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Impacts of Global Warming on Agriculture

The full and proper name for us is *Homo sapiens sapiens*, a kind of taxonomic stutter meaning 'double-wise man'. (James Shreeve, *The Neandertal Enigma*, p. 8)

INTRODUCTION

As Shreeve (1995) goes on to point out, our genus *Homo* includes several species that coexisted in pre-history 'carry[ing] no wisdom at all in their names' (p. 9). Are we now wise enough to recognize the bounds of our knowledge, our ignorance? There is the story of the drunk looking for car keys under the street lamp, rather than back in the alley where he heard them drop in the dark. When asked why he was looking in the wrong place, he replied that he could only look where he could see.

The best work done to date to illuminate future patterns of warming couples ocean and air general circulation models (GCMs) of the globe to project regional climates, based upon the assumption that the ambient concentration of CO_2 equivalent gases will double from the level before the Industrial Revolution, causing the radiative forcing of the atmosphere to increase (IPCC, 1996). Using their output from the GCMs as input for crop simulation models (CSMs), Rosenzweig and Parry (1994) and Adams *et al.* (1988, 1990, 1995a, 1995b) have projected the changes in regional potential yield and product; Adams *et al.* (1995b) include wheat, corn, soybeans, oranges, tomatoes, pasture, range land and livestock. Using output from CSMs as input to non-linear programming models of the United States and models of international agricultural trade, they have estimated changes in the net producer and consumer surpluses from a doubling of CO_2 equivalent gases. But there is no reason to expect that the ambient concentration of gases will double from our economic activities. A doubling will simply be a transitory state during a rapid expansion to well beyond that level.

Less compelling is the work by Mendelsohn *et al.* (1994), Williams *et al.* (1996), and Mendelsohn and Nordhaus (1996), who use a quadratic function to regress about 300 cross-section county land values (land and buildings per acre) on 30-year weighted (by location of weather station) county averages for temperature and precipitation (January, April, July and October), and on county averages for soil type (sand, clay, moisture capacity, permeability), physical

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characteristics of the land (solar flux – latitude, altitude, salinity, flood-prone, wetland, soil erosion, slope length), income per capita and population density. The regressors are in deviations from the mean. They use weighted least squares, so their model is given by

$$Y_i / w_i = \alpha / w_i + \beta X_i / w_i + \varepsilon_i / w_i \qquad (1)$$

They propose two sets of weights, based on cropland or on revenue. The cropland weights are county agricultural land as a percentage of total land in the county. The crop-revenue weights are county agricultural revenue as a percentage of total US agricultural revenue. Mendelsohn *et al.* (1994) then forecast land values, given an increase in temperature of 2.78°C and rainfall of 8 per cent, uniformly across the United States and uniformly across the seasons. The change in land values is their estimate of the impact on land rent from a doubling of CO_2 equivalent gases. Williams *et al.* (1996) extend this analysis by forecasting the change in land values based upon temperature and precipitation data forecasts that vary by region and season, where the weather data are forecasts from 16 GCMs calibrated for a doubling of CO_2 equivalent gases. Among other problems with this general approach, a doubling will simply be a transitory state during a rapid expansion to well beyond that level.

Figure 1 presents three projections of atmospheric CO_2 concentrations (in ppmv). Each one is a combination of one of three models of the economy (Nordhaus and Yohe, 1983; Reilly *et al.*, 1987; Manne and Richels, 1990); one of three assumptions about the amount of economically available coal (from

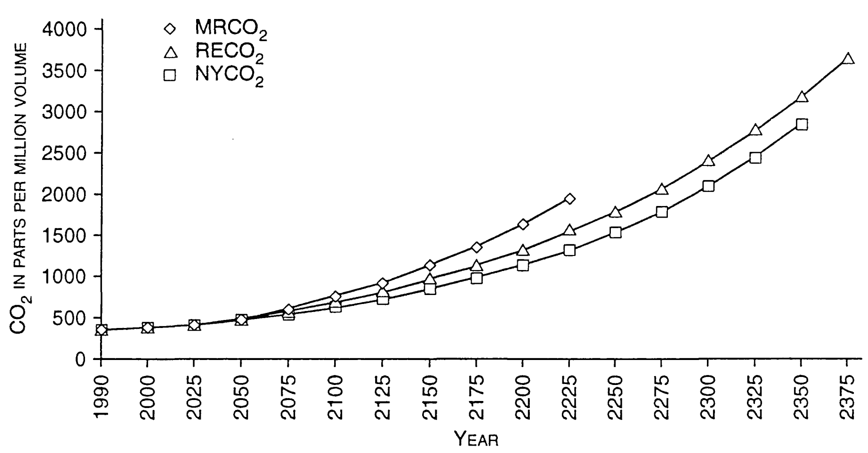

FIGURE 1 *Ambient CO_2 for three scenarios without policy intervention*

Edmonds and Reilly, 1985); and one of three assumptions relating to the sensitivity of climate to a doubling of emissions. The high, mid-range and low projections assume that the economically available coal reserves, respectively, are 20 000, 15 000 and 9500 gigatons (gt.). The computations follow those of Cline (1992). The ambient concentration of CO_2 is projected to rise from that of about 350ppmv in 1990, to a range of values: for the three projections, 1925, 2830 and 3635ppmv, increases of 550, 800 and over 1000 per cent. This is why analysis based upon a doubling of gas concentrations is like the drunk looking for his keys under the street lamp.

The IPCC (1990) report concluded that a doubling of emissions would increase the mean global temperature in the range of 1.5 to 4.5°C, with a mid-range value of 3.0 to 3.5°C. Lags between emissions and changes in equilibrium global temperature and the effects of aerosols, which are emitted when coal is burned (among other sources), help to explain discrepancies between actual temperature today and GCM projections of what should have occurred as a result of the emission of gases since the Industrial Revolution. The IPCC (1996, WG I, p. 39; WG III, p. 188) report suggests that there may be a transient effect which has lowered the sensitivity of warming to the range of 1.0 to 3.5°C, with a mid-range of 2.0°C. In their reply to Cline (1996), Mendelsohn and Nordhaus (1996) justify having used too low a temperature increase (2.78°C) relative to the mid-range values of 3.0 to 3.5°C as a downward adjustment of the warming to account for aerosols, although this adjustment is transient because the aerosols are not long-lived like CO_2. With a downward adjustment of Cline's (1992) computations, the warming for the three scenarios is projected in Figure 2 (Hall, 1996a). Since the transient nature of aerosols is ignored, downward adjustment makes these projections too low.

Figure 3 juxtaposes the mean global temperature of the last quarter-million years with a conditional prediction of the next two to four hundred years. The basis for the prediction is that we continue to use the economically available fossil fuels, rather than fashioning policies to bear the expense of research, development and substitution of alternative energy technologies for fossil fuels. Figure 3 shows the bounds of our ignorance. During the last quarter-million years, *Homo sapiens* evolved into *Homo sapiens sapiens*. Our species has experienced neither the abruptness nor the magnitude of the warming to come.

Over the last 5 million years, the ecosystem in Africa shifted from woodlands to grasslands, and the first hominids emerged, including *Australopithecus*, branching into *Homo*. Looking back in time even that far, the earth did not experience a climate as warm as the mid-range projection in Figures 2 and 3. The 'geo-economic time frame' (Hall, 1996a), when the earth was as warm as projected in Figure 2, extends back 50 to 100 million years to the Cretaceous period, the age of dinosaurs (Crowley, 1996). It is in this context that I will risk illuminating the impact of global warming on agriculture.

