emissions on the basis of current experience, we will not take into account the future warming that we are locking ourselves into. Scientists concerned about greenhouse warming consequently are unified in asking policy makers to consider the predicted future effects of current actions.

The gradually increasing concentrations of greenhouse gases will lead to gradually increasing global temperatures and more precipitation. The global temperature increases, however, are not likely to be uniform across the planet. Most climate models agree that the temperature increases will be larger in the higher latitudes and that they will be greater at night than during the day. That is, global warming will increase average temperatures but it will also decrease the range of temperatures both through the day (diurnal cycle) and across latitudes. Most climate models, however, disagree about the remaining seasonal and geographic patterns of climate change. That is, the models do not provide a consistent pattern of seasonal changes nor do they predict consistent local patterns of change. Local temperatures and precipitation can vary across a much wider range than average annual global temperatures. What will happen to local farmers over time will depend on what happens to local climate outcomes. Thus, outcomes for individual farmers are highly uncertain. What happens to farmers in the aggregate however can be stated with more certainty as the local climate perturbations average out.

In order to estimate how greenhouse gases will impact farming, we must examine the range of climate change predictions. We also must predict what farming will look like in the distant future. Climate change will occur slowly. The impacts we are concerned about will occur in the second half of the 21st century. It is consequently important to project what agriculture will look like in 50 to 100 years because it is this future system that will be affected. How large will the farming sector become, what practices will they use, where will future farms be located? We can only predict with uncertainty what future farmers will be like. For example, farm productivity has been increasing at a rate of 1-2 percent a year for many decades. This will likely continue in the near future as new technological tools such as biotechnology are exploited. However, no one can be certain whether the speed of advances can continue at this pace or whether it will gradually fall over time. How modern or technologically intensive will future farms become? As farms continue to modernize, will the new technologies be less sensitive to climate or more sensitive? Where will new farms be located? Will they continue to expand in tropical zones as they have the last few decades or will they move to the temperate zone? The answers to these basic questions about future agriculture will help determine what global warming will likely do to the agricultural sector.

In the following calculations, we assume that agriculture will expand at one-half the rate of GDP. Because developing countries are growing faster than OECD countries, their agricultural sectors will also be growing faster. In Table 1, we present estimates of current and future agricultural GDP by continent. The OECD currently provides about one third of the world's agriculture but by 2100, the OECD is predicted to provide only about one quarter. The model consequently predicts that agriculture will shift towards the tropics where it will be more vulnerable to warming. However, agriculture is also predicted to modernize. Thus, it is likely that farms in countries that are developing today will be fully modernized by 2100.

TABLE 1
Current and future agricultural GDP
(000 million 1990 US$)

Continent	1990	2050	2100
Africa	84	202	416
Asia	492	1 125	2 259
Latin America	89	213	441
W. Europe	191	337	542
E.. Europe	231	421	694
N. America	127	224	360
Oceania	16	28	47
TOTAL	1 230	2 551	4 759

Eastern Europe includes the former Soviet Union.

Finally, the climate sensitivity of agri-culture is also uncertain. Studies around the world indicate that crops are sensitive to changes in long-term temperature and precipitation (Reilly *et al*., 1996). Every crop has an optimal climate. If temperatures are too cold or too dry relative to this optimum, the crop will grow more slowly. Similarly, if temperatures are too hot or too wet, crop yields will be lower. Global warming will consequently have a complex impact on farming across the globe. Places that are on the cool side may find the warming is beneficial. Places that are near optimal may be only mildly affected by small changes in climate. Finally, places that are already too hot are going to find warming strictly harmful. Increases in rainfall may help mitigate these temperature effects but increases in rainfall will likely vary from place to place. Studies also indicate that crops will benefit from higher levels of carbon dioxide (Reilly *et al.,* 1996; Allen Jr *et al*., 1996; Van de Guijin *et al*., 1996). The higher levels of carbon dioxide are expected to help plants cope with the higher temperatures. The increase in carbon dioxide will consequently mitigate the potential damage of warming and may lead to an overall increase in global crop yields.

Crop studies have also revealed that crops are highly sensitive to interannual variations in climate. Year-to-year fluctuations in temperature and precipitation lead to large annual losses for farmers across the world. Mid-continental locations with higher climate variance have lower farm values (Mendelsohn *et al*., 1996). If global warming increases interannual variance, this will lead to additional damages. This effect has not been incorporated into global warming impact assessments because climate scientists are not yet certain how variance will change. The climate scientists do predict that diurnal variance will fall. This will be beneficial to crops. The climate models, however, do not provide a clear prediction about interannual variance. All that can be said at this moment is that a reduction in variance would benefit farming and an increase in variance would damage farming.

Although there have been numerous studies of climate sensitivity, the bulk of these studies have been conducted in temperate highly industrialized countries. The effect of warming on agriculture in developing countries is uncertain because these countries use more labour intensive methods and they are located in lower latitudes (warmer climates) (Winters *et al*., 1999; Kaiser, 1999; Lewandroski and Schimmelpfennig, 1999). Will developing country farmers be able to adapt? How well will these farmers be able to monitor climate over time? Farmers in developing countries may be poorly equipped to monitor climate change. They may have neither the tools to measure weather nor access to good climate forecasts. Will farmers in developing countries adopt new methods more suited to new climates? Will farmers be able to deploy more irrigation in response to warming or will water supplies become too scarce? Will technology change and specifically address warmer climates? Does climate sensitivity vary with technology? Will higher concentrations of carbon dioxide fertilize crops across the landscape as much as predicted in crop experiments? Predictions of impacts in developing countries will have to address all of these questions concerning climate sensitivity.

Because the climate sensitivity of agricultural crops is so central to what global warming may do to agriculture, we devote the next three sections reviewing methods to measure climate sensitivity. Section 3 deals with the cross sectional method, Section 4 deals with the agronomic-economic approach, and Section 5 deals with the agro-ecological zone approach. We summarize the empirical results concerning the climate sensitivity of agriculture in developing countries in Section 6. We then return to the integrated assessment model in Section 7 and discuss the final impacts on agriculture given the range of climate predictions, future agricultural systems, and agricultural sensitivity.

3. CROSS-SECTIONAL METHOD

The cross-sectional approach examines farm performance across climate zones (Mendelsohn *et al*., 1994; 1996; Mendelsohn and Dinar, 1999; Sanghi, 1998; Sanghi *et al*., 1998; Kumar and Parikh, 1998a). The technique has been named the Ricardian method because it draws heavily from an observation by Ricardo that land values would reflect land productivity at a site (under competition). The approach has been used to value the contribution environmental measures make to farm income. By regressing land value on a set of environmental inputs, one can measure the marginal contribution of each input to farm income. The approach has been applied to the United States (Mendelsohn *et al*., 1994; 1996; 1999) and Brazil (Sanghi, 1998). A corollary of the approach has also been used in India where annual net revenue was substituted for land value (Sanghi *et al*., 1998; Kumar and Parikh, 1998). In all these studies, the countries are large enough to contain a sample with a wide range of climates. The range of climates in all these countries is relatively large in comparison to the predicted change in temperature over the next century of 1-3.5 C (IPCC 1996). By estimating the economic performance of farms across this range of climates, one can measure climate sensitivity in each country. Economic performance is measured using farmland value in the United States and Brazil and annual net income in India.

