5

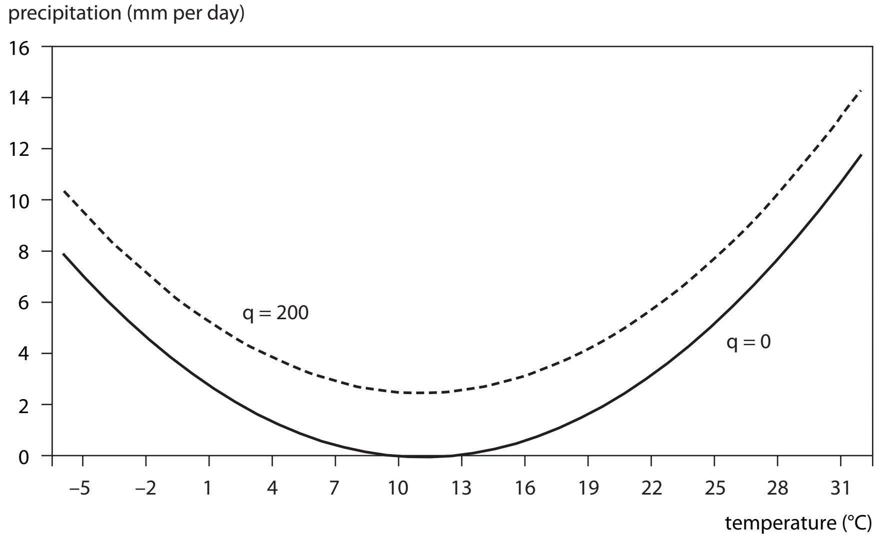
Country-Level Agricultural Impact Estimates

This chapter sets forth the method and results for this study's country-level estimates of the potential effect of global warming by the 2080s on agriculture. The chapter first reviews the two main families of models: Ricardian and crop models. It then specifically examines a series of agricultural impact models, beginning with estimates by Mendelsohn and Schlesinger (1999) reflecting both of the alternative schools, then turning to a series of Ricardian country or regional model estimates, and concluding with the principal set of crop model estimates (Rosenzweig and Iglesias 2006). The analysis applies detailed climate projections to the various agricultural impact models to develop a set of alternative impact estimates. It then arrives at a set of preferred estimates, applying judgmental weighting of estimates by likely reliability. With preferred estimates in hand from the array of models without taking carbon fertilization into account, the analysis then incorporates this study's preferred quantification of carbon fertilization.

Mendelsohn-Schlesinger Agricultural Response Functions

It is useful to begin the review of agricultural impact models with the two summary statistical models, reduced form and cross section, provided by Mendelsohn and Schlesinger (1999), or MS, because their two alternative models reflect, respectively, the crop model and the Ricardian model approach. The reduced form, process-based model is derived from a summary statistical estimate based on underlying results from an agronomic model of crop growth and a linear-programming model of US farms (in

Figure 5.1 Iso-production curves for the Mendelsohn-Schlesinger reduced form function



Mendelsohn and Neuman 1999). It states the agricultural impact of temperature, precipitation, and atmospheric concentration of carbon dioxide as follows:

$$y = 2.16 \times [-308 + 53.7T - 2.3T^2 + 0.22P + 36.5\ln(c/350)] \qquad (5.1)$$

where y is annual agricultural output in 1990 dollars per hectare of agricultural land, T is average annual temperature in degrees Celsius, P is average annual precipitation in millimeters, and c is atmospheric concentration of carbon dioxide (parts per million, or ppm).[1] Note that in the base period (broadly the present), carbon concentration is 350 ppm, so that the final term becomes 36.5 times the natural logarithm of unity, which is zero, so the carbon fertilization term drops out when examining the present influence of climate on agriculture.

Figure 5.1 shows curves corresponding to zero output and output of $200 per hectare on the basis of equation (5.1). Both curves show the optimal temperature at 11.7°C. At this temperature, output is $200 per hectare at daily precipitation of about 2.5 mm. With zero precipitation,

1. Mendelsohn and Schlesinger (1999) state this function as $W_a = 2.16\ L_a$ [. . .], where the elements in brackets are the same as in equation (5.1) here; W_a is agricultural output in billions of dollars, and L_a is land area. Although they do not identify the units for land area, Robert Mendelsohn has confirmed by personal communication that when both sides are divided by L_a, the result is output in dollars per hectare.

output is zero even at this optimal temperature. At higher temperatures, more precipitation is required to keep productive potential positive. For example, at average temperature of 22°C, output would be zero if precipitation were only 3 mm per day. Output of $200 per hectare would require precipitation of 5.5 mm per day at this temperature. In comparison, present-day averages for the south of Brazil are 22°C and 4 mm per day (table 4.2), placing it above the zero curve but below the $200 curve.

In principle the MS reduced form model takes account of the potential for adaptation. As the authors state, "The analysis improves upon earlier studies . . . by adding fruits and vegetables (not just cereals), including livestock, and exploring farm adaptation" (Mendelsohn and Schlesinger 1999, 363). The underlying study (Adams et al. 1999) on which the MS function is based emphasizes that the improved models used take account of the scope for shifting crop mixes from corn, wheat, and soybeans to more heat-tolerant crops such as cotton, sorghum, fruits, and vegetables. That study also further takes account of adaptation through incorporating such adjustments as changes in fertilizer, irrigation, and timing of planting and harvesting (Adams et al. 1999, 18–20). It observes in broad terms that

> a reasonable first approximation is that adaptation could potentially offset roughly half of the negative impacts of a moderate climate change. However, the evidence suggests that adjustment possibilities are smaller for larger temperature changes (p. 32).

Mendelsohn and Schlesinger (1999) also present a cross-section or Ricardian agricultural impact function. This model was an early entry in a now relatively long series of studies that trace their lineage to Mendelsohn, Nordhaus, and Shaw (1994), as noted in chapter 2.

The cross-section Ricardian function identified in Mendelsohn and Schlesinger (1999) is

$$v = r \times g \times [-475.5 + 223.2T - 7.87T^2 + 0.063P - 0.000026P^2 + 480\ln(c/350)] \tag{5.2}$$

where r is the interest rate and g is a factor for the growth rate of agricultural output, set at 0.03 and 1.02, respectively.[2] In the cross-section function, the value in brackets is the capital value of land per hectare; multiplying it by the interest rate yields the estimated rental equivalent opportunity cost of land per hectare, v, in dollars per hectare. In principle this amount should be significantly smaller than the output value per hectare in the reduced form (equation 5.1), because it is only the land factor share of output rather than total output.

2. These parameter values were clarified in a personal communication with Mendelsohn, July 15, 2006.

Mendelsohn, Morrison, Schlesinger, and Andronova (2000), or MMSA, also present versions of equations (5.1) and (5.2) with slightly modified parameter values. However, the set of equations in this second study performs less well in predicting actual base-period agricultural productivity than the Mendelsohn and Schlesinger (1999) equations, which are applied in the estimates in appendix F.[3]

Mendelsohn-Schlesinger Estimates for the United States

Appendix F develops the application of the MS models to obtain comprehensive country-specific estimates of the agricultural impact of climate change. Because the models are based on the United States, the results are of most direct relevance only for the United States. Nonetheless, as discussed later, the MS model will be applied as the default version for the Ricardian estimate when no region- or country-specific model is otherwise available. For the United States, the MS models when applied to the future climate estimates of the present study yield the results shown in table 5.1 for the case without carbon fertilization (see appendix F for more complete discussion).

The reduced form crop model specifies the dependent variable directly as output per hectare. However, the Ricardian model generates an estimate of land rental equivalent per hectare. For the latter, it is necessary to translate the percent change in land rental equivalent into a corresponding expected change for output. This step is ambiguous. One can certainly conceive of land value (or land rental value) changes that translate directly to corresponding proportionate changes in output potential. If a nuclear explosion were to contaminate a land area and make it unusable for decades, its land value would go to zero and so would its output potential. For less extreme changes, however, the output potential change will be only a fraction of the percentage change in land rental value. From one standpoint, it will simply be the factor share of land multiplied by the percent change in land rental value. From another standpoint, in principle compatible with the first, the percent change in output potential will be the percent change in land rental value multiplied by the ratio of net revenue to total output, because land value is the capitalized value of net revenue. The final column in table 5.1 estimates the percent change in output potential in the Ricardian model by multiplying the percent change in

3. For the 116 countries, regions, or subzones, the reduced form equation in Mendelsohn and Schlesinger (1999) yields negative predicted base output in 53 percent of the cases, whereas the MMSA (2000) reduced form equation produces negative base output in 63 percent of the cases. The two studies both yield 22 percent negative base output cases for the cross-section model.

Table 5.1 Impact of baseline global warming by the 2080s on US agricultural potential using the Mendelsohn-Schlesinger functions (without carbon fertilization) (percent)

Region	Farm area (millions of hectares)	Output, 2003 (billions of dollars)	Reduced form crop model	Ricardian model	
				Land value	Output potential
United States	379.3	98.5	–14.8	11.5	4.7
Lakes, Northeast	74.3	30.5	9.1	35.4	14.5
Pacific Northwest	13.1	4.2	24.5	40.6	16.6
Rockies, Plains	113.3	15.1	74.6	65.8	27.0
Southeast	58.0	22.2	–67.9	–33.3	–13.6
South Pacific Coast	11.2	12.7	–5.7	—	0.04
Southwest Plains	109.1	13.8	–100.0	–27.0	–11.1

— = not available. See table F.2, note b.

land rental equivalent by the average ratio of net revenue to agricultural value added, 0.41 in the 2002 agricultural census.[4]

Both the reduced form crop model and the Ricardian model show agricultural losses for the Southeast and the Southwest Plains regions, and these losses are severe in the case of the reduced form model. There are also mild losses in the Southern Pacific Coast region. In the aggregate, there are losses of about 15 percent in the reduced form crop model but gains of about 5 percent in the Ricardian model. As reported in appendix F, the reduced form model losses are smaller (2.9 percent) when carbon fertilization is included using the MS parameter value, and the Ricardian model swings to major gains (+20 percent).

Ricardian Estimates for Developing Countries and Canada

For the Ricardian estimates used in this study, the Mendelsohn and Schlesinger (1999) cross-section model estimated for the United States provides a default model for application to climate projections for countries and regions in which no directly estimated function is available, as discussed later. More recent models estimated explicitly for several important developing countries and regions provide a preferable basis for the estimates developed in the present study for those countries and regions.

4. In 2003, GDP originating in agriculture was $98.5 billion (appendix table E.1). "Net cash income of operations" in 2002 was $40.5 billion (USDA 2004). On this basis, net revenue was 41 percent of output as measured by agricultural value added.

Mendelsohn, Dinar, and Sanghi (2001) provide estimates for India; Kurukulasuriya et al. (2006) provide estimates for Africa; and a series of studies sponsored by the World Bank provide new estimates for major Latin American countries (see appendix G).[5] For all three sets of estimates, the model structure is as follows:

$$z = \Sigma_i \,[\alpha_i T_i + \beta_i T_i^2 + \gamma_i P_i + \delta_i P_i^2] + K \qquad (5.3)$$

where z is the measure of agricultural productivity (net revenue per hectare for Africa, natural logarithm of net revenue per hectare for India, and land value per hectare for the Latin American studies), T is average temperature, P is average monthly precipitation, i refers to the season, and K is a composite variable that reflects the regression constant as well as the influence of other control variables in the particular model estimated.[6] The impact of business as usual global warming through the 2080s is then obtained using this equation to estimate the difference between agricultural productivity using the base period (1961–90) and future period (2070–99) climate estimates of this study. Application of these models requires applying the relevant seasonal monthly averages for future temperature and precipitation from the climate models, rather than the annual averages. The effect of carbon fertilization is not incorporated in these regional Ricardian estimates and must be added subsequently to obtain the overall impact of future climate change.

It is necessary to translate the change in net revenue from climate change to the corresponding percent change in output from the base level of output. In principle the change in net revenue will be the same in absolute terms as the change in output.[7] In order to estimate this change as

5. Note that the Mendelsohn, Dinar, and Sanghi (2001) study also provides a model for Brazil. However, application of the model results in estimates of complete shutdown of agriculture from global warming, which as in the Brazil finding with the MS functions strains credibility. In part because of ambiguities in the data (including nonavailability of average land price for the study), the more recent World Bank study for Brazil is used instead as the preferred estimate for that country, as discussed later.

6. Note, however, that in the India model, the underlying variables are expressed as differences from their means (for example, $T-\check{T}$, for temperature, or $(T-\check{T})^2$, for temperature squared, where $\check{T}$ is base average temperature). This approach has the property that the coefficient on the linear term shows the marginal impact of the climate variable (e.g., temperature), because the square term causes symmetric damage for either a rise or a decline in temperature and has a marginal impact of zero at the original base temperature, where the influence of an increase in temperature is shifting from positive to negative. In contrast, in the Africa and Latin America models, the levels rather than differences from means are the underlying variables.

7. That is, $NR = Q - \Sigma_i X_i$, where NR is net revenue per hectare and X_i is the amount of purchased input i per hectare (mainly hired labor and fertilizer). With such inputs held constant, a yield shock from climate change translates directly into the same change in net revenue: $\Delta NR = \Delta Q$.

a percent of output, it is necessary to know the base level of output that corresponds to the base level of net revenue.