The pathways through which global warming is expected to affect agriculture, and adaptations expected to mitigate the impacts, are discussed in the next section. It is followed by a summary of the results of a few of the better known estimates of the impact on agriculture from a doubling of CO_2 equivalent gases. These are the comparative static analyses noted above. The approach by Mendelsohn and Nordhaus cannot be extended to a comparative dynamic

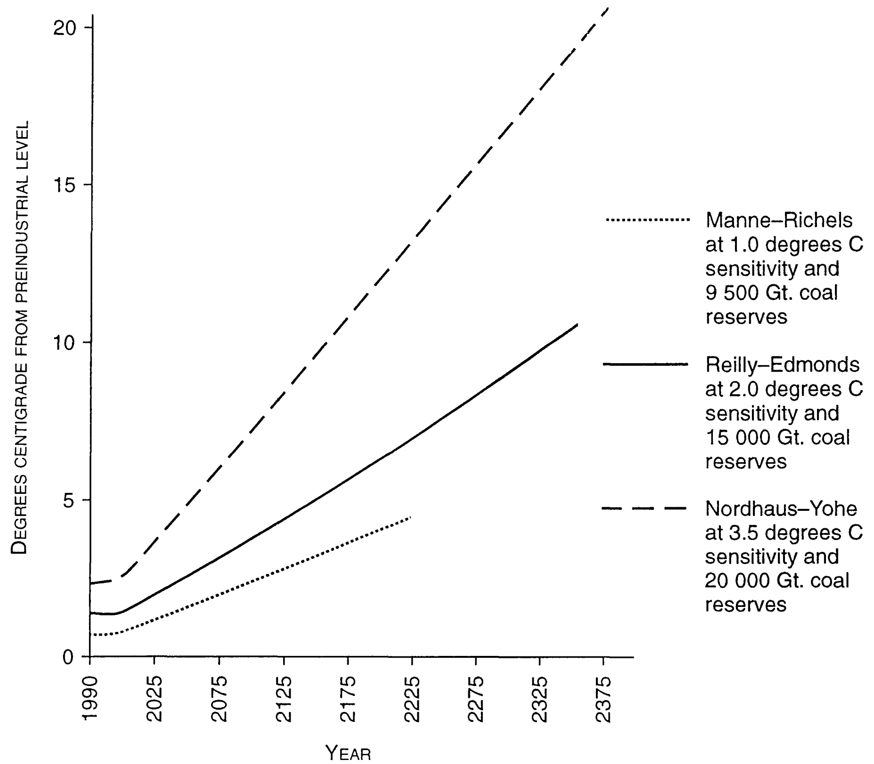

FIGURE 2 *Mean global temperature increase*

Note: Based upon the IPCC sensitivity of 1.5°C to 4.5°C, Cline (1992) extended three models (Manne and Richels, 1990; Nordhaus and Yohe, 1983; Reilly *et al.*, 1987) to the next 375 years. This figure adjusts down Cline's analysis to account for the lower sensitivity of an increase between 1.0°C and 3.5°C for a doubling of warming gases in the atmosphere. The computations follow those of Cline (1992).

analysis, but the approach by Rosenzweig and Adams can. Later the work of Adams *et al.* (1995b) is extended to regimes beyond a doubling, presenting the comparative dynamics in the form of time paths projecting the impact on agriculture from anthropogenic increases in greenhouse gases. Possible outcomes are illustrated, though it is next argued that the outcomes are optimistic.

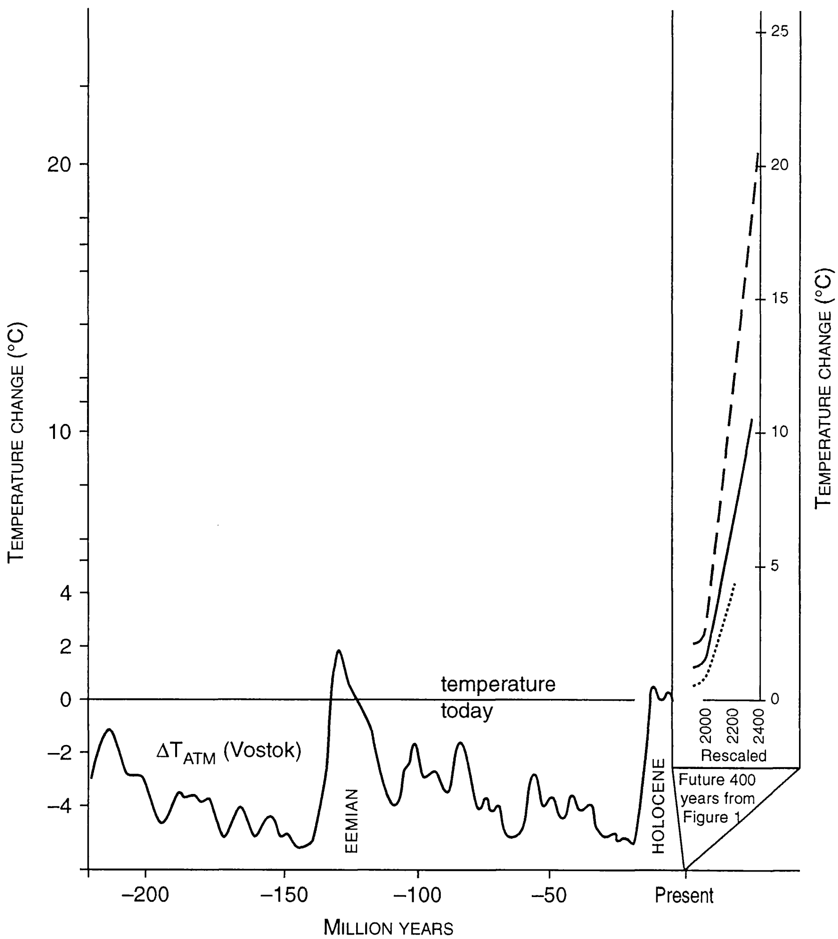

FIGURE 3 *Past and future mean global temperature*

Source: Adapted from IPCC (1996) and Figure 1.

PATHWAYS OF EFFECTS AND ADAPTIVE RESPONSES

The impact of global warming on agriculture stems from effects on the process of photosynthesis (Rich, 1996; Rosenzweig and Hillel, 1995). In very broad outline, the Calvin cycle is one in which plants draw moisture and nutrients from the soil. Atmospheric CO_2 passes through stomata in the leaves and combines with water to produce carbohydrates (sugar, starches and cellulose). The green colour in plants comes from chlorophyll molecules, similar to haemoglobin that gives blood its red colour, which are made of proteins. Amino acids are the primary units of proteins. Each amino acid has at least one carboxyl (COOH) group, which is basic, and the acid, or amine, is derived from ammonia, NH_3. Chlorophyll molecules are arranged in chloroplasts (organelles inside plant cells), which contain manganese, sulphur, iron, copper and phosphorus, in combination with other essential elements necessary for photosynthesis. Within chlorophyll molecules, light is altered to produce an electric charge. In the presence of CO_2, H_2O is broken down by electrolysis, and the result is sucrose, starches and oxygen. An oversimplified model is given by $6CO_2 + 6H_2O = C_6H_{12}O_6 + 6O_2$. Oxygen and water are transpired through the stomata.

The opposite of photosynthesis is respiration. For energy, animals burn sugar; oxygen is combined with hydrocarbons, releasing energy and CO_2. Plants use energy to draw water and nutrients from the soil, to grow and reproduce, to store energy, and in the process of photosynthesis. Photorespiration decreases the efficiency of photosynthesis, particularly at high temperatures, or when a plant is water-stressed and the stomates close to avoid loss of water by transpiration. Nutrients from the soil include nitrogen, phosphorus and potassium. When plants die, some of the carbon originating from the atmosphere is sequestered underground in the form of hydrocarbons. Fossil fuels contain atmospheric CO_2 from billions of years of photosynthesis; the atmosphere now has significantly more oxygen and less CO_2 than it once had.

Within the next 200 to 400 years, we can release billions of years' worth of stored carbon by burning coal. As atmospheric CO_2 rises, the stomata do not have to open as wide for plants to obtain it for photosynthesis. Consequently, less water is transpired. Soil moisture is used more efficiently, with less lost to the atmosphere from transpiration. So there is a beneficial interaction in the productivity of water and ambient CO_2. If nutrients and soil moisture are available, photosynthesis should increase, with a higher concentration, which is the CO_2 'fertilization effect' that is expected to accompany global warming. However, increased cloud cover would be expected to reflect and reduce the solar radiation, reducing the amount of light available for photosynthesis.

