
Key Issues: Carbon Fertilization, Irrigation, and Trade

Before proceeding to the main estimates of this study, it is important to highlight three major issues. The first is carbon fertilization. The estimates developed in this study depend crucially on the yield enhancement assumed for this effect. As set forth in this chapter, recent scientific studies using open-field rather than laboratory conditions find a considerably lower enhancement than often used in past studies. Accordingly, this chapter considers these recent estimates to develop an independent central carbon fertilization effect for use in the estimates of this study. This carbon fertilization effect is then imposed on the without-carbon fertilization results from the agricultural impact models applied to obtain the estimates including carbon fertilization.

The second issue is irrigation. This chapter reviews the controversy on whether model estimates have adequately taken irrigation into account. There is still considerable room for doubt that they have done so. The estimates in this study, however, do not attempt to quantify any corresponding correction.

The third issue is whether to incorporate feedback from international trade when examining the impact of global warming on agriculture. This chapter sets forth the reasons why such effects are not incorporated in the country-specific impact estimates of this study.

Carbon Fertilization

The extent to which carbon fertilization could alleviate any adverse effects of global warming on agriculture has been a central issue in analysis of

the severity of these effects. Carbon dioxide is an input in photosynthesis, which uses solar energy to combine water and carbon dioxide to produce carbohydrates, with oxygen as a waste product.¹ In addition, higher atmospheric concentrations of carbon dioxide reduce plants' stomatal (pore) openings and hence the loss of water to respiration. So-called C3 crops, which include rice, wheat, soybeans, fine grains, legumes, and most trees, benefit substantially from additional atmospheric carbon dioxide. Benefits for C4 crops, which include maize, millet, sorghum, and sugarcane, are much more limited.²

Recent research based on experiments with the free air concentration enrichment (FACE) method suggests that past estimates of the carbon fertilization effect have been substantially overstated as a consequence of relying on "studies made within chambers at small scales" rather than "field crops under fully-open-air conditions at an agronomic scale." Thus, Long et al. (2005, 1, 5) find that with carbon dioxide elevated to 550 to 575 parts per million (ppm), the FACE experiments show "the yield increase is 11% for C3 crops and 7% for all five major food crops, which is one-third to one-quarter of the direct effect of CO₂ modelled in the recent assessment for Europe and the USA by Darwin & Kennedy (2000)."

In a more recent study, Long et al. (2006) report that FACE studies indicate that at 550 ppm carbon dioxide concentration, yield increases amount to 13 percent for wheat in contrast to 31 percent in laboratory studies, 14 percent instead of 32 percent for soybeans, and 0 percent instead of 18 percent for C4 crops. Among the major crops, C3 species account for roughly three-fourths and C4 for one-fourth of total value.³ If the central C3 increment is set at 12 percent, considering the two Long et al. studies, and a

1. This process occurs in two stages. In the first, a light-dependent reaction, the pigment chlorophyll absorbs light and loses an electron, which becomes stored in the high-energy molecules NADPH and ATP. In the second, a light-independent reaction, these high-energy molecules are used along with the enzyme RuBisCO to capture carbon dioxide from the atmosphere in what is called the Calvin cycle.

2. In C3 crops RuBisCO is located in mesophyll cells, which are in contact with the atmosphere through stomatal pores in the epidermis. In these cells, "RuBisCO is not CO₂ saturated in today's atmosphere. . . . In contrast, in C4 crops . . . RuBisCO is localized to bundle sheath cells in which CO₂ is concentrated to three to six times atmospheric [levels. This is] sufficient to saturate RuBisCO and in theory would prevent any increase in CO₂ uptake with rising [CO₂]" (Long et al. 2006, 1918). However, these crops may also benefit indirectly from increased efficiency in water use as a consequence of reduced stomatal conductance with rising carbon dioxide.