The most important advantage of the Ricardian approach is its ability to incorporate efficient private adaptation. Private adaptation involves changes that farmers have made to tailor their operations to their environment in order to increase profits. Because private adaptation enriches the farmer, there is every reason to expect that it will occur. One of the most important adaptations that farmers will make is crop choice. Depending on what climate a farmer finds himself in; there is a particular crop that will be optimal. As climate changes, the farmer should change crops. For example, Figure 1 shows three potential grains that could be grown: wheat, corn, and rice. Each crop is best suited for a specific temperature (and precipitation). For example, wheat is the optimal choice in a cool temperate site. If the temperature warms, however, the wheat yields for the farmer in a cool site such as in Figure 1 will fall and his net revenue will fall as well. If this farmer, however, switches to corn, his net revenues will rise. It is very important to model optimal crop switching in order to avoid misestimating climate change impacts.

Technology is another important issue that must be addressed in climate change studies. For example, both India and Brazil have had large and successful drives to enhance farming technology. These drives tended to be concentrated on the more temperate farmlands in both countries. In Brazil, farm technology centres were originally concentrated around Sao Paulo and in India around the Ganges River delta. There consequently was a possibility that technology was facilitating improvement in temperate versus tropical climate zones and would affect climate sensitivity. This hypothesis was examined for India (McKinsey and Evenson, 1998). The study reveals that technology has increased farm performance over the last two decades. It is consequently critical to include technical change in forecasts. However, technological change has not affected climate sensitivity to date. Because technological development has not specifically been designed to enhance heat tolerance, the historic interaction between technology and climate appears to be minimal.

One of the drawbacks of the cross-sectional method is that the experiment is not carefully controlled across farms. Farms may vary for many reasons in addition to just climate. In order to control for this problem, the Ricardian studies try to include other important variables such as soil quality, market access, and solar radiation. However, it is often not possible to get perfect measures of these variables so that all of these factors may not be taken into account. This is specifically a problem in many developing countries where data is often incomplete. For example, household labour and animal power are two important variables in many developing country farms that are difficult to control for. This serious weakness of the cross-sectional approach is paradoxically a strength of the agronomic model. The agronomic model, by relying on carefully controlled experiments, does not fall prey to this problem of extraneous variables.

Another important criticism that has been raised concerning existing cross-sectional models is that they have not taken into account water supply (Darwin, 1999). The existing models examine the effect of county climate on county production. However, the models do not consider water that might come from distant counties through rivers and other water supplies. Unfortunately, data have not been available predicting the magnitude of these water supplies and how they in turn would be affected by climate change. Similarly, effects from flooding have also been omitted. Advanced watershed analyses are just beginning to be able to make these connections. Future efforts should be able to incorporate runoff predictions as part of the model. Integrating this information into the cross-sectional approach is an important future advance. In fact, integrating water systems into the agricultural analysis will be important to all of the approaches.

Another valid criticism of the cross-sectional approach is that it rarely considers price effects. Because the existing studies rely on a cross-section within a country, there is little price variation across farms. The studies have consequently been unable to estimate the consequence of prices. Ricardian studies have generally assumed that prices are constant which leads to a bias in the welfare calculations (Cline, 1996). The cross-sectional approach only measures the loss to producers from the climate change. By ignoring the price change that would occur if supply changed, changes in consumer surplus are omitted. The Ricardian studies consequently underestimate damages (omit lost consumer surplus) and overestimate benefits (overstate value of increased supply).

Although it is easy to criticize the Ricardian studies for assuming prices are constant; it is quite difficult to include price effects carefully using any method. First, for most crops, prices are determined in a global market. In order to predict what would happen to each crop, one would need a global model. Unfortunately, global crop models are poorly calibrated so that it is difficult to predict what will happen to the global supply of any single crop in a new world climate. Second, the few global analyses completed to date predict that the range of warming expected for the next century should have only a small effect on aggregate supply (Reilly *et al*., 1994; 1996). Third, if aggregate supply changes by only a moderate amount, the bias from assuming prices are constant is relatively small. For example, even if aggregate supply changed by 25 percent, the bias from assuming constant prices would be less than 7 percent (Mendelsohn and Nordhaus, 1996). Unless scenarios suggest catastrophic consequences, the fact that prices are held constant may not be a serious problem for the Ricardian approach.

Another important limitation of the cross sectional approach is that the method cannot evaluate the fertilization effect of carbon dioxide concentrations since they are relatively uniform across the world. Even with a time series, it would be difficult to estimate the effect of carbon dioxide because it has been monotonically increasing for decades and would be easily confused with many other phenomena that also have been increasing over time (such as technical change). Unfortunately, carbon fertilization effects must be added exogenously based on the results from agronomic experiments.

The Ricardian model regresses farm values or net revenue on climate, soils, and other control variables. For example, Sanghi and Mendelsohn (1999) examined both Brazil and India. The dependent variable in the Brazilian regression is farm value. Climate includes monthly normals from March (fall), July (winter), September (spring), and December (winter). Both precipitation and temperature averages over a 30-year period are included. In addition, the squared terms are included so that one can capture the expected non-linearity of the relationship. The climate values have been demeaned so that one can interpret the linear coefficient as the marginal effect evaluated at the sample mean. Other variables included in the model are a host of dummy variables for soils and economic pressures.

The Brazilian regression is shown in Table 2. The squared terms on climate were significant as expected. Further, the seasonal effects are important. A change in temperature in the summer, for example, has the opposite effect from a change in temperature in the fall. Higher summer tempera-tures are damaging whereas higher fall temperatures are beneficial. These seasonal patterns resemble results found in the United States as well (Mendelsohn *et al*., 1994; 1996). The results indicate that both precipitation and temperature are important. However, contrary to agronomic studies, the results show that temperature is relatively more important than precipitation. Overall, increases in temperature are expected to be mildly harmful.

TABLE 2
Cross-sectional results for Brazil

Variable	Coefficient	Variable	Coefficient
Intercept	-47 300 (6.62)		
Winter Temp	-12 000 (13.12)	Winter Precip	219 (7.71)
Spring Temp	16 300 (14.82)	Spring Precip	44 (0.94)
Summer Temp	-19 400 (11.19)	Summer Precip	-309 (15.53)
Fall Temp	10 100 (5.95	Fall Precip	715 (11.10)
Winter Temp Squared	1 490 (12.05)	Winter Precip Squared	-0.1 (0.52)
Spring Temp Squared	-3 690 (31.99)	Spring Precip Squared	-5.1 (15.11)
Summer Temp Squared	-309 (15.53)	Summer Precip Squared	0.2 (2.09)
Fall Temp Squared	715 (3.81)	Fall Precip Squared	-0.3 (3.67)
Soil 1	-2 600 (1.41)	Soil 4	-6 200 (1.62)
Soil 2	14 700 (7.53)	Soil 5	-45 000 (8.78)
Soil 3	-42 500 (14.50)		
R-squared	0.89	Observations	14 823

Dependent variable is pooled land values. T-statistics are in parentheses.
Source: Sanghi and Mendelsohn, 1999.