India

Table 5.2 reports the results of applying the Mendelsohn, Dinar, and Sanghi (2001) model for India to the base and 2080s climate variables identified in the present study. The model applies seasonal monthly climate data (see appendices G and H). The table first reports the levels and change in the dependent variable, which is the logarithm of net revenue per hectare. It then identifies the corresponding percent change from the base level of net revenue.[8] The final column restates the change as a percent of base output.[9]

The results for India are sobering, with reductions in output potential ranging from about 30 to 35 percent in the southern regions to about 60 percent in the northern regions. As discussed later, this model does not include the favorable effect of carbon fertilization. Even after inclusion of carbon fertilization effects, however, the losses would be severe.[10]

Africa

The World Bank has recently carried out a massive farm survey in Africa to examine the relationship between agricultural productivity and climate

8. Given an initial actual net revenue or land value of q_0 and base level model-estimated logarithm z_o, the implied value of the missing constant is $K = ln(q_0) - z_0$. With the change in logarithm resulting from change in temperature and precipitation estimated as $z_1 - z_0$, the absolute level changes from q_0 to $q_1 = exp(K + z_1)$. The proportionate change is then $(q_1 - q_0)/q_0$. For moderate changes, this proportionate change will be approximately equal to $z_1 - z_0$.

9. A rough estimate for India is that average net revenue per hectare in the estimation period amounts to two-thirds of output per hectare. This estimate is obtained as follows: According to Dinar et al. (1998, 98), average net revenue in the India sample was 1,424.7 rupees of 1980 per hectare. The data referred to the period 1966–86. Total farm area in India amounted to about 170 million hectares. In 1976, the midpoint of the period, agriculture accounted for 47 percent of GDP, or $43.7 (World Bank 1978, 80). By 1982, agriculture's share of GDP was down to 33 percent, amounting to $49.8 billion (World Bank 1984, 222). Taking the average of these two estimates, and using the 1980 exchange rate (7.86 rupees per dollar), agricultural value added in the base period was 367 billion rupees of 1980, or 2,160 rupees per hectare. Average net revenue was thus 1,425 / 2,160 = 66 percent of agricultural output. Correspondingly, for a given estimate of the percent change in net revenue, the appropriate estimate for percent change in output will be only two-thirds as large.

10. The counterintuitive greater losses in the higher latitude regions appear to stem from the following influences. First, the increase in temperatures in the northern regions is greater than that in the southern regions, even though the base temperatures are higher in the south. Second, the impact of changes in precipitation turns out to be positive in the south but negative in the north.

Table 5.2 Impact of global warming by the 2080s on Indian agricultural productivity[a] using the Mendelsohn-Dinar-Sanghi model[b]

Region	Present climate	Implied constant *K* for other variables	Future climate	Change in log	Percent change: Net revenue	Percent change: Output
Northeast	2.1006	9.3625	–0.3408	–2.441	–91.3	–60.9
Northwest	–2.3678	4.8941	–4.3992	–2.031	–86.9	–57.9
Southeast	–4.5516	2.7103	–5.1900	–0.633	–46.9	–31.3
Southwest	–4.3051	2.9568	–5.1085	–0.803	–55.2	–36.8

a. Logarithm of net revenue per hectare.
b. Mendelsohn, Dinar, and Sanghi (2001). See appendix G.

(see appendix G). A summary analysis estimates cross-section Ricardian functions relating net revenue per hectare to linear and quadratic terms for seasonal temperature and precipitation. Once again nonclimate variables have the effect of shifting the net revenue estimate by a constant *K*. Application of the base and future climate variables provides the basis for estimating the change in net revenue from climate change (excluding the effect of carbon fertilization and changes in water runoff, a variable in these cross-Africa functions).

Table 5.3 shows the results of applying the World Bank Ricardian functions for Africa to the base and future climates, again using seasonal monthly climate data (see appendix G for model parameters and appendix H for country-level averages of the underlying grid-level monthly climate data, although the actual estimates are calculated at the much more detailed standard grid level). It then expresses the change in net revenue per hectare as a percent of the all-Africa average base level of output per hectare.[11] Even though average net revenue and output per hectare will

11. Once again it is necessary to estimate the relationship of base net revenue per hectare to base output. As reported in table 5.4, for all of the African countries considered, total dryland farm area is 193.4 million hectares, and total irrigated farm area 13.44 million hectares. Agricultural value added for the region is a total of \$100.2 billion. The World Bank sample showed average net revenue per hectare for irrigated land was four times as large as that for dryland. Using this same ratio, agricultural GDP can be estimated to have averaged \$405 per hectare for dryland and \$1,622 per hectare for irrigated land. That is, $13.44 \times 10^6 \times q_d \times 4 + 193.4 \times 10^6 \times q_d = \$100.2 \times 10^9$. Solving for output per dryland hectare, $q_d = \$405$, and output per irrigated hectare is four times as much, or \$1,622. From the sample, net revenue was an average of \$319 per hectare for dryland and \$1,261 per hectare for irrigated land. Net revenue is thus a relatively high 78 percent of agricultural GDP per hectare. The high ratio likely reflects substantial incidence of the use of family labor relative to hired labor and purchased inputs in a relatively low-income region.

Table 5.3 Impact of climate change by the 2080s on African agriculture, World Bank Ricardian models (without carbon fertilization)

	Net revenue per hectare estimate excluding nonclimate variables (2005 dollars)					**Change as percent of base output/hectare, Africa average**		
	Base		**Future**					
Country/region	**Dryland**	**Irrigated**	**Dryland**	**Irrigated: A**	**Irrigated: B**	**Dryland**	**Irrigated: A**	**Irrigated: B**
Algeria	–133	–739	–403	86	–637	–66.6	50.8	6.3
Angola	–130	4,485	–237	4,736	4,059	–26.3	15.5	–26.2
Burkina Faso	–431	4,298	–498	5,095	4,638	–16.5	49.1	20.9
Cameroon	57	8,383	–21	8,258	7,870	–19.1	–7.7	–31.6
Democratic Republic of the Congo	118	1,832	95	2,731	2,208	–5.5	55.4	23.2
Egypt	–164	–993	–367	–126	–781	–50.1	53.5	13.1
Ethiopia	–212	1,992	–339	1,724	1,118	–31.4	–16.5	–53.9
Ghana	–170	3,637	–182	3,454	2,963	–3.0	–11.3	–41.6
Ivory Coast	–96	4,905	–111	4,151	3,702	–3.6	–46.5	–74.2
Kenya	–305	626	–272	1,320	963	8.3	42.8	20.8
Madagascar	31	6,824	–52	7,196	6,558	–20.5	22.9	–16.4
Malawi	–152	7,249	–289	7,687	7,083	–33.6	27.0	–10.2
Mali	–481	1,457	–670	1,922	1,265	–100.0	28.6	–11.9
Morocco	60	–1,370	–117	–739	–1,458	–43.7	38.9	–5.5
Mozambique	–187	5,905	–311	6,511	5950	–30.6	37.4	2.8
Niger	–485	131	–664	1,168	720	–100.0	64.0	36.3
Nigeria	–245	5,797	–300	6,130	5,768	–13.7	20.5	–1.8

(table continues next page)

Table 5.3 Impact of climate change by the 2080s on African agriculture, World Bank Ricardian models (without carbon fertilization) *(continued)*

	Net revenue per hectare estimate excluding nonclimate variables (2005 dollars)					Change as percent of base output/hectare, Africa average		
	Base		Future					
Country/region	**Dryland**	**Irrigated**	**Dryland**	**Irrigated: A**	**Irrigated: B**	**Dryland**	**Irrigated: A**	**Irrigated: B**
Other Equatorial Africa	240	1,767	247	1,872	1,409	1.6	6.5	–22.0
Other Horn of Africa	–388	–887	–439	–395	–772	–100.0	30.3	7.1
Other Southern Africa	–201	1,010	–413	864	142	–52.5	–9.0	–53.5
Other West Africa	162	14,028	98	13,120	12,690	–15.6	–56.0	–100.0
Senegal	–396	5,822	–482	5,578	4928	–100.0	–15.1	–55.2
South Africa	33	1,046	–175	1,083	403	–51.5	2.3	–39.6
Sudan	–383	1,683	–498	2,348	1838	–100.0	41.0	9.5
Tanzania	–185	6,313	–251	6,807	6,296	–16.3	30.4	–1.1
Uganda	–79	1,102	–86	1,502	1,024	–1.7	24.6	–4.8
Zambia	–211	4,549	–408	4,668	3,938	–48.5	7.4	–37.7
Zimbabwe	–164	2,676	–376	3,069	2,421	–52.4	24.2	–15.7

Irrigated: A = model including Egypt
B = model excluding Egypt

Note: Base average net revenue per hectare: dryland, $319; irrigated, $1,261 (Kurukulasuriya et al. 2006).
Base output per hectare: dryland, $405; irrigated, $1,622 (see text).

Source: Author's calculations. See appendix G.

vary among countries, because the parameters of the models are uniform across all countries in the region, it is appropriate that estimated net revenue changes be compared with the regional average rather than country-specific output per hectare.

For irrigated agriculture, variant A is from the model reported in Kurukulasuriya et al. (2006) for all observations including those in Egypt, which alone accounts for 58 percent of the observations for irrigated agriculture. The authors note that Egypt may be atypical because of the massive availability of irrigation from the Nile River; indeed, there are no dryland farms at all in the sample for Egypt. They therefore also report the key marginal parameters for temperature and precipitation separately for the full model including Egypt and for a model excluding Egypt, designated here as A and B, respectively (see appendix G). Table 5.3 reports estimates for model B by applying the differences in these marginal parameters to the change in temperature and precipitation and adding the result to the estimated change in net revenue in model A.[12]

There is a predominant pattern of large negative changes from business as usual warming (excluding carbon fertilization) in dryland African agriculture. The median change is –31 percent. In contrast, for variant A of the irrigated agriculture model (including Egypt), the median change is +24.4 percent. However, when variant B of the irrigated agriculture model is applied (excluding Egypt in the parameter estimation), negative results also dominate irrigated agriculture, with the median change at –11.1 percent.

One pattern that stands out in table 5.3 is the dispersion of results. There is a high frequency of severely adverse effects for dryland agriculture, as five of the 28 countries or regions have complete shutdown. Another six have reductions in agricultural capacity by about half or more. However, four countries have only modest declines averaging about 3 percent, and two countries or regions have modest increases. Even so, the dominant pattern is of serious loss.

A second pattern is that several countries show major gains for irrigated agriculture if the model heavily influenced by Egypt and its Nile water is used (variant A), but the pattern shifts to dominant losses even in irrigated agriculture if the function omitting the Egypt observations is applied (variant B).

Because the results differ substantially between dryland and irrigated agriculture (even when variant B is used), to obtain meaningful estimates it is necessary to weight the two types of agriculture. Table 5.4 reports the

12. That is, the full model A yields the estimates shown in the second and fourth columns of table 5.5. The future net revenue estimate for model B is obtained by adding the following value to that in the fourth column of the table for model A: $\Delta y_B - \Delta y_A = (\eta_B - \eta_A)\ \Delta T + (\theta_B - \theta_A)\ \Delta P$, where T is temperature (degrees Celsius), P is precipitation (mm per month), y is net revenue per hectare, Δ refers to change from climate change, η is the marginal parameter for temperature, and θ is the marginal parameter for precipitation. The values for ΔT and ΔP are taken from the present and future annual averages shown in table 4.2.

Table 5.4 Weighted average impact of global warming by the 2080s on the African agriculture
(percent and millions of 2005 dollars)

Country/region	Dryland (without carbon fertilization)	Irrigated (without carbon fertilization)	Irrigated share of cropland		Weighted average		Base output (millions of dollars)
			Area	Value	Without carbon fertilization	With carbon fertilization	
Algeria	–66.6	6.3	7.0	27.2	–46.7	–38.7	6,657
Angola	–26.3	–26.2	7.0	27.2	–26.3	–15.2	1,188
Burkina Faso	–16.5	20.9	0.0	0.0	–16.5	–4.0	1,298
Cameroon	–19.1	–31.6	2.0	9.2	–20.3	–8.3	5,499
Democratic Republic of the Congo	–5.5	23.2	1.0	4.8	–4.1	10.2	3,292
Egypt	–50.1	53.5	100.0	100.0	53.5	76.5	13,189
Ethiopia	–31.4	–53.9	0.0	0.0	–31.4	–21.2	2,748
Ghana	–3.0	–41.6	3.0	13.3	–8.2	5.6	2,748
Ivory Coast	–3.6	–74.2	1.0	4.8	–7.0	7.0	3,574
Kenya	8.3	20.8	19.0	53.7	15.0	32.3	2,302
Madagascar	–20.5	–16.4	1.0	4.8	–20.3	–8.3	1,587
Malawi	–33.6	–10.2	2.0	9.2	–31.5	–21.2	651
Mali	–100.0	–11.9	31.0	69.0	–39.0	–29.9	1,645
Morocco	–43.7	–5.5	2.0	9.2	–40.1	–31.1	7,436

Mozambique	–30.6	2.8	5.0	20.7	–23.6	–12.1	1,122
Niger	–100.0	36.3	15.0	46.6	–36.1	–26.5	1,094
Nigeria	–13.7	–1.8	3.0	13.3	–12.1	1.1	15,180
Other Equatorial Africa	1.6	–22.0	1.0	4.8	0.5	15.6	1,429
Other Horn of Africa	–100.0	7.1	1.0	4.8	–94.8	–94.1	20
Other Southern Africa	–52.5	–53.5	1.0	4.8	–52.5	–45.4	619
Other West Africa	–15.6	–100.0	5.0	20.7	–33.2	–23.2	1,832
Senegal	–100.0	–55.2	10.0	35.5	–84.0	–81.6	1,105
South Africa	–51.5	–39.6	11.0	38.0	–47.0	–39.0	6,395
Sudan	–100.0	9.5	4.0	17.1	–81.1	–78.3	6,944
Tanzania	–16.3	–1.1	0.0	0.0	–16.3	–3.7	4,629
Uganda	–1.7	–4.8	6.0	24.0	–2.5	12.1	2,016
Zambia	–48.5	–37.7	3.0	13.3	–47.1	–39.1	1,000
Zimbabwe	–52.4	–15.7	5.0	20.7	–44.7	–36.4	3,018
Total					–18.6	–6.3	100,215
Excluding Egypt					–29.5	–18.9	
Median					–28.9	–18.2	

Sources: Table 5.3 using non-Egypt irrigated model B except for Egypt; World Bank (2006).

share of farm area under irrigation and the corresponding estimate of the share of total crop value from irrigated farming in each country.[13] In table 5.4, the with-Egypt irrigated function is applied only for Egypt; for all others the without-Egypt function is used (variant B in table 5.3).