3. Global production value circa 2004 stood at the following estimated levels: wheat, \$94 billion; rice, \$120 billion; soybeans, \$49 billion; cotton, \$23 billion, or a total of \$286 billion for the four major C3 crops; and at \$68 billion for maize, \$25 billion for sugarcane, and \$6 billion for sorghum, or a total of \$99 billion for the three major C4 crops. These estimates are compiled from USDA (2005, 2006), IMF (2006), UN FAOSTAT database, and Federal Register (2006). It is assumed that the sugar output yield of sugarcane is 0.063, the ratio for Brazil, and the Philippines price for sugar is applied.

modest allowance of 3 percent yield increase for C4 crops is made, then the weighted average increment in yield from carbon fertilization would be 9 percent at 550 ppm.

This study examines the period 2070–99. At the midpoint of 2085, the central scenario used in this study—scenario A2 of the Special Report on Emissions Scenarios (SRES) from the Intergovernmental Panel on Climate Change (IPCC)—places atmospheric carbon dioxide concentration at 735 ppm (IPCC 2001a, 807). The carbon fertilization effect rises less than linearly with atmospheric carbon concentrations (Long et al. 2006, Mendelsohn and Schlesinger 1999). If Mendelsohn and Schlesinger (1999) is followed and the relationship is specified as logarithmic, then at 735 ppm the effect should be about two-thirds larger than at 550 ppm.⁴ On this basis, the central estimate of the carbon fertilization effect by the 2080s is set in this study at a 15 percent increase in yield. This impact is considerably smaller than that assumed in some past studies.⁵

Two past studies in particular are of relevance to this study: Mendelsohn and Schlesinger (1999), or MS; and Mendelsohn, Morrison, Schlesinger, and Andronova (2000), or MMSA. Using an atmospheric concentration of 735 ppm of carbon dioxide by the 2080s, and applying the future world average temperature and precipitation for land weighted by farmland area—16.2°C and 2.44 mm per day (see table 4.3 in chapter 4)—the MS “reduced form” equation for output per hectare gives an estimate of \$333.2 without carbon fertilization and \$376.6 with carbon fertilization, an increase of 13 percent.⁶ Applying the MS Ricardian function gives corresponding estimates of land rental equivalent of \$34 per hectare without carbon fertilization and \$45.9 with carbon fertilization, an increase of 32.1 percent.⁷ As discussed in chapter 5, for the Ricardian estimates it is necessary to translate the percent change in land rental equivalent into corre-

4. With the present concentration at 350 ppm, the typical 550 ppm concentrations are a ratio of 1.57 to today’s concentration, and a future concentration of 735 ppm would be 2.1 times today’s concentration. The ratio of the logarithm of the latter to that of the former is 1.64 to 1.

5. Note that Tubiello et al. (2007) have argued that Long et al. (2006) overstate the difference between FACE and non-FACE experimental results and contend that in any event the principal crop models have applied much more conservative carbon fertilization than those cited by Long et al. For the purposes of the present study, the most important point in this debate is that the central estimate used here, 15 percent yield enhancement at 735 ppm against a 350 ppm base, is fully consistent with the preferred crop model cited in Tubiello et al. (2007). Namely, the agroecological zone model cited in table 2 of Tubiello et al. (2007) indicates that a rise from 350 to 735 ppm would boost yields by 16 percent for wheat and rice, 21 percent for soybeans, and 7 percent for maize. Applying the corresponding world output value shares, the weighted increase would be 14.8 percent.

6. See equation (5.1) in chapter 5.

7. See equation (5.2) in chapter 5.

sponding potential output changes, which are about half as large.⁸ When this translation is done, the 32 percent MS Ricardian carbon fertilization for land rental equivalent represents an output impact on the order of 16 percent. For both the MS “reduced form” and Ricardian functions, then, the carbon fertilization effect is relatively similar to the 15 percent used in this study (for 735 ppm).

