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Brief Survey of Existing Literature

The voluminous literature on the impact of global warming on agriculture broadly contains three types of quantitative estimates: those from application of agronomic crop models (e.g., Adams et al. 1990, Rosenzweig et al. 1993, Reilly et al. 2001), Ricardian models (e.g., Mendelsohn, Nordhaus, and Shaw 1994), and land zone studies premised on the shift of geographical areas from one agronomic class to another due to climate change (e.g., Darwin et al. 1995). In general, there has been some trend from pessimism toward optimism over time, especially for the United States.[1] But as discussed later, there are grounds to doubt the extent of this swing toward optimism. At the same time, there has been a relatively persistent diagnosis that developing countries stand to lose disproportionately from the agricultural effects of global warming, in large part because these countries are predominantly located in the lower latitudes, where temperatures are already near or above optimal levels for agriculture. This chapter briefly reviews some of the main studies in the existing literature.[2]

Environmental Protection Agency (1989). The US Environmental Protection Agency (EPA 1989) provided important early estimates of the impact on US agriculture by 2060 of a doubling of atmospheric concentration of carbon dioxide (CO_2) above preindustrial levels, or benchmark $2 \times CO_2$

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[1] Thus, my estimates in Cline (1992, 131) based on the studies then available placed US agricultural losses from benchmark $2 \times CO_2$ warming at 0.3 percent of GDP; Nordhaus and Boyer (2000, 76) placed them at 0.07 percent based on Darwin et al. (1995); and Mendelsohn and Neumann (1999, 320) estimated *gains* amounting to 0.2 percent of GDP.

[2] For helpful surveys, see NAST (2001) and Kurukulasuriya and Rosenthal (2003).

warming, based primarily on crop model analysis subsequently published in Adams et al. (1990). The study identified net losses of about \$6 billion to \$34 billion at 1982 prices if carbon fertilization effects were excluded and a range of about ±\$10 billion if carbon fertilization effects were included assuming a boost from 330 parts per million (ppm) to 660 ppm atmospheric concentration of CO_2. In Cline (1992), I argued that attributing this much carbon fertilization was inappropriate because carbon-equivalent doubling would include noncarbon gases with less than carbon doubling and because equilibrium long-term warming from 660 ppm carbon concentration would be considerably higher than realized warming by 2060 because of ocean thermal lag. On this basis I gave two-thirds weight to non–carbon fertilization estimates and one-third weight to with–carbon fertilization estimates and, after converting to 1990 dollars, arrived at a central estimate of \$17.5 billion losses, or 0.3 percent of 1990 US GDP (Cline 1992, 92–94).

Rosenberg and Crosson (1991) Study on Missouri, Iowa, Nebraska, and Kansas. A study prepared for the US Department of Energy (Rosenberg and Crosson 1991) at about the same time studied four states in depth: Missouri, Iowa, Nebraska, and Kansas (MINK). The study used actual climate conditions in the 1930s as an analogy for the climate by the 2030s. It concluded that warming by the 2030s would reduce agricultural production in the MINK area by 17.1 percent without considering carbon fertilization, by 8.4 percent after allowing for carbon fertilization from a rise in carbon concentration from 350 to 450 ppm, and by only 3.3 percent after further taking farmer adaptation into account (Rosenberg and Crosson 1991, 11–12). The study's result, that losses might be relatively modest, was for much less warming than the usual benchmark $2 \times CO_2$ warming.

Environmental Protection Agency (1994). Rosenzweig and Iglesias (1994) extended the EPA analysis to the global level. As set forth in Rosenzweig et al. (1993), the new set of estimates used the crop model approach to analyze the impact of benchmark $2 \times CO_2$ global warming on yields for wheat, rice, maize, and soybeans in 18 countries. The study included a world food trade model that translated the yield impact estimates into corresponding impact on food production, food prices, and the number of people globally at risk of hunger. The query-based system in Rosenzweig and Iglesias (2006) that reports yield estimates from the country models developed in Rosenzweig et al. (1993), using various climate models and scenarios, serves as one of the two broad sets of models used in the present study and is discussed in chapter 5. For purposes of this chapter, the following discussion refers to Rosenzweig et al. (1993).

The crop models in Rosenzweig et al. (1993) relied on the following agronomic influences of global warming:

> Higher temperatures during the growing season speed annual crops through their development (especially grain-filling stage), allowing less grain to be produced.

> This occurred at all sites except those with the coolest growing-season temperatures in Canada and the former USSR. . . . At low latitudes . . . crops are currently . . . nearer the limits of temperature tolerances for heat and water stress. Warming at low latitudes thus results in . . . greater yield decreases than at higher latitudes. . . . . [Other causes of falling yields are a] [d]ecrease in water availability . . . due to a combination of increase in evapotranspiration in the warmer climate, enhanced losses of soil moisture and, in some cases, a projected decrease in precipitation in the climate change scenarios; [and] poor vernalization . . . [i.e.,] the requirement of some temperate cereal crops, e.g. winter wheat, for a period of low winter temperatures to initiate or accelerate the flowering process (p. 14).