For each country or region, the weighted average impact of climate change is calculated by weighting the dryland and irrigated estimates by their respective value shares in the base period. This estimate excludes the carbon fertilization effect. When this estimate is aggregated across all African countries and regions by weighting by base period agricultural output, the result is that African agricultural capacity would decline by an estimated 18.6 percent by the 2080s, before taking account of carbon fertilization. Excluding Egypt, the decline would be about 30 percent. A comparable set of estimates including carbon fertilization is obtained by applying a uniform 15 percent enhancement of yields from this effect by the 2080s, as discussed above. The result is a still substantial aggregate decline of 6.3 percent in the aggregate and about 19 percent excluding Egypt.

These averages mask greater declines in the majority of countries in the region. The weighted averages are buoyed by the highly favorable results for Egypt, which has the second largest output base in the continent, and an unusually small net decline for Nigeria, which has the largest output base. This masking is evident in the fact that the median changes in agricultural capacity are almost identical to the output-weighted average changes when Egypt is excluded.

Latin America

In another recent study coordinated by the World Bank, farm sample survey data were compiled and used to estimate Ricardian functions for the impact of climate on land value per hectare. These studies also used relatively standardized versions of equation (5.3) above. All included equations for land value per hectare. Some included equations for net revenue per hectare, and some distinguished between small- and large-farm equations.

Appendix table G.3 reports the coefficients estimated in these equations for Argentina, Brazil, Chile, and Ecuador. The equations shown there are applied to the detailed grid-level climate projection data of this study (averages of which are shown at the country level in appendix H) to estimate the percent change in land value from business as usual global warming by the 2080s. The results of this calculation are shown in the third column of table 5.5. Difficulties in interpretation of variables or data values in the source studies precluded application here of the equations estimated in this series for Colombia and Venezuela.

13. The African average net revenue per hectare in irrigated farming is about four times as high as that for dryland farming. The irrigated value shares are correspondingly higher than area shares.

Table 5.5 Impact of global warming by the 2080s on agricultural potential in major Latin American countries (without carbon fertilization), World Bank studies (percent)

Country	Implied by underlying study: Land value	Basis	Model application in present study: Land value	Average: Land value	Average: Output potential
Argentina	–17.9	A	1.4	–8.2	–4.1
Brazil	–22.0	A	2.1	–10.1	–5.0
Amazon	n.a.		–76.0	–49.0	–24.5
Northeast	n.a.		–18.0	–20.0	–10.0
South	n.a.		10.0	–6.0	–3.0
Chile	–3.6	B	–86.0	–44.8	–22.4
Colombia	–34.1	B	n.a.	–34.1	–17.0
Ecuador	–6.9	A	–100.0	–53.5	–26.8
Venezuela	–75.4	A	n.a.	–75.4	–37.7

n.a. = not available

A = average of 2060 and 2100 results in underlying study

B = application of marginal temperature and precipitation parameters in underlying study to climate change estimated in present study

Source: See text and appendix G.

The underlying studies themselves included either outright estimates of the impact of future climate change (Argentina, Brazil, Ecuador, and Venezuela) or parametric results indicating the impact that could be expected from alternative amounts of warming (2.5°C and 5°C) and change in precipitation (±10 percent; the cases of Chile and Colombia). The studies used three climate models: the Parallel Climate Model (PCM), Center for Climate System Research (CCSR), and Climate Crisis Coalition (CCC), from Washington et al. (2000), Emori et al. (1999), and Boer, Flato, and Ramsden (2000), respectively. However, they did not report the emissions scenarios assumed or the climate projections of these models.

It is possible to take account of the climate impact estimates of the studies themselves as well as the estimates obtained when applying the present study's climate estimates to the models in these studies. For the four studies reporting direct impacts (labeled "A" in table 5.5), the simple average agricultural impact estimate is taken across the three climate models and the two benchmark years 2060 and 2100 as the central estimate for 2080 comparable to the estimates of the present study. In cases where there are both small-farm and large-farm estimates, the average of both is used. In the other two studies without direct impact projections, the parametric effects of changes in temperature and precipitation are applied to the present study's estimate of climate change (table 4.2) to obtain the implied climate impact from the underlying study (cases labeled "B" in table 5.5).

The resulting estimates show relatively large divergence between the impact estimates in the underlying Latin American studies and the corresponding estimates of the present study using their models. There is no systematic direction of the difference, as the underlying studies show more severe effects than the calculations in this study for Argentina and Brazil but less severe for Chile and Ecuador. The divergences could arise because of divergent future climate estimates, differences between the large- and small-farm estimates (the models applied here are either the aggregate model or a weighted average), and differences in regional detail. In Brazil, in particular, the underlying study does not distinguish among regions, whereas the estimates here differentiate among three geographical zones.

Because of the fairly large divergences, the most prudent approach would seem to be to take a simple average of the impact estimates indicated (directly or implied) in the underlying studies and the impact estimates obtained here by applying the present study's climate projections to the Ricardian equations taken from these studies. This average estimate is shown in the next to last column of table 5.5.

Once again it is necessary to translate the percent change in land value from the models into corresponding change in output potential. Following the discussion for US estimates above, the land factor share or ratio of net revenue to value added is the fraction appropriate to apply for this purpose, with the caveat that it could understate the loss in output potential in extreme cases in which the land becomes essentially unusable. For Latin America, this ratio is set at 50 percent, intermediate between the US ratio (41 percent) and the ratio for India (67 percent) in view of the likely intermediate factor share of land at an intermediate stage of development. The final column in table 5.5 applies this fraction to arrive at the impact on potential output.

Canada

Reinsborough (2003) has prepared Ricardian estimates for the impact of climate change on agriculture in Canada. She emphasizes that this approach "presents an upper bound on the benefits of climate change" because it "assumes perfect adjustment to climate change and no costs other than change in land value" (pp. 22, 25). She estimates farmland value per hectare as a function of seasonal temperature, temperature squared, precipitation, and precipitation squared (for January, April, July, and October), as well as control variables. When she applies the estimated coefficients to a postulated climate change of 2.8°C temperature increase and 8 percent increase in precipitation, she finds a negligible change in farmland values.[14]

Preliminary subsequent work by Mendelsohn and Reinsborough (2007) confirms that there is a statistically significant difference between Ricar-

14. A total rise of only about $1 million for the whole of Canada (Reinsborough 2003, 32).

dian function estimates for Canada and those for the United States. On this basis, it would be misleading to use the default MS Ricardian estimates in appendix F for Canada. The approach adopted later will instead simply place the Canadian estimates in the Ricardian family at zero, based on the Reinsborough (2003) results. Because Russia is located in a similar latitude range as Canada, the preferred estimates developed later set climate impact effects at zero for Russia as well, because once again application of the default MS function could be seriously misleading.

It should be emphasized that if instead the default US-based MS Ricardian model estimates were used, large gains in agricultural potential from global warming would be identified for Canada and Russia (see appendix F).[15] Because the Reinsborough (2003) estimates are directly for Canada, however, they should be seen as strictly dominating the default MS estimates for that country. Note moreover that the zero-impact results in the Canadian study are much more consistent with the estimates for Canada from the Rosenzweig and Iglesias (2006) crop models, discussed later.

Sensitivity to Climate Models

The spirit of this study is to apply a "consensus" projection of the business as usual climate to the agricultural response functions to obtain a central estimate of the implications of global warming for agriculture. It is fair to ask, however, whether this approach masks an extreme degree of variability that would be found if each of the climate models were applied individually for this task. Appendix I examines the degree of dispersion of future temperature and precipitation estimates among the six climate models in the IPCC Data Distribution Centre (listed in table 4.1).

To examine the corresponding dispersion of estimates for agricultural impact, it is useful to consider the results of the standard default MS Ricardian model when applied to each of the underlying climate models separately. Table 5.6 reports these results for 30 major countries or regions to provide a sense of the range of dispersion. Each of the countries in the table is in category "a" in appendix table F.2, the category in which it is

15. The case of Russia is more ambiguous, and application of the Canadian zero-impact result to Russia (rather than the default MS model) rests on the proposition that given its latitudinal location it resembles Canadian conditions much more than those of the United States. The US-based MS Ricardian function would instead place the impact on Russia at a remarkable 152 percent rise in agricultural capacity even without carbon fertilization, and applying that estimate would boost the estimated global impact in table 5.8 by 0.86 percentage point. However, such a large contribution from Russia would surely raise questions of political economy and in particular the question of "Dutch disease." As a major energy exporter, Russia could well have such a strong exchange rate that its firms would not have much incentive to make the country a major agricultural exporter.

Table 5.6 Dispersion of Mendelsohn-Schlesinger Ricardian model estimates across climate models (without carbon fertilization) (percent change in land rental equivalent)

Country	CCSR	HadCM	GFDL	ECHAM	CSIRO	CGCM	Consensus estimate	Coefficient of variation
Angola	–100.0	–89.5	–67.5	–100.0	–63.4	–83.1	–84.1	0.42
Argentina	–20.5	–17.0	–9.8	–11.6	–15.1	–15.7	–14.8	0.57
Brazil, Southern	–100.0	–100.0	–67.1	–100.0	–86.8	–89.7	–99.2	0.32
Chile	18.7	16.8	18.2	16.8	18.2	19.7	18.2	0.14
China, Central	26.4	23.5	23.5	28.9	29.2	23.5	27.1	0.24
China, South Central	–47.3	–34.8	–22.2	–29.3	–26.2	–32.5	–31.4	0.61
Colombia	–100.0	–100.0	–100.0	–100.0	–100.0	–100.0	–100.0	0.00
Germany	31.2	28.8	28.3	32.2	26.6	24.7	30.6	0.22
Madagascar	–95.9	–77.8	–74.1	–97.0	–70.8	–80.6	–81.6	0.30
Malawi	–100.0	–100.0	–68.3	–100.0	–58.1	–76.1	–84.8	0.50
Mexico	–100.0	–80.8	–60.3	–68.9	–53.8	–52.8	–71.8	0.59
Morocco	–68.9	–32.9	–23.2	–44.5	–31.6	–35.3	–38.5	0.91
Mozambique	–100.0	–100.0	–100.0	–100.0	–100.0	–100.0	–100.0	0.00
New Zealand	6.0	10.5	11.7	11.9	10.3	11.3	10.0	0.48
Peru	–95.9	–100.0	–57.1	–86.3	–57.0	–59.8	–78.1	0.60
Poland	33.2	35.6	32.7	38.4	33.6	32.3	37.2	0.15
Portugal	–27.0	–12.4	–11.0	–23.2	–10.1	–10.2	–14.7	1.07
Romania	16.1	24.2	22.1	24.8	23.7	22.8	24.8	0.32
Russia, Caspian Black Sea	33.8	41.0	33.9	41.9	40.1	40.0	41.1	0.21
South Africa	–42.4	–39.5	–32.3	–43.5	–30.5	–39.6	–37.7	0.32
Syria	–75.1	–38.1	–26.5	–39.2	–39.3	–37.0	–41.9	0.88
Tanzania	–100.0	–100.0	–77.2	–100.0	–69.8	–77.8	–95.4	0.36
Turkey	–7.7	2.8	5.8	4.1	3.4	5.3	3.5	4.89
Uganda	–100.0	–100.0	–85.2	–99.9	–74.3	–74.7	–94.9	0.32
United Kingdom	26.9	18.4	22.8	25.4	21.1	18.5	23.4	0.35
US Lakes and Northeast	25.9	32.9	32.8	36.9	36.1	33.3	35.4	0.26
US Southeast	–64.6	–34.8	–23.9	–22.6	–31.2	–31.0	–33.3	0.99
Venezuela	–100.0	–100.0	–100.0	–100.0	–100.0	–100.0	–100.0	0.00
Zambia	–100.0	–99.9	–69.1	–100.0	–67.8	–90.5	–91.3	0.39

Note: For climate models, see table 4.1.

possible to compare the change in land rental equivalent directly against the model's prediction for the base period. The table considers the case without carbon fertilization.

It is evident in table 5.6 that there is relatively close agreement among the underlying climate models in terms of the resulting agricultural impacts estimated for each country when applied to the MS cross-section model. The US Lakes-Northeast region, for example, generates estimates lying in a relatively narrow range, from an increase in land rental equivalent of about 26 percent to an increase of about 36 percent. The next to last column, labeled "consensus," is the central estimate using the average of the six climate models.[16] The final column reports the coefficient of variation for the country.[17] The median value for the coefficient of variation is 0.34, indicating in rough terms that typically the variability of the estimates as measured by the standard deviation is some ± 17 percent of the average estimate.[18]

The central message of the experiment reported in table 5.6 is that the estimates here should be relatively robust with respect to variation among climate models. All six models tend to agree on whether the agricultural impact will be substantially positive in a particular region (e.g., Germany or Poland) or strongly negative (e.g., Colombia or Mozambique). For some countries and regions, alternative impact estimates in this study based on alternative agricultural-economic models are considerably different from those in appendix tables F.1 and F.2. The relatively close adherence of the various climate model estimates when applied to the same impact model (in the case of table 5.6, the MS Ricardian model) suggests that in estimating country-specific impacts, variability across the agricultural-economic models is more important than variability across the climate models. This diagnosis also tends to support the use of the consensus climate model approach adopted for this study and the focus on differing results from differing agricultural-economic models rather than from differing climate models.