In contrast, in the subsequent MMSA study, the version of the MS model used to arrive at global (rather than just US) estimates, the exercise just outlined generates a Ricardian model increase of land rental equivalent from \$34 per hectare to \$49.6 per hectare, an increase of 45.9 percent. Again applying a global ratio of about half, carbon fertilization as estimated in MMSA would boost output potential by about 23 percent, which is considerably larger than the 15 percent used in this study. The MMSA function explicitly increased the carbon fertilization parameter used in the MS equation, but it would appear that this increase resulted in a significant overstatement of carbon fertilization.⁹

The Irrigation Question

A persistent question about the Ricardian statistical estimates of how agriculture responds to changing climate has been whether they have adequately taken account of irrigation. One issue is whether benefits attributed to warmer climates are overstated because in fact these benefits reflect high values of land and output per hectare attributable instead to irrigation combined with the fact that there is a higher incidence of irrigation in warmer regions. Another issue is whether climate impact projections using these models address the availability of water for irrigation.

Evapotranspiration (the combined loss of moisture from soil through evaporation and plants through stomatal transpiration) increases with temperature. The need for irrigation rises as conditions become drier. It rises as a function of the difference between evapotranspiration and precipitation. Because global warming will increase both temperature and precipitation, the implications for soil moisture and the need for irrigation depend on the outcome of the race between rising temperature and rising precipitation.

An extremely simple test for the United States shows the incidence of irrigation is positively related to temperature and negatively related to

8. The ratios of net revenue per hectare to output per hectare used in chapter 5 range from a low of about 40 percent in the United States to a high of 78 percent in Africa. This ratio is applied to the percent change in land rental equivalent to obtain the corresponding percent change to be expected in output potential.

9. The MMSA Ricardian function is similar to equation (5.2) in chapter 5 (the MS function) but changes the coefficient on the logarithm of the ratio of carbon concentration to today’s 350 ppm from 480 to 687 (Mendelsohn et al. 2000, 559).

precipitation. Using state data for agriculture and state capital data for temperature and precipitation, figure 3.1a shows the relationship across US states between the ratio of irrigated crop area to harvested crop area (percent) and annual average daily temperature (°C). Figure 3.1b shows the same incidence of irrigation as related to average annual precipitation (mm per year).¹⁰

Broadly the scatter diagrams show higher incidence of irrigation for higher temperatures and lower incidence of irrigation with higher precipitation. There are three states that are outliers to the temperature trendline: Nevada (irrigation incidence at 136 percent of harvested cropland), Utah (114 percent), and Wyoming (119 percent).¹¹ All three have extremely high irrigation incidence but relatively low temperatures. The anomaly is explained by the low precipitation in all three, as they become the upper-left observations in figure 3.1b.¹² Many of the states have low irrigation incidence, but some have extremely high incidence, as indicated by the difference between median (8.2 percent) and average irrigation (29.5 percent).

A simple statistical regression for these data shows the following, with *t*-statistics in parentheses:

$$Z = 24.1 + 3.73 T - 0.0455 P; \text{ adj. } R^2 = 0.21$$

(1.57) (3.22) (3.29)

Although the degree of explanation is moderate at only about 20 percent, the coefficients on temperature (T) and precipitation (P) are highly significant.

To anticipate the following climate analysis, for the United States the estimates in this study indicate that baseline global warming by the 2080s would cause the farmland-weighted averages for annual temperatures to rise by 5.4°C and the corresponding averages for precipitation to fall by 4.3 mm per year.¹³ If these changes are applied to the simple regression equation, the incidence of irrigation would need to rise by 20.3 percentage points as a consequence of climate change. The increase would be almost entirely from higher temperature; the slight decline in precipitation would have little effect, except in the sense that the failure of precipitation to rise would mean that the race between temperature and precipitation would be won hands down by temperature.

10. Temperature and precipitation are from NOAA (2007). Irrigated and harvested crop land are from USDA (2004).

11. Greater than 100 percent incidence implies that some irrigated land is used for pasture rather than crops and/or that some irrigated land is left fallow.

