Climate Change, Agriculture, and Developing Countries: Does Adaptation Matter?

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Because most developing countries depend heavily on agriculture, the effects of global warming on productive croplands are likely to threaten both the welfare of the population and the economic development of the countries. Tropical regions in the developing world are particularly vulnerable to potential damage from environmental changes because the poor soils that cover large areas of these regions already have made much of the land unusable for agriculture.

Although agronomic simulation models predict that higher temperatures will reduce grain yields as the cool wheat-growing areas get warmer, they have not examined the possibility that farmers will adapt by making production decisions that are in their own best interests. A recent set of models examines cross-sectional evidence from India and Brazil and finds that even though the agricultural sector is sensitive to climate, individual farmers do take local climates into account, and their ability to do so will help mitigate the impacts of global warming.

As scientists have become more confident that greenhouse gases will lead to a rise in global temperatures (Houghton and others 1996), developing countries have grown increasingly concerned about the economic impact of climate change on agriculture (Watson and others 1996). Most of the empirical work to date has focused on the industrial countries (Bruce, Lee, and Haites 1996; Reilly and others 1996), and although experts have extrapolated the results of their findings worldwide (see, for example, Fankhauser 1995, Tol 1995, or Pearce and others 1996), little research has focused specifically on the developing nations.

To assess the likely effects of climate change, researchers have pursued three approaches: agronomic models, agroeconomic models, and Ricardian models (which draw on the work by Ricardo showing that land values reflect a site's productivity).

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The agronomic research that applies to developing countries focuses on the vulnerability of farmland in less productive tropical climates (Rosenzweig and Parry 1994; Reilly and others 1996) and on the likelihood that warming will push even more farmland into this zone. Experts are further concerned that small-scale farmers who have very little capital will not be able to pursue the new strategies that will be required to adapt to the change in climate. Unfortunately, agronomic studies have not examined the actual behavior of individual farmers. Farmer responses are strictly hypothetical in these models, although the results demonstrate that adaptation will significantly affect production outcomes (Rosenzweig and Parry 1994). Economists argue that only efficient adaptations should be included in forecasts of climate impacts, claiming that farmers will adopt new methods only if the benefits exceed the costs.

Agronomic models of climate sensitivity indicate that higher temperatures are likely to be harmful in many developing countries where the climate is marginal, water is inadequate, and temperatures are high (Rosenzweig and Parry 1994; Reilly and others 1996). A further increase in temperatures will make many agricultural areas less productive—and some completely unsuitable. In these models, no effort is made to examine the impacts of warming on all crops. Studies of vast territories, such as Rosenzweig and Parry's, have examined only grains and thus do not take account of crops that prefer tropical climates. Nor, as just noted, have these studies examined efficient adaptation. Thus such research may overestimate the damages from global warming. Their perspective has been limited to arbitrary adaptation measures; even these, however, indicate that adaptation will have a major impact on outcomes.

Research suggests that climate change is not likely to have an adverse effect on agriculture in the United States. The results come from two sources—agroeconomic and Ricardian models. Both approaches find that adaptation by farmers would reduce some of the damages from climate change.[1] Using agroeconomic models to examine farmers' alternatives and determine the most efficient choices under each climate scenario, Kaiser and others (1993a) and Easterling and others (1993) predict that farmers in midwestern regions of the United States will make decisions regarding crops, varieties, and farming practices to mitigate potential reductions in yield. The Ricardian models, which examined a cross-section of farming systems across counties in the United States, found that the effects of higher temperatures ranged from mildly harmful to unequivocally beneficial (Mendelsohn, Nordhaus, and Shaw 1994, 1996). Moreover, substantial evidence from laboratory and field experiments shows that elevated levels of carbon dioxide serve as a fertilizer and can stimulate growth and make plants more drought resistant. A doubling of the amount of carbon dioxide in the atmosphere is predicted to raise crop yields by an average of 30 percent (Reilly and others 1996). Although the exact magnitude of this carbon fertilization is uncertain, the positive outcomes were almost universal. In a study that incorporates the assumptions of carbon fertilization and farmer adaptation, Adams and others (1999) suggest that climate warming is likely to increase crop yields in the United States. These benefits, however, do not necessarily extend to the rest of the world because the climate in the United States is temperate and would remain temperate even with a little warming and because Americans rely on capital-intensive agriculture that can adapt to a range of climates. It is not clear whether labor-intensive agriculture has the same flexibility.