Rosenzweig et al. Crop Model Results

Rosenzweig and Iglesias (2006) provide a query-based database that returns estimates of the impact of prospective global warming, under alter-

16. The entries in appendix table F.2 correspond to those in the final column of table 5.6 after shrinkage to take account of the ratio of net revenue to output.

17. The coefficient of variation is calculated as the square root of the sum of squared residuals of each of the six estimates from the average of the six, divided by the average (and reported in absolute value).

18. The coefficient of variation is increasingly misleading as the average value approaches zero. The high coefficient of variation for Turkey reflects this fact.

native climate scenarios and using alternative GCMs, on four major crops: wheat, rice, coarse grains (maize, barley, and others), and soybeans. The underlying research was developed in the 1990s by a team of agricultural scientists from 18 countries, who estimated compatible crop models at 125 agricultural sites using consistent climate change scenarios (see Rosenzweig et al. 1993, as discussed above; and Parry, Rosenzweig, and Livermore 2005). The process-based dynamic crop growth models incorporate the effects of change in temperature, precipitation, and solar radiation; the effect of carbon fertilization from increased atmospheric concentrations of carbon dioxide; and crop management, particularly with respect to timing of planting and extent of fertilization and irrigation. The estimates are for three levels of adaptation: 1) no adaptation; 2) level 1 (L1): shifts in planting dates by less than one month, shifts to other available varieties and crops, and increased irrigation using existing systems; and 3) level 2 (L2): more intensive adaptations involving higher costs, including change in date of planting by more than one month; installation of new irrigation systems; and development of new varieties.

The GCMs and climate scenarios in the query system include three models with results for equilibrium carbon concentrations of 555 ppm (double preindustrial levels) and two "transient" model variants for expected conditions by the 2080s. For the transient model used here (HadCM3, Hadley Centre for Climate Prediction and Research Coupled Model 3), the IS95a scenario is used, which is the same as the IS92a "business as usual" scenario in the IPCC's Second Assessment Report of 1995.[19] This scenario has a modestly lower path of rising emissions than the SRES A2 scenario in the Third Assessment Report of 2001, used for the projections in the first part of this study (see table 4.2). Thus, by 2040 fossil fuel and industrial process emissions stand at 12.66 gigatons of carbon equivalent (GtC) in IS92a and 15.01 GtC in SRES A2; by 2080 the comparison is 17.0 versus 22.97 GtC, respectively (IPCC 2001a, 801).

The equilibrium and transient models tend to generate relatively similar results at 555 ppm equilibrium and 731 ppm transient warming.[20] This is presumably because ocean thermal lag means the ultimate equilibrium warming associated with any given atmospheric concentration of carbon is greater than will be observed at the date this concentration is first attained (see Cline 1992, 92).

19. Rosenzweig and Iglesias (2006) also report results for Hadley model HadCM2. However, these results show much greater divergence from the results of the other three models used here (GISS, GFDL, and UKMO) than do the results for HadCM3. The HadCM3 results, being more representative, are thus chosen for the analysis here. (For the regions shown in table 5.7, the sum of squared residuals of percent deviation from the average estimate from the other three models is 11,414 for HadCM2 but only 3,116 for HadCM3.)

20. See the color maps on the methodology page in Rosenzweig and Iglesias (2006).

Table 5.7 reports the results compiled in the Rosenzweig-Iglesias database for the impact of global warming by the 2080s on yields of the four major grains and oilseeds, again interpreting the equilibrium 555 ppm results as proxies for realized impact by the 2080s. These estimates are all for the moderate level of adaptation (L1) and full carbon fertilization effects. Analysis of the difference between results with and without carbon fertilization indicates that the Rosenzweig-Iglesias estimates place the carbon fertilization impact at about +17 percent by the 2080s.[21] This impact is close to the 15 percent identified above as the proper target for carbon fertilization by this period on the basis of the recent free air concentration enrichment (FACE) field experiments.

Synthesis of Preferred Estimates

The two basic frameworks discussed above (Ricardian statistical models, on the one hand, and crop models on the other) provide the basis for identifying a set of preferred estimates that synthesize the alternative model results. In the first group five studies are from the same family of models and even share key authors.[22] The first of these, and the default model for this framework, is Mendelsohn and Schlesinger (1999). This set of estimates, designated source 1, comprises the cross-section estimates in appendix table F.2. As noted earlier, this model was estimated using data for the United States. Although the model provides a basis for estimation for other countries in the absence of statistical studies specific to those countries, climate responses elsewhere could be substantially different from those for the United States, and the ranges in temperature (especially) could extend beyond those included in the US database on which the models were estimated. This is especially so for the tropics and other latitudes not represented in the United States.

The second study within the first framework is the set of estimates for Africa developed in the World Bank study (Kurukulasuriya et al. 2006) and applied here with results shown in table 5.4. The third set of estimates

21. The Rosenzweig and Iglesias (2006) results are reported as percent change in yield from the base period. If we call this "a" (expressed as a proportion) for results with carbon fertilization and "b" without, the median for the ratio (1+a)/(1+b) across the regions shown in table 5.7 is 1.159 for GISS, 1.154 for GFDL, and 1.179 for UKMO (using comparisons for the L0 adaptation levels only, because results are not reported without carbon fertilization for the L1 adaptation cases for these three models). For the HadCM3 model, with L1 adaptation, this ratio has a median of 1.208. Note that these implied enhancement ratios are broadly consistent with the crop-specific ratios reported above in the summary of Rosenzweig et al. (1993).

22. Robert Mendelsohn is coauthor of three of the four studies and a project coordinator for the fourth (the World Bank project on Latin America). All of the Ricardian estimates, moreover, trace their origins to Mendelsohn, Nordhaus, and Shaw (1994).

Table 5.7 Rosenzweig-Iglesias agricultural impact estimates for the 2080s, four major grains and oilseeds (percent change in yield)

Region	HadCM3	GISS	GFDL	UKMO	Average
Africa LICX	–13	–16	–26	–21	–19.0
Africa LICM	–13	–21	–21	–26	–20.3
Africa MICX	–14	–1	4	–12	–5.8
Africa MICM	–13	–13	–13	–18	–14.3
Africa OilX	–13	–7	–12	–17	–12.3
Argentina	5	–3	–7	–10	–3.8
Australia	–7	6	6	6	2.8
Brazil, similar	–25	–12	–7	–21	–16.3
Canada	–1	24	25	2	12.5
China, similar	–2	8	2	3	2.8
Egypt, similar	–13	–17	–13	–32	–18.8
Europe	5	8	2	3	4.5
Far East Asia HMICX	–1	–24	–16	–20	–15.3
Far East Asia HMICM	0	4	2	–2	1.0
Far East Asia LI	–3	–12	–11	–23	–12.3
India	–13	–4	–13	–27	–14.3
Indonesia	–1	–14	–6	1	–5.0
Japan	–2	14	10	7	7.3
Kenya	–9	–14	–14	–14	–12.8
Latin America HICX	–27	–14	–9	–25	–18.8
Latin America HICM	–16	–15	–11	–12	–13.5
Latin America MLI	–16	–17	–8	–27	–17.0
Mexico	–17	–27	–20	–31	–23.8
Northeast Asia MLI	–16	–20	–20	–25	–20.3
Northeast Asia OilX	–16	–10	–15	–20	–15.3
New Zealand	8	29	24	14	18.8
Nigeria	–19	–6	–16	–6	–11.8
Pakistan	–18	–29	–5	–50	–25.5
Former Soviet Union, Eastern Europe	–16	16	5	–7	–0.5
Thailand	–4	–19	–8	–24	–13.8
Turkey	–12	–5	–15	–15	–11.8
United States	–5	5	–2	–13	–3.8

CM = calorie importers; CX = calorie exporters; HI = high income; HMI = high and middle income; LI = low income; MI = middle income; MLI = middle and low income; OilX = oil exporters; GFDL = Geophysical Fluid Dynamics Laboratory; GISS = Goddard Institute for Space Studies; HadCM3 = UK Hadley Centre for Climate Prediction and Research Coupled Model 3; UKMO = UK Meterological Office

Note: All estimates are for "level 1" adaptation and include full carbon fertilization effect. The four major grains are wheat, rice, maize, and soybeans.

Source: Calculated from Rosenzweig and Iglesias (2006).

in the same Ricardian family is the series of recent World Bank–supported studies on Latin America, with results of the models as applied here reported in table 5.5. The fourth source is for India, based on Mendelsohn, Dinar, and Sanghi (2001) and with results as applied here reported in table 5.2. The fifth source is the Reinsborough (2003) study for Canada, whose finding of zero impact of climate change is applied to both Canada and its latitudinal peer Russia.

In the second framework, the estimates come from a different conceptual approach, which uses crop models developed on the basis of agricultural science rather than statistical regressions across climate regions of large countries and which directly calculates the effects of reasonable levels of adaptation rather than assuming that cross-section regressions capture adaptation. The Rosenzweig-Iglesias estimates provide the sole basis for the crop model estimates for all countries except the United States. For the United States, the reduced form crop model function by Mendelsohn and Schlesinger (1999) is available as an alternative model synthesizing this school, and its estimates (table 5.1) are given equal weight with the Rosenzweig-Iglesias estimates for the United States.

The synthesis of preferred estimates then follows two alternative procedures. For those countries for which the Ricardian estimates are available from models specifically estimated for the country or region in question, the Ricardian estimates and the crop model estimates are given equal weight. This set of countries includes the United States, Canada, Africa, most of Latin America, and India. Russia is also treated in this fashion, for the reasons discussed above. This first category of preferred estimates encompasses about half of the total number of countries and 35 percent of global agricultural production.

The second alternative approach applies to those countries without specific regionally based Ricardian models, for which the default US model (MS cross-section, appendix table F.2) must be applied. Because of the potential misleading results when the US model is applied to other countries (as illustrated by the case of Canada), less weight is given to the Ricardian estimate than to the crop model estimate in these countries.[23] For these countries, the weight is set at one-third for the default MS Ricardian estimates and two-thirds for the Rosenzweig-Iglesias crop model estimates.

These are the preferred estimates for the case with no carbon fertilization. The corresponding set of estimates including carbon fertilization then simply applies a 15 percent yield increase to the estimates without

23. As discussed above, the Reinsborough (2003) Ricardian model estimated directly for Canada shows virtually zero impact of future global warming on agricultural potential as proxied by farmland value. In contrast, the MS cross-section Ricardian model for the United States shows a remarkable doubling or more of Canadian agricultural potential from future global warming (appendix table F.2).

carbon fertilization, based on the FACE studies as discussed above.[24] In practice, the preferred estimates accept the underlying Mendelsohn-Schlesinger, Mendelsohn-Dinar-Sanghi, World Bank Africa, World Bank Latin America, and Rosenzweig-Iglesias estimates for the non–carbon fertilization case but apply this study's own preferred measure of the boost from carbon fertilization rather than accepting the corresponding estimates in the underlying studies.[25]

Table 5.8 reports the results of the preferred estimates. The table first shows farm area, output per hectare, and corresponding total output for each country or region for 2003. These output estimates serve as the basis for weighting to obtain regional and global aggregates. Column D then reports the preferred framework 1 estimate in the Ricardian statistical model family, as just discussed. Column E reports the source or basis for each of these estimates. Column F shows the crop model–based estimates. For all countries but the United States, these are the Rosenzweig and Iglesias estimates from table 5.7 converted to magnitudes excluding carbon fertilization (by removing a uniform 17.5 percent boost, the average for the four climate models in the Rosenzweig-Iglesias estimates). As noted, for the United States the crop model estimates are an average of these adjusted Rosenzweig-Iglesias estimates and the MS reduced form estimates (from appendix table F.1). Column G reports the geographical grouping that is the source of the Rosenzweig-Iglesias estimate for the country in question.

Column H reports the preferred estimate for agricultural impact without carbon fertilization, following the procedure just discussed (equal weight for Ricardian and crop models where the regional or country Ricardian model is available—indicated as 1 in column I; one-third and two-thirds weight, respectively, where the general default Ricardian model must be used—indicated as 2 in column I). The corresponding preferred estimate including carbon fertilization is reported in column J. This estimate includes the effect of a uniform boost of 15 percent in yield from carbon fertilization. These two respective percentage changes in agricultural productivity are then applied to each country's base output to estimate the implied absolute change in output potential, reported in columns K and L. Aggregating these changes in potential output and comparing the

24. With a uniform yield increase, the with–carbon fertilization estimates are a strict transformation of the without–carbon fertilization estimates because the expansion factors out of the detailed calculations regardless of the level of aggregation. Thus, with q as average output per hectare (for example), and with $q = \Sigma q_i\, \varphi_i$ where φ_i is the weight applied to the disaggregated components of the aggregate in question, then the estimate q' including carbon fertilization will uniformly be 1.15 x q, because $\Sigma\, 1.15\, q_i\, \varphi_i = 1.15\, \Sigma q_i\, \varphi_i$. For its part, q expressed as an index with value of 1 for base period productivity is simply $q = 1 + d/100$ for the future period, where d is the estimate of the percent change in productivity from climate change without including carbon fertilization.

25. Note that the World Bank–sponsored studies for Africa and Latin America do not estimate carbon fertilization effects.