12. Note also that Carson City at 4,687 feet elevation and average annual temperature of 10.7°C may not be as representative of statewide conditions as is the case for most capitals. Thus, also in Nevada, Las Vegas at 2,028 feet has average annual temperature of 20.1°C.

13. Calculated from table 4.2 and appendix table E.1.

Figure 3.1a Irrigation and temperature for US states

irrigated crop area as percent of harvested crop area

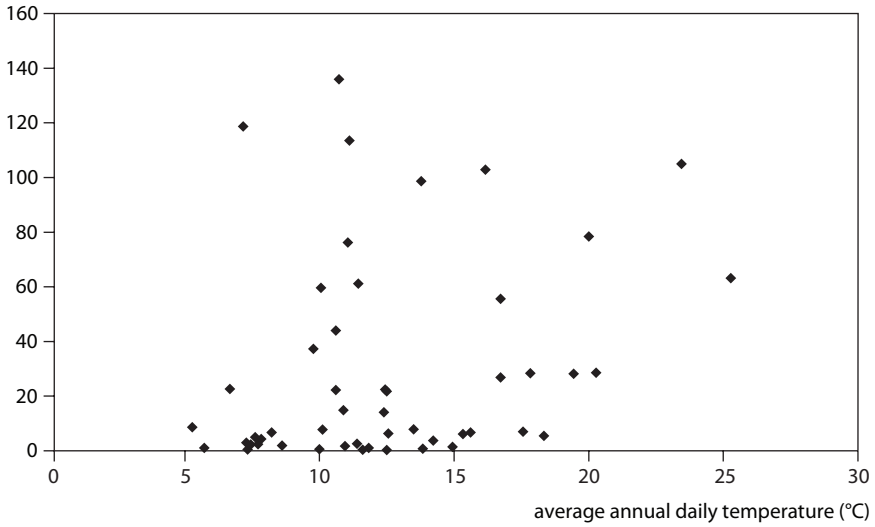
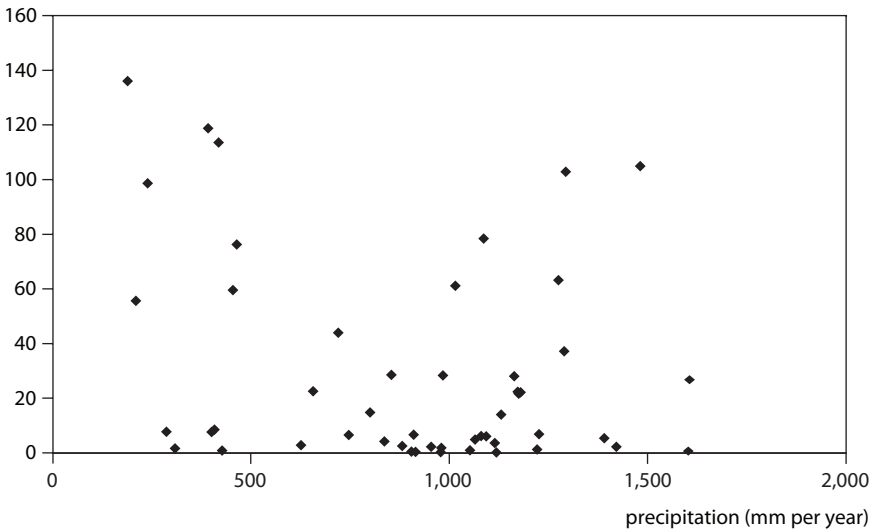


Figure 3.1b Irrigation and precipitation for US states

irrigated crop area as percent of harvested crop area



Viewed in this way, the irrigation issue raises two questions for most model estimates. First, have they included the costs of additional irrigation, which requires large capital outlays? Second, have they carefully considered the availability of water for additional irrigation? The broad answer to both questions would seem to be in the negative, suggesting that the Ricardian models may well tend toward an optimistic bias regarding treatment of irrigation.