The study used three climate models (GISS, GFDL, and UKMO) that, for benchmark 2 × CO_2 warming by 2060, generated estimated global mean warming of about 4°C (GISS and GFDL models) to 5.2°C (UKMO model).[3] The study reported that it used the following yield enhancements for carbon fertilization at 550 ppm: 21 percent for soybeans, 17 percent for wheat, and 6 percent for rice. As discussed in chapter 3, these enhancements may have been somewhat overstated in light of more recent open-field experimental results.

For wheat, the yield impacts identified in the study showed large negative effects globally without carbon fertilization, mixed results with carbon fertilization, and negative results even with carbon fertilization for the developing countries reported (excluding China). Thus, under level 1 adaptation and without carbon fertilization, global wheat yields fell in the range of 16 to 33 percent for all three climate models.[4] With carbon fertilization, however, global yields fell in only one model (UKMO by 13 percent) while rising in the other two (GISS by 11 percent and GFDL by 4 percent). In contrast, for five developing countries (Brazil, Egypt, India, Pakistan, and Uruguay), the simple average impact on yields ranged from –36 to –57 percent without carbon fertilization and from –10 to –42 percent with carbon fertilization. The chief exception among developing countries was China, for which yields fell by a range of 5 to 17 percent without carbon fertilization but rose by 0 to 16 percent with carbon fertilization. The United States experienced yield declines of 21 to 33 percent without carbon fertilization but declines of only 2 to 14 percent with carbon fertilization.

At the global level the impacts were most severe for maize, which showed reductions of 20 to 31 percent without carbon fertilization and reductions of 15 to 24 percent with carbon fertilization. Rice also showed negative global results, at a range of –2 to –5 percent with carbon fertilization and –25 percent without. Soybeans in contrast showed a pattern across models that resembled that for wheat: uniform losses without carbon fertilization (by 19 to 57 percent) but mixed results with carbon fer-

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[3] GISS, GFDL, and UKMO stand for Goddard Institute for Space Studies, Geophysical Fluid Dynamics Laboratory, and United Kingdom Meteorological Office, respectively.

[4] As discussed in chapter 5, the study included three levels of adaptation: none, moderate (level 1), and intensive (level 2).

tilization; gains in two models (GISS and GFDL, 5 to 16 percent) but losses in the third (UKMO, –33 percent). The overall results of the study were negative, showing an increase in world cereal prices by 10 to 100 percent even with level 1 adaptation and a corresponding rise in the number of people globally at risk from hunger from a baseline of 641 million to a range of 681 million to 941 million.

Intergovernmental Panel on Climate Change (1996). In the Second Assessment Report of the Intergovernmental Panel on Climate Change (IPCC 1996), the authors of the chapter on agriculture concluded that

> global agricultural production can be maintained relative to baseline production in the face of climate changes likely to occur over the next century (i.e., in the range of 1 to 4.5°C) but . . . regional effects will vary widely . . . [and] it is not possible to distinguish reliably and precisely those areas that will benefit and those that will lose. . . . [L]ower-latitude and lower-income countries have been shown to be more negatively affected. . . . Low-income populations depending on isolated agricultural systems, particularly dryland systems in semi-arid and arid regions, are particularly vulnerable to hunger and severe hardship. Many of these at-risk populations are found in Sub-Saharan Africa . . . (IPCC 1996, 429–30).

The survey reported temperature thresholds from underlying crop physiology as follows: for wheat, optimum range of 17°C to 23°C with minimum of 0°C and maximum of 35°C; potatoes similarly at 15°C to 20°C optimum, 5°C minimum, and 25°C maximum; and rice and maize located at higher optima (25°C to 30°C), minima (7°C to 8°C), and maxima (37°C to 38°C) (IPCC 1996, 432). The authors noted that "higher temperatures would . . . increase crop water demand. Global studies have found a tendency for increased evaporative demand to exceed precipitation increase in tropical areas" (p. 433–34). Regional tables reported results of various studies, typically for benchmark $2 \times CO_2$ warming, with wheat, maize, soybeans, and rice the most frequently studied crops but including others as well. The study summaries typically showed large ranges of either losses or gains for most regions. However, there were nearly uniformly negative and large impacts on yields in two regions: Africa–Middle East and Latin America. Losses tended to dominate but in smaller magnitudes in South and Southeast Asia, East Asia, the United States, and Canada; moderate gains tended to dominate in Australia–New Zealand, the former Soviet Union, and Western Europe.[5] As discussed later, these patterns broadly resemble those found in the present study (except for Australia, where significant losses are identified).