In an approach based on the Ricardian model, Dinar and others (1998) and Sanghi and Mendelsohn (1999) use a cross-sectional approach to examine the sensitivity of agriculture in developing countries to changes in climate. By examining the actual performance of farms across India and Brazil, these studies explore this question using the Ricardian model first developed for the United States (Mendelsohn, Nordhaus, and Shaw 1994). By regressing farm performance (land value or net income) on a set of environmental factors, traditional inputs (land and labor), and support systems (infrastructure), it is possible to measure the contribution of each factor to the outcome and to detect the effects of long-term climate change on farm values.[2] Because farmers adjust to their local climates, the cross-sectional method automatically incorporates farmer adaptation. The results suggest that warming will do less damage than predicted by the agronomic models (which do not include adaptation). When Ricardian results are compared with agronomic models that do not include efficient adaptation, however, the results are consistent. It appears that the Ricardian model does a good job of including efficient adaptation in its predictions.

Methodology

Three techniques have been used to measure the impacts of global warming on agriculture: agronomic-economic simulation, agroecological zone analysis, and Ricardian cross-sectional analysis.

Agronomic-economic models. Agronomic-economic simulation uses a crop model that has been calibrated from carefully controlled experiments in which the crops are grown in field or laboratory settings that simulate different climates and levels of carbon dioxide (Adams, Glyer, and McCarl 1989; Adams and others 1990, 1993, 1999; Easterling and others 1993; Kaiser and others 1993a, b; Rosenzweig and Parry 1994; Kumar and Parikh 1998b). Farming methods are not allowed to vary across experimental conditions so that all differences in outcomes can be assigned to the variables that are being tested (temperature, precipitation, or carbon dioxide). The estimates do not include adaptation. The yields are then entered into economic models that predict aggregate crop outputs, prices, and net revenue. Because each crop requires extensive experimentation, only the most important crops have been studied. Thus, almost all of these studies have focused on grains. A notable exception is the work by Adams and others (1999), which includes citrus fruits and tomatoes along with grains to account for more heat-tolerant crops.

Agroecological zone analysis. In this approach, crops are assigned to each agroecological zone and the yields are predicted (FAO 1996). As climate changes, the agroecological zones—and crops—change. By examining these changes, it is possible to predict the effect of alternative climate scenarios on crop yields. The yield changes can then be entered into an economic model that will predict overall supply and market effects (Darwin and others 1995; Darwin forthcoming). The climate scenarios can be relatively simple stories of uniform changes across a country, or they can involve complex geographic distributions of changes. These geographic distributions vary substantially across global climate models. Consequently, most impact studies examine multiple climate scenarios.

Ricardian models. The Ricardian cross-sectional approach, which has been used to value the contribution that environmental measures make to farm income, includes work by Mendelsohn, Nordhaus, and Shaw (1994, 1996, 1999); Kumar and Parikh (1998a); Sanghi (1998); Sanghi, Mendelsohn, and Dinar (1998); and Sanghi and Mendelsohn (1999). In all these studies, the countries (Brazil, India, and the United States) are large enough to contain a sample with a wide range of climates. Table 1 presents the range of seasonal temperatures and precipitation in Brazil and India. The range of climates in both countries is large relative to the predicted 1–3.5°C change in temperature within the 21st century (Houghton and others 1996). Many uncertainties cloud the forecast of expected climate change, but the IPCC (Intergovernmental Panel on Climate Change) report (Houghton and others 1996), which includes the most recent research on the topic, is used in this article. By estimating the economic performance of farms across this range of climates, one can

Table 1. *Mean and Range of Temperature in India and Brazil*

Season	*Mean*	*Minimum*	*Maximum*
India			
January (winter)	18.4	9.2	25.7
April (spring)	29.4	19.4	32.4
July (summer)	27.9	21.9	32.5
October (fall)	25.7	19.8	28.4
Brazil			
June (winter)	20.0	7.2	32.8
September (spring)	22.3	10.1	31.6
December (summer)	24.4	15.9	33.4
March (fall)	17.3	14.1	29.4

Note: All temperatures are Celsius.
Sources: India: Sanghi, Mendelsohn, and Dinar (1998); Brazil: Sanghi (1998).

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.