The Indian regression relied on annual net revenue as a measure of farm performance because land values were difficult to obtain in India. The climate normals are for January (winter), April (spring), July (summer) and October (fall). Both precipitation and temperature were included as well as a set of soil variables. Several other variables were introduced to control for other factors in India. The fraction of farmers who are self-employed was included to try to capture the effect of home labour. The number of livestock was included to capture animal power. Two measures of technology were included: tractors and special hybrid crop varieties. These technology variables were trying to control for the range of technologies across farms in India. Although the variables included in the Indian study did control for a number of confounding effects, the controls were not perfect. The number of home labourers was not known, nor the number of hours worked. Many details of the technology were not known and could not be included. The access of the farm to markets was not known. These flaws do not necessarily imply the study was biased but they indicate one must be cautious interpreting the results.

TABLE 3
Cross-sectional results for India

Variable	Coefficient	Variable	Coefficient
Intercept	4 660 (8.92)		
Winter Temp	-133	Winter	18.5

	(3.38)	Precip	(6.11)
Spring Temp	-372 (16.71)	Spring Precip	-14.4 (8.00)
Summer Temp	-103 (2.84)	Summer Precip	-0.4 (2.11)
Fall Temp	486 (7.35)	Fall Precip	2.3 (2.23)
Winter Temp Squared	-39.3 (11.40)	Winter Precip Squared	-0.16 (1.57)
Spring Temp Squared	-80.3 (12.48)	Spring Precip Squared	0.28 (10.58)
Summer Temp Squared	35.0 (4.62)	Summer Precip Squared	0.01 (3.89)
Fall Temp Squared	-68.1 (6.77)	Fall Precip Squared	-0.04 (7.34)
Winter Temp x Precip	-3.62 (4.57)	Summer Temp x Precip	-0.21 (1.97)
Spring Temp x Precip	8.21 (11.59)	Fall Temp x Precip	3.01 (5.83)
Soil 1	193 (9.28)	Soil 4	13 (0.41)
Soil 2	221 (8.59)	Soil 5	-10 (0.22)
Soil 3	-153 (4.39)	Soil 6	81 (1.56)
Cultivators	-27 (0.78	Tractors/ha	28 680 (8.98)
Bulls/ha	50 (1.16)	Literacy	770 (6.85)
Pop. density	14 (2.16)	HYV %	137 (1.87)
Latitude	-174 (7.83)		
R squared	0.44	Observations	5 690
Dependent variable is pooled net revenues. T-statistics are in parentheses. A set of dummy variables for each year is also included but not shown. Source: Sanghi and Mendelsohn, 1999.			

The Indian results are presented in Table 3. The squared terms for the climate variables were significant as expected. The seasonal effects were also important. Once again, warmer summer temperatures are bad and warmer fall temperatures are good. Temperature effects are more important than precipitation. Overall, increases in temperature are more harmful in India than in Brazil. Further, comparing the result with findings from studies of the United States suggests that the Indian climate sensitivity is much greater than the American sensitivity. Of course, all these Ricardian results are being measured without carbon fertilization. In order to get an accurate prediction of final outcomes; the effect of carbon fertili-zation must also be included. The complete effects are discussed in Section 7.

4. AGRONOMIC-ECONOMIC METHOD

The agronomic-economic method begins with a crop model that has been calibrated from carefully controlled agronomic experiments (Adams *et al*., 1989; 1990; 1993; 1998; Easterling *et al*., 1993; Kaiser *et al*., 1993a; 1993b; Rosenzweig and Parry, 1994; Kumar and Parikh, 1998b). Crops are grown in field or laboratory settings under different possible future climates and carbon dioxide levels. No changes are permitted to farming methods across experimental conditions so that all differences in outcomes can be assigned to the variables of interest (temperature, precipitation, or carbon dioxide). The estimates do not include adaptation. The changes in yields are then entered into economic models that predict aggregate crop outputs and prices. Because each crop requires extensive experiments, only the most important crops have been studied to date. Almost all of the agronomic studies have consequently focused on grains. A notable exception is the study by Adams *et al*. (1998) that not only includes grains but also citrus and tomatoes in order to account for more heat-tolerant crops.

Because the link between climate and crop yields is determined through controlled experiments, the crop modelling approach has a dependable prediction of how climate affects yields. However, the experiments are costly so that few locations can be tested. This raises a question about whether the experiments are representative of the entire farm sector. In heavily tested areas, such as the United States, this may not be a serious problem. However, in developing countries, there are only a few experimental sites and the results may not be generalized. Further, the conditions in developing countries may require special adaptations such as irrigation that may or may not be included in the analysis.

Because the underlying experimental process holds farmer behaviour constant, the crop modelling literature must explicitly include adaptation. The crop modelling literature (e.g., El-Shaer *et al*., 1997; Kapetanaki and Rosenzweig, 1997; Iglesias and Minguez, 1997, Jin *et al*., 1994) addresses adaptation by simulating alternative methods of changes in growing a crop. Unfortunately, the alternatives rarely take into account economic considerations and human capital limitations, both of which affect actual farm-level decisions, making it hard to interpret the adaptation scenarios explored by agronomists. For example, El-Shaer *et al*. (1997) examine climate-related adaptation strategies for Egyptian agriculture (changes in water, land, and crop management), but they do not estimate quantitative outcomes. Kapetanaki and Rosenzweig (1997) adjust planting dates and new varieties for maize in Greece, and find that yields increase but they do not estimate what happens to net revenue. Iglesias and Minguez (1997) test new hybrids, changes in sowing dates, and double cropping for wheat and maize in Spain and find that yields increase but again they do not measure net revenue effects.

The most successful introduction of adaptation into crop simulation models has come from agronomic-economic models. These farm-level studies begin with agronomic models but then examine efficient responses by farmers to climate change using an economic model of the farm. For example, Kaiser *et al*. (1993a; 1993b) alter crop mix, crop varieties, sowing times, harvesting dates, and water saving technologies (tillage) for farms in the United States and find that these adaptations reduce the damages from climate change. Comparing nearby geographical sites in the U.S., crop models (e.g., Rosenzweig *et al*., 1994) and farm-level models (Mount and Li, 1994; Kaiser *et al*., 1993a; 1993b; Reilly, 1994; 1995) suggest that adaptation reduces the negative impact of warming on crop yields by up to 50 percent (Reilly *et al*., 1996). This careful inclusion of microeconomic farm responses is unfortunately expensive and so it has been done rarely. Almost all the examples come from the United States. Most agronomic models in developing countries do a poor job of including adaptation.

The agronomic models have also historically ignored adoption of new technologies. Almost all studies impose climate change scenarios on current agricultural systems. This is problematic because climate change will not impact agricultural systems for decades. By the time climate actually changes, the farming systems could dramatically evolve from their current form. It is important to capture the technical change in the farming system in order to predict what climate change will do when it occurs. Adams *et al*. (1998) deal with this dilemma by explicitly forecasting how farming would change in the United States by 2060. Although these forecasts were simply extrapolations of past technical progress, they at least attempted to measure future baseline conditions. Including adoption is especially important in developing countries that are rapidly moving to more advanced technologies. **The farming system that will actually experience climate change is likely to be very different from the system in place today.** In developing countries, it is important to model adoption; the transition from low input labour-intensive agriculture to high input modern farming. By examining a range of assumptions concerning the speed of this transition, one can determine how sensitive climate change results are to assumptions about baseline conditions.