Plants, which have adapted the process of photosynthesis to different climates, are categorized by the number of carbon atoms that are fixed in the first stage of photosynthesis. C3 crops include wheat, rice, soybeans, fine grains, legumes, root crops and most trees. They should benefit most from CO_2 fertilization. Many tropical and subtropical plants in the C4 category (corn, sorghum, sugarcane, millet) have adapted to the heat by fixing carbon at night, and closing the stomata during the day.

As the global temperature increases, the growing season will increase in mid- and high-latitude regions, which should increase yields for small increases in temperature. At the same time, plant growth cycles will speed up, with an adverse effect on yield. At higher temperatures, photorespiration will reduce yields. Depending on the ability of soil types to hold and retain moisture, moderate increases in precipitation will improve yield. Even under optimal conditions, at some level further precipitation decreases yield, owing to root rot and interference with nutrient uptake.

Farmers have learned to adapt crops to different regional climates with pesticides, fertilizers and irrigation. We can expect that, as climate changes, regional and international trade will allow shifts of crop production to those regions where they are best suited. Regions now not suitable for growing crops will become major centres of production, and crop migration will occur to the extent that soils and terrain are suitable. Over time, countries with significant research infrastructure will develop crop varieties to take advantage of higher CO_2 concentration, to withstand higher temperatures and better fit changes in the growing season, and to adapt to water stress in regions with less precipitation.

UNDER THE STREET LAMP

It is believed that a doubling of emitted gases may be beneficial for the United States and other mid-latitude countries, but horrific for some developing poor countries. In their excellent article, Rosenzweig and Parry (1994) estimate the worldwide number of people at risk of hunger, accounting for food prices and income relative to nutritional requirements, as a result of global warming from a doubling of CO_2 equivalent gases. Their estimates are based on crop simulation models applied and calibrated for 18 countries and regions worldwide. The CSMs account for increased rates of photosynthesis and reduction in stomata reported from laboratory experiments, where plants are provided with ideal combinations of water and nutrients to maximize the benefit, as well as for temperature increases that can alter the period of the growing season, shorten the time during crop development stages and cause heat and water stress. The CSMs also incorporate the impact of precipitation on yields and deal with the impact of seasonal and geographic changes in temperature and precipitation, as well as looking at the effects of increasing ambient CO_2, based upon forecasts from three GCMs. Farm-level adaptations appear which involve altering planting and harvesting dates, crop and variety switching, and applications of fertilizer and irrigation in response to changes in precipitation. World trade is incorporated using a linked set of 34 economic models in a general equilibrium system, linking trade, prices and financial flows. In order to compare situations 'with' and 'without' global warming, growth rates for population, GDP and crop yield are used to estimate a base case for the year 2060, when a CO_2 equivalent doubling is forecast to occur. The mean global temperature increases from the GCMs are 4.2, 4.0, and 5.2°C, with growth in average global precipitation of 11, 8 and 15 per cent, respectively.

Depending on the GCM forecast, world cereal production falls between 11 and 20 per cent, but most of these losses are made up through CO_2 fertilization, and a small additional mitigation is achieved through adaptation. The distribution of effects, however, adversely affects 60 to 360 million additional people who are at risk of hunger. Even so, the predictions are optimistic in several respects, which Rosenzweig and Parry carefully acknowledge. A review of the logic underpinning the economic calculus reveals the nature of the optimism.

Mendelsohn *et al.* (1994) use cross-section data and regress farm land value on temperature and rainfall, using a quadratic function to capture the possibility that, beyond some temperature and rainfall, the third stage of production may be reached, with detrimental effects. Using the least squares technique shown in equation (1), they estimate that global warming will increase land rent when the analysis is based on crop revenue weights. These are claimed to be superior to the cropland weights, use of which suggests that global warming will decrease land rent. The estimated rent is taken to be the present value of future producer surplus, in what is termed a 'Ricardian approach'.

Cline (1996) criticizes Mendelsohn *et al.* (1994) for 'seriously understating greenhouse damage for three main reasons': the conceptual framework, infinitely elastic supply of water at today's prices and the assumption that mean global warming and precipitation is uniform across the United States at only 2.78°C for a doubling. Cline expands the 'conceptual framework' criticism by suggesting that (1) the Ricardian approach is 'a partial equilibrium analysis that assumes relative prices are unchanged' and food demand is inelastic, and (2) the Ricardian model implicitly assumes that, as US grain production declines, somewhere else in the world there is an equivalent increase.

Mendelsohn and Nordhaus (1996) respond first by calculating the percentage of bias introduced by ignoring demand and supply elasticity, showing that only if demand is highly elastic and supply highly inelastic will the bias be large. For inelastic demand, the bias is less than 2.3 per cent for a 25 per cent reduction in yield. They ignore the criticism that grain production needs to come from somewhere. In their second riposte, Mendelsohn and Nordhaus claim that Cline is wrong about the infinitely elastic supply of irrigation water. The Ricardian approach implicitly assumes that land value reflects cross-sectional water availability conditioned on existing precipitation and temperature across countries. So a hotter, drier climate produces water availability that mirrors the amounts available in the hotter, drier western United States today. This is a weak response. When El Niño sends warm storms to California, the snow melt can double or even triple the water flow, so that reservoirs cannot be kept filled to provide summer irrigation because a reserve capacity must be maintained for flood control. Since the snow is melted by the storms, it turns to storm run-off, losing that means of storing water on the mountain tops. The marginal cost of water is steep in the southwestern United States (Hall, 1996b) and clearly shifts upward with warming.

Mendelsohn and Nordhaus then cite Williams *et al.* (1996) in response to Cline's third criticism. Williams *et al.* re-estimate quadratic equations using cross-section data in the same manner as Mendelsohn *et al.* (1994). They regress county land values on weather, soil and socioeconomic variables, using weighted regression as given in equation (1) above, with quadratic forms. Then they estimate the impact of global warming on land rent, using the seasonal and regional dispersed temperature and precipitation changes from 16 GCMs. The average of those results differs slightly from the original results in Mendelsohn *et al.* (1994). There is an increase in revenue-weighed results over their original values, with a decrease in cropland-weighted results. In their reply to Cline, Mendelsohn and Nordhaus (1996) claim, 'the average results from the GCMs are consistent with a uniform change scenario of 4.5°C, which is the average predicted temperature change from these global climate models' (p. 1313). This is a misleading claim: the mean global temperature increase in the 16 GCMs averages less than 3.5°C, according to my calculation from the Appendix of Williams *et al.* (1996). Perhaps Mendelsohn and Nordhaus (1996) are referring to the average increase in the United States, a mid-latitude country which is expected to warm by more than the global average.

Mendelsohn and Nordhaus (1996) also point out that their favourable results could be even better because of the moderating influence of aerosols on temperature, and the benefits of CO_2 fertilization. While it is true that aerosols will moderate temperature in regions that burn coal and have high levels of tropospheric air pollution, it is also true that sulphur compounds and ozone reduce agricultural yields (Adams, 1986). Moreover, the effect of aerosols on cloud formation and precipitation affects solar flux and soil moisture, with impacts on photosynthesis. It is not clear that, on the balance of effects, aerosols will increase yields. Most importantly, the 'Ricardian approach' they use cannot be adjusted to capture the important effects of soil moisture, solar flux and CO_2 fertilization. This weakness is critical, since Rosenzweig and Parry (1994) have shown that fertilization is more important than adaptation, the sole claim of superiority of the 'Ricardian approach'.