The seminal empirical Ricardian function for the United States is that estimated in Mendelsohn, Nordhaus, and Shaw (1994). In an early comment (Cline 1996), I argued that the application of their results to global warming scenarios faced the problem that such an exercise implicitly assumed that water was infinitely available for irrigation at the present price, whereas there were strong grounds for concern about water scarcity and increased incidence of droughts as a consequence of global warming. In a subsequent comment, Darwin (1999) suggested that the Mendelsohn-Nordhaus-Shaw function itself could contain a statistical bias by failing to remove the influence of irrigation on the measured relationship of productivity to temperature and precipitation (along the lines just suggested). Quiggin and Horowitz (1999) further criticized the Mendelsohn-Nordhaus-Shaw function by pointing out that its quadratic term for October temperature had the wrong sign (positive), indicating that there was no limiting optimal temperature for that term. The two authors also usefully sharpened the argument on the Ricardian approach by pointing out that whereas some crop models lacking attention to adaptation might be subject to the “dumb farmer” critique, the Ricardian approach instead “implicitly assumes zero adjustment costs and therefore yields a lower-bound estimate of the costs of climate change” (Quiggin and Horowitz 1999, 1044).

In response to the critique of Darwin (1999) about possible irrigation bias, Mendelsohn and Nordhaus (1999) reestimated their model as follows. First they estimated an equation for irrigation as a function of the climate and control variables. Then they included predicted irrigation from this equation as an independent variable in an expanded climate impact Ricardian function. They argued that it would be incorrect to include irrigation directly (rather than predicted irrigation) because of the endogeneity of irrigation to climate. Then when they conducted their climate change impact exercise using the revised Ricardian function, they found that the effects were somewhat more rather than less favorable after removing the influence of irrigation.¹⁴ They concluded that concerns about irrigation bias were not warranted.

14. The authors found that in the function without irrigation, a temperature increase of 2°C and precipitation increase of 8 percent would boost net revenue by 3.3 percent, whereas in their revised function removing the influence of irrigation, crop net revenue would rise by 10.4 percent.

Their equation for incidence of irrigation has key information in itself, however, that could instead suggest concern about a possible substantial rise in the need for irrigation in a hotter, drier climate. If their equation is applied to their suggested climate scenario (+2°C temperature, +8 percent precipitation), the result is an estimated 19 percentage point increase in the incidence of irrigation.¹⁵ If the temperature increase were considerably larger and precipitation change negligible or slightly negative, as suggested above for the 2080s baseline examined here, by implication the expected increase in irrigation would be much larger, using the Mendelsohn-Nordhaus equation. So once again there are two key questions for their analysis: Who would pay for the extra irrigation, and would it be feasible given possible water constraints?

Moreover, their conclusion of benign results turns crucially on the precipitation variable. Their two-stage results boost the marginal effect of an extra 1 inch per month in precipitation from \$123 per hectare to \$218 per hectare. Their interpretation is that once the influence of irrigation is removed, precipitation is relatively more important to agricultural performance. But then their large boost to precipitation in their climate change scenario becomes the key to the favorable impact, and as noted the set of climate model estimates presented below shows a much less favorable precipitation change in the baseline by the 2080s.¹⁶

More fundamentally, however, the Mendelsohn-Nordhaus reestimation failed to escape the problem of the wrong sign for a key quadratic term on temperature. Indeed, a closer inspection of their equation shows that it has entirely implausible estimates for high warming as a result. In particular, in their formulation the underlying variables are temperature in degrees Fahrenheit minus the average temperature, with both linear and quadratic terms on this “demeaned” temperature variable. This yields the following structure:

15. Calculated from their seasonal temperature and precipitation linear and squared coefficients applied to demeaned variables from the base US climate from table 4.2, for the base, and their specified changes in temperature and precipitation.