Advantages and Disadvantages of the Methodologies

Researchers using all three methods generally agree that the extent to which farmers adapt to the new conditions can be very important. Agroeconomic and agroecological models must explicitly model adaptation, however, in order to include it. The analyst must be able to determine which adaptations are economically desirable. In practice, such determinations are difficult to make, and so they have been done largely on an ad hoc basis. The adaptation involves a change in agricultural practices in response to a change in climatic conditions. It includes changes in management practices, such as timing of sowing and harvesting, the intensification of inputs, and changes in the crop mix. Of course, adaptation assumes that farmers have access to alternative practices and technologies that are already practiced elsewhere.

Adaptation and Agronomic Studies

The agronomic literature (which includes the agricultural components of the agronomic-economic approaches and the agroecological zone analyses) addresses adaptation by simulating changes in the growth parameters of various crops according to the latest scientific advances. This approach does not take into account economic considerations and human capital limitations, both of which affect actual farm decisions. Therefore, it is hard to interpret the adaptation scenarios frequently explored by agronomists. El-Shaer and others (1997) identify possible climate-related adaptation strategies for Egyptian agriculture, but they do not provide quantitative estimates of the changes in crop performance associated with these strategies. Kapetanaki and Rosenzweig (1997) identify several adaptation strategies for maize in Greece, including adjusted planting dates and the introduction of new maize varieties. Simulations for three sites suggest that earlier planting dates (10–30 days earlier than the norm) increase yields by nearly 10 percent at all sites. The introduction of new varieties fully mitigated the negative impacts of climate change on yield at one site but only partially at the two southern sites. A combination of earlier planting dates and new varieties completely offset the negative impact of climate change at all sites. Iglesias and Minguez (1997) evaluate several adaptation strategies for wheat and maize in various climatological regions in Spain and find no reductions in yields. The adaptation strategies they tested include combinations of new hybrids, changes in sowing dates, and double cropping, using short-cycle maize varieties as a second crop along with lentils and a vetch–forage barley mixture. This strategy not only reduced the impact of increased temperatures on yields but also permitted more intensive use of water and land. In Spain water efficiency improved by 1–10 percent in southern regions and 40–80 percent in northern regions. Jin and others (1994), who examine adaptation strategies in southern China, find that a new rice cultivar increased yields at five out of seven sites. Changing the planting dates of the currently used cultivars increased rice yields at the northern sites, but not at the southern sites. Combining both changes—the cultivars and the planting dates—significantly increased yields at six of the seven sites.

Schimmelpfennig and others (1996) and Lewandrowski and Schimmelpfennig (1999) review the literature that examines how farmers adapt to climate changes in the United States. For example, Kaiser and others (1993a, b) include adaptation practices such as crop mix, crop varieties, sowing and harvesting dates, and water-saving technologies (tillage). Based on a comparison of nearby geographic sites, crop models (for example, Rosenzweig and others 1994) and farm-level models find that adaptation reduced the negative impact of warming on crop yields by up to 50 percent (Kaiser and others 1993a, b; Mount and Li 1994; Reilly 1994, 1995; Reilly and others 1996).