Table 5.8 Preferred estimates of impact of baseline global warming by the 2080s on world agriculture

				Impact without carbon fertilization				Preferred estimates			Change in output (millions of 2003 dollars)	
				Ricardian		Crop models						
Country	Farm area (1,000 hectares) (A)	Output per hectare (2003 dollars) (B)	Output (millions of 2003 dollars) (C)	Estimate (percent) (D)	Basis[a] (E)	Estimate (percent) (F)	Grouping[b] (G)	Without carbon fertilization (percent) (H)	Basis[c] (I)	With carbon fertilization (percent)[d] (J)	Without carbon fertilization (K)	With carbon fertilization (L)
Afghanistan	7,827	313	2,448	–9.5	1	–32.1	24	–24.7	2	–13.4	–604	–327
Algeria	8,459	787	6,653	–46.7	2	–25.3	5	–36.0	1	–26.4	–2,394	–1,756
Angola	3,300	360	1,187	–26.3	2	–25.3	5	–25.8	1	–14.7	–306	–174
Argentina	172,106	83	14,256	–4.1	3	–18.1	6	–11.1	1	2.2	–1,581	320
Australia	455,723	29	13,059	–55.1	1	–12.6		–26.6	2	–15.6	–3,471	–2,033
Southeast	192,824	16	3,147	–11.6	1	–12.6	7	–12.2	2	0.9	–385	29
Southwest	84,778	14	1,212	–15.3	1	–12.6	7	–13.5	2	–0.5	–163	–6
Central East	22,955	146	3,357	–45.5	1	–12.6	7	–23.4	2	–11.9	–787	–401
Central West	84,838	14	1,213	–80.9	1	–12.6	7	–35.1	2	–25.4	–426	–308
North	70,327	59	4,131	–100.0	1	–12.6	7	–41.4	2	–32.6	–1,711	–1,348
Bangladesh	8,429	1,355	11,421	–14.3	1	–25.3	15	–21.7	2	–9.9	–2,475	–1,133
Belgium	1,428	2,114	3,019	2.2	1	–11.1	12	–6.7	2	7.3	–202	220
Brazil	353,611	84	29,540	–5.1	3	–28.7		–16.9	1	–4.4	–4,976	–1,292
Amazon	41,593	29	1,215	–24.5	3	–28.7	8	–26.6	1	–15.6	–323	–190
Northeast	95,062	48	4,574	–10.0	3	–28.7	8	–19.4	1	–7.3	–886	–332
South	216,956	109	23,751	–3.0	3	–28.7	8	–15.9	1	–3.2	–3,767	–770
Burkina Faso	6,830	190	1,296	–16.5	2	–32.1	2	–24.3	1	–13.0	–315	–168
Cambodia	3,807	378	1,438	–53.5	1	–14.0	14	–27.1	2	–16.1	–389	–232
Cameroon	7,160	768	5,496	–20.3	2	–19.8	3	–20.0	1	–8.0	–1,100	–441
Canada	67,504	254	17,146	0.0	5	–4.3		–2.2	1	12.5	–364	2,150
Arctic	0	0	0	0.0	5	–4.3	9	–2.1	1	12.6	0	0
Central	44,401	254	11,268	0.0	5	–4.3	9	–2.1	1	12.6	–240	1,414
Northwest Territories	0	0	0	0.0	5	–4.3	9	–2.1	1	12.6	0	0
Pacific Coast	13,121	254	3,330	0.0	5	–4.3	9	–2.1	1	12.6	–71	418
Southeast	9,980	254	2,533	0.0	5	–4.3	9	–2.1	1	12.6	–54	318

(table continues next page)

Table 5.8 Preferred estimates of impact of baseline global warming by the 2080s on world agriculture *(continued)*

				Impact without carbon fertilization				Preferred estimates			Change in output (millions of 2003 dollars)	
				Ricardian		Crop models						
Country	Farm area (1,000 hectares) (A)	Output per hectare (2003 dollars) (B)	Output (millions of 2003 dollars) (C)	Estimate (percent) (D)	Basis[a] (E)	Estimate (percent) (F)	Grouping[b] (G)	Without carbon fertilization (percent) (H)	Basis[c] (I)	With carbon fertilization (percent)[d] (J)	Without carbon fertilization (K)	With carbon fertilization (L)
Central America	7,624	1,429	10,892	–12.3	1	–29.4	22	–23.7	2	–12.3	–2,586	–1,340
Central Europe	11,563	1,150	13,294	7.3	1	–11.1	12	–5.0	2	9.3	–664	1,231
Chile	26,502	246	6,517	–22.4	3	–26.4	21	–24.4	1	–13.1	–1,590	–851
China	153,956	1,381	212,550	3.8	1	–12.6		–7.2	2	6.8	–15,340	14,241
Beijing Northeast	38,907	1,040	40,480	22.1	1	–12.6	10	–1.1	2	13.7	–457	5,547
Central	31,600	845	26,702	16.3	1	–12.6	10	–3.0	2	11.5	–811	3,073
Hong Kong Southeast	13,599	2,829	38,471	–3.8	1	–12.6	10	–9.7	2	3.9	–3,722	1,491
Northwest	9,436	774	7,308	17.2	1	–12.6	10	–2.7	2	11.9	–199	868
South Central	19,250	997	19,197	–18.8	1	–12.6	10	–14.6	2	–1.8	–2,808	–349
Tibetan Plateau	1,226	788	966	39.9	1	–12.6	10	4.8	2	20.5	46	198
Yellow Sea	39,938	1,989	79,426	–2.7	1	–12.6	10	–9.3	2	4.3	–7,390	3,415
Colombia	50,706	186	9,438	–17.0	3	–29.4	22	–23.2	1	–11.7	–2,188	–1,100
Cuba	3,788	285	1,078	–56.3	1	–30.9	20	–39.3	2	–30.2	–423	–325
Democratic Republic of the Congo	7,800	422	3,289	–4.1	2	–25.3	5	–14.7	1	–1.9	–484	–64
Ecuador	12,356	176	2,176	–26.8	3	–30.9	20	–28.8	1	–18.1	–627	–394
Egypt	3,751	3,516	13,188	53.5	2	–30.9	11	11.3	1	28.0	1,494	3,696
Ethiopia	11,047	253	2,794	–31.4	2	–31.1	1	–31.3	1	–20.9	–873	–585
France	29,898	1,176	35,152	2.3	1	–11.1	12	–6.7	2	7.3	–2,339	2,583
Germany	19,098	881	16,822	13.8	1	–11.1	12	–2.9	2	11.7	–483	1,967
Ghana	6,331	434	2,745	–8.2	2	–19.8	3	–14.0	1	–1.1	–384	–30
Greece	3,875	2,400	9,299	–1.2	1	–11.1	12	–7.8	2	6.0	–726	560

India	170,115	777	132,140	−49.2	4	−27.0		−38.1	1	−28.8	−50,391	−38,129
Northeast	64,870	777	50,389	−60.9	4	−27.0	16	−43.9	1	−35.5	−22,143	−17,906
Northwest	37,528	777	29,151	−57.9	4	−27.0	16	−42.5	1	−33.8	−12,382	−9,867
Southeast	42,767	777	33,220	−31.3	4	−27.0	16	−29.1	1	−18.5	−9,682	−6,151
Southwest	24,950	777	19,381	−36.8	4	−27.0	16	−31.9	1	−21.7	−6,184	−4,205
Indonesia	33,700	1,051	35,413	−15.3	1	−19.1	17	−17.9	2	−5.6	−6,330	−1,967
Iran	17,088	883	15,086	−30.9	1	−27.9	25	−28.9	2	−18.2	−4,356	−2,746
Iraq	4,591	370	1,697	−67.8	1	−27.9	25	−41.1	2	−32.2	−697	−547
Italy	19,607	1,648	32,303	0.1	1	−11.1	12	−7.4	2	6.5	−2,387	2,101
Ivory Coast	6,900	518	3,571	−8.8	2	−19.8	3	−14.3	1	−1.5	−511	−52
Japan	4,762	9,032	43,009	0.4	1	−8.7	18	−5.7	2	8.4	−2,464	3,618
Kazakhstan	21,671	110	2,380	65.6	1	−15.3	29	11.4	2	28.1	271	669
Kenya	5,162	446	2,300	15.0	2	−25.7	19	−5.4	1	8.8	−123	203
Madagascar	3,550	447	1,587	−20.3	2	−32.1	2	−26.2	1	−15.1	−416	−240
Malawi	2,440	267	651	−31.5	2	−31.1	1	−31.3	1	−21.0	−204	−137
Malaysia	7,585	1,368	10,374	−11.6	1	−27.9	13	−22.5	2	−10.9	−2,336	−1,130
Mali	4,700	350	1,644	−39.0	2	−32.1	2	−35.6	1	−25.9	−585	−426
Mexico	183,839	136	25,043	−35.9	1	−35.1	23	−35.4	2	−25.7	−8,856	−6,428
Morocco	9,283	801	7,434	−51.0	2	−27.0	4	−39.0	1	−29.9	−2,899	−2,219
Mozambique	4,435	253	1,123	−23.6	2	−19.8	3	−21.7	1	−10.0	−244	−112
Myanmar	10,611	386	4,095	−67.5	1	−25.3	15	−39.3	2	−30.1	−1,607	−1,234
Nepal	3,294	728	2,399	−0.9	1	−25.3	15	−17.3	2	−4.8	−414	−116
Netherlands	2,239	4,568	10,230	1.2	1	−11.1	12	−7.0	2	6.9	−719	708
New Zealand	15,640	254	3,979	4.5	1	1.1	26	2.2	2	17.5	87	697
Niger	4,500	243	1,092	−36.1	2	−32.1	2	−34.1	1	−24.2	−373	−265
Nigeria	33,000	460	15,181	−12.1	2	−24.9	27	−18.5	1	−6.3	−2,809	−953
North Korea	2,700	2,222	6,000	6.3	1	−14.0	14	−7.3	2	6.6	−440	394
Other Central Asia	4,383	605	2,652	13.3	1	−15.3	29	−5.9	2	8.2	−156	218
Other Equatorial Africa	2,989	478	1,429	−94.8	2	−25.3	5	−60.1	1	−54.1	−859	−773
Other Horn of Africa	1	20,118	20	−1.1	2	−32.1	2	−16.6	1	−4.1	−3	−1

(table continues next page)

Table 5.8 Preferred estimates of impact of baseline global warming by the 2080s on world agriculture *(continued)*

				Impact without carbon fertilization				Preferred estimates			Change in output (millions of 2003 dollars)	
				Ricardian		Crop models						
Country	Farm area (1,000 hectares) (A)	Output per hectare (2003 dollars) (B)	Output (millions of 2003 dollars) (C)	Estimate (percent) (D)	Basis[a] (E)	Estimate (percent) (F)	Grouping[b] (G)	Without carbon fertilization (percent) (H)	Basis[c] (I)	With carbon fertilization (percent)[d] (J)	Without carbon fertilization (K)	With carbon fertilization (L)
Other South America	23,818	118	2,808	–70.7	1	–29.4	22	–43.0	2	–34.4	–1,207	–967
Other Southern Africa	14,066	44	620	–66.7	2	–27.0	4	–46.9	1	–38.9	–291	–241
Other West Africa	4,372	419	1,833	–33.2	2	–32.1	2	–32.7	1	–22.6	–599	–414
Pakistan	22,120	856	18,935	–17.9	1	–36.6	28	–30.4	2	–20.0	–5,762	–3,786
Peru	35,382	171	6,058	–39.1	1	–26.4	21	–30.6	2	–20.2	–1,852	–1,221
Philippines	10,700	1,054	11,280	–14.3	1	–27.9	13	–23.4	2	–11.9	–2,639	–1,342
Poland	19,325	239	4,610	16.7	1	–15.3	29	–4.7	2	9.5	–219	440
Portugal	5,189	713	3,697	–6.6	1	–11.1	12	–9.6	2	4.0	–355	147
Romania	13,940	490	6,834	11.2	1	–15.3	29	–6.6	2	7.4	–450	508
Russia	250,182	87	21,643	0.0	5	–15.3		–7.7	1	6.2	–1,658	1,340
Caspian Black Sea	49,157	87	4,252	0.0	5	–15.3	29	–7.7	1	6.2	–326	263
Far Eastern	11,868	87	1,027	0.0	5	–15.3	29	–7.7	1	6.2	–79	64
North European	46,332	87	4,008	0.0	5	–15.3	29	–7.7	1	6.2	–307	248
North Urals Siberia	11,230	87	971	0.0	5	–15.3	29	–7.7	1	6.2	–74	60
Northeast Siberia	12,742	87	1,102	0.0	5	–15.3	29	–7.7	1	6.2	–84	68
South Urals Siberia	61,495	87	5,320	0.0	5	–15.3	29	–7.7	1	6.2	–407	329
Southeast Siberia	57,358	87	4,962	0.0	5	–15.3	29	–7.7	1	6.2	–380	307
Saudi Arabia	4,046	2,654	10,737	–9.8	1	–27.9	25	–21.9	2	–10.2	–2,351	–1,093
Scandinavia	22,742	397	9,027	55.4	1	–11.1	12	10.9	2	27.5	981	2,483
Senegal	2,506	441	1,104	–84.0	2	–19.8	3	–51.9	1	–44.7	–573	–493
South Africa	15,712	407	6,395	–47.0	2	–19.8	3	–33.4	1	–23.4	–2,134	–1,495
South Korea	1,877	8,707	16,344	0.2	1	–14.0	14	–9.3	2	4.3	–1,525	698
Southeast Europe	13,243	949	12,566	5.0	1	–15.3	29	–8.6	2	5.1	–1,084	638
Spain	42,181	716	30,191	–4.5	1	–11.1	12	–8.9	2	4.8	–2,691	1,434