Some of the problems that plague the cross-sectional approach apply as well to the economic-agronomic model. Large uncertainties about economic development and political stability make it difficult to predict what the future sector will look like. Few of the agronomic efforts have even considered the implications of projecting impacts into the future. Technical progress is also difficult to predict. Developing countries have experienced a wide range of success incorporating modern farming methods. In some countries, productivity has risen dramatically whereas in others (notably Africa) the increases have been disappointing. Modelling water needs to be incorporated into the agronomic models as well so that the effect of irrigation can be carefully integrated.

5. AEZ METHOD

The third approach to measuring climate sensitivity utilises agro-ecological zones (FAO 1996). The biggest advantage associated with the agro-ecological zones is that they have been measured and published for all developing countries (FAO, 1992). Detailed information is available about the climate and soil conditions, crops, and technologies being used throughout the tropical zone. Like the agronomic approach, the AEZ model relies heavily on natural science relationships. However, rather than taking an agronomic approach, the AEZ model develops a detailed ecophysiological process model. Various factors that explain plant growth are inputs to the model, such as length of growing cycle, yield formation period, leaf area index, and harvest index. Existing technology, soil, and climate are combined to predict Land Utilization Types (LUT). Combining these variables, the model determines which crops are suitable for each cell. The impact of changes in temperature and precipitation on potential agricultural output and cropping patterns on a global scale can thus be simulated

The AEZ uses a simulation of crop yields, rather than measured crop yields. The AEZ model was developed to look at potential production capacity across various ecological zones, not what was actually occurring. Partly, this focus on predicted values reflected the lack of reliable and accurate yield data on a widespread basis. Maximum potential yields for a given production area are estimated using a yield biomass simulation model. This model uses information on radiation and temperatures associated with the specific latitude and longitude of the proposed growing site, together with the photosynthetic capacity of crops, and an index of economically harvestable yield to produce an estimate of maximum potential yield. Within the AEZ model, this maximum attainable yield is then adjusted to reflect varying levels of technology (low, medium and high) as well as the impact of agro-climatic factors such as length of growing period, water stress, presence of disease, pests etc.

One advantage of having a model based on detailed ecophysiological relationships is that future technology and genetic strains could be modelled if their impact on specific parameters were known. The disadvantage of this process modelling is that one cannot predict final outcomes without explicitly modelling all relevant components. Even with relatively simple agronomic systems, it is difficult to build a general model that will predict actual yields across most locations. Just the omission of one major influence would damage the predictions of the model. One way in which this problem is addressed in AEZ modelling efforts has been to check simulated yields against reported yields and substitute in field data where major discrepancies have occurred.

AEZ simulation results are highly sensitive to climate change impacts on precipitation and cloud cover and to a lesser extent on temperature changes. Temperature changes enter the model through: (i) the definition of the thermal regime; (ii) impacts on soil moisture and evapotranspiration and thus on the length of growing period; and (iii) yield impacts through the yield biomass model. Each of these is discussed briefly below.

In the AEZ, the thermal regime is defined as the amount of heat available for plant growth and development during the growing period. The thermal regime is usually defined by the mean daily temperature during the growing season. The thermal regime is a critical determinant of crop suitability across zones in the subtropical and temperate regions. In the tropical zones, heat availability is not a constraint, so thermal regime is not a critical limiting variable to crop production. In the AEZ model, thermal regimes are defined on a discrete scale. For average temperatures falling within two extremes of hot and cold (e.g. >25 degrees and <10 degrees Celsius) the thermal zone scale is divided into discrete units, each with a spread of 2.5 degrees Celsius. The discrete scale of thermal zones could distort measuring impacts due to temperature changes. Small temperature changes within a unit will not result in any change in thermal regime and no predicted effect. Small changes near the upper or lower limit of the regime, however, could result in a shift across regimes and a large predicted effect.

The length of growing period is calculated using a simple moisture balance of precipitation and potential evapotranspiration in the AEZ model. In earlier versions, temperature entered into the calculation of LGP solely through impacts on evapotranspiration. Later models refined the calculation of moisture balance to reflect different temperature regimes (e.g. cold period, transition period and growing period). Temperature also enters the AEZ model through the yield biomass model. The average daytime temperature over the length of the growing period determines the photosynthetic rate and impacts the respiration rate of the plant - both of which determine biomass production. In this case, the temperature/yield relationship is modelled as a continuous function.

Technology adoption, as well as adaptation to climate change specific impacts can be captured in the AEZ by generating static scenarios with changes in technological parameters. Technology is one factor built into the scenario through the definition of the LUT. The AEZ model can therefore account for changes in technology through a change from one LUT to another (e.g. from a level of low capital input to higher levels of capital input). One can simulate technological change by moving from a low input level LUT to a high input level LUT. However, using the AEZ to model technological change would require the development of new functions in the model that captured technical change. To date, technical change has not been explicitly modelled in any AEZ scenarios. Because of the importance of technical change, this would be a severe limitation for using the AEZ model as a forecasting tool. In practice, AEZ gives an assessment of the present state of the soil and climate potential for crop production, which has been used alongside considerable additional information as background for establishing long-term projections.

Although the AEZ was not built to perform economic analysis, economic variables may be linked into the AEZ model through a linear optimization component. Individual country studies for Kenya and Bangladesh have been linked with an economic optimization program to look at economic issues such as revenue optimization or cost minimization. Within such linear programming models, sensitivity analysis on economic variables may be done. However, economic data and the relationships between variables are not an existing part of the cross-country AEZ data set, and would need to be collected and inputted for each country if widespread economic analysis were to be undertaken using the AEZ.

The AEZ model was not created to model climate change, however it can be used to look at the impact of various aspects of climate change on potential crop production over a wide geographic area. One of the major strengths of the AEZ model is the coverage of developing countries, where little climate change research has been done, and where data constraints may preclude the use of other methods. In terms of looking at climate change impacts, the AEZ can simulate the impacts of changing precipitation and cloud cover on potential crop production, and to a lesser extent simulate impacts of temperature changes.

For all climate change models, estimating the impacts of climate change on future agriculture is fraught with uncertainty, because it is unclear what technological conditions will apply far into the future. In the AEZ model, yields are derived from biophysical relationships devoid of technology (as opposed to yields based upon observed field conditions). This feature could be turned into a strength of the model by exploring a range of future baseline agricultural technologies with the AEZ. This could capture different baseline assumptions about adoption. However, technical adaptation behaviour in specific response to climate change would need to be added to the model to capture the full impacts of climate change in the AEZ. Likewise, additions to the AEZ would be required in order to capture the economic impacts of climate change on a broad scale. This would involve a significant effort in data collection and economic modelling. The inclusion of new technologies over time would have to be modelled and the economic behaviour of farmers would have to be integrated into the model. A serious new investment would be required for the AEZ model to be used as a predictive device in climate change.

6. CLIMATE SENSITIVITY

The reported climate sensitivity of agriculture around the world varies, reflecting alternative methods of measurement, starting climate conditions, assumed economic conditions, and climate scenarios. Some of the studies include adaptation, carbon fertilization, and adoption of technical change whereas other studies ignore all three factors. Some of the studies use old climate scenarios that involve large temperature changes, whereas other studies examine the more modest climate scenarios now considered more likely. Each approach relies on different information to link climate change and crop performance. Some studies were calibrated to narrowly defined locations whereas others ranged over large territories. For all of these reasons, there is a lot of variation across the results.

