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Introduction and Overview

In the long list of potential damages from global warming, the risk to world agriculture stands out as among the most important.[1] In the development of international policy on curbing climate change, it is important for policymakers to have a sense of not only the aggregate world effects at stake but also the distribution of likely impacts across countries, for reasons of equity.

This study seeks to sharpen understanding of the prospective impact of unarrested global warming on world agriculture for two reasons. First, there has been some tendency in the literature in the past decade toward the view that agricultural damages over the next century will be minimal and indeed that a few degrees Celsius of global warming would be beneficial for world agriculture. This study seeks to provide a rigorous and comprehensive evaluation of whether the aggregate global agricultural impact should be expected to be negative or positive by late in this century and of how large the aggregate impact is likely to be.

Second, there is relatively wide recognition that developing countries in general stand to lose more from the effects of global warming on agriculture than the industrial countries. Temperatures in developing countries, which are predominantly located in lower latitudes, are already close to or beyond thresholds at which further warming will reduce rather than increase agricultural potential, and these countries tend to have less capacity to adapt. Moreover, agriculture constitutes a much larger fraction of GDP in developing countries than in industrial countries, so a given percentage loss in agricultural potential would impose a larger propor-

1. Others include sea level rise, species loss, loss of water supply, tropospheric ozone air pollution, hurricane damage, impact on human health and loss of life, forest loss, and increased electricity requirements. For an early quantitative analysis, see Cline (1992).

tionate income loss in a developing than in an industrial country. This study seeks to provide more detailed and systematic estimates than previously available for the differential effects across countries, and in particular between industrial and developing countries.

To assess the impact of climate change on agriculture, it is essential to take account of the effects through at least the latter part of this century. A small amount of warming through, say, the next two or three decades might provide aggregate global benefits for agriculture (albeit with inequitable distributional effects among countries). But policy inaction premised on this benign possibility could leave world agriculture on an inexorable trajectory toward a subsequent reversal into serious damage. The delay of some three decades for ocean thermal lag before today's emissions generate additional warming is a sufficient reason not to stop the clock at, say, 2050 in an analysis of the stakes of climate change policy for world agriculture over the coming decades.[2] For this reason, this study chooses the final three decades of this century (the "2080s" for short) as the relevant period for analysis. Climate projections for several climate general circulation models (GCMs) are available for this period within the program of standardized analysis compiled by the Intergovernmental Panel on Climate Change (IPCC).

This study reaches two fundamental conclusions. The first is that by late in this century unabated global warming would have at least a modest negative impact on global agriculture in the aggregate, and the impact could be severe if carbon fertilization benefits (enhancement of yields in a carbon-rich environment) do not materialize, especially if water scarcity limits irrigation. This finding contradicts optimistic estimates such as those by Richard Tol (2002) and Mendelsohn et al. (2000), who find that baseline warming by late in this century would have a positive effect on global agriculture in the aggregate (discussed later). Moreover, in the business as usual baseline, warming would not halt in the 2080s but would continue on a path toward still higher global temperatures in the 22nd century, when agricultural damages could be expected to become more severe. The second broad conclusion is that the composition of agricultural effects is likely to be seriously unfavorable to developing countries, with the most severe losses occurring in Africa, Latin America, and India. Although past studies have tended to recognize that losses will tend to be concentrated in developing countries, this study provides more comprehensive and detailed estimates on such losses than previously available.

2. Warming at the ocean's surface is initially partially dissipated through heat exchange to the cooler lower layers of the ocean. Only after the lower levels warm sufficiently to reestablish the equilibrium differential from the surface temperature does the "committed" amount of warming from a given rise in carbon concentration become fully "realized."

Main Features of the Book

The principal features of this study that distinguish it from previous analyses include the following: First, this study provides unusual geographical detail. The estimates are obtained in a systematic methodology for more than 100 countries, regions, and regional subzones of the largest countries. In contrast, previous studies have tended either to provide global estimates with breakdowns only by a few large regions (often continental) or to focus on one or more specific countries without developing comparable estimates for other countries and regions.

Second, there is a direct link from the GCM estimates to highly detailed country climate change estimates. In contrast, other studies have often tended to prepare country models for agricultural impact functions but then apply broad hypothesized changes in temperature and precipitation to illustrate but not formally quantify the corresponding climate change impacts on agriculture.

Third, this study uses a central or "consensus" climate projection approach. Many studies instead show a wide range of climate outcomes. Although for some purposes it is desirable to consider such ranges, they tend to leave the diagnosis so ill-defined that they risk policy paralysis. The experience of the past two decades shows that a wide spectrum of estimates tends to be invoked as evidence that there is too much uncertainty to warrant action, even though in principle greater uncertainty could justify greater action if policymakers are risk averse.

Fourth, this study seeks a preferred synthesis of the two main families of quantitative estimates: summary statistical "Ricardian" models and detailed crop process models. This approach permits a more balanced set of estimates than applying models from one family to the exclusion of the other.

It should be noted at the outset that the estimates developed in this study would not have been possible without the benefit of the previous contributions of researchers who developed the agricultural impact models applied. In particular, they include Robert Mendelsohn in the Ricardian school and Cynthia Rosenzweig in the crop model school.

Plan of the Book

Chapter 2 briefly surveys the findings of several leading existing studies on the agricultural impact of climate change. Chapter 3 discusses three fundamental issue areas: carbon fertilization, irrigation, and induced effects from international trade. Gauging the influence of higher atmospheric concentrations of carbon dioxide on crop yields ("carbon fertilization") is crucial to arriving at meaningful estimates of agricultural impact.