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[5] As summary indicators, the number of negative and positive entries, respectively, in the yield impact tables and the median entry were as follows: Africa–Middle East, 9 negative, 1 positive, and –29 percent median; Latin America, 16, 3, and –17; South and Southeast Asia, 27, 17, –6; East Asia, 18, 11, –6; Australia–New Zealand, 4, 6, +11; former Soviet Union, 5, 5, +4; Western Europe, 3, 5, +10; United States, 9, 7, –6; and Canada, 5, 3, –16.

The IPCC authors cited the findings of Reilly, Hohmann, and Kane (1994), who incorporated the Rosenzweig et al. (1993) estimates of losses for benchmark 2 × CO_2 warming into a different trade model to calculate economic effects (change in producer and consumer surplus) against the present global agricultural base. They estimated that without carbon fertilization or adaptation, benchmark warming would impose global damage ranging from $116 billion (at 1989 prices) to $248 billion across three climate models but that after incorporating carbon fertilization and level 1 adaptation, the range of impacts would shrink to +$7 billion for GISS, –$6 billion for GFDL, and –$38 billion for UKMO (IPCC 1996, 452). They found that some agricultural exporting countries could gain even though they experienced yield reductions because of higher world prices and similarly that food-importing countries could lose despite yield increases domestically, for the same reason.

Importantly, this Second Assessment Report reported relatively high carbon fertilization impacts, which the authors set at +30 percent for C3 crops (most crops except maize, millet, sugarcane, and sorghum [IPCC 1996, 429]). As discussed later, the estimates from more recent open-field research are considerably lower. The report may thus have been overly optimistic about agriculture. Moreover, its central conclusion that "global agricultural production can be maintained" disguised two key issues: at what cost and with what differential impacts especially on developing countries?

US Department of Agriculture (1995). In 1995 researchers at the Economic Research Service of the US Department of Agriculture (USDA) prepared estimates of the world agricultural impact of global warming using a completely different framework from the crop model estimates previously dominant: land zone change (Darwin et al. 1995). They classified global agricultural land into six categories based on length of growing season. These were LC1, < 100 days and cold (e.g., Alaska); LC2, < 100 days and dry (e.g., Mojave Desert); LC3, 101 to 165 days (e.g., Nebraska); LC4, 166 to 250 days (e.g., Northern European Union); LC5, 251 to 300 days (e.g., Tennessee and Thailand); and LC6, >300 days (e.g., Florida and Indonesia). They judged LC1 and LC2 as mainly usable for rough grazing, LC3 for short-season grains, LC4 for maize, LC5 for cotton and rice, and LC6 for sugarcane and rubber. They placed the current global distribution of land across the six classes (from LC1 to LC6) at 17.3, 32, 13, 10, 7.7, and 19.7 percent, respectively, with global land area at a total of 13.1 billion hectares (Darwin et al. 1995, 9).[6] Considering that LC1 and LC2 are marginal for agricultural production, it is sobering that about half of world land area is currently in these two categories. The authors divided the

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[6] Note that this compares with my estimate of 3 billion hectares in farmland; see table E.1 in appendix E.

world into eight regions.[7] They identified production profiles characteristic of each land class in each region for four agricultural sectors (wheat, other grains, nongrain crops, and livestock) and nine other economic sectors.[8] They placed the value of crops at 2.5 percent of world output and livestock at 1.4 percent.

The authors applied their future agricultural resources model (FARM) to simulate the impact of climate change on world agriculture "by altering water supplies and the distribution of land across the land classes within each region" (Darwin et al. 1995, 16). For this purpose, they use equilibrium $2 \times CO_2$ results from four climate models: GISS, GFDL, UKMO, and OSU (Oregon State University). The resulting averages across the four models show the following percent changes in global land class coverage: LC1, –45.6 percent; LC2, –9.8 percent; LC3, +28.2 percent; LC4, +47.5 percent; LC5, +11.3 percent; LC6, –23.0 percent (Darwin et al. 1995, 20). Weighting by current rents, they find that "the total value of existing agricultural land declines . . . [so] climate change will likely impair the existing agricultural system" (p. 20). In one aggregation, they identify changes in "agriculturally important land" in three groupings. The average across the four climate models shows an increase in such land by 34.2 percent in the high latitudes, a decrease by 32.7 percent in the tropics, and a small increase (1 percent) in other areas. So once again the stylized fact of gains in the high latitudes and losses in the low latitudes tends to be supported, this time by a land zone rather than crop model approach.