There are some general observations, however, that one can make. For example, there are some strong patterns in the agronomic studies assessed by the IPCC (Table 4 in Reilly *et al*., 1996). Across developing countries (Africa, South Asia, China, and Latin America), the results are largely negative, with 25 negative outcomes and only six positive outcomes out of 43 studies. Across the developed countries (Europe, United States, Japan, and Oceania), however, the results lean more toward the positive side with nine outright positive results and only three negative outcomes out of a total of 27 studies. The agronomic studies suggest that the developed countries of the temperate and polar zones will likely gain productivity whereas the developing countries of the subtropical and the tropical zones are likely to lose productivity.

TABLE 4
Agro-economic results: change in yields

Region	Crop	Negative	Mixed	Positive
Africa	Wheat Maize	1 4	0 0	0 1
South Asia	Wheat Rice Maize	2 5 2	2 8 0	0 4 0
China	Wheat Rice	1 3	0 2	0 0
Latin America	Wheat Maize	4 3	0 0	0 1
Europe	Wheat Maize	0 1	1 0	4 3
United States	Wheat Maize	0 2	4 3	0 0
Japan	Wheat Rice Maize	0 0 0	1 3 1	0 1 0
Oceania	Wheat	0	2	1

Source: Reilly *et al*., 1996.

Examining India specifically, the Indian agronomic studies suggest that extensive warming could cause significant reductions in yields in the absence of adaptation and carbon fertilization. Grain yields would fall in India by 25-40 percent if temperatures rise by 4C (Rosenzweig and Parry, 1994). Rice yields would fall 15-25 percent and wheat yields would fall 30-35 percent for a similar temperature increase (Kumar and Parikh, 1998). Of course, not all grains are necessarily temperature sensitive. Rao *et al*. (1989) find that sorghum and millet are stable across climates compared to other grains.

Of course, the agronomic results cited above do not include carbon fertilization or efficient adaptation. The agronomic-economic studies suggest that including adaptation would reduce the magnitude of losses (Kaiser *et al.,* 1993a; 1993b; Adams *et al*., 1998). The experiments in laboratories and the field suggest that elevated carbon dioxide levels will also have a dramatic positive effect (Allen *et al*., 1996; Van de Guijun *et al*., 1996; Reilly *et al*., 1996). The IPCC estimates that doubling carbon dioxide will roughly increase farm productivity by 30 percent for most crops (Reilly *et al*., 1996). These effects must be included in the empirical calculations.

The Ricardian results for India, which includes adaptation but not carbon fertilization (Sanghi *et al*., 1998 and Kumar and Parikh, 1998a), suggest only modest agricultural damage estimates (see Table 5). Although all the studies predict agricultural losses from warming, the cross-sectional studies find smaller losses than the agronomic studies. Using pooled analysis, the Sanghi et al. study finds that a 2C warming would reduce average Indian net revenues by only about 4 percent. Using repeat annual analyses, Kumar and Parikh determine that a 2C warming would decrease revenues by about 8 percent. Even with a 3.5C warming, the Sanghi et al. study finds damages of only about 15 percent while Kumar and Parikh predict damages of about 23 percent. The Ricardian study of Brazil (Sanghi, 1998) suggests that land values would fall by about 8 percent with a 2 C warming and by about 11 percent with a 3.5C warming. These estimates are considerably smaller than the agronomic predictions.

TABLE 5
Ricardian results: percent reduction in net income

Country		Impact % reduction	Source
United States	2C	-3% to +2%	Mendelsohn *et al*., 1994
United States	2C	-3% to +2%	Mendelsohn *et al*., 1996
India	2C	-3% to -6%	Sanghi *et al*., 1998
India	3.5C	-3% to -8%	Sanghi *et al*., 1998
India	2C	-7% to 19%	Kumar and Parikh, 1998a
India	3.5C	-20% to -26%	Kumar and Parikh, 1998a
Brazil	2C	-5% to -11%	Sanghi, 1998
Brazil	3.5C	-7% to -14%	Sanghi, 1998

These estimates do not include carbon fertilization, which is expected to add 30% to crop productivity. Climate scenario assumes a 7% increase in precipitation.

Comparing the Ricardian results for the United States and India can test whether the climate sensitivity of agriculture appears to be the same in both countries (Mendelsohn *et al*., 2000). Figure 2 uses the empirical climate functions from the two countries to predict what climate change should do to India. Both climate response functions suggest that India should suffer damages because initial temperatures are so high. However, the results using the Indian response function are more damaging than the results from the American response function. It would appear that the more capital-intensive agricultural systems of the United States are less climate sensitive. The more capital-intensive systems appear to be able to substitute purchased inputs for climate more readily. The result suggests that developing countries are likely to be more sensitive to climate change than developed countries. Of course, the results also suggest that as technical change proceeds, the agricultural sectors in developing countries will become less sensitive over time.

Comparing the damages predicted by the agronomic-simulations to the cross-sectional studies provides an estimate of the importance of adaptation. In India, for example, the agronomic approach predicts damages of about 28 percent for severe warming whereas the cross-sectional results predict damages of between 15 and 23 percent. If this difference is due to adaptation, private adaptation could reduce potential climate damages by between one-fourth and one-half. A similar comparison in the United States predicted that adaptation could remove 50 percent of the damages (Reilly *et al*., 1996). Note that these comparisons do not involve technical change. The adaptations being considered simply allow farmers to adjust their techniques using existing technology.

The cross-sectional studies reported in Table 5 also reveal that climate has important seasonal patterns. Net revenues in India fall precipitously with warmer winter, spring, and summer temperatures. However, warmer fall temperatures increase net revenues. Land values in Brazil also fall with warmer summer and winter temperatures and rise with warmer falls. These results are similar to patterns found in the United States. The only seasonal exception is in Brazil where warmer springs are beneficial. The harmful effects of warmer spring and summer temperatures in India are expected given that temperatures are quite hot already in India during this period. In Brazil, on the other hand, a warmer spring may simply extend the growing season. The effect of a warmer fall in all locations is expected to be beneficial as the warmer temperatures help ripen and dry the harvest. The winter temperature effect is more controversial. Some agronomic models ignore winter temperatures because targeted crops are not growing then. However, farm income may be very sensitive to winter temperatures because cold temperature help control pests. This can be important even if winter temperatures remain above freezing as they do in most of India and Brazil. Net revenues are also sensitive to seasonal precipitation, but the effects are smaller and offsetting. Wetter winters are beneficial but wetter summer and springs are not. In India, additional summer rains are not helpful because most of India enjoys a monsoon during this period. Because rainfall is often not uniform across the year and because the marginal value of more rainfall varies by season, the pattern of seasonal changes is likely to be important.

The cross-sectional studies reveal that the effect of climate change is not uniform across India. Even if the warming was the same throughout the country, some areas would lose heavily, most would be moderately damaged, and some areas would even benefit slightly. Warming would most heavily damage the Western coastal districts. Districts in several Eastern states along the coast would benefit. Interestingly, the desert and marginal dry areas are not very sensitive to warming. The productivity in these areas is already so low, that additional warming cannot harm them much further.

The climate technology study of India (McKinsey and Evenson, 1998) explores whether the advent of the green revolution affected climate sensitivity. The authors find that technical change during the study periods increased farm revenue per hectare dramatically. However, they find that technology did not affect climate sensitivity over this period. The green revolution was not focused on making crops more suitable for warmer climates, but rather simply on increasing yields. The technology consequently had little effect on climate sensitivity.