Pros and Cons of Agroecological Models

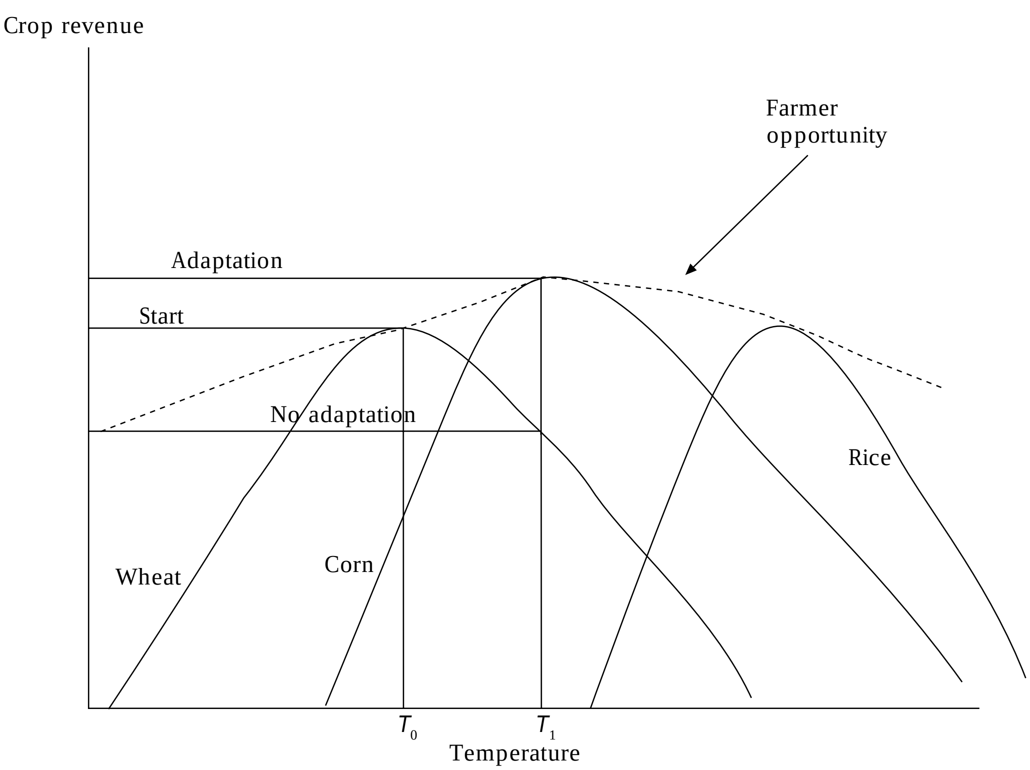
The biggest advantage associated with agroecological zones is that they have been carefully studied and the geographic distribution of the zones in developing countries has been published (FAO 1992). The current models using the zonal approach, however, have many problems. The climate zones represent large temperature categories, so that subtle shifts within a zone have no effect but a small shift from one zone to another has a dramatic consequence. The key measures of productivity have not yet blended soils and climate together; the effect of each is computed independently. Nor is it clear how tightly climate zones can predict which crops should be grown or what their yields will be. The approach is subject to the same limitations as the agroeconomic models in that researchers must explicitly account for adaptation. Finally, the existing application of the method predicts large price changes along with small changes in aggregate supply, suggesting that there may be problems with the calibration of the underlying economic model (Darwin and others 1995; Darwin forthcoming). Although the technique has potential, the available models are currently crude.

The Ricardian Approach

The most important advantage of the cross-sectional Ricardian approach is its ability to incorporate the changes that farmers would make to tailor their operations to a warmer climate. Because these adaptations benefit the farmer, there is every reason to expect that they will occur. One of the most crucial adaptation strategies is the choice of crop. Depending on the effects of a warmer climate, a particular crop will be the optimal choice. Of the three grains shown in figure 1, for example, each is best suited for a specific temperature (and level of precipitation). If the temperature warms, however, wheat yields will fall and net revenues will fall as well. If the farmer switches to corn, net revenues will rise. Optimal crop switching is an important component of measuring the agricultural impact of climate change.

One of the drawbacks of the Ricardian method is that the experiment is not carefully controlled across farms. Farms may vary for many reasons in addition to those incorporated in the variables of interest. To control for this problem, the studies include other important variables such as soil quality, market access, and solar radiation. But it is rarely possible to get perfect measures of all these variables, and one cannot guarantee that all of these processes and interactions have been taken into account; some may not be measured at all. Paradoxically, this weakness is a strength of the agronomic model, which relies on carefully controlled experiments and thus does not fall prey to this problem of extraneous variables.

Figure 1. *Crop Choice: Adapting to a Warmer Climate*



Source: Authors' calculations.

Another valid criticism of the Ricardian approach is that it does not consider price variations; all farms face the same prices. The models have consequently been forced to assume that prices are constant, leading to a bias in the welfare calculations (Cline 1996). The cross-sectional Ricardian studies measure only the loss to producers. By ignoring the price change that would occur if supply changed, the approach overlooks any loss in consumer surplus and consequently underestimates the damages and overestimates the benefits.

Although it is easy to criticize these studies for assuming that prices are constant, including price effects is difficult in any method. In most cases prices are determined in a global market. A global model would be needed to predict how climate changes would affect crop yields. Unfortunately, we do not have accurate global crop models, so predicting what will happen to the global supply of any crop as a result of a change in climate is difficult. Moreover, because the few global analyses completed to date predict that the range of warming in the 21st century should have only a small effect on aggregate supply, the bias from assuming that prices are constant is likely to be small (Reilly, Hohmann, and Kane 1994; Reilly and others 1996). 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).