Finally, Mendelsohn and Nordhaus (1996) cite Reilly's (1996) survey which argues that, compared with earlier estimates from CSMs, the later results based on CSMs with adaptation have results closer to those of Mendelsohn and Nordhaus. They cite Adams *et al.* (1995b) as an example. The logic behind the Ricardian approach is that farmers adapt their methods and techniques to different local climate conditions, just as farmers will adapt to future climate change. I agree that farmers will adapt to future climate change, but not in the ways that farmers adapt to local climate conditions. For example, if the grainbelt becomes hot and dry, the models of Mendelsohn *et al.* predict that the central portion of the United States will have land values like portions of Arizona and Texas, where cotton is produced. We will have plenty to wear and houses in which to retire, but nothing to eat. Mendelsohn *et al.* (1994) do not account for demand, our preference for a varied diet. According to these comparative static, Ricardian models, we will also be able costlessly to build irrigation systems in the grainbelt and operate them as we do in Arizona and California today. For example, when the ambient concentration of CO_2 equivalent gases quintuples, as opposed to doubling, land values will plummet to levels now prevailing in Central America, but Mendelsohn *et al.* omit that possibility. Williams *et al.* (1996) complain that regression coefficients show that land values are sensitive to August precipitation rates, particularly in the grainbelt, so aggregation of economic impacts using acreage as weights gives large damages for some GCM climate forecasts. But GCMs do not project the frequency of droughts or monsoons as a function of global warming. 'Ricardian models' forecast minimal damage from global warming, while failing to consider the essential elements that will determine the outcome.

There are three further criticisms of the work done by Mendelsohn and Nordhaus. One is that the weights chosen for equation (1) must not be correlated with the dependent variable, or they will introduce bias in the estimates. Indeed, crop revenue is correlated with land rent. Only expensive items like strawberries are grown near urban centres, while the last bit of speculative value is wrung from the land. The crop revenue weights introduce bias in the estimation. Interestingly, the results from the crop revenue approach are consistently different from the coefficients estimated using cropland weights. In fact, the estimated impact from global warming is negative using the latter weights, and positive using the former.

The second criticism is that land rents capture producer surplus. Global warming can reduce yield, increasing producer surplus, but reducing total surplus, a well known and well studied phenomenon in agriculture. The third and most important criticism is that the Ricardian approach has nothing to say about dynamics. What we want to know is the impact of global warming on agriculture. A comparative static analysis could answer the hypothetical, 'What if global warming were imposed on agriculture today and the agricultural industry were able to respond instantaneously and move to a new equilibrium?'

It is not enough to say that research and development will allow us to adapt to warming. Presumably, without warming, research and development would continue to improve yields. We want to estimate the impact of warming, not compare agriculture today with a warmer future. A second comparative static analysis could answer the hypothetical, 'What if global warming were imposed on agriculture between now and the year 2060 and the agricultural industry were over time able to respond and move to a new equilibrium?' That is what Rosenzweig and Parry (1994) do. Their counterfactual requires the construction of an estimate of agricultural surplus without warming, to compare it with agricultural surplus with warming.

In summary, the only advantage of the Ricardian approach is that it captures the effect of adaptation. It does not account for international trade, CO_2 fertilization or dynamics. In comparison, Mendelsohn and Nordhaus (1996) acknowledge that the alternative approach of linking CSMs with models of the agricultural economy has now captured adaptation and has results comparable to their own. They cite Adams *et al.* (1995b) as an example. This latter approach can account for international trade and CO_2 fertilization, and can be extended to comparative dynamics.

A comparative dynamic analysis can answer the question we are really interested in, without straining reason by ignoring global warming after the year 2060. The Ricardian approach forces the analyst to forget that a doubling of CO_2 equivalent gases will simply be a transitory state during a rapid expansion to well beyond that level. Intoxicated with analytical and computational prowess, the analyst ignores the fundamental feature of global warming, which is a continual, though potentially discontinuous, change. A Ricardian analysis, based upon a doubling of CO_2 equivalent gases, is like the drunk looking for his keys under the street lamp.

IN THE DARK ALLEY WITH ROSE-COLOURED GLASSES

In this section, I use data generated by Adams *et al.* (1995b) to study the comparative dynamics of the impact of global warming on US agriculture. I first discuss the work by Adams *et al.* and how they generated the data. Then I estimate a dynamic representation of agricultural surplus that depends on the time path for climate change. I previously adjusted Cline's (1992) analysis, lowering the projected mean global temperature to account for aerosols (Hall, 1996a). Using these projections of climate, I calculate time paths for agricultural surplus, with and without climate change.

The Adams *et al.* (1995b) report is the culmination to date of their previous work (Rosenzweig and Parry, 1994; Adams *et al.*, 1988, 1990, 1995a). Their approach is to combine GCMs with dynamic growth CSMs, and introduce changes in crop yields into an economic quadratic programming model. They compare regional climate predictions from different GCMs, to consider the possibilities of a milder, wetter climate compared to a drier, hotter climate. The CSMs were originally for soybeans, corn and wheat (Adams *et al.*, 1990), but later (Adams *et al.*, 1995b) cotton, potatoes, tomatoes and citrus fruit, forage and livestock were added. The CSMs account for solar radiation, precipitation, temperature, soil properties that capture moisture, and the enhanced yield 'fertilizing effect' of increased carbon dioxide in the atmosphere. The results from the CSMs are extrapolated to other crops in the economic model.

In their update, Adams *et al.* (1995a) correct their previous analysis to account for the difference between ambient CO_2 and a CO_2 equivalent doubling, a correction discussed in Cline (1992). They clarify that the convention of a doubling is from the pre-Industrial Revolution level of 280ppmv. The GCM studies vary in the level of CO_2 equivalent increases, from 600ppmv to 640ppmv. They perform a sensitivity analysis of the CO_2 fertilization effect, considering no increase in ambient CO_2, an increase to 440ppmv, and an increase to 555ppmv. For reference, in 1990 the level was 353ppmv.

Adams *et al.* (1995b) consider 64 climate configurations: precipitation changes (–10, 0, 7 and 15 per cent), temperature changes (0, 1.5, 2.5 and 5.0°C) and ambient CO_2 fertilization (355, 440, 530 and 600ppmv). Each configuration is assumed to spread uniformly across the United States. For each region, they change present climate data by these amounts and run the crop simulation models. In addition, they run the CSMs for regional climate changes predicted by two GCMs.

The CSMs project the impact of warming, depending on the agricultural product (Adams *et al.*, 1995b). The speed of wheat, corn and soybean crop development increases with temperature, causing yield decreases and higher water demand. Increases in ambient CO_2 decrease water demand by increasing the efficiency of water use. Cotton has decreased yield from temperature, since it reaches maturity in fewer days, but increased yield from precipitation. For irrigated areas, no change in cotton yield is expected from changing precipitation. Similarly, potatoes, tomatoes and citrus fruits are modelled to have no effect from precipitation since they are irrigated. Increases in citrus yield were assumed, although the reason is 'poorly substantiated in the present literature' (ibid., p. 10). Temperature decreases citrus yield in the south and increases yield in the north because of the loss of a suitable dormant period, but the sandy soils do not exist in the north, constraining potential migration. Potato yields fall with temperature, and rise with CO_2. Tomato yields increase with CO_2 and with temperature up to +1.5 to 2.5 degrees, then fall.

Adams *et al.* use two CSMs for forage production and livestock, one for the more arid west of the United States and another for the east. These were calibrated for various locations, using existing weather data to get a baseline prediction and then modifying the amounts of precipitation and temperature. For example, changes in precipitation were 'applied uniformly to each monthly value' (ibid., p. 16). The impacts varied by location, generally with increases in precipitation and CO_2 fertilization raising yields, but with mixed effects for temperature, depending on the existing level and the size of the increase. On balance, increases in yields are predicted; where there were reductions they were small reductions (ibid., p. 15), but in other locations rather large increases are projected, depending on the climate configuration. Direct effects on livestock include appetite-suppressing temperature increases, and decreased energy needed in the winter to stay warm. On balance, livestock production falls.