16. Note further that the change in the temperature coefficient in their two-stage results is problematic. The marginal impact of 1°F swings from -\$17 per hectare originally to +\$4 per hectare. If one accepts the notion that US agriculture on average is below optimal temperature, then this marginal effect might not be implausible. But then the real question becomes whether their coefficients on the squared terms for temperature are reliable, because it is the nonlinear adverse effect of going well beyond optimal temperature that is the concern. By the construction of their variables, which are “demeaned” (subtract mean temperature from temperature and mean precipitation from precipitation), their model unfortunately forces the nonlinear effects to be symmetrical for both a decline and an increase in temperature. As noted above, recent studies suggest instead an adverse asymmetry for temperature increases. Moreover, the mixture of positive and negative coefficients for the squared temperature terms across different seasons means that their function is not strictly hill-shaped but questionably gives nonlinear positive gains to October temperatures, as noted by Darwin (1999).

$$y = \alpha + \sum_i \beta_i \Delta T_i + \sum_i \gamma_i (\Delta T_i)^2$$

where y is crop revenue per acre per year, α is a constant term, i is the seasonal month (January, April, July, or October), and ΔT_i is the increase in temperature (in degrees Fahrenheit) above the base period averages. The level of base temperature itself does not appear because in the base period the temperature term disappears: Temperature *is* average temperature for the month, and the base demeaned variable is zero.

For a climate scenario with an increase in temperature specified as ΔT uniformly across the four seasons,¹⁷ the change in revenue per hectare is then simply:

$$\Delta y = \Delta T \sum_i \beta_i + (\Delta T)^2 \sum_i \gamma_i$$

In the reestimated Ricardian function in Mendelsohn and Nordhaus (1999), the sum of the linear coefficients on demeaned temperature is \$4.10 per acre, and the sum of the quadratic coefficients is \$1.52.¹⁸ So there is an unlimited rise in net revenue per hectare with higher temperatures. An extra 2°F boosts the net revenue output measure by about \$14 per hectare. As the temperature increase doubles successively to 4°F, 8°F, 16°F, and 32°F, the boost to output per hectare becomes respectively \$41, \$130, \$455, \$1,688, and so forth. The climate function states literally that if temperature rose to that on the sun (11,000°F), net revenue would rise by \$121 million per hectare. In short, it violates both common sense and the underlying hill-shaped Ricardian function postulated by the authors.

What one seems to be left with in the reestimated Mendelsohn-Nordhaus analysis of irrigation is one reliable result and one failed result. The reliable result is that irrigation does indeed rise for hotter and drier counties. The failed result is a Ricardian function for the impact of climate on agriculture. The empirical estimate should be rejected just as an empirical estimate of an upward-sloping demand curve (higher price offered, larger volume purchased by consumers) should generally be rejected, regardless of the t -statistics. On this basis, the irrigation issue stands as follows: First, there should indeed be concern that additional irrigation will be required under global warming. Second, there simply remains ambiguity as to whether the Ricardian functions successfully elim-

17. As indicated in appendix tables H.1 and H.2, the change in average temperature by 2070–99 for the US Lakes-Northeast region, for example, is almost identical at 6.3°C for January, April, and July and almost the same at 5.3°C for October.

18. The seasonal detail is as follows, for January, April, July, and October, respectively: linear, -133, +91.1, -128, and +174; quadratic, -1.88, -4.66, 0.17, and 7.89 (Mendelsohn and Nordhaus 1999, 1054).

inate any bias in estimate from irrigation, because in the specific test designed for this purpose Mendelsohn and Nordhaus instead estimate a function that must be rejected on first principles.¹⁹

Trade as Moderator?