Sri Lanka	1,916	1,808	3,465	–9.5	1	–25.3	15	–20.1	2	–8.1	–697	–282
Sudan	16,653	417	6,939	–81.1	2	–31.1	1	–56.1	1	–49.5	–3,892	–3,435
Syria	5,421	912	4,945	–25.2	1	–27.9	25	–27.0	2	–16.0	–1,334	–792
Tanzania	10,764	430	4,634	–16.3	2	–32.1	2	–24.2	1	–12.8	–1,122	–595
Thailand	19,367	738	14,295	–25.3	1	–26.6	30	–26.2	2	–15.1	–3,739	–2,156
Turkey	28,523	935	26,682	1.6	1	–24.9	31	–16.2	2	–3.6	–4,312	–956
Uganda	7,200	280	2,015	–2.5	2	–31.1	1	–16.8	1	–4.3	–338	–86
Ukraine	33,457	207	6,935	15.3	1	–15.3	29	–5.2	2	9.0	–361	625
United Kingdom	16,528	760	12,564	10.5	1	–11.1	12	–3.9	2	10.5	–495	1,315
United States	379,343	260	98,537	4.7	1	–16.5		–5.9	1	8	–5,791	8,120
Alaska	365	62	23	0.0	1	–9.0	e	–4.5	1	10	–1	2
Lakes, Northeast	74,276	411	30,515	14.5	1	–4.5	e	5.0	1	21	1,526	6,332
Pacific Northwest	13,117	320	4,198	16.6	1	3.2	e	9.9	1	26	417	1,109
Rockies, Plains	113,276	133	15,077	27.0	1	28.3	e	27.6	1	47	4,164	7,050
Southeast	58,046	383	22,214	–13.7	1	–43.0	e	–28.3	1	–18	–6,294	–3,906
South Pacific Coast	11,170	1,135	12,673	0.0	1	–11.9	e	–5.9	1	8	–752	1,036
Southwest Plains	109,094	127	13,836	–11.1	1	–59.0	e	–35.1	1	–25	–4,851	–3,503
Uzbekistan	4,827	721	3,482	–5.5	1	–15.3	29	–12.1	2	1	–421	38
Venezuela	30,071	114	3,416	–37.5	3	–26.4	21	–31.9	1	–22	–1,091	–742
Vietnam	8,895	969	8,616	–17.2	1	–14.0	14	–15.1	2	–2	–1,300	–202
Yemen	1,669	973	1,625	–20.2	1	–32.1	24	–28.2	2	–17	–458	–283
Zambia	5,289	189	997	–47.1	2	–32.1	2	–39.6	1	–31	–395	–305
Zimbabwe	3,350	901	3,018	–44.7	2	–31.1	1	–37.9	1	–29	–1,144	–863
World	3,097,935	380	1,175,860	–10.1		–18.9		–15.9		–3.2	–186,510	–38,107
median				–9.8		–19.8		–16.7		–4.2		

a. 1= on the basis of Mendelsohn-Schlesinger (appendix table F.2); 2 = World Bank Africa (table 5.4); 3 = World Bank Latin America (table 5.5); 4 = Mendelsohn-Dinar-Sanghi India (table 5.2); 5 = Reinsborough (2003); see text.

b. Number refers to grouping in table 5.7.

c. 1 = average, Ricardian and crop model; 2 = 1/3 weight Ricardian, 2/3 weight crop model.

d. Equals without–carbon fertilization estimate adjusted for 15 percent yield increase.

e. Equals average between Mendelsohn-Schlesinger (appendix table F.1) and Rosenzweig-Iglesias (table 5.7) adjusted for non–carbon fertilization.

results with aggregated base output provides the basis for obtaining the percent change in agricultural potential at the global (table 5.8) and regional levels (discussed later). As discussed in chapter 3, these output effects represent direct supply impact before taking into account induced effects from price changes and from adjustments in international trade.

The global result in the preferred estimates is that business as usual climate change by the 2080s would reduce world agricultural production capacity by about 16 percent if carbon fertilization is omitted and by about 3 percent if it is included. A 16 percent reduction would be severe and would potentially cause major price increases because of the inelasticity of demand for food. These price increases would need to be taken into account in estimating resulting global welfare losses.

Even if the moderate global reduction of 3 percent assuming carbon fertilization were the outcome, the large disparity of results across countries would mean much more serious losses for many countries and regions. Generally, the developing countries would tend to fare much worse than the industrial countries, as examined later.

There are 21 countries, regions, or subzones of large countries in which production capacity falls by more than one-third without carbon fertilization and 7 in which it does so even with carbon fertilization. If the threshold is set at a loss of 20 percent or greater, there are 53 countries and regions with severe losses without carbon fertilization and 29 even with carbon fertilization.

For the United States, there would be moderate results overall but sharp disparities among regions. Without carbon fertilization, there would be a loss of 5.9 percent for the United States, but this outcome masks dispersion between gains as high as 28 percent in the Rockies and Plains and losses in the range of 30 percent in the Southeast and Southwest Plains.[26] For the US results including carbon fertilization, the corresponding estimates are an overall average gain of 8 percent, with impacts as favorable as +47 percent in the Rockies and Plains but as unfavorable as –18 percent in the Southeast and –25 percent in the Southwest Plains.

India would face a major loss on the order of 30 percent even with carbon fertilization. The loss would be about 35 percent in the Northeast and Northwest. In the key case of China, the aggregate gains would be about 7 percent assuming carbon fertilization but losses of 7 percent if carbon fertilization failed to materialize. Moreover, in the case without carbon fertilization, losses would be as high as 15 percent in the South Central region, which accounts for about 140 million people (appendix E and ERS 2006a).

---

26. The Rockies-Plains gains are probably overstated, moreover, by using land area rather than output value to aggregate from the standard grid level up to the region. This would tend to give substantial weight to supposed gains from warming in the cold mountainous areas even though their topography constrains agricultural potential.

Figures 5.2 and 5.3 portray the preferred results graphically. The substantially more favorable results when carbon fertilization is included (figure 5.3) are evident in most regions. These maps also underscore the concentration of damage in the latitudes closer to the equator and of gains in latitudes closer to the poles. With the exception of New Zealand, the Southern Hemisphere is nearly uniform in experiencing losses, reflecting the paucity of land masses in the latitudes south of about 35°S. Losses are also predominant in the Northern Hemisphere below about 35°N, but a much smaller fraction of total land area lies between the equator and 35°N than in the corresponding zone in the Southern Hemisphere.

The underlying components shown in table 5.8 for the preferred estimates provide a basis for a broad comparison between results from the Ricardian family and those from the crop model family. As discussed above, only those countries or regions with specific Ricardian function estimates are given full equal weight to the crop model estimates, so it is most useful to limit the comparison to these countries and regions (indicated by 1 for the basis for the preferred estimates in column I of table 5.8).

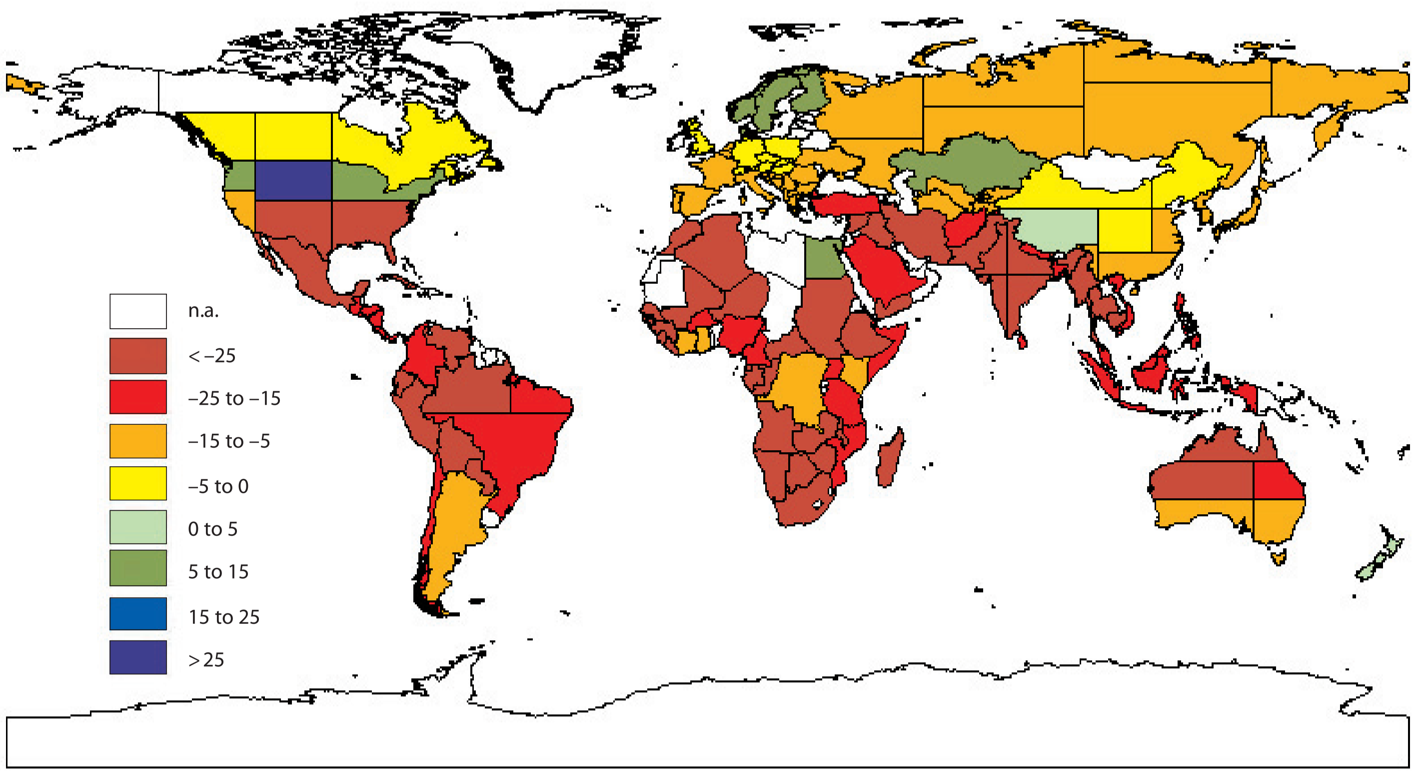
Figure 5.4 plots the percent change in agricultural potential (without carbon fertilization) for the 47 regions for which a regionally or country-specific Ricardian estimate exists, showing the Ricardian estimate on the vertical axis and the crop model (Rosenzweig-Iglesias for all but the United States) estimate on the horizontal axis. The scale of the two axes immediately confirms one major pattern: The crop model results show considerably less dispersion than the Ricardian results. The wider dispersion of the Ricardian estimates is confirmed by their standard deviation, which is 28 percentage points versus 12.1 percent for the crop model estimates. One underlying reason seems to be that the Rosenzweig-Iglesias crop model findings tend to be linear with regard to the magnitude of climate change, whereas at least the models in the Ricardian family are nonlinear.[27]

The pattern of the scatter diagram indicates that there is a reasonable degree of agreement between the two sets.[28] Given the figure scale, complete agreement would place all observations along the 17.5° line. The agreement is far from complete. Nonetheless there is a clear upward slope in the scatter, meaning that high estimates in one set are also high in the other, and the large negative estimates in one set also tend to be large negative estimates in the other. The two sets of estimates yield comparable

27. Thus, Parry, Rosenzweig, and Livermore (2005, 2136) state that: "Without the counteracting direct CO_2 effects, crop production responds approximately linearly to temperature increases across the suite of scenarios."

28. The simple correlation coefficient between the two sets of estimates is 0.38. A regression of the Ricardian estimates on the crop model estimates yields a statistically significant coefficient of 0.73 (t-statistic of 2.3). Note that the observation of greatest disagreement is that for Egypt, with 53 percent gain in the Ricardian estimate but 31 percent loss in the crop model estimates.

Figure 5.2 Impact on agricultural productivity without carbon fertilization (percent)



Note: In both maps, n.a. refers to "not applicable" for Alaska, Northern Canada, and Antarctica and "not available" otherwise.