Adams *et al.* allow for changes in technology and adaptation. There will be adjustments to warming. Research will develop heat and drought-tolerant varieties, while farmers will adjust inputs and the timing of planting and harvesting. Crop migration may occur unless constrained by soil barriers that cause significant yield losses. Adams *et al.* rely on time-series regression to relate improvements in yields over time and with crop migration, with cross-section regression accounting for adjustments and adaptation of farmers to regional differences. The crop simulation results are compared with the regression of county yield on temperature and precipitation. Yields do not fall as much with increases in temperature (but that could be due to correlation with solar radiation). For some regions, wheat yields rise and then fall with temperature. Regressions show yields rising with precipitation, but not by as much as projected by CSMs. Yields fall with April precipitation, reflecting the monsoon effect. Intense precipitation damages crops. On the basis of their examination of these results, Adams *et al.* assume that at least 50 per cent of the damage from 2.5°C mean global warming can be mitigated through soil amendments, irrigation, crop migration and technological change. For 5°C, they assume 25 per cent mitigation of yield losses.

The economic model accounts for differences in crop demand, precipitation, costs of surface and ground water, crop selection to maximize consumer and producer surplus, costs of feed for livestock as a secondary industry, plus regional and international trade. It allows for future trends of basic variables, based upon those over the past 40 years, to account for increase in demand through population growth, quantities of inputs, and import levels and supplies. Inputs are adjusted to account for changes in yields over time. Forecasts are developed for the years 1990 and 2060, with and without the effects of climate change discussed next.

The authors then calculate net consumer and producer surplus for each region of the United States, as given in the economic model, and sum the impacts to obtain an aggregate for the United States (including foreign consumer surplus for exports). The exercise is repeated for each of the 64 climate combinations. For each year, 1990 and 2060, they then regress the economic value against precipitation, temperature and ambient CO_2, using a quadratic form, and also a simple analysis of variance. The result is a climate change response function. For each climate combination, they compare the predicted net surplus with the prediction conditioned on 353 ppmv of CO_2 (today's ambient concentration), with no change in precipitation or in temperature. The 1990 regression results amount to a comparative static experiment similar to that of Mendelsohn and Nordhaus (1996), predicting the impact of climate change if it were imposed on agriculture today, and the agricultural industry could instantaneously respond. The 2060 regression results are equivalent to the comparative static experiment of imposing climate change over time, with research and development to adapt, and comparing agricultural surplus in 2060 to the 2060 surplus if there were no warming, but with research and development continuing to improve yields.

The comparative static results for 1990 conditions are smaller relative to those for the year 2060. The impact of global warming is larger given the adjustments for technology and economic conditions. Whether the impact is positive or negative depends on the climate configuration. Overall, it is suggested that the impact is positive, but there are some cases in which the opposite result is obtained.

I use the data generated by Adams *et al.* (1995b) from both years simultaneously, 1990 and 2060, to estimate a generalized power function (GPF), which is of the form:

$$Y = \beta_0 X_1^{\beta X} X_2^{\beta X} \ldots X_N^{\beta X} \exp(\phi X + \varepsilon) \quad (2)$$

where β and ϕ are vectors. This function is quite general (de Janvry, 1972). A simple version is given by:

$$Y = \beta_0 X^{\beta 1 + \beta 2 X} \exp(\beta_3 X + \varepsilon) \quad (3)$$

If $\beta_2 = 0$, this function has the desirable property that the marginal surplus of the climate input variable can take on 15 shapes (see Table 1), only four of which are consistent with theory. For each case in Table 1, the results are shown in Figure 4. The hypotheses to be tested allow for rejection of the functional form.

The alternative shapes of the functions are consistent with the hypothesized impacts of precipitation, temperature and ambient CO_2 on agricultural surplus. Moreover, it is possible to specify interaction terms, for example, accounting for increased efficiency in water use as emissions increase. Finally, technical change can be both embodied and disembodied, affecting all inputs equally, or having an influence through one or more of the inputs.

TABLE 1 *Correspondence among coefficients in equation (3) and 15 cases in Figure 4 (β_2=0)*

	$\beta_3 < 0$	$\beta_3 = 0$	$\beta_3 > 0$
$\beta_1 < 0$	11	12	13
$\beta_1 = 0$	21	22	23
$0 < \beta_1 < 1$	31	32	33
$\beta_1 = 1$	41	43	43
$\beta_1 > 1$	51	52	53

Since a power function cannot include zero values for the explanatory variables, the Adams *et al.* data cannot be used directly and base case values for surplus, temperature and precipitation must be added. These were 15°C and 50 inches, respectively. (The mean global temperature is now estimated at about

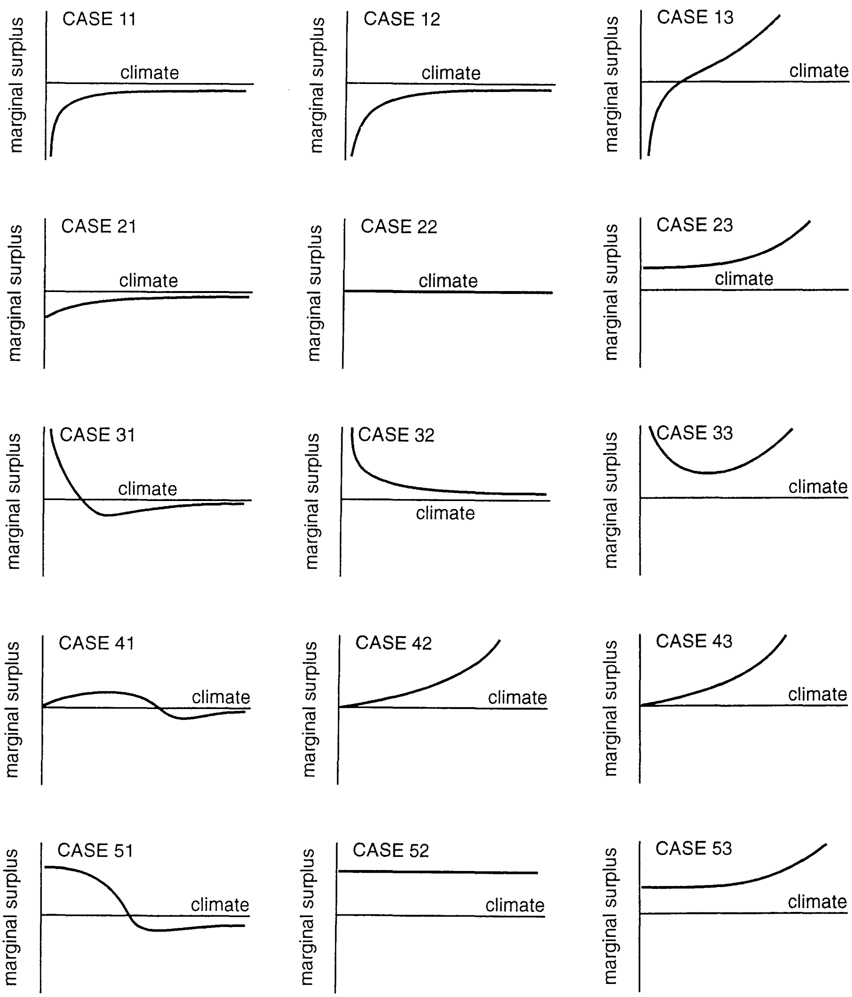

FIGURE 4 *Shapes of the GPF marginal surplus curves*

Note: Each case corresponds to values of the parameters given in Table 1.

15°C: IPCC, 1990, p. xxxvii). Adams *et al.* use a linear-dummy variable specification to estimate the impact of temperature, precipitation and CO_2 fertilization effect on total surplus (consumer, producer, foreign) for the United States. The intercept coefficient in Adams *et al.* (1995b, Appendix Table 3) is 1239.412, which I take to be the value of surplus for US agriculture, measured in dollars of 1990 purchasing power. Similarly, the intercept coefficient in year 2060 is 1750.594 in Hall (1996a, Appendix Table 4), which I take to be the total surplus in the base case for the year 2060 in similar units.