Finally, a crucial conceptual issue is whether to examine the impact of global warming on agriculture with or without incorporating induced effects operating through international trade. The estimates of this study do not incorporate trade feedbacks for the following reasons.²⁰

First and foremost, there is a “let them eat cake” flavor to the notion that trade will greatly reduce losses from global warming. Poorer nations are most likely to experience greater agricultural losses. A focus on trade implicitly argues that these countries can limit their losses from global warming by shifting to agricultural imports rather than producing those products at home. The problem is that they may face difficulties increasing export earnings from other goods in order to pay for their new food import needs. Incorporation of world trade moderation of global warming damage to agriculture should at the minimum include corresponding estimates of the terms-of-trade losses of the poorer countries as they find it necessary to export additional volumes of (likely) labor-intensive manufactures in order to import more food.

Second, Cline (1992, appendix 3A) shows that in a closed system, which is the case for the world as a whole, the welfare losses from a negative shock to agricultural yields are at least as large in percentage terms as the percent decline in yields. Basically consumer surplus losses exceed pro-

19. Nor does the further work by Mendelsohn and Dinar (2003) appear to lay this issue to rest, because it asks a different question: “whether farmers that have access to irrigation water have higher farm values” (p. 331). Not surprisingly, it finds that they do. But the study does not attempt to simulate the costs of additional irrigation, or investigate the availability of water for the additional irrigation, that could be necessitated by a hotter and drier (or hotter and only marginally wetter) climate.

20. Note that although the regions for which average yield impacts are reported in the crop model source used in this study (Rosenzweig and Iglesias 2006) are defined for consistency with one such trade model (the basic linked system [BLS]), the yield impact estimates themselves are for the direct effect of climate change without considering such induced effects (see table 5.7 in chapter 5). In general incorporation of induced effects, whether domestic or from international trade, would be unlikely to change the direct yield estimates by much. For example, an area experiencing a negative yield shock from climate change would be likely to encounter a positive second-round yield offset from the standpoint of greater applications of fertilizer and other nonland inputs but a negative second-round aggravation from the incorporation of more marginal land. Trade would tend to moderate both effects, because less of the new shortfall of output would be resolved by higher prices and induced domestic output response; but this trade moderation would be of the second-round yield effects, not of the first-round direct climate impact.

ducer surplus gains.²¹ Reduction in global average yields from climate change cannot be offset by recourse to trade at the global level.

Third, studies that focus on world agricultural output change, rather than direct yield impact or ex ante impact on agricultural potential, tend to generate impact estimates that are misleadingly small because they tend to report output change but not losses in net welfare after accounting for loss of consumer surplus. Demand for food is price inelastic. As an illustration, suppose demand were completely price inelastic but yields fell 50 percent. Output would have to rise back to the original level at what could be enormous costs of additional inputs; yet a study reporting the “output” effect would find that there was no impact whatsoever.

Fourth, trade feedbacks are omitted in the present study in part because to include them would add an additional layer of hypothetical and circumstantial analysis to an already difficult analysis focused on biophysical effects. It is not even clear that there are particularly meaningful medium-term agricultural supply functions available on a multicountry basis in today’s international economy, yet it would be necessary not only to identify them but also to project them for the distant future. It is useful to recall that in 1973 the United States imposed an embargo on soybean exports in order to avoid inflationary effects of rising prices; it is also the case that many nations are inclined to impose agricultural import barriers in the name of food self-sufficiency. Incorporating probabilities of such distortions would further complicate adding trade feedbacks to the analysis.

In sum, for several reasons incorporating induced effects based on a trade model could easily obscure rather than clarify the central diagnosis of prospective effects of unmitigated global warming on world agriculture.

21. Consumer surplus is the amount of saving by consumers represented by the difference between what they actually have to pay for the good and the amount they would be willing to pay if necessary. Producer surplus is the corresponding difference between what producers receive and what they would be willing to accept if necessary. The sum of the two is the area between the downward-sloping demand curve and the upward-sloping supply curve. Because a reduction in agricultural yield shifts the supply curve upward without a corresponding upward shift in the demand curve, it unambiguously reduces the sum of consumer and producer surplus. The percent reduction in the sum of producer and consumer surplus is likely to be at least as large as the percent reduction in yield.