The Ricardian Approach Modified

The application of a cross-sectional approach to agriculture in developing countries raises some additional difficulties that researchers addressed in the Brazilian and Indian studies. Although many prices are constant throughout the sample, some are not. Not only are these prices endogenous, but because they may not be accurate, it is difficult to control for their influence. For example, household members form a large fraction of the agricultural labor pool in developing countries. No wages are paid to household members, nor are there data on the number of hours that family members work (Bennholdt-Thomsen 1982; Grepperud 1997). In Brazil and India, therefore, researchers were forced to control for this factor using a dummy variable that identified those farms that relied heavily on household labor. This dummy variable is difficult to interpret because it signifies unpaid labor, which implies a positive sign on net revenue, but the dummy also signifies a smaller and more marginal farm, which implies a negative sign. Another input that is difficult to price is animal work. In India, for example, there is an official price for a bullock—the purchase price, in other words. But bullocks also have to be fed and managed. Farms that already grow feed may find it cheaper to maintain a bullock than do farms that have to purchase animal feed. To try to control for the price of animal power, the Indian study (Dinar and others 1998) includes the number of bullocks per hectare as a control variable. Although this is an imperfect solution because the number of animals is endogenous, the researchers believe that it reduces the potential bias animal power may have on the climate coefficients.

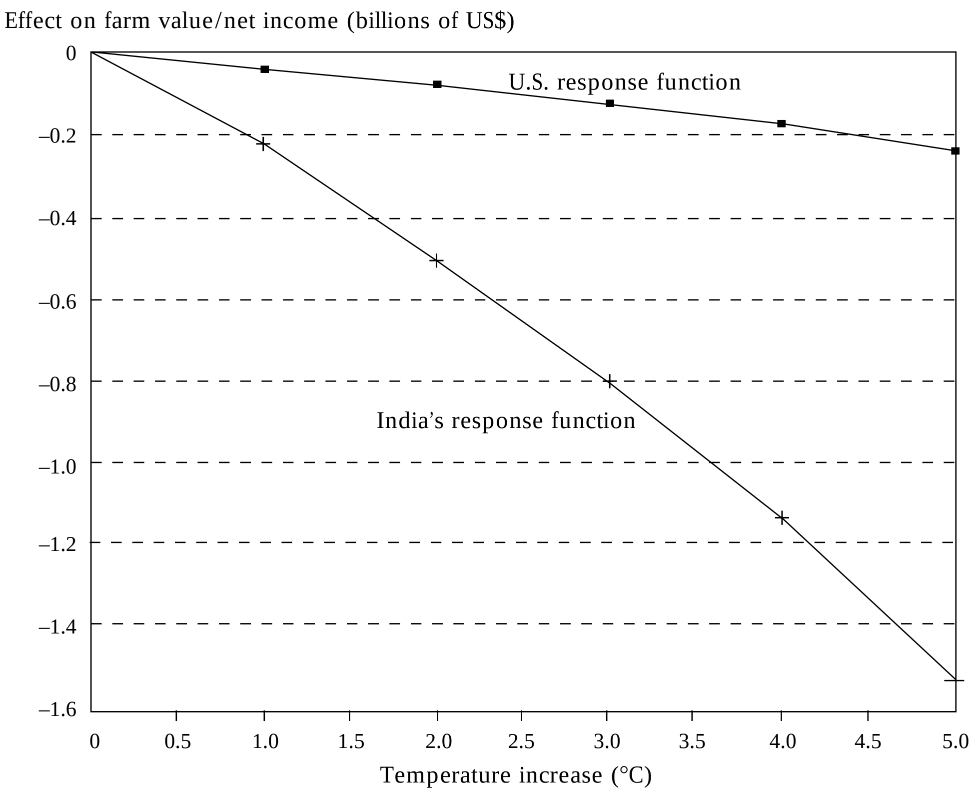
Another issue on the input side is technology. Both India and Brazil have mounted large and successful drives to enhance farming technology. These drives tended to be concentrated on the more temperate farmlands in both countries. Farm technology centers were originally concentrated around São Paulo in Brazil and around the Ganges River delta in India. Consequently, it was possible that the technology was facilitating improvement in temperate climates, but not in tropical climates, making warm areas relatively less productive. McKinsey and Evenson (1998) examined this hypothesis for India and found that technology had increased the output of farms over the last two decades, but because technological development had not specifically addressed the problems of heat tolerance, the interaction between technology adoption and climate appeared to be minimal.