After considering alternative specifications, I chose the model with the best fit that also conserves parsimony and in which all terms are statistically significant. In this specification, there is an interaction term between CO_2 fertilization and precipitation, and there is both technical change embodied in CO_2 and disembodied technical change:

$$S = \beta_0 P^{\beta_1} T^{\beta_2} C^{\beta_3} \exp(\beta_4 P \cdot C + \beta_5 T + \beta_6 C \cdot Y + \beta_7 Y + \varepsilon) \qquad (4)$$

where S = producer plus consumer plus foreign surplus, P = precipitation, T = temperature in °C, C = ambient CO_2 in ppmv of carbon, and Y = number of years (set to zero for 1990, increasing by one for each five-year period of the analysis). After taking logs of both sides, equation (4) is estimated, with the results presented in Table 2.

After estimating the parameters, the predicted values for the surplus are generated for the base case with no global warming, and for the three global warming scenarios computed in Hall (1996a), based on the work of Cline (1992): MR, RE and NY. The MR scenario couples the Manne–Richels (1990)

TABLE 2 *Regression results*

Variable	Coefficient	Std Error	t-Statistic	Prob.
C	3.252285	0.599388	5.426006	0.0000
LNP	0.260045	0.049319	5.272713	0.0000
P*CO_2	–6.57E-06	1.94E-06	–3.384783	0.0010
LNT	0.975737	0.221270	4.409707	0.0000
T	–0.063395	0.012682	–4.999005	0.0000
LNCO_2	0.216033	0.046847	4.611487	0.0000
Y*CO_2	3.32E-06	1.66E-06	2.006004	0.0471
Y	0.023649	0.000813	29.09319	0.0000

R-squared	0.995771	Mean dependent var.	7.299164
Adjusted R-squared	0.995522	S.D. dependent var.	0.179658
S.E. of regression	0.012022	Akaike info. criterion	–8.781129
Sum squared resid.	0.017199	Schwarz criterion	–8.601968
Log likelihood	385.3965	F-statistic	4002.918
Durbin–Watson stat.	1.650496	Prob. (F-statistic)	0.000000

Note: Dependent variable is LNS; number of observations: 127.

macromodel with a low climate sensitivity to greenhouse gases of a 1.0°C mean global temperature increase for a doubling of CO_2 equivalent gases, and a low estimate of 9500gt. of economically available coal. The RE scenario couples the macromodel of Reilly *et al.* (1987) with a climate sensitivity of 2.0°C and a mid-range estimate of 15 000gt. of coal. The NY scenario couples the Nordhaus–Yohe (1983) macromodel with a 3.5°C climate sensitivity and 20 000gt. of coal. The temperature increases and ambient CO_2 levels are in the Appendix of Hall (1996a) for the years 1990, 2000, 2025 and so on, in 25-year intervals, until the coal runs out. The coal is exhausted between the years 2250 and 2375, depending on the macromodel and the assumed amount of coal.

To predict the time path of the economic surplus, some adjustments in the forecast temperature data and the amount of precipitation that corresponds to each temperature must be specified. The ambient concentration of CO_2 is set equal to 353ppmv in 1990. The value grows for the three scenarios as given in the Appendix in Hall (1996a). The change in temperature is calculated as the mean global temperature increase for the three global warming scenarios: MR, RE and NY. Note that the values for 1990 are 0.6, 1.3 and 2.2°C. The temperature for 1990 was set equal to 15°C, so the future temperatures for each scenario are calculated by adding the change to the previous time period temperature. This procedure follows that of the accepted norm in the GCM literature. GCMs are used to predict the present temperature and the temperature for an equivalent doubling of CO_2. The difference in temperature is calculated, and this difference is added to current temperature to get the predicted temperature.

The predicted temperature requires an additional upward adjustment to account for the hotter climate in higher latitudes across the United States, relative to the global mean. On p. xxiv of IPCC (1990), for a mean global warming of 1.8°C, the projected warming varies from 2 to 4°C in winter and 2 to 3°C in summer. Thus, the ratios of average United States warming to the global mean is 3/1.8 = 1.67. This ratio is high compared to the figures in Table 3, which average 1.12. Aerosols are expected to moderate more in the region affected. Thus, aerosols moderate the mean global temperature, but moderate the temperature in the United States by more than the global mean; hence the ratio should be adjusted downward. In the analysis that follows, in fact, no adjustment is made. It is just one reason why this section has the title it does.

In IPCC (1990), United States precipitation is projected to increase by up to 15 per cent in winter and decrease by 5 to 10 per cent in summer. This does not easily compare with the three GCMs in Table 3. Consequently, results are presented that include a sensitivity analysis to precipitation.

In a review of 16 GCMs, Williams, Shaw, and Mendelsohn (1996) present mean global temperature increases and precipitation. The temperature increase averaged across GCMs is about 3.5°C, with an increase in precipitation equal to 7 per cent. But there are duplicate numbers for mean global temperature and precipitation increases, presumably because some of the 'models' are closely related in their construction to one another. Mendelsohn, Nordhaus and Shaw (1994) state they are following the IPCC with an 8 per cent increase in precipitation corresponding to a 3°C warming for a doubling of CO_2 equivalent gases. Since I am using 50 inches annually as the base case, precipitation will be proportionately increased by 8 per cent per increase of 3°C. I set the amount

TABLE 3 *Comparison of GCMs*

General circulation model (GCM)	Δ°C global mean[1]	%Δ precipitation global mean[1]	Δ°C US average (winter, summer)[2]	%Δ precipitation US average (winter, summer)[2]
Goddard Institute for Space Studies (GISS)	4.20	11.0	4.32 (5.46, 3.50)	20 (13, 24)
Geophysical Fluid Dynamics Laboratory (GFDL)	4.00	8.3	5.09 (5.25, 4.95)	9 (19, –8)
Oregon State University (OSU)	2.84	7.8	2.95 (2.95, 3.10)	17 (24, 11)

Notes: [1]From Williams *et al.* (1996).
[2]From Adams *et al.* (1988).

of precipitation equal to, for example in the MR scenario, mrrain=50* (1 + 0.08* (mrt–15) /3).

For the base case and the three scenarios MR, RE and NY, the predicted surplus is given by:

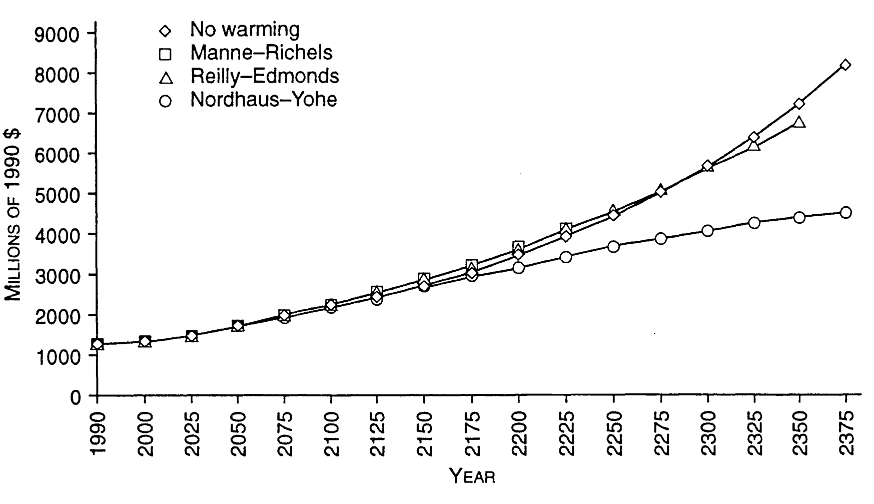

FIGURE 5 *Total agricultural consumer, producer, foreign surplus for four scenarios: no warming and three rose-coloured scenarios*