For the United States, the authors find that cold LC1 declines (by an average of 54 percent), whereas land suitable for agriculture rises. However, "most of this impact will occur in Alaska" (Darwin et al. 1995, 22). As will be shown in table 4.2, even with global warming by late this century, average temperatures in Alaska would remain close to zero (rising from –5.1°C to 1.1°C), which casts serious doubt on how meaningful the rise in agricultural land would be. As for existing farmland as opposed to newly suitable land, climate change would shift about 7 percent of agricultural land to shorter growing seasons, weighting by existing rents (four-model average). Moreover, there would be a decline of about 25 percent in land in category LC4, "suggesting potential negative effects in the U.S. Corn Belt;" and an average 1 percent decline in LC6 and a 2 percent rise in LC2, which "implies that soil moisture losses may reduce agricultural possibilities" (p. 22).

The study then goes on to calculate changes in output and prices in the world regions and sectors, but it does not present any equations revealing

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[7] The eight regions are the United States, Canada, European Community, Japan, other East Asia (China, Hong Kong, Taiwan, and South Korea), Southeast Asia (Thailand, Indonesia, Philippines, and Malaysia), Australia–New Zealand, and rest of world.

[8] The sectors are forestry; coal, oil, and gas; other minerals; fish, meat, and milk; other processed foods; textiles, clothing, and footwear; other nonmetallic manufactures; other manufactures; and services.

the basis for the calculations. It first reports the change in "supply," defined as changes in the amounts firms would be willing to sell at unchanged prices. These changes must inherently be broadly the change in expected yields, although the authors do not explicitly say so. The four-model average places this change for cereals and with no adaptation at –23.6 percent for the world and –33.5 percent for the United States, and the authors state that these results are extremely close to those estimated by Rosenzweig et al. (1993) for the three overlapping climate models. Including farm-level adaptation shrinks the supply impact to an average decline of 4.3 percent globally and 17.8 percent for the United States. The next step in the analysis shrinks the effects much further, however. The authors emphasize the change in production, defined as changes in what firms are willing to sell and consumers are willing to buy *at new market prices*. These changes shift to a four-model average *increase* of 0.6 percent globally and a decrease for the United States of only 3.8 percent (p. 28).

So the Darwin et al. (1995) study arrives at minimal changes in production globally in large part because it expects the adverse impact on yields to push up prices and clear the market at little change in actual output. Surely, however, this approach ignores the major loss in consumer surplus that would be associated with this outcome. It would thus seem that the "production" results of the study are much less relevant than the "supply" results as a guide to welfare impact. Indeed, Cline (1992, annex 3A) shows that the welfare loss should be expected to be at least as large (in percentage terms) as the decline in yields. Implicitly the Darwin et al. (1995) study assumes resources are drawn away from other sectors of the economy to help keep up agricultural production, but it does not explicitly address the opportunity cost of this increased call on resources from the rest of the economy.

Even the supply effects may be unduly sanguine because they seem likely to exaggerate easy gains from adaptation. The authors argue that the simple adaptation measure of "allowing farmers to select the most profitable mix of inputs and crops on existing cropland" would eliminate 78 to 90 percent of the initial climate-induced reductions in world cereal supply (p. 28). No reported equations spell out the components of this shift, and this effect far exceeds that in Rosenzweig et al. (1993, table 6). Those authors find, for example, that for wheat in Argentina, the United States, and Eastern Europe and the former Soviet Union, the inclusion of level 1 adaptation (which would clearly encompass changing the crop pattern and input mix) reduces the impact of benchmark warming on yields from –21 to –12 percent (UKMO model). Their shrinkage of loss through adaptation amounts to only about 40 percent (i.e., 9/21), less than half the Darwin et al. (1995) estimate.

Finally, the study obtains a small but positive net world output effect only after including newly suitable land. But as noted, it is mostly in Alaska for the United States and Siberia for Russia and so should be taken with a grain of salt. The study does omit carbon fertilization and understates gains from that standpoint. Broadly, however, its approach seems less satisfactory than the crop model approach because of its ascription of production characteristics by extremely aggregated land classes and regions and especially because of its focus on output rather than yields and corresponding inattention to losses in consumer surplus.

Reilly et al. (2001). For the United States, an even more optimistic set of estimates was subsequently prepared by the Agriculture Sector Assessment Team of the US National Assessment of the Potential Consequences of Climate Variability and Change within the US Global Change Research Program (Reilly et al. 2001). Primarily supported by the USDA, the study cautiously summarized that "climate changes . . . will not imperil crop production in the US during the 21st century" (p. xi). Its actual estimates were much more dramatic. Under the transient climate predicted for 2090, averaging the two climate models employed, the authors showed US dryland yields with farm-level adaptation rising by an average of 89 percent for cotton, 80 percent for soybeans, 29 percent for corn, 24 percent for wheat, and 11 percent for rice, with the only decline to be found in potatoes (by 11 percent) (p. 39). The corresponding changes in irrigated yields with adaptation were estimated at 110 percent for cotton, 36 percent for soybeans, 11 percent for rice, 4 percent for corn, 4 percent for wheat, and –14 percent for potatoes (p. 41).