Figure 5.3 Impact on agricultural productivity with carbon fertilization (percent)

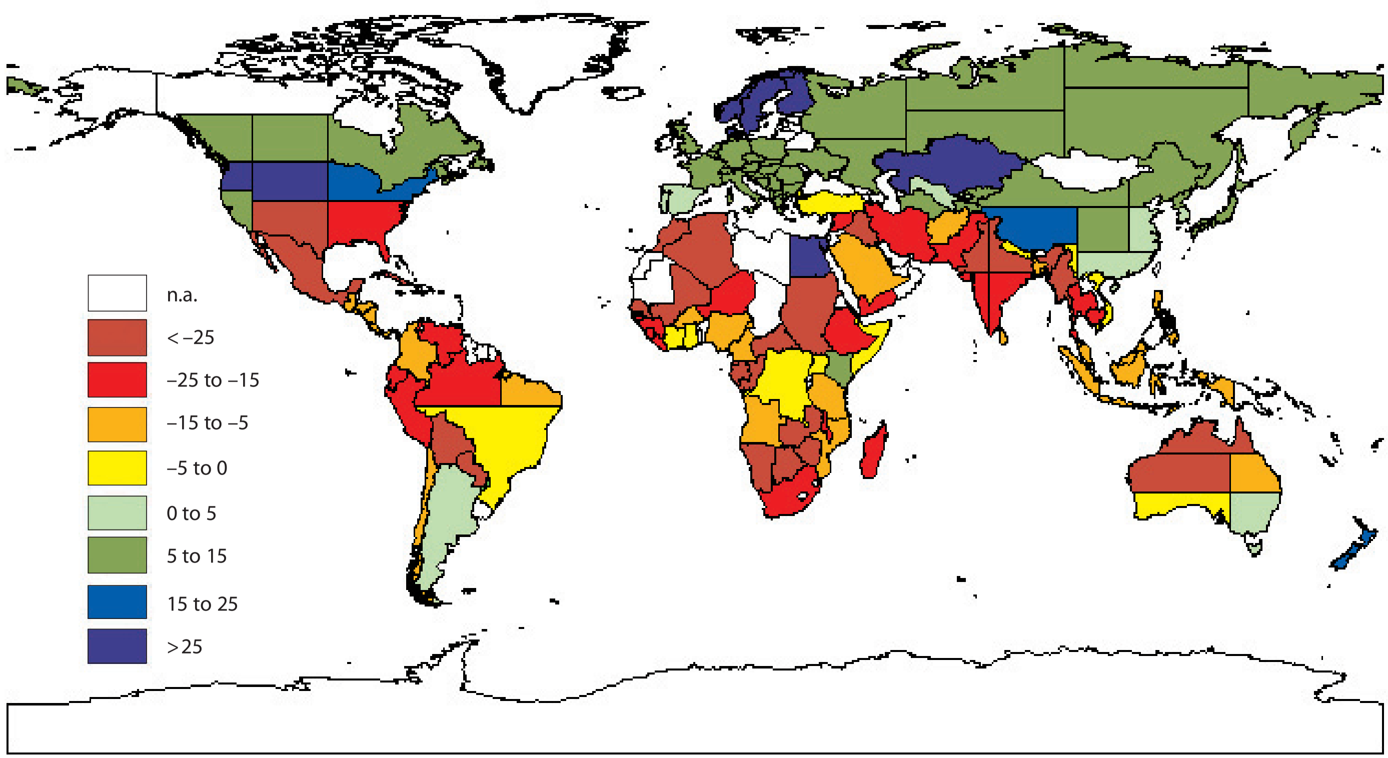
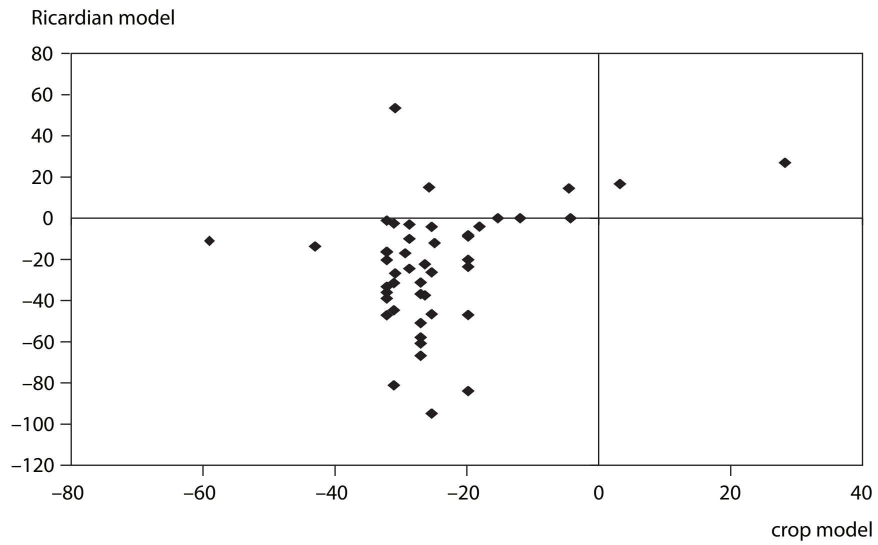


Figure 5.4 Percent change in agricultural capacity by the 2080s in 47 countries and regions (without carbon fertilization)



central results, although the Ricardian estimates show modestly milder effects than the crop model results. The median impact for the Ricardian estimates is –21.3 percent; that for the crop models is –27 percent. The corresponding average impacts are –23.4 and –25 percent, respectively.

Broadly, then, for the subset of countries and regions for which the Ricardian estimates are based on data for the countries in question, the two sets of underlying estimates tend to show similar patterns, with the median and average Ricardian losses only modestly smaller than those of the crop model estimates. The greater difference is that in crop model estimates the disparities between the winners and losers would not be as extreme as in the Ricardian estimates. The two approaches show wider divergence in the averages once the full set of countries is considered, after including those for which the Ricardian estimates must be based on the default US parameters (appendix table F.2). This conclusion is evident in table 5.8, which shows that the global output-weighted impact is an average of –10 percent for the Ricardian estimates versus –18.9 percent for the crop model estimates, and the two respective global medians are –9.8 and –19.8 percent. The implication is that the subset of less reliable (default-based) Ricardian estimates tends to understate global losses. For example, the large positive estimates in this subset may be an overstatement of gains, such as those for Kazakhstan (66 percent) and Scandinavia (55 percent).

Table 5.9 restates the preferred results in terms of aggregates for the Rosenzweig-Iglesias regions. This grouping of estimates facilitates comparison of the framework 1 Ricardian estimates against the framework 2

Table 5.9 Change in agricultural capacity by regional aggregates (percent)

Region[b]	Without carbon fertilization: Ricardian	Without carbon fertilization: Crop model	Without carbon fertilization: Preferred	With carbon fertilization[a]: Ricardian	With carbon fertilization[a]: Crop model	With carbon fertilization[a]: Preferred
Africa LICX	–52.6	–31.1	–41.8	–45.5	–20.7	–33.1
Africa LICM	–26.1	–32.1	–29.1	–15.0	–21.9	–18.4
Africa MICX	–28.3	–19.8	–24.2	–17.5	–7.8	–12.8
Africa MICM	–52.2	–27.0	–39.6	–45.0	–16.1	–30.5
Africa OilX	–28.4	–25.3	–32.2	–17.7	–14.1	–22.0
Argentina	–4.1	–18.1	–11.1	10.3	–5.8	2.2
Australia	–55.1	–12.6	–26.6	–48.3	0.6	–15.6
Brazil, similar	–5.0	–28.7	–16.8	9.3	–18.0	–4.4
Canada	0.0	–4.3	–2.1	15.0	10.1	12.6
China, similar	3.6	–12.6	–7.2	19.2	0.6	6.7
Egypt, similar	53.5	–30.9	11.3	76.5	–20.5	28.0
Europe	5.1	–11.1	–5.7	20.8	2.3	8.4
Far East Asia HMICX	–13.0	–27.9	–23.0	0.0	–17.1	–11.4
Far East Asia HMICM	–5.7	–14.0	–11.3	8.5	–1.1	2.0
Far East Asia LI	–22.2	–25.3	–24.3	–10.5	–14.1	–12.9
India	–49.2	–27.0	–38.1	–41.6	–16.1	–28.9
Indonesia	–15.3	–19.1	–17.9	–2.6	–7.0	–5.6
Japan	0.4	–8.7	–5.7	15.4	5.0	8.4
Kenya	15.0	–25.7	–5.4	32.3	–14.6	8.8
Latin America HICX	–36.6	–30.9	–32.3	–27.0	–20.5	–22.1
Latin America HICM	–31.9	–26.4	–28.3	–21.7	–15.3	–17.6
Latin America MLI	–21.3	–29.4	–25.8	–9.5	–18.8	–14.7
Mexico	–35.9	–35.1	–35.4	–26.3	–25.4	–25.7
Northeast Asia MLI	–13.8	–32.1	–26.1	–0.9	–21.9	–15.0
Northeast Asia OilX	–25.0	–27.9	–26.9	–13.7	–17.1	–15.9
New Zealand	4.5	1.1	2.2	20.2	16.2	17.5
Nigeria	–12.1	–24.9	–18.5	1.1	–13.6	–6.3
Pakistan	–17.9	–36.6	–30.4	–5.6	–27.1	–20.0
Former Soviet Union, Eastern Europe	8.1	–15.3	–6.7	24.3	–2.6	7.3
Thailand	–25.3	–26.6	–26.2	–14.1	–15.6	–15.1
Turkey	1.6	–24.9	–16.2	16.8	–13.6	–3.6
United States	4.7	–16.5	–5.9	20.4	–3.9	8.2
World						
Median of regions	–14.5	–25.5	–23.6	–1.7	–14.4	–12.1
Total	–10.0	–18.9	–15.9	3.5	–6.8	–3.2
Developing countries						
Median of regions	–21.3	–27.0	–25.8	–9.5	–16.1	–14.7
Total	–16.9	–22.5	–21.0	–4.5	–10.8	–9.2
Industrial countries						
Median of regions	2.4	–9.9	–5.7	17.8	3.6	8.4
Total	1.9	–11.9	–6.3	17.2	1.3	7.8
Economies in transition (former Soviet Union, Eastern Europe)	8.1	–15.3	–6.7	24.3	–2.6	7.3

a. Equals without carbon fertilization result plus effect of uniform 15 percent yield increase.
b. See table 5.7.

Source: Table 5.8.

crop model estimates. The table shows them individually along with the preferred regional estimates.

Several important findings are evident in table 5.9. First, at the global level and weighting by base output, the two sets of underlying estimates once again tend to show more severe effects in the crop model estimates than in the Ricardian estimates. In the case without carbon fertilization, global output capacity would fall by about 10 percent in the Ricardian model–based estimates and about 19 percent in the crop model estimates (the same as in table 5.8). The corresponding median changes show a somewhat wider divergence as well as larger damages for both, at about –15 and –26 percent, respectively. In the results including carbon fertilization, the differences persist, with a global average gain of 4 percent for the Ricardian models but a loss of 7 percent for the crop model estimates and corresponding median impacts across the various regions at –2 and –14 percent, respectively.

Second, once again there is less dispersion between severe negative effects and large positive effects in the crop model results than in the Ricardian results. In the groupings of table 5.9 the simple average impact for the worst quintile (6 groupings) is –44 percent for the Ricardian estimates (without carbon fertilization) versus –33 percent for the crop model estimates. Conversely, the most favorable quintile of results shows an average of +15 percent for the Ricardian estimates but –8 percent for the crop model estimates.

Third, in both sets of results most countries and regions would experience larger losses than would be seen if attention focused solely on global aggregates, as indicated by the differences between the average and median estimates already noted. For the 32 regions, in the Ricardian-based estimates the median losses are about 50 percent larger than the global average in the case without carbon fertilization. With carbon fertilization there are losses for the median region (1.7 percent) but a slight gain for the global aggregate (3.5 percent). The median losses are also higher than the global averages in the crop model estimates but to a lesser degree (multiples of 1.35 and 2 for the without and with carbon fertilization cases, respectively), reflecting the previous point about dispersion of results in the two sources.

Fourth, and in this same vein, both sets of estimates confirm that developing countries would fare substantially worse than industrial countries. In the case including carbon fertilization, for developing countries the median change in productive potential is a decline of about 16 (crop model) to 10 percent (Ricardian). In contrast, for industrial countries, the corresponding medians show an increase of about 4 (crop model) to 18 percent (Ricardian).

Finally, the detailed preferred results of table 5.8 can be aggregated into an alternative grouping of developing and industrial countries based on more usual geographical regions than in the Rosenzweig-Iglesias analysis in order to consider further the differences in impact between the two sets

Table 5.10 Agricultural impact by major regions: Developing and industrial countries

Country/region	Base output (billions of 2003 dollars)	Population (millions)	Change in agricultural output potential preferred estimates (percent): Without carbon fertilization	With carbon fertilization
Developing countries	838	5,202	–19.7	–7.7
Excluding Europe	745	4,807	–21.0	–9.1
Africa	73	660	–27.5	–16.6
Nigeria	15	136	–18.5	–6.3
South Africa	6	46	–33.4	–23.4
Asia	500	3,362	–19.3	–7.2
China	213	1,288	–7.2	6.8
India	132	1,064	–38.1	–28.8
Indonesia	35	215	–17.9	–5.6
Middle East North Africa	61	280	–21.2	–9.4
Algeria	7	32	–36.0	–26.4
Egypt	13	68	11.3	28.0
Iran	15	66	–28.9	–18.2
Latin America	111	506	–24.3	–12.9
Argentina	14	37	–11.1	2.2
Brazil	30	177	–16.9	–4.4
Mexico	25	102	–35.4	–25.7
Europe	93	395	–9.4	4.1
Poland	5	38	–4.7	9.5
Russia	22	143	–7.7	6.2
Turkey	27	71	–16.2	–3.6
Industrial countries	338	846	–6.3	7.7
Australia	13	20	–26.6	–15.6
Canada	17	32	–2.2	12.5
Germany	17	83	–2.9	11.7
United Kingdom	13	59	–3.9	10.5
United States	99	291	–5.9	8.2
World	1,176	6,049	–15.9	–3.2
Population-weighted			–18.2	–6.0

Source: Table 5.8.

of countries. In addition, it is possible to obtain overall weighted results using population weights to examine how the implications differ from global averages weighting by agricultural production. Table 5.10 presents these alternative aggregations.

At the most aggregate level, the comparison between narrowly defined developing countries and industrial countries is the same in tables 5.9 and 5.10. Namely, including carbon fertilization, output-weighted agricultural potential rises for industrial countries by a preferred estimate of 7.7 percent, whereas for developing countries defined as excluding developing Europe it falls by 9.1 percent. The additional regional information in table 5.10 shows that in the preferred estimate (and including carbon fertilization), output potential falls by about 17 percent in Africa excluding North Africa, by 7 percent in Asia, 9 percent in the Middle East and North Africa, and 13 percent in Latin America. In contrast, for developing Europe it rises by 4 percent, the same broad range as the 7 percent in table 5.9 for the former Soviet Union and Eastern Europe.[29]

These results indicate that Africa (excluding Egypt and other North Africa) and Latin America are the two developing regions most vulnerable to global warming. This finding is consistent with the IPCC (1996) pattern noted in the survey above. Asia on average is less vulnerable, but this masks the divergence between more favorable results for China in particular and more unfavorable results for India, reflecting in part the difference in their latitudes.