$$\text{shtbase} = \exp(c(1) + c(2)*\log(50) + c(3)*50*353 + c(4)*\log(15) \\ +c(5)*15 + c(6)*\log(353) + c(7)*\text{yr}*353 + c(8)*\text{yr}) \quad (5)$$

$$\text{mrsurplus} = \exp(c(1) + c(2)*\log(\text{mrrain}) + c(3)*\text{mrrain}*\text{mrco2} + c(4) \\ *\log(\text{mrt}) +c(5)*\text{mrt} + c(6)*\log(\text{mrco2}) + c(7)*\text{yr}*\text{mrco2} + c(8)*\text{yr}) \quad (6)$$

$$\text{resurplus} = \exp(c(1) + c(2)*\log(\text{rerain}) + c(3)*\text{rerain}*\text{reco2} + c\,(4) \\ *\log(\text{ret}) + c(5)*\text{ret} + c(6)*\log(\text{reco2}) + c(7)*\text{yr}*\text{reco2} + c(8)*\text{yr}) \quad (7)$$

$$\text{nysurplus} = \exp(c(1) +c(2)*\log(\text{nyrain}) + c(3)*\text{nyrain}*\text{nyco2} + c(4) \\ *\log(\text{nyt}) + c(5)*\text{nyt} + c(6)*\log(\text{nyco2}) + c(7)*\text{yr}*\text{nyco2} + c(8)*\text{yr}) \quad (8)$$

Figure 5 shows the projected impacts of global warming on economic surplus for the base case of no warming and the three scenarios. The MR scenario ends in year 2225 and is indistinguishable from the RE scenario. Figure 6 shows the difference between the three cases with warming and the case without warming. For the NY scenario, the agricultural sector fails. The present value of the three scenarios are illustrated in Figure 7 for two social discount rates: 1 per cent and 5 per cent. At 5 per cent, even though the NY scenario is a

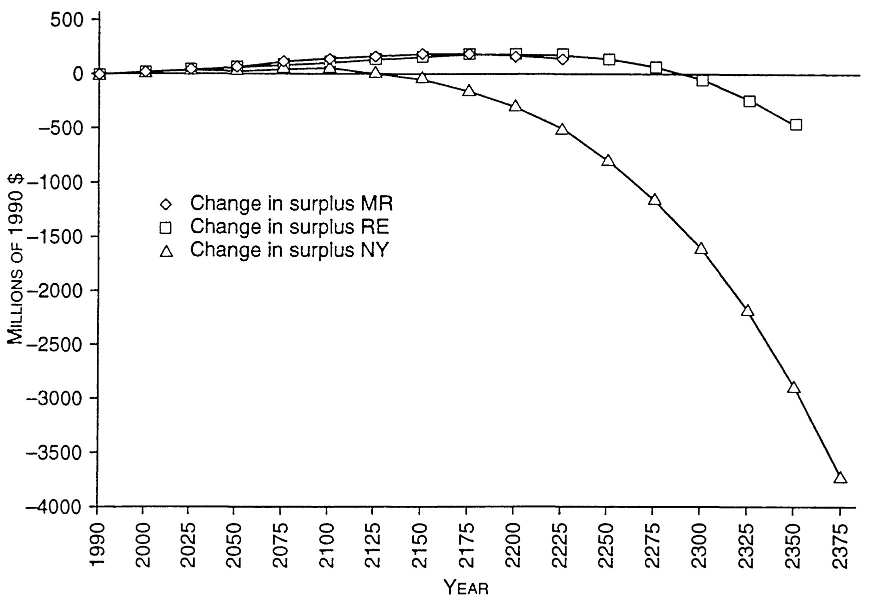

FIGURE 6 *Changes in surplus for three rose-coloured scenarios*

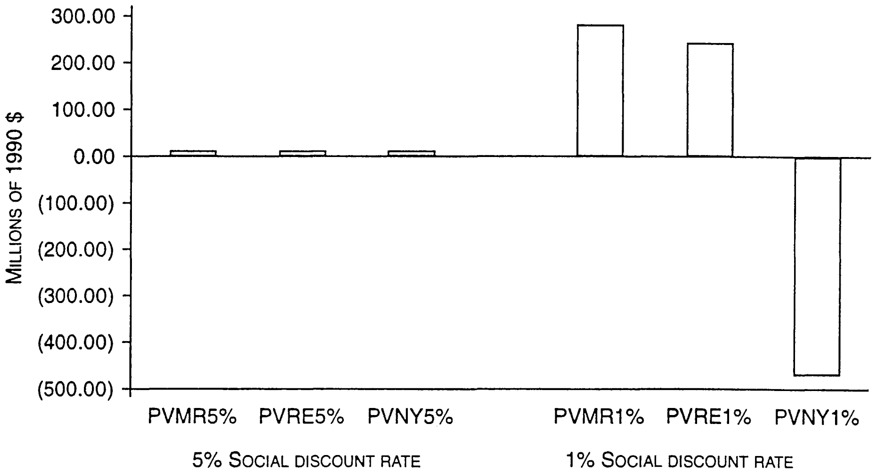

FIGURE 7 *Present value of three rose-coloured scenarios*

disaster, the present values of the three scenarios are almost identical. Only for a 1 per cent social discount rate is the present value of the NY scenario negative.

NOT JUST A QUESTION OF VALUES, THE OSTRICH EFFECT AND POLICY

After looking at these results it is tempting to terminate the analysis and ask, 'How much time do we have and what actions do we have to initiate now?' The apparent answer is that we have an entire century, even if the worst of the rose-coloured scenarios occurs. Those are the tinted glasses through which most economists are looking. Hoping for reliable, steady rain is a bit like relying on rain dances. Possibly the interior of the United States will become hot and dry, according to the IPCC (1990). Rather than the 2°C warming for the mid-case scenario above, assume that climate warms at 3.5°C for a doubling, the mean of the GCMs examined by Williams *et al.* (1996). This is in line with the mid-range scenario of Cline (1992), so assume his mid-range case of 10 000gt. of economically available coal, which he obtained from Edmonds and Reilly (1985). Now consider two possible cases. In case I, assume that precipitation falls by 25 per cent for a doubling. In case II, assume that precipitation increases by 35 per cent (rather than 8 per cent) for a doubling.

$$\text{Dry Case I:} \quad \text{nyrainI} = 50*(1 - 0.25*(\text{nyt}-15)/3.5) \tag{9}$$

$$\text{Wet Case II:} \quad \text{nyrainII} = 50*(1 + 0.35*(\text{nyt}-15)/3.5) \tag{10}$$

The surplus is predicted with the following equations:

$$\text{nysuri} = \exp(c(1) + c(2)*\log(\text{nyraini}) + c(3)*\text{nyraini}*\text{nyco2} + c(4) *\log(\text{nyt}) + c(5)*\text{nyt} + c(6)*\log(\text{nyco2}) + c(7)*\text{yr}*\text{nyco2} + c(8)*\text{yr}) \tag{11}$$

$$\text{nysurii} = \exp(c(1) + c(2)*\log(\text{nyrainii}) + c(3)*\text{nyrainii}*\text{nyco2} + c(4) *\log(\text{nyt})+c(5)*\text{nyt} + c(6)*\log(\text{nyco2}) + c(7)*\text{yr}*\text{nyco2} + c(8)*\text{yr}) \tag{12}$$

If it is either wetter, and particularly if it is drier, than the beneficial 8 per cent increase in precipitation I assumed in the previous section, for a CO_2 equivalent doubling, disaster strikes US agriculture, as shown in Figure 8. Return to the question, 'How much time do we have and what actions do we have to initiate now?' In answer, consider the next 150 years, where the change in economic surplus is shown in Figure 9. If it is drier, adverse affects could begin as soon as 25 years from now. Even so, if the discount rate is 5 per cent, Figure 10 shows that we are better off with minuscule gains over the next 25 years since they more than compensate for the complete collapse of agriculture shown in Figure 9 for the –25 per cent rain scenario. If the social discount rate is 1 per cent, as favoured by Khanna and Chapman (1996) and Arrow *et al.*