The source of these extremely favorable estimates is an enigma.[9] Reilly et al. (2001) states that the 1989 EPA study had been "in many ways the most comprehensive assessment to date" (p. 17). Yet as noted earlier, the EPA study showed US losses of 2 to 14 percent for wheat yields even after taking account of carbon fertilization, a sharp divergence from the 24 percent gain identified in Reilly et al. (2001). Even though the latter study is once again a crop model approach (based on estimates at 45 sites), the authors do not explain why their results are so much more favorable than earlier crop model estimates. Nor does the report state the amount of yield enhancement assumed from carbon fertilization, although it indicates that this effect accounts for one-third to one-half of the yield increases simulated and their estimates of it "should be regarded as upper limits to actual responses in the field" (p. xi).

The report indicates that the temperature increases indicated in the climate models used are 5.8°C by 2095 for the Canadian model and 3.3°C by then for the Hadley model, and the corresponding precipitation changes

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[9] Nor does a further examination of the underlying studies seem to shed much light. Consider the results for wheat in Tubiello et al. (2002), an underlying study. It reports losses of 4 to 30 percent by 2090 for winter wheat and of 16 to 24 percent for spring wheat, using the Canadian climate model (pp. 265–66). In contrast, the National Assessment Synthesis Team (NAST) summary study reports all wheat results for the Canadian model as positive, in a range of 4 to 14 percent (Reilly et al. 2001, 39).

are 17 and 23 percent (Reilly et al. 2001, 30). These precipitation increases seem unduly large. Thus, in table 4.2 based on six climate models, US precipitation by the 2080s under "business as usual" global warming would be expected to rise by 49 percent in Alaska (where there is almost negligible agricultural land) but by 11.5 percent in the Southern Pacific Coast, 5.6 percent in the Pacific Northwest, 5.1 percent in the Rockies-Plains, and only 3.5 percent in the Lakes-Northeast region. Precipitation would decline by 2.3 percent in the Southeast and by 11 percent in the Southwest and Plains (see appendix table D.1 for definitions of regions). Reilly et al. (2001) do acknowledge "the 'wet' nature of the scenarios employed" (p. xi). For temperature increases, for the six US regions in table 4.2 excluding Alaska, the unweighted average would be an increase of 5.1°C, comparable to the Canadian model result but much higher than the Hadley model used in Reilly et al. (2001).

Taken together, the climate model scenarios used would seem to exaggerate increased precipitation seriously and understate temperature increases. The authors are cautionary about their carbon fertilization effects and avoid summary language that would be much more consistent with the dramatic gains they report ("massively beneficial" would be more apt than their "will not imperil"). There seems to be no reason to disagree with their caution, so the estimates in the study would seem to provide little more than a qualitative result that previous crop model estimates may have understated potential US gains.

Fischer et al. (2002). An important recent study in the land zone school is that by Fischer et al. (2002). They develop an agroecological zone model that identifies suitability of land for agricultural production and simulates the change in the availability of suitable agricultural land that can be expected from climate change. For the present climate, they use the same detailed dataset at the 0.5° latitude by 0.5° longitude grid level[10] used in the present study. They apply the FAO/UNESCO Soil Map of the World for information on soils, elevation, and slope. Their database incorporates information on land use and population distribution. A key concept in their model is the length of growing period, defined as the number of days per year when both water availability and temperature permit crop growth. They identify four groupings of major food products: two adapted to higher temperatures (C3: soybeans, rice, and cassava; C4: millet, sorghum, maize, and sugarcane) and two adapted to lower temperatures (C3: wheat and potatoes; C4: sorghum and maize). They develop five "thermal climate" categories: tropics, subtropics, temperate, boreal, and arctic. Thresholds for these classifications are the number of months with average temperatures above 18°C, below 5°C, and between 10°C and 18°C. They then

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[10] From the IPCC Data Distribution Center Web site, http://ipcc-ddc.cru.uea.ac.uk maintained for the IPCC by Climate Research Unit, University of East Anglia, United Kingdom.

identify 154 “land utilization types” that match crops to climate zones.[11] Potential yields correspondingly vary by land utilization type.

The authors then apply three of the same general circulation models (GCMs) used in the present study to simulate the impact of climate change by the 2080s on agricultural production.[12] They find that for rainfed cereal production based on one crop per year, land currently under cultivation would experience a decrease in production potential by 3.5 percent globally. However, they also find that if multiple cropping is allowed (more than one crop per year) where the length of growing period is sufficient, there would instead be a gain of 4 percent. If irrigation is further considered, under the assumption that “(i) water resources of good quality are available, and (ii) irrigation infrastructure is in place” (Fischer et al. 2002, 35), the global gain reaches 9 percent. They also find, however, that developing countries would experience worse results than industrial countries. Among 117 developing countries, the average impacts across the three GCMs indicate that 39 with a population of 2.5 billion (in 2080) would gain 5 percent or more in agricultural potential; 29 with 1.1 billion people would experience no change; and 49 with a population of 4.2 billion would experience losses of 5 percent or more, causing aggregate net losses of about 89 million metric tons of cereal capacity for the developing countries as a group (or about 5 percent).[13]