Technology is nonetheless an important component of climate sensitivity. Although new technologies have not pushed agriculture towards more temperate climates, modern technologies appear to reduce the sensitivity of agriculture to temperature. The chronic concern in development of improving technological adoption has climate change implications (Antle, 1995). As more modern farming techniques get adopted, farmers in developing countries are likely to be able to cope with warming more easily. The adoption of new technologies can free farmers from previous environmental constraints, through new varieties, irrigation technologies, and other methods (Dinar and Zilberman, 1991; Dinar *et al*., 1992). Warming may still be harmful in developing countries but the adoption of new technologies may reduce some of the potential damages.

7. PREDICTIONS OF FUTURE IMPACTS

Given the climate and future size of agriculture predicted in Section 2, and the climate sensitivity discussed in Section 6, what will global warming do to agriculture in developing countries? There are some clear qualitative results. First, the research on climate sensitivity suggests that most crops have a hill shaped relationship with temperature. At the coldest range of their habitat, the crops can survive but at low productivity. As it warms, their productivity increases until an ideal climate is reached. Further warming then takes a toll on productivity and it gradually decreases. In practice, this is a complex story intertwined with precipitation and seasonal patterns. However this basic view of climate sensitivity reveals an important insight. Places that are currently cool are likely to benefit from modest warming. Places that are near ideal will be only slightly affected. Places that already are too hot for most crops are likely to be hurt by further warming. Most developing countries tend to be too hot now and so further warming will hurt them.

Of course, the critical issue is not qualitative but rather quantitative. How much will the agriculture in developing countries be hurt by likely warming scenarios? How badly developing countries will be affected depends upon the magnitude of the climate change that they will have to endure. The climate scientists currently predict only a modest increase in temperatures for the next century (IPCC, 1996a). The predicted temperature increase in the low latitudes is expected to be even smaller than the global average (IPCC, 1996a). Modest increases of less than 1-3.5C will be deleterious but manageable. Further, adaptation and carbon fertilization are expected to mitigate most of these effects. Current predictions suggest impacts in most developing countries that range from small losses to small gains.

In order to cast some light on these predictions, we explore a low, medium and high climate scenario of 1, 2, and 3.5 C global temperature increase. This range of temperatures is partly due to a range of possible CO2 concentrations. We consequently assume that the 1C scenario has a 2100 CO2 concentration of 700 ppmv, the 2C scenario is 800 ppmv and the 3.5C scenario involves a 1000 ppmv concentration. Country-specific changes in temperature and precipitation are predicted using UIUC 11 (Schlesinger and Andronova ,1995; Schlesinger and Verbitsky, 1996) for each of these three climate scenarios. Agricultural impacts are then predicted using country-specific future agricultural projections along with two climate sensitivities. A pessimistic prediction is taken from agronomic-economic results and an optimistic prediction is taken from cross-sectional results (Mendelsohn and Schlesinger, 1999). The result is a range of 6 possible outcomes for developed and developing countries.

As shown in Table 6, developed countries are likely to benefit in every scenario as carbon fertilization effects are expected to more than compensate for climate effects. The agricultural GDP in the OECD is expected to increase between 4 percent to 11 percent by 2100 from global warming. The biggest winners are Eastern Europe and the former Soviet Union which are expected to gain between 9 percent and 48 percent of agricultural GDP. Developing countries, however, may experience losses. The range of effects for developing countries is between a gain of 4 percent to a loss of 20 percent of agricultural GDP.

TABLE 6
Agricultural impacts (000 million US$)

Continent	Pessimistic Sensitivity				Optimistic Sensitivity		
	1C	2C	3.5C		1C	2C	3.5C
Africa	-23	-85	-165		16	-1	-30
Asia	14	-77	-245		74	66	47
Latin America	-14	-61	-142		19	11	-1
W. Europe	15	17	17		12	15	18
E. Europe	132	221	334		63	95	137
N. America	57	85	117		36	49	66
Oceania	-1	-9	-21		4	3	1
TOTAL	181	103	-105		223	237	239

Negative numbers imply damages and positive numbers imply benefits. Effects are annual impacts in the year 2100. CO2 is assumed to be 700, 900, and 1000 ppmv in the three respective scenarios. Eastern Europe includes the former Soviet Union. Global agricultural GDP in 2100 is assumed to be 4759 000 million dollars.

Although a 20 percent loss is a large effect, this would only happen in a single scenario. Global warming will most likely not have a dramatic effect on the aggregate output of developing countries. Although warming may well be deleterious, adaptation and carbon fertilization are expected to mitigate some of these effects. Developing countries may still be relatively worse off as climate change is expected to benefit developed countries. Thus warming may result in slight reductions in agricultural prices as aggregate supply expands. These price changes are expected to be mildly harmful to farmers in developing countries, though they will have beneficial effects for consumers worldwide.

Warming, however, could have serious local impacts on selected regions that experience more dramatic changes in climate suitability. Many local areas that are currently marginal could find themselves to be unsuitable for agriculture in the future. If people are engaged in subsistence agriculture in damaged regions, they will be vulnerable to these changes. Countries must be prepared to cope with these permanent changes by adopting long-term solutions to local low productivity outcomes.

8. CONCLUSION AND POLICY IMPLICATIONS

The literature to date suggests that global warming will not damage aggregate global food supplies over the next century. Existing models predict that there will be sufficient food to feed future populations, even with global warming. Global warming is not expected to affect aggregate production in most developing countries. However, it is likely that global warming will increase production in most temperate and polar countries leading to small increases in overall supply. The resulting small reductions in the price of food may hurt developing country producers although it will help consumers. Despite this overall positive assessment, it is expected that productivity will fall in selected locations across the planet because of reductions in rainfall and increased temperatures. To the extent that there are subsistence farmers in these areas, they will be vulnerable to these adverse conditions. Global warming may act like long-term climate variability. Some areas will do worse with warming. The major difference is that these areas may be permanently harmed.

Although there are now several examples of each type of climate impact assessment method applied to developing countries, the studies do not yet provide a comprehensive picture of what may happen to all developing countries. There are only a handful of studies from around the world. In particular, Africa is a continent where climate studies are very weak. Further studies on climate change impacts in developing countries are therefore needed. More resources are needed for data collection, empirical analysis, and simulation modelling efforts. Different methods have different strengths. Although it is difficult to assess precisely which techniques should be employed in every situation, a wise strategy is to explore a portfolio of studies and methods.

Another important area of work is to help developing countries prepare policies to mitigate the potential damages from climate change. Future climate damages may well resemble current problems with climate variability. Efforts to adapt to climate impacts may be modelled on current variability mitigation efforts. The major difference is that climate shifts are likely to be permanent, whereas climate variability is often concerned with only temporary setbacks. With climate variability, some solutions can be temporary until the weather returns to being suitable again. However, with climate change, the problems are more permanent and so more permanent solutions must be given more weight.

With climate variability, a mixture of assistance to improve agricultural productivity and the provision of food assistance are often applied. Agricultural productivity assistance such as modernized farm techniques, irrigation, and new crop varieties can all help farmers cope with marginal environments. Food assistance can help the poor bridge the gap between one good harvest and the next. These strategies are well suited for climate variability.