At the world level the aggregates are again the same as in tables 5.8 and 5.9. Weighting by output, global agricultural potential falls by about 16 percent without carbon fertilization and 3 percent with carbon fertilization. Table 5.10 also reports the global impact weighting by population rather than output. In this case, output potential falls by a weighted average of 18 percent without carbon fertilization and by about 6 percent with carbon fertilization. The greater decline in output potential weighting by population reflects the predominance of more severe adverse effects in developing countries in contrast to milder losses or even gains in industrial countries.

Comparison to Estimates in the Model-Source Studies

The analysis above has applied models developed by other authors to detailed future climate data as calculated in this study to obtain estimates of the impact of global warming on agricultural potential. The authors of these models have in some cases provided their own estimates of global warming impact, so it is important to compare their results with those here.

29. Developing Europe in table 6.1 shares Russia, Poland, Romania, Southeastern Europe, and Ukraine with former Soviet Union and Eastern Europe in table 5.10. It adds Turkey and Central Europe but drops Kazakhstan, Uzbekistan, and other Central Asia, which are reallocated to Asia.

Mendelsohn, Morrison, Schlesinger, and Andronova

The Mendelsohn and Schlesinger (1999) models used in appendix tables F.1 and F.2 were not used by their authors to calculate the impact of global warming on world agriculture, but a subsequent study by Mendelsohn, Morrison, Schlesinger, and Andronova (MMSA; 2000) made such estimates. The models in MMSA are almost identical to the reduced form and cross-section models in Mendelsohn and Schlesinger (1999). The only substantial difference is that in the cross-section model the MMSA coefficient for carbon fertilization is 43 percent larger than the corresponding coefficient in the MS version (equation 5.2 above). With the benefit of hindsight in view of the recent FACE agronomic results, this increase appears to have been ill-advised.

Applying their models, MMSA arrive at a very benign prognosis of the impact of global warming by 2100 for the world as a whole.[30] They state:

> The aggregate impacts are projected to be beneficial in every scenario relative to the current climate and carbon dioxide levels. . . . With the Ricardian model, benefits climb for the first 2°C of warming and then they decline. . . . With the reduced-form model, warming benefits climb through 1°C and then just begin to decline at 2°C. Warming begins to be harmful between 1 and 2°C. The overall magnitude of the market impacts [including forestry, coastal resources, energy, and water] is small in all cases, being less than 0.16% of world GDP. Thus, these initial results imply that global warming over the next century is not a serious threat to the world economy, and is likely to be a small benefit (Mendelsohn, Morrison, Schlesinger, and Andronova 2000, 560).

MMSA find small global net losses in the other market sectors they include, and their conclusion just cited is entirely attributable to their estimate that there would be global gains from agriculture, amounting to $297 billion at 1990 prices in the cross-section model and $171 billion in the reduced form model, against a global economy of $172 trillion by 2100 in the central case. Chapter 6 of this study suggests that by 2085 global agricultural demand is likely to expand by a multiple in the range of 2.7 to 3.7 times the 2005 level. With world agricultural output at about $1.2 trillion in 2003 (appendix E), by 2085 world agricultural output would be on the order of $3.8 trillion. The potential gain from global warming of about $300 billion estimated by MMSA in their Ricardian model would

30. It should be noted that nowhere in their study do MMSA report the paradox encountered in the present study when applying both the reduced form and cross-section models: A high incidence of negative base period agricultural productivity is calculated when these US-based models are applied to the temperature and precipitation averages for other countries. Correspondingly, they do not report how they address this problem or whether they use the approach applied here of considering the change in output per hectare from climate change against an estimate of base period actual productivity, even where the predicted base level is negative.

thus represent a favorable impact of 8 percent of world agricultural output potential.

The results in the present study using the same underlying MS models are much less favorable (appendix tables F.1 and F.2). Thus, even including the MS carbon fertilization estimates, their reduced form model is estimated here to generate a global loss of 13 percent in agricultural potential, rather than a sizable gain. One key source of the difference is that the climate model MMSA use (University of Illinois) generates 2°C mean global warming by 2100, whereas the suite of climate models used for the present study places mean global warming at 3°C by the 2080s. Because their models find improvement at up to 1 to 2°C warming, it is no coincidence that using 2°C mean warming does not show damage and in fact shows small gains.[31] The other likely source of the difference in aggregate results is from carbon fertilization. The MMSA version of the cross-section model would appear to overstate the carbon fertilization effect. When applied to the 2080s climate, the MMSA carbon fertilization parameter boosts land rental equivalent by 46 percent above levels it would otherwise have reached, which globally would correspond to an increase in output potential by about half as much or 23 percent, well above the 15 percent adopted in the present study (see chapter 3). In short, the basic sources of the difference between the benign global effects in MMSA and the more adverse ones in the present study using the same basic models would seem to be the use of lower expected future warming and higher carbon fertilization in the MMSA study than in the present study.[32]

In contrast to the divergence in global aggregate estimates, for the pattern of regional and country winners and losers there is more similarity between the results here in appendix F using the MS models and those in MMSA. Both identify Canada and Russia as large beneficiaries (MMSA place Russia's agricultural gains at $124 billion to $351 billion at 1990 prices and Canada's gains at $19 billion to $49 billion). This same pattern of large gains in Canada and Russia is found for the MS reduced form and Ricardian estimates shown in appendix F, but as noted above, for the main estimates of this study the zero impact findings of Reinsborough (2003) are instead applied, for both countries. The strong MMSA gains for

31. Although it is not quite that simple: As discussed above, the relevant warming over land areas significantly exceeds the global mean, so the land areas even in MMSA should show warming higher than 2°C.

32. It is also possible that the coarser grid specification in the MMSA climate model than that in this study contributes to the difference. With grids of 4º latitude and 5º longitude, instead of 2º latitude and 3º longitude used in this study, their grid areas are 3.2 times as large as those in this study. Even so, simple back-of-the-envelope application of the functions in equations (5.1) and (5.2) to the much more aggregative country climate averages shown in table 4.2 generates results broadly similar to the detailed results of this study built up from the grid level, so grid size seems unlikely to account for much of the difference between the MMSA results and those in this study.

China ($39 billion to $65 billion) and the United States ($17 billion to $35 billion) are in the same direction, although larger, than the results from application of the MS models in appendix F of the present study.

For developing countries, the MMSA results generally parallel those found here. In the reduced form model, India and Brazil both experience large losses (by $86 billion and $106 billion annually, respectively). The reduced form model in MMSA gives severe losses for Africa ($131 billion) and Latin America as a whole ($49 billion). However, the Ricardian (cross-section) model in MMSA shows gains even for these two regions, in contrast to the results here. The MMSA finding of positive results for the cross-section function in all regions is in sharp contradiction to the cross-section findings in the present study in appendix table F.2. This divergence may in particular reflect the much stronger carbon fertilization effect used in MMSA than in the estimates here. Overall, nonetheless, it is fair to say that there is much more agreement between the MMSA findings and those here, especially using the reduced form rather than Ricardian cross-section model, on the differential effects among countries (including the broad pattern of losses in Africa and Latin America, in particular, in contrast to more favorable results in industrial countries) than on the severity of the losses and the overall global balance of results.

Mendelsohn, Dinar, and Sanghi

The model used for India is from Mendelsohn, Dinar, and Sanghi (2001). In that study, however, the authors focus on how the level of development affects the climate sensitivity of agriculture. They do not include specific calculations of the impact of prospective global warming on agriculture.

An earlier study by the same authors does provide impact estimates for India. Sanghi, Mendelsohn, and Dinar (1998, 107) develop a Ricardian model for Indian agriculture and calculate that benchmark global warming ($2 \times CO_2$) would reduce net revenue by 12.3 percent. However, their calculation applies 2°C rise in temperature and 7 percent rise in precipitation for benchmark climate change. Instead, it is evident from table 4.2 that the consensus estimate from the six climate models considered in the present study would place climate change by the 2080s at much greater warming—a rise of 3.6°C for annual average temperature across the four subzones. Although the corresponding estimate in the present study for precipitation is also higher (at 17 rather than 7 percent), in the model in question the favorable impact of higher precipitation is much smaller than the unfavorable impact of higher temperatures.[33] One reason the authors

33. The 7 percent boost in precipitation raises average net revenue by 14.4 rupees per hectare (at 1980 prices) whereas the 2°C increase in temperature reduces net revenue by 208 rupees per hectare (Sanghi, Mendelsohn, and Dinar 1998, 98).

apply much less warming than used in the present study may be that they have implicitly assumed the change for India is the same as the global average, whereas the increase for land areas would tend to be greater than the global average including the oceans (as emphasized above).

World Bank Studies

Africa. In the recent World Bank study on Africa (Kurukulasuriya et al. 2006), the authors do not apply their models to a postulated future climate with global warming, so once again there is no basis for direct comparison with the results of the present study. Qualitatively, however, the study appears to conclude that global warming has a neutral effect on Africa because gains for irrigated agriculture approximately offset losses in dryland agriculture. In particular, they find that for a 1°C temperature increase, the models calculate a "slight and insignificant *increase* [emphasis added] in net revenue across African farms . . ." (p. 13).

The use of 1°C warming as the gauge makes this finding essentially irrelevant to the question of effects by the end of this century. In particular, by the 2080s the simple average rise in annual average temperature for the African countries and regions shown in table 4.2 is 4°C. Even within the confines of the minimal 1°C warming, the result is misleading because it depends on applying the with-Egypt function for irrigated farming. As discussed above, the without-Egypt function shows a negative rather than positive response to warming, and Egypt's atypical access to the Nile River (and its atypical 100 percent irrigated farming in contrast to only about 6 percent for Africa as a whole) would surely counsel use of the without-Egypt function to assess the impact on irrigated agriculture outside Egypt, as is done here.

Perhaps more fundamentally, the "irrigation compensation" message in the World Bank study does not come to grips with the problem that less water may be available for irrigation in a hotter and drier future. Thus, IPCC (2001b, 289) finds that

> Africa is the continent with the lowest conversion factor of precipitation to runoff . . . . Although the equatorial region and coastal areas of eastern and southern African are humid, the rest of the continent is dry subhumid to arid. The dominant impact of global warming is predicted to be a reduction in soil moisture in subhumid zones and reduction in runoff.

Indeed, the question of water availability for future irrigation poses a problem for the applicability of the Ricardian models that do not evaluate irrigated agriculture separately (the MS cross-section model in particular), because one of the prime reasons farms can adjust in hotter and drier climates is through increased irrigation. To the extent that the US-based MS function implicitly relies on greater irrigation as the vehicle for benign effects of warming, it will give an unduly optimistic picture of future agricultural prospects in those areas where irrigation would be increasingly constrained because of adverse effects on water availability.

In a related study using the World Bank Africa surveys, Kurukulasuriya and Mendelsohn (2006) apply alternative climate models to each country. They find that by the end of this century, and excluding carbon fertilization, Africa as a whole could experience agricultural impacts ranging from annual losses of $48 billion if the future climate were "hot and dry" to annual gains of $97 billion if it were "mild and wet" (p. 7). The effects are not uniform across countries, and the hotter and drier regions of Africa fare the worst in all scenarios. The African estimates in the present study suggest, however, that this wide range, and especially its average of +$25 billion, are likely to be misleading and that instead the best guess using a consensus climate model is that large losses would predominate.

Latin America. The discussion above of the recent World Bank–sponsored studies for Latin America, and the estimates presented in table 5.5, directly address the climate impact estimates contained in that set of studies in comparison with the corresponding results obtained using their models with the climate assumptions of the present study.

Rosenzweig-Iglesias

The most relevant study from the Rosenzweig-Iglesias set of research for comparison with results here is that by Parry, Rosenzweig, and Livermore (2005). They confirm their earlier finding

> that climate change is likely to reduce global food potential and that risk of hunger will increase in the most marginalized economies. . . . [C]limate change scenarios excluding the direct physiological effects of CO_2 predict decreases in simulated yields in many cases, while the direct effects of increasing atmospheric CO_2 mitigate the negative effects primarily in mid and high latitudes. . . . At low latitudes crops are grown nearer the limits of temperature tolerance and global warming may subject them to higher stress. In many mid and high latitude areas, increasing temperatures may benefit crops, otherwise limited by cold temperatures and short growing seasons in the present climate (pp. 2127–28).

Citing their estimates from the early 1990s, they report that under conditions by 2060 as predicted by three climate models (GISS, GFDL, and UKMO), with level 1 adaptation (discussed above), global warming would boost cereal production by an average of about 8 percent for developed countries, reduce it by 11 percent in developing countries, and reduce global production by about 3 percent (Parry, Rosenzweig, and Livermore 2005, 2129, figure 2). Revisiting their estimates in light of the IPCC scenarios in the 2001 Third Assessment Report, they find that in the SRES A2 scenario (the one used in the climate estimates of this study) the number of people globally at risk of hunger would increase by about 550 million above the no climate change reference level of 800 million, although this outcome is more attributable to a rise in global population to a level (15 billion) higher than in their reference scenario than to a decline in yields.

In broad terms the results using the Rosenzweig-Iglesias model query system in the present study are similar to those in Parry, Rosenzweig, and Livermore (2005). This similarity is to be expected because the calculations here directly apply the results for the specified scenarios in Rosenzweig and Iglesias (2006) with the minor modification that the carbon fertilization effect by the 2080s is curbed from an average 17.5 percent boost in yields to 15 percent.