The meaning of the multiple-cropping and irrigation results would seem ambiguous, because there is no clear analysis of whether the corresponding potential of both has already been exploited and hence whether the increment from future global warming could be expected to occur because of the relaxation of current constraints. Nor is there an analysis of the prospective availability of irrigation water, a key issue as discussed in chapter 3. Perhaps more importantly, however, results of the agroecological zone model appear to be buoyed crucially by the expectation of large gains in the high latitudes, where today’s temperatures are the coldest. Thus, output potential is calculated to rise by 20 to 50 percent for both Canada and Russia. In contrast, the crop models (Rosenzweig and Iglesias 2006) used in the present study indicate that Canada and Russia would experience losses without carbon fertilization and negligible to modest gains even including carbon fertilization (see table 5.8 in chapter 5). Similarly, Ricardian model estimates for Canada show virtually no change in

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[11] For example, there is one land utilization type for sugarcane: tropics and subtropics. In contrast, for wheat there are 4 for hibernating (boreal, temperate, and subtropics) and 12 for nonhibernating (boreal, temperate, subtropics, and tropics).

[12] The models are ECHAM4/OPYC3, HadCM2, and CGCM1. The latter two are earlier versions of the corresponding models applied in the present study (see table 4.1 in chapter 4).

[13] The 5 percent interpretation here is based roughly on global cereal production shown in table 6.1 after allowing for 30 percent expansion in future production by developing countries.

productive potential from global warming (Reinsborough 2003). It would thus seem that the land zone transformation school may tend to overstate global gains from climate change by attributing excessive benefit to the warming of cold high-latitude regions, in contrast to prospective effects identified by more detailed biophysical treatment in the crop models on the one hand and revealed by economic behavior models in the Ricardian school on the other hand.

Recent Secondary Studies. In their influential study of economically optimal response to climate change, Nordhaus and Boyer (2000) rely heavily on the estimates of Darwin et al. (1995) in calibrating regional impacts on agriculture. As a result, their impact estimates for warming associated with a doubling of CO_2 are highly optimistic. They show agricultural *gains* of about 0.5 percent of GDP for China and Japan and about 1 percent of GDP for Canada, Australia, New Zealand, and Russia. They identify only a slight loss for the United States (0.07 percent of GDP). In contrast, they estimate sizable agricultural losses for OECD Europe and Eastern Europe (0.6 percent of GDP). The largest agricultural losses they apply are from two sources other than Darwin et al. (1995): Sanghi, Mendelsohn, and Dinar (1998) for India, discussed later, and a study attributed to Sanghi but not bibliographically referenced for Brazil. These two studies form the basis for their agricultural losses of about 1.5 percent of GDP for India and for middle-income countries.

Tol (2002) draws upon several underlying studies to identify agricultural impact of benchmark warming for nine regions. His table of the "original" estimates for five studies (including some of those examined above) shows significant and dominant negative results for 2.5°C warming. Of a total of ten variants of the studies and hence 90 regional outcomes, all but 22 are negative. For Africa, 9 out of the 10 variants are negative, with a median outcome of –0.68 percent of agricultural GDP impact (and an average of –1.2 percent). After he makes his own adjustments to the estimates by adding the influence of carbon fertilization to those results omitting it, and adding an estimate of the contribution of adaptation based on Darwin et al. (1995) when otherwise not present, he arrives at the remarkable conclusion that the effect of benchmark warming would be positive in all regions, with gains ranging from a low of 0.47 percent of agricultural GDP in Africa to 2.65 percent in Central Europe and the former Soviet Union and 3.1 percent in centrally planned Asia. On average his inclusion of adaptation contributes a positive impact equivalent to 1.24 percent of agricultural GDP. As argued above, however, the Darwin et al. (1995) results appear seriously to overstate the impact of adaptation. In addition, Tol's heavy reliance on Darwin et al. (1995) is vulnerable to its misleading focus on output rather than yields without considering corresponding opportunity costs of resources required from the rest of the economy and losses in consumer surplus. Moreover, it seems likely from the vintage of the studies considered by Tol that several of them include what would now be seen as an overstatement of the carbon fertilization effect.

Even within the generally overoptimistic estimates prepared by Tol, the usual latitudinal pattern of regional differences emerges. Latin America, the Middle East, and Africa have the lowest gains (and hence largest losses if the whole set of estimates is too optimistic), whereas Russia and Eastern Europe have among the largest gains. (His highest gains for centrally planned Asia are somewhat of an anomaly, considering that China is not usually included as among the biggest winners.)