Attempts to address negative climate change impacts may incorporate these same strategies. However, the productivity reductions from climate change are far more permanent than with climate variability. Some approaches that are suitable for temporary productivity shortfalls are not as attractive with more permanent problems. For example, food aid is acceptable as a method of dealing with a short-term gap in production. Most countries, however, would balk at providing a permanent supply of food for free to an area that is no longer suitable for agriculture. Consequently more permanent solutions to the more long-lasting problems that climate change may introduce to select local areas need to be considered. In designing such a strategy the relative advantages of each of the following need to be considered: (i) maintaining agriculture in affected areas; (ii) providing alternative development strategies; and (iii) encouraging people to migrate away from adverse sites.

REFERENCES

Adams, R., Glyer, D. and McCarl, B. 1989. "The Economic Effects of Climate Change in US Agriculture: A Preliminary Assessment" in D. Tirpak and J. Smith (eds.) *The Potential Effects of Global Climate Change on the United States: Report to Congress*, Washington D.C.: US Environmental Protection Agency, EPA-230-05-89-050.

Adams, R., Rosenzweig, C., Pearl, R., Ritchie, J., McCarl, B., Glyer, J., Curry, R., Jones, J., Boote, K. and Allen, L. 1990. "Global Climate Change and US Agriculture," *Nature* 345: 219-224.

Adams, R., Fleming, R., Chang, C., McCarl, B. and Rosenzweig, C. 1993. "A Reassessment of The Economic Effects of Global Climate Change in US Agriculture," US Environmental Protection Agency, Washington D.C.

Adams, R., McCarl, B., Segerson, K., Rosenzweig, C., Bryant, K.J., Dixon, B.L., Conner, R., Evenson, R.E., and Ojima, D. 1998. "The Economic Effects of Climate Change on US Agriculture" in Mendelsohn, R. and Neumann, J. (eds.). *The Economic Impact of Climate Change on the Economy of the United States.* Cambridge University Press, Cambridge, UK.

Allen, Jr. L. et al. 1996 "The CO2 Fertilization Effect: Higher Carbohydrate Production and Retention as Biomass and Seed Yield" F. Bazzaz and W. Sombroek (eds.) Global Climate Change and Agricultural Production, Wiley and FAO, Rome.

Antle, J. 1995. "Climate Change and Agriculture in Developing Countries", *American Journal of Agricultural Economics*, 77:741-746.

Bennholdt-Thomsen, V., 1982. "Subsistence Production and Extended Reproduction; A Contribution to the Discussion About Models of Production." *Journal of Peasant Studies* 9:241-254.

Cline, W. 1996. "The Impact of Global Warming on Agriculture: Comment" *American Economic Review* 86: 1309-1312.

Darwin, R. 1999a. "The Impact of Global Warming on Agriculture: A Ricardian Analysis: Comment" *American Economic Review* 89: 1049-1052.

Darwin, R. 1999b. A FARMer's View of the Ricardian Approach to Measuring Agricultural Effects of Climatic Change" *Climatic Change* (forthcoming).

Darwin, R. et al. 1999c. "Climate Change, World Agriculture, and Land Use" F. Frisvold and B. Kuhn (eds.) Global Environmental Change and Agriculture, Edward Elgar Publication, UK.

Darwin, R., Tigras, M., Lewandrowski, J. and Raneses, A. 1995. "World Agriculture and Climate Change: Economic Adaptations". US Dept. of Agriculture, Economic Research Service, Publication # AER-703, Washington, D.C.

Dinar, A. and R. Mendelsohn. 1999. "Climate Change, Agriculture and Developing Countries: Does Adaptation Matter?"*The World Bank Research Observer* 14(2): 277-293.

Dinar, A., and D. Zilberman. 1991. "The Economics of Resource-Conservation, Pollution-Reduction Technology Selection, The Case of Irrigation Water" *Resources and Energy* 13:323-348.

Dinar, A., M. Campbell, and D. Zilberman. 1992. "Adoption of Improved Irrigation and Drainage Reduction Technologies Under Limiting Environmental Conditions" *Environmental and Resource Economics* 2:373-398.

Dinar, A., R. Mendelsohn, R. Evenson, J. Parikh, A. Sanghi, K. Kumar, J. McKinsey, S. Lonergan (eds.). 1998. *Measuring the Impact of Climate Change on Indian Agriculture*, World Bank Technical Paper No. 402, Washington, D.C.

Dowlatabadi, H. and M. Morgan. 1993. A Model Framework for Integrated Assessment of the Climate Problem. *Energy Policy* 21: 209-221.

Easterling, W., Crosson, P., Rosenberg, N., McKenney, M., Katz, L., and Lemon, K. 1993. "Agricultural Impacts of and Response to Climate Change in the Missouri-Iowa-Nebraska-Kansas (MINK) Region" *Climatic Change* 24: 23-61.

El-Shaer, H. M., C. Rosenzweig, A. Iglesias, M. H. Eid, and D. Hillel. 1997. "Impact of Climate Change on Possible Scenarios for Egyptian Agriculture in the Future" *Mitigation and Adaptation Strategies for Global Change* 1:233-250.

Fankhauser, S. 1995. *Valuing Climate Change: The Economics of the Greenhouse*, Earthscan, London.

Food and Agriculture Organization of the United Nations (FAO). 1992. *Agrostat.* Rome, Italy.

Food and Agriculture Organization of the United Nations (FAO). 1996. *Agro-ecological zoning: Guidelines*. (FAO Soils Bulletin 73) Rome, Italy.

Hope, C., J. Anderson, P. Wenman. 1993. Policy Analysis of the Greenhouse Effect: An Application of the PAGE Model. *Energy Policy* 21: 327-338.

IPCC (Intergovernmental Panel on Climate Change). 1996a. Houghton, J., L. Meira Filho, B.Callander, N. Harris, A. Kattenberg, and K. Maskell, (eds.). *Climate Change 1995: The State of the Science.* Cambridge University Press: Cambridge.

IPCC (Intergovernmental Panel on Climate Change). 1996b. Watson, R., M. Zinyowera, R. Moss, and D. Dokken (eds.) *Climate Change 1995: Impacts, Adaptations, and Mitigation of Climate Change: Scientific-Technical Analyses* Cambridge University Press: Cambridge.

Iglesias, A., and M. I. Minguez. 1997. "Modelling Crop-Climate Interactions in Spain: Vulnerability and Adaptation of Different Agricultural Systems to Climate Change" *Mitigation and Adaptation Strategies for Global Change* 1:273-288.

Jin, Z., D. Ge, H. Chen, and J. Fang. 1994. "Effects of Climate Change on Rice Production and Strategies for Adaptation in Southern China" In: Rosenzweig, C. and A. Iglesias (eds.) *Implications of Climate Change for International Agriculture: Crop Modelling Study*, EPA 230-B-94-003.

Kaiser, H. 1999. "Assessing Research on the Impacts of Climate Change on Agriculture" F. Frisvold and B. Kuhn (eds.) *Global Environmental Change and Agriculture*, Edward Elgar Publication, UK.

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

Kaiser, H. M., S. J. Riha, D. S. Wilkes, D. G. Rossiter, and R. K. Sampath. 1993b. "A Farm-Level Analysis of Economic and Agronomic Impacts of Gradual Warming" *American Journal of Agricultural Economics* 75:387-398.