Although technological adoption appears to have occurred in all climate zones in India, new technologies can still affect climate sensitivity by giving farmers increased flexibility (Antle 1995). The adoption of modern farming methods can free farmers from previous environmental constraints with new crop varieties, irrigation technologies, and chemical controls (Dinar and Zilberman 1991; Dinar, Campbell, and Zilberman 1992). For example, figure 2 compares the climate senstitivity function for the United States and India as it applies to Indian conditions. Both climate response functions suggest that India is likely to suffer damages because initial temperatures are so high. The results using the Indian response function are more damaging, however, than the results from the American response function. It would appear that capital-intensive agricultural systems are less sensitive to climate, perhaps because they can control so many more inputs. Alternatively, the modern technologies may simply be more able to substitute purchased inputs for climate. Of course, the results also suggest that as developing countries get richer, their agricultural sectors will become less sensitive to changes in climate.

Results of Studies

The agronomic results around the world vary, reflecting alternative methods, starting conditions, and climate scenarios (Reilly and others 1996). Some of the studies included some adaptation and carbon fertilization, whereas other studies ignored both factors. Some of the studies used old climate scenarios that tended to predict large temperature changes, whereas other studies examined the more modest climate scenarios now considered likely. Each of the studies was based on agronomic experiments in selected locations, and so they started from different initial conditions. Some of the studies were based on narrowly defined locations, whereas others ranged over large territories. Although table 2 shows great variation across all regions, some

Figure 2. *Predicted Effect of Increased Temperatures in India and the United States*



Source: Authors' calculations.

general observations can be made. In the developing countries studied (China and countries in Africa, South Asia, and Latin America), there are 25 negative and only 6 positive outcomes (of 43 studies). The results for industrial regions (Europe, United States, Japan, and Oceania) are more positive, however, with 9 outright positive results and only 3 negative outcomes (of a total of 27 studies). The agronomic studies suggest that the countries of the temperate and polar zones could gain productivity, whereas developing countries in the subtropical and tropical zones are likely to lose productivity.

If carbon fertilization and adaptation are ignored, agronomic studies of India suggest that extensive warming could cause significant reductions in yields. Grain yields would fall 25–40 percent if temperatures rose by 4°C (Rosenzweig and Parry 1994). These findings are confirmed by Kumar and Parikh (1998a, b), who predict that rice yields will fall by 15–25 percent and wheat yields by 30–35 percent. Not all grains

Table 2. *Agroeconomic Results: Change in Yields*

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

Source: Reilly and others (1996).

are necessarily temperature sensitive; Rao, Rao, and Acharya (1989) find that sorghum and millet are more stable across climates than other grains.

The cross-sectional studies suggest only modest agricultural damage in India (table 3). Using pooled analysis, Sanghi, Mendelsohn, and Dinar (1998) find that a 2°C warming would reduce average net income by only about 4 percent. Using repeat annual analyses, Kumar and Parikh (1998a) determine that a 2°C warming would decrease net income by about 8 percent. Even with a 3.5°C warming, Sanghi,

Table 3. *Ricardian Results: Change in Net Income Resulting from a Temperature Increase*

Country	Temperature increase (Celsius)	Change in income (percent)	Source
United States	2.0	–3 to +2	Mendelsohn, Nordhaus, and Shaw (1994)
United States	2.0	–3 to +2	Mendelsohn, Nordhaus, and Shaw (1996)
India	2.0	–3 to –6	Sanghi, Mendelsohn, and Dinar (1998)
India	3.5	–3 to –8	Sanghi, Mendelsohn, and Dinar (1998)
India	2.0	–7 to –9	Kumar and Parikh (1998a)
India	3.5	–20 to –26	Kumar and Parikh (1998a)
Brazil	2.0	–5 to –11	Sanghi (1998)
Brazil	3.5	–7 to –14	Sanghi (1998)

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

Mendelsohn, and Dinar find 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 3.5°C warming. These estimates are considerably smaller than the agronomic predictions.

Comparing the damages predicted by the agronomic simulations with the results of 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. Note that private adaptation does not involve technical change; farmers simply adjust their techniques using existing technology.