Jorgenson et al. (2004, 9) draw on the estimates of Reilly et al. (2001), on the optimistic side, and Adams et al. (1990), on the pessimistic side, to estimate that in a central climate scenario with 2.4°C global mean warming and 3.1°C US warming by 2100, the average impact on agriculture over the present century would range from a decline of 26 percent to an increase of 20 percent. They note, "Under the pessimistic view, the unit costs for crop agriculture . . . rise continuously with rising temperatures . . . However, under the optimistic view [there are initial benefits that begin to reverse] when the rise in U.S. mean temperature reaches a threshold of just under 3.3°C . . ." (Jorgenson et al. 2004, 10).

In a recent survey prepared for the OECD, Hitz and Smith (2004) find that agricultural impacts of global warming are uncertain below about a 3°C temperature increase but that at larger temperature increases the literature broadly indicates reductions in yield. Grain yields decline above temperature thresholds, CO_2 fertilization effects eventually saturate, and "eventually . . . geographical shifting cannot compensate for higher temperatures" (p. 44). They note that Parry et al. (1999) find adverse effects even at 1°C increase in global mean temperature and that Rosenzweig, Parry, and Fischer (1995) find sharply increasing adverse effects above 4°C, even with adaptation, in contrast to benefits at 2.3°C global mean temperature increase. Hitz and Smith (2004) argue that the potential reductions are small relative to baseline increases in agricultural output. They judge that

> the existing disparities in crop production between developed and developing countries were estimated to increase. These results are a reflection of longer and warmer growing seasons [as a consequence of global warming] at high latitudes, where many developed countries are located, and shorter and drier growing seasons in the tropics, where most developing countries lie. Results in mid-latitude regions are mixed (Hitz and Smith 2004, 43).

Stern Report for the UK Government. At the time this study was being completed, a particularly important study prepared for the UK government was released. The Stern Review (2006) provides an overall evaluation of the prospective damages of global warming and costs of limiting climate change through abatement of emissions of CO_2 and other greenhouse gases. It is notable for providing substantially higher estimates of damage than most past studies, in a range of 5 to 20 percent of GDP by

2200 (as well as "now and forever" when the indefinite future is converted to once-for-all equivalence), and for estimating significantly lower abatement costs than in most previous studies, at only 1 percent of GDP to keep atmospheric concentration of greenhouse gases from rising above 550 ppm equivalent of CO_2.

For purposes of this study the report provides a useful metastudy on agricultural impacts of global warming. Key evaluations in the study include the following: First, there is a parabolic "hill function" for agricultural impact, and location on the hill depends on geographic location and other factors. For 1°C warming there would be "modest increases in cereal yields in temperate regions." With 2°C already there would be "sharp declines in crop yield in tropical regions (5–10% in Africa)." At 3°C warming there would be 150 million to 550 million additional people at risk of hunger if carbon fertilization is weak, and agricultural yields in higher latitudes would be likely to peak. At 4°C warming agricultural yields would decline by 15 to 35 percent in Africa, and entire regions would move out of production (e.g., parts of Australia) (Stern Review 2006, 57).

Water stress is one reason for adverse agricultural effects. The review judges that already dry areas such as the Mediterranean basin and parts of southern Africa and South America would experience a 30 percent decline in water runoff for 2°C warming and 40 to 50 percent reductions for 4°C, although there would be increased water availability in South Asia and parts of Northern Europe and Russia. The review cites recent Hadley Centre results indicating that the proportion of land area experiencing extreme droughts would increase from 3 to 30 percent and that in Southern Europe 100-year severity droughts would increase to 10-year frequency with 3°C warming (Stern Review 2006, 62).

The review summarizes agricultural effects as follows:

> In tropical regions, even small amounts of warming will lead to declines in yield. In higher latitudes, crop yields may increase initially for moderate increases in temperature but then fall. Higher temperatures will lead to substantial declines in cereal production around the world, particularly if the carbon fertilization effect is smaller than previously thought, as some recent studies suggest (p. 67).

The review notes that whereas work based on the original predictions for carbon fertilization suggested rising yields for such crops as wheat and rice (but not maize) for 2°C to 3°C of global warming but declines once temperatures reach 3°C or 4°C, the "latest analysis from crops grown in more realistic field conditions suggests that the effect is likely to be no more than half that typically included in crop models." The review estimates that with weak carbon fertilization, worldwide cereal production declines by 5 percent for 2°C warming and by 10 percent for 4°C warming (with some entire regions potentially too hot and dry to grow crops in the latter case). At higher temperatures such as 5°C to 6°C warming, "Agricultural collapse across large areas of the world is possible . . . but clear empirical evidence is still limited." The review argues that previous crop studies using a quadratic functional form, as in Mendelsohn, Nordhaus, and Shaw (1994), which give a symmetrical reduction in yields for either temperature increases or decreases from the optimal level, tend to understate damage from warming. Recent studies suggest that instead the relationship is highly asymmetrical, with temperature increases above the optimal level "much more harmful than comparable deviations below it" (Stern Review 2006, 67).