Kapetanaki, G. and C. Rosenzweig. 1997. " Impact of Climate Change on Maize in Central and Northern Greece: A Simulation Study with Ceres-Maize" *Mitigation and Adaptation Strategies for Global Change*, 1:251-271.

Kumar, K. and Parikh, J. 1998a. "Climate Change Impacts on Indian Agriculture: The Ricardian Approach". In: A. Dinar, R. Mendelsohn, R. Evenson, J. Parikh, A. Sanghi, K. Kumar, J. McKinsey, S. Lonergan (eds.) *Measuring the Impact of Climate Change on Indian Agriculture,* World Bank Technical Paper No. 402, Washington, D.C.

Kumar, K. and Parikh, J. 1998b. "Climate Change Impacts on Indian Agriculture: Results From a Crop Modelling Approach" In: A. Dinar, R. Mendelsohn, R. Evenson, J. Parikh, A. Sanghi, K. Kumar, J. McKinsey, S. Lonergan (eds) *Measuring the Impact of Climate Change on Indian Agriculture*, World Bank Technical Paper No. 402, Washington, D.C.

Lewandrowski, J. and D. Schimmelpfennig. 1999. "Economic Implications of Climate Change for U.S. Agriculture: Assessing Recent Evidence" *Land Economics* 75(1) 39-57.

Manne, A. Mendelsohn, R., and Richels, R. 1995. "MERGE: A Model for Evaluating Regional and Global Effects of GHG Reduction Policies" *Energy Policy* 23: 17-34.

McKinsey, J. and Evenson, R. 1998. "Technology-Climate Interactions: Was The Green Revolution in India Climate Friendly?" In: A. Dinar, R. Mendelsohn, R. Evenson, J. Parikh, A. Sanghi, K. Kumar, J.McKinsey, S. Lonergan (eds) *Measuring the Impact of Climate Change on Indian Agriculture*, World Bank Technical Paper No. 402, Washington, D.C.

Mendelsohn, R. and A. Dinar. 1999. "Climate Change Impacts on Developing Country Agriculture" *World Bank Research Observer* 14: 277-293.

Mendelsohn, R. and Neumann, J. (eds). 1998. *The Economic Impact of Climate Change on the Economy of the United States* Cambridge University Press, Cambridge, UK.

Mendelsohn, R. and W. Nordhaus. 1996. "The Impact of Global Warming on Agriculture: Reply" *American Economic Review* 86: 1312-1315.

Mendelsohn, R. and M. Schlesinger. 1999. "Climate Response Functions" *Ambio* 28: 362-366.

Mendelsohn, R., A. Dinar, and A. Sanghi. 2000. "The Effects of Development on the Climate Sensitivity of Agriculture" *Environment and Development Economics* (forthcoming).

Mendelsohn, R., W. Nordhaus, and D. Shaw. 1994. "The Impact of Global Warming on Agriculture: A Ricardian Analysis" *American Economic Review* 84: 753-771.

Mendelsohn, R., W. Nordhaus, and D. Shaw. 1996. "Climate Impacts on Aggregate Farm Values: Accounting for Adaptation" *Agriculture and Forest Meteorology* 80: 55-67.

Mendelsohn, R., W. Nordhaus, and D. Shaw. 1998. "The Impact of Climate Variation on US Agriculture" In Mendelsohn, R. and Neumann, J. (eds). *The Economic Impact of Climate Change on the Economy of the United States* Cambridge University Press, Cambridge, UK

Mount T. and Z. Li. 1994. "Estimating the Effects of Climate Change on Grain Yield and Production in the U.S." Cooperative Agreement U.S. Department of Agriculture, Economic Research Service, Washington, DC.

Nordhaus, W. 1991. "To Slow or Not to Slow: The Economics of the Greenhouse Effect" *Economic Journal* 101: 920-37.

Nordhaus, W. 1994. *Managing the Global Commons: The Economics of Climate Change* MIT Press, Cambridge, MA.

Peck, S. and T. Teisberg. 1992. CETA: A Model for Carbon Emission Trajectory Assessment. *The Energy Journal* 13: 55-77.

Rao, N., G. Rao, and H. S. Acharya. 1989. "Yield Stability of Sorghum and Millet Across Climates" In: Climate and Food Security. *International Symposium on Climate Variability and Food Security in Developing Countries*, 5-9 February, Manila Philippines: International Rice Research Institute and Washington, DC.

Reilly, J. 1994. "Crops and Climate Change" *Nature*, 367:118-119.

Reilly, J. 1995. "Climate Change and Global Agriculture: Recent Findings and Issues" *American Journal of Agricultural Economics*, 77:727-733.

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

Rosenzweig, C. and Parry, M. 1994. "Potential Impact of Climate Change on World Food Supply" *Nature* 367: 133-138.

Rosenzweig, C., B. Curry, J. T. Ritchie, J. W. Jones, T. -Y. Chou, R. Goldberg, and A. Iglesias. 1994 "The Effects of Potential Climate Change on Simulated Grain Crops in the United States". In: C. Rosenzweig and A. Iglesias (eds.), *Implications of Climate Change for International Agriculture: Crop Modelling Study,* EPA 230-B-94-003.

Sanghi, A. 1998. "Global Warming and Climate Sensitivity: Brazilian and Indian Agriculture." Ph.D. Dissertation, Dept. of Economics, University of Chicago, Chicago.

Sanghi, A. and R. Mendelsohn. 2000. "The Climate Sensitivity of Indian and Brazilian Agriculture". Yale FES, New Haven, CT, USA.

Sanghi, A., Mendelsohn, R. and Dinar, A. 1998. "The Climate Sensitivity of Indian Agriculture" In: A. Dinar, R. Mendelsohn, R. Evenson, J. Parikh, A. Sanghi, K. Kumar, J.

McKinsey, S. Lonergan (eds.) *Measuring the Impact of Climate Change on Indian Agriculture*, World Bank Technical Paper No. 402, Washington, D.C.

Schimmelpfennig, D., J. Lewandrowski, J. Reilly, M. Tsigas, and I. Parry. 1996. "Agricultural Adaptation to Climate Change" Economic Research Service, USDA, Agricultural Economic Report Number 740, Washington, DC.

Schlesinger, M. E. and Andronova, N. G. 1995. `CO_2-induced equilibrium surface-air temperature and precipitation-rate changes and variability by country, simulated by an atmospheric general circulation/mixed-layer ocean model, and observed surface-air temperature and precipitation rate by country', *Urbana*, IL 68 pp.

Schlesinger, M. E. and Verbitsky, M. 1996. `Simulation of glacial onset with a coupled atmospheric general circulation/mixed-layer ocean-ice-sheet/asthenosphere model', Palaeoclimates-Data and Modelling 2, 179-201.

Van de Guijin, S. et al. 1996. "The Effects of Elevated CO2 and Temperature Changes on Transpiration and Crop Water Use" F. Bazzaz and W. Sombroek (eds.) *Global Climate Change and Agricultural Production*, Wiley and FAO, Rome.

Winters, P. et al. 1999. "Climate Change and Agriculture: Effects on Developing Countries" F. Frisvold and B. Kuhn (eds.) *Global Environmental Change and Agriculture*, Edward Elgar Publication, UK.