The cross-sectional studies also reveal that climate has important seasonal patterns (table 4). Although using a uniform value to represent the change in climate conditions across various regions may not represent the situation in each region, it provides useful comparable information. For example, it allows differentiation among growing seasons that may have different levels of impact across regions. In the cases

Table 4. *Ricardian Results: Marginal Climate Sensitivity Coefficients*

Variable	*India*[a]	*India*[b]	*Brazil*[c]
Temperature			
Winter	–133.0	–95.0	–12.0
	(3.38)	(6.81)	(13.12)
Spring	–372.0	–174.0	16.3
	(16.71)	(11.96)	(14.62)
Summer	–103.0	–141.0	–19.4
	(2.84)	(5.20)	(6.62)
Fall	486.0	458.0	10.1
	(7.35)	(13.06)	(5.95)
Precipitation			
Winter	18.5	7.5	0.22
	(6.11)	(4.39)	(7.71)
Spring	–14.4	–4.5	0.44
	(8.00)	(8.91)	(0.94)
Summer	–0.4	–0.4	–0.31
	(2.11)	(3.86)	(15.53)
Fall	2.3	6.4	0.24
	(2.23)	(10.78)	(11.10)

Note: Marginal effects measured at the mean for each season. *t*-statistics are in parentheses.

a. From Sanghi, Mendelsohn, and Dinar (1998). Dependent variable is net income in 1980 rupees.

b. From Kumar and Parikh (1998a). Dependent variable is net income in 1980 rupees.

c. From Sanghi (1998). Dependent variable is the log of farm value.

presented in table 4, for example, it allows a comparison of the impact of a change in climate on agriculture during the four seasons in Brazil and India. Net incomes in India decline precipitously with warmer winter, spring, and summer temperatures, whereas warmer fall temperatures increase net revenues. Land values in Brazil also decline with warmer summer and winter temperatures and rise with warmer falls. These results are similar to patterns found in the U.S. studies. 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 because the temperatures are quite hot already in India during this period. In Brazil, however, 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 higher 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 at that time. Farm income may be very sensitive to winter temperatures, however, because cold temperatures 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 the country already enjoys a monsoon during this period.

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

Policy Implications

Many agronomic studies predict large agricultural losses in developing countries. These estimates appear to be too pessimistic for three reasons. First, the pessimistic results generally do not account for the powerful fertilizing effect of carbon dioxide. Second, these studies tend to underestimate the importance of efficient adaptation as a mechanism to reduce damages. Third, almost all of the agronomic studies focus on grains, which tend to prefer temperate climates, and do not include tropical and subtropical crops. Taking these mitigating factors into account, climate change is not likely to reduce dramatically aggregate productivity in developing countries.

In contrast, global warming is likely to increase productivity in industrial countries in the temperate and polar regions. As these cooler regions become more productive, the increased supply is likely to depress world prices, making farmers in developing countries worse off. Although these price effects are likely to be small, developing country agriculture will be relatively worse off.

The adaptation measured in the cross-sectional studies entails individual actions, but enlightened public policy could facilitate further changes. First, public policy could help farmers adjust their cropping patterns and methods by monitoring the weather and providing better climate forecasts. Second, the government could advise farmers on how to adjust to alternative climates. Third, the government could invest in new technology by, say, funding research on heat-tolerant crops as an incentive to introduce such crops into warmer climate zones.

Although scientific models provide important insights into the sensitivity of developing country agriculture to changes in temperature, little is known about many regions, especially Africa and Oceania, and there is little information about how warming will affect subsistence farmers. Agricultural GNP in developing countries may not be severely damaged by warming because many developing countries—even those near the equator—have significant pockets of highly productive temperate farmlands. But poor farmers in marginal territories may be very vulnerable. Studies are also vital to the future of other sectors of developing economies, such as timber, energy, water, and coastal properties, all of which may be damaged by warming. Nonmarket factors such as changes in ecosystems, health, and aesthetics need to be considered. As we enter a world where climate is likely to change, it is important that we learn as much as possible about the consequences of warming for the Earth's systems in order to prepare ourselves and to avoid the most serious impacts.

Notes

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1. Although we refer only to "private adaptation," it is assumed implicitly that the availability of some management and other technologies by which farmers can adapt to climate change may also be the result of public research and development.

2. Variables that were used in the Ricardian models applied to India and Brazil include the following (not all nonclimate variables were used in both countries): temperature and precipitation (annual, monthly, seasonal); various measures of soil property; latitude; labor; machinery; animals; human capital variables; and technology level (measured in shares of high-yielding varieties). Variables measuring infrastructure were hard to obtain at the level at which the analysis was conducted, so proxies were used in the form of population density and distance from market.

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