Impact estimates may be unduly optimistic if they fail to adequately account for additional irrigation requirements, or if they rely on statistical models that conflate benefits from warmer climates with the greater incidence of irrigation in such climates. Studies that incorporate induced effects of world trade may give an unduly benign view of the impact of global warming by reducing estimated output losses without calculating the additional costs or considering the ability of poor countries to pay for additional food imports.

Chapter 4 develops the baseline projections of temperature and precipitation used in this study. These are business as usual projections premised on the absence of serious international programs of emissions taxes or restraints. They therefore provide a benchmark for judging the possible damages from inaction and hence benefits of abatement. As set forth later, both the baseline emissions scenario chosen and the set of GCMs for which projections are available should be seen as intermediate rather than extreme at either the high or low end.

It is well known that there is less agreement among the GCMs about climate change prospects at the regional level than at the global level. This study seeks to overcome this problem by taking the average across six GCMs of detailed geographical results on future climate change. The principle for policymaking should not be to ignore the country-specific profile of climate effects because there is uncertainty but to take the best central estimate available, which in the absence of quality weightings by GCM will simply be the average.

This approach nonetheless requires overcoming two important obstacles. First, each GCM has a different "grid resolution," or size of geographical unit with specific results (measured in degrees of latitude height and longitude width of the grid cells). Second, even for a single model, results typically are not mapped to countries. This study converts individual GCM results to estimates at a standardized global grid resolution (90 latitude cells of 2° height by 120 longitude cells of 3° width), as discussed in appendix A, and maps these standardized cells into corresponding national territories, as discussed in appendix B.

Chapter 5 then turns to the application of the projected climate changes to two frameworks of models of agricultural impact to estimate the corresponding prospective effects for agricultural capacity by country, regional grouping of smaller countries, or subnational zones of the largest countries. The first is a family of "Ricardian" or cross-section models relating agricultural capacity statistically to temperature and precipitation on the basis of statistical estimates from farm survey or county-level data across varying climatic zones. The classical economist David Ricardo developed the theory that the value of land depends on the difference between its fertility and that of the least fertile land just brought into cultivation at the margin. The seminal Ricardian agricultural impact model (Mendelsohn, Nordhaus, and Shaw 1994) argued that statistical regressions relating land values to climate differences could capture the impact of climate on agricultural productivity and thus be used to calculate prospective effects of global warming.

Model estimates in this family are available for the United States (Mendelsohn and Schlesinger 1999), Canada (Reinsborough 2003), many countries in Africa (from the World Bank farm surveys reported in Kurukulasuriya et al. 2006), major countries in Latin America (also from World Bank farm surveys; see appendix G), and India (Mendelsohn, Dinar, and Sanghi 2001). These country-specific models in the first framework are applied to countries accounting for 35 percent of global agricultural output and about half of the number of countries. Where country-specific studies are not available, the estimates apply the Mendelsohn-Schlesinger Ricardian model for the United States to the climate estimates for the country in question. However, in these cases the weighting given to the Ricardian estimates in arriving at the final preferred estimates is reduced and the weighting of crop models is increased, because of the considerably lesser reliability of US model parameters when applied to other countries.[3] The Mendelsohn-Schlesinger Ricardian results are also used in chapter 5 to investigate the sensitivity of results to variability among the six climate models used.

Chapter 5 then turns to the second framework for the impact estimates, which consists of region-specific calculations synthesized from estimates by agricultural scientists in 18 countries as applied to alternative GCM projections of climate scenarios (Rosenzweig and Iglesias 2006, Rosenzweig et al. 1993). This framework is based on crop models and may thus be seen more as a set of input-output process calculations, in contrast to the approach of indirect inference of climatic effects using the Ricardian land value approach. For the United States, Mendelsohn and Schlesinger (1999) also provide a reduced form impact equation summarizing crop model results. Regional estimates within the United States are obtained by applying this model to the corresponding climate estimates. The overall crop model estimates for the United States are then obtained as the simple average of the Rosenzweig-Iglesias and Mendelsohn-Schlesinger estimates. For all other countries the crop model estimates are from Rosenzweig and Iglesias (2006).

A synthesis of these two sets of estimates then provides the basis for the preferred estimates of this study. Together the Ricardian and crop model frameworks should provide a relatively comprehensive basis for evaluating the impact of global warming on agriculture. This study does not use the third approach that has sometimes been applied. This approach categorizes existing land area by land "types" with related productive potential and investigates the change in the distribution of these categories

3. See, for example, the discussion of Ricardian estimates for the United States versus Canada later.

as a consequence of global warming. As discussed later, Darwin et al. (1995) apply this approach. However, both the specific results of that study and more fundamentally the underlying concept (which in the case of the Darwin et al. study uses length of growing season as the key determinant for categorization) seem considerably less reliable than the Ricardian and crop model approaches used in this study. Chapter 5 concludes with a comparison of the estimates in this study with impact estimates from some of the underlying model studies themselves.

Chapter 6 turns to dynamic considerations, in particular the question of whether technological change can be expected to be so rapid and profound that policymakers should not worry about possible adverse effects of global warming on agriculture because such effects will simply be swamped by gains from improved varieties and other technological changes. Chapter 7 presents this study's principal findings and policy conclusions.

The appendices first discuss the climate projections: the method for converting different climate model results to a standardized grid (appendix A), the method for translating the standardized results into country-level estimates (appendix B), and the method of calculating grid land area at different latitudes (appendix C). They next present detail on the definition of the regions and subzones in this study (appendix D) and on the development of the database on agricultural land and output (appendix E). Country results are then presented in detail for the Mendelsohn-Schlesinger models as applied in the present study (appendix F), and further detail is provided on the parameters of the India, Africa, and Latin America models (appendix G). Appendix H reports the present and future temperature and precipitation estimates by country in monthly detail, and appendix I reports the analysis of the degree of dispersion across GCMs in future climate projections.