The review considers that agricultural impacts will be strongest across Africa and Western Asia (including the Middle East), with crop yields falling 25 to 35 percent with weak carbon fertilization (and 15 to 20 percent even with strong carbon fertilization) once warming reaches 3°C to 4°C. It notes that because maize does not benefit much from carbon fertilization, maize-based agriculture in parts of Africa and Central America would likely suffer declines in yields.

The review takes note of studies that are optimistic about adaptation and incorporation of newly suitable land at high latitudes but points out that transition costs are often ignored and that population movements needed to realize such opportunities could be very disruptive. It adds that many existing estimates do not include the impacts of short-term weather events such as floods, droughts, and heat waves.

In its most specific summary agricultural estimate, the review cites the Parry, Rosenzweig, and Livermore (2005) analysis using Rosenzweig and Parry (1994) data to estimate that benchmark global warming of about 3°C would boost cereal production by 3 to 13 percent in developed countries, reduce it by 10 to 13 percent in developing countries, and cut global production by 0 to 5 percent in simulations of three climate models (GISS, GFDL, and UKMO). The review thus appears to judge the multicountry crop model results of the suite of studies reviewed above (Rosenzweig et al. 1993; Rosenzweig and Iglesias 1994, 2006) as still the most reliable despite numerous successive studies. The review does not mention the optimistic studies of Darwin et al. (1995) and Reilly et al. (2001) discussed above. Nor does it mention the country-specific estimates of Mendelsohn et al. (2000), whose results are reviewed in chapter 5 in comparison to the results of the present study.

Intergovernmental Panel on Climate Change (2007). Finally, as this study went to press, the IPCC released the policymakers' summary of its Working Group II contribution to the Fourth Assessment Report (IPCC 2007b), with release of the full report scheduled for later in the year. For agriculture, the report endorses the prognosis of modest initial gains followed by subsequent losses in the middle and higher latitudes but early losses in the lower latitudes. It states:

> Crop productivity is projected to increase slightly at mid to high latitudes for local mean temperature increases of 1–3°C depending on the crop, and then decrease beyond that in some regions. At lower latitudes, especially seasonally dry and tropi-

> cal regions, crop productivity is projected to decrease for even small local temperature increases (1–2°C), which would increase risk of hunger. Globally the potential for food production is projected to increase with increases in local average temperature over a range of 1–3°C, but above this it is projected to decrease. Adaptations such as altered cultivars and planting times allow low and mid- to high latitude cereal yields to be maintained at or above baseline yields for modest warming. Increases in the frequency of droughts and floods are projected to affect local production negatively, especially in subsistence sectors at low latitudes (p. 6).

In terms of vulnerable regions, the report notes that already "in the Sahelian region of Africa, warmer and drier conditions have led to a reduced length of growing season with detrimental effects on crops" (p. 4). It notes that as early as 2020, between 75 million and 250 million people in Africa are projected to be exposed to increased water stress from climate change.

> Agricultural production, including access to food, in many African countries and regions is projected to be severely compromised by climate variability and change. The area suitable for agriculture, the length of growing seasons and yield potential, particularly along the margins of semi-arid and arid areas, are expected to decrease. This would further adversely affect food security and exacerbate malnutrition in the continent. In some countries, yields from rain-fed agriculture could be reduced by up to 50% by 2020 (p. 10).

For other regions,

> crop yields could increase up to 20% in East and Southeast Asia while it [sic] could decrease up to 30% in Central and South Asia by the mid-21st century. . . . As a result of reduced precipitation and increased evaporation, water security problems are projected to intensify by 2030 in southern and eastern Australia. . . . Production from agriculture and forestry by 2030 is projected to decline over much of southern and eastern Australia. . . . In Southern Europe, climate change is projected to worsen conditions (high temperatures and drought) in a region already vulnerable to climate variability, and to reduce water availability. . . . In Central and Eastern Europe, summer precipitation is projected to decrease, causing higher water stress. . . . In Northern Europe, climate change is initially projected to bring mixed effects, including some benefits such as . . . increased crop yields. . . . However, as climate change continues, its negative impacts . . . are likely to outweigh its benefits." In North America, "Moderate climate change in the early decades of the century is projected to increase aggregate yields of rain-fed agriculture by 5–20%, but with important variability among regions. Major challenges are projected for crops that are near the warm end of their suitable range or depend on highly utilized water resources (pp. 11–12).

Unfortunately, the policymakers' summary is silent on the crucial question of recent scientific estimates of prospective carbon fertilization. It also tends to focus on the next few decades rather than the latter part of this century. Broadly, however, the report is consistent with the findings of this study.