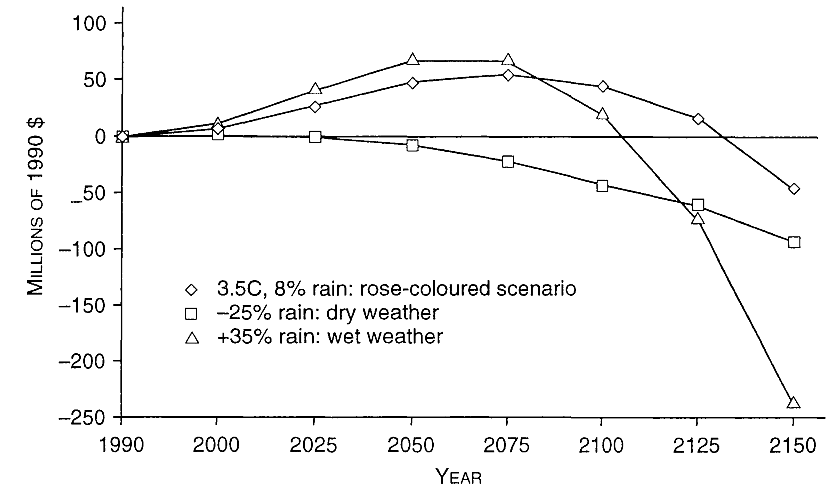

FIGURE 8 *Change in agricultural surplus with wetter and drier weather*

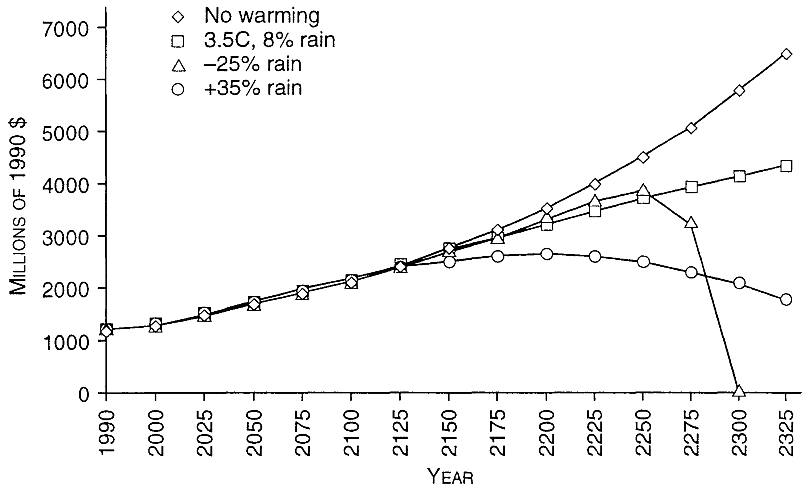

FIGURE 9 *Agricultural surplus with wetter and drier weather*

(1996), agriculture would be better off without global warming relative to all three of these scenarios. Does this mean that it is merely a question of values, whether we care about the future generations? If we use a 5 per cent discount rate, disaster seems bearable. Or is it that policy to alter the future would require government intervention in the economy, a change incompatible with our world view?

These assumptions do not capture the impact of a long-term drought, which would be harsh, turning the interior Great Plains of the United States to desert. These assumptions do not capture the impact of torrential rains, stripping the land of topsoil. Nor do they capture the possibility that the fluctuation between floods and droughts that we have experienced in the last 15 years could amplify, both washing away the topsoil and baking into laterite (McNeil, 1964) what soil remains. Erickson (1993) has a more complete set of reasons to be concerned.

Adams *et al.* (1990) acknowledge several critical omissions in their work and caution that their main contribution is 'highlighting uncertainties' (ibid., p. 219). The GCMs do not 'include changes in the space and time distributions of climate events. Therefore many significant climate and biophysical features are ignored'. They further caution (ibid., p. 220) that they do not account for changes in climate variability, such as frequency of droughts, 'mesoscale convection complex' rainfall and hail damage. The crop simulation models assume no limits to soil nutrients, and no pests that limit crop growth.

Adams *et al.* (1995b) explain that the CSMs allow amounts of fertilizer to vary for optimal results. For water supply, as long as the annual constraint is

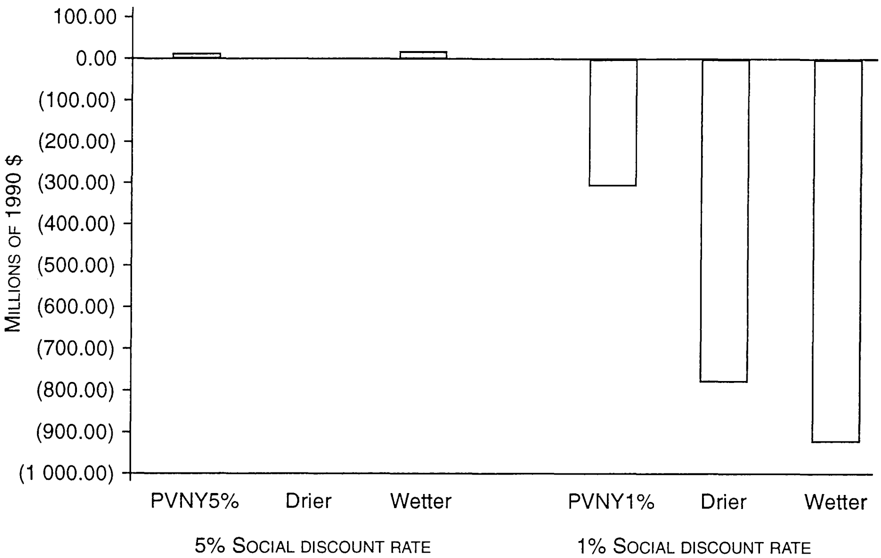

FIGURE 10 *Present value with wetter and drier weather*

not exceeded, the amounts needed over the growing season were allowed to optimize crop growth. The CSMs for corn, soybeans and wheat assume optimal pest management, and no nutritional limits in the soil that could limit CO_2 fertilization.

The results presented above are rosy indeed when comparisons are made between the impacts of global warming on US agriculture and on the developing countries. There are two important reasons. The first is that the United States has a greater ability to adapt. All the adaptation expected in the United States presumes that the present government policy of subsidizing research and development continues. The world view held by many economists is antagonistic to government intervention in the economy. Yet agriculture in the United States has the best possibility to adapt because of the Agricultural Experiment Stations and Extension Service. The institutional structure for adaptation in most of the developing parts of the world is minimal to non-existent.

In Africa, various studies cited in Reilly *et al.* (1996) predict near disaster for agriculture as the result of a mere doubling of greenhouse gases. Sivakumar (1993) compared the warmer period of 1965–88 with the cooler period of 1945–64 and found the growing season reduced by 5 to 20 days in Niger and West Africa. Akong'a *et al.* (1988) found significant reductions in maize and livestock productivity in Kenya owing to increased frequency of droughts. Downing (1992) estimated substantial decreases in yields of maize and millet in Zimbabwe, Senegal and lower elevations of Kenya owing to a warming of 2–4°C, but if precipitation increases Kenya at least comes out better nationally by shifting production to higher elevations. Schulze *et al.* (1993) and Muchena (1994) find substantial yield losses in South Africa and Zimbabwe, after fertilizer and irrigation adaptations, owing to a doubling of greenhouse gases. Eid (1994) finds substantial wheat and maize yield losses in Egypt as a result of a doubling.

In most of Latin America, the studies cited in Reilly *et al.* (1996) predict substantial losses for agriculture from a mere doubling of greenhouse gases. Baethgen (1994) estimates barley and wheat losses between 15 to 25 per cent in Uruguay, with adaptation. Baethgen (1994), Siquera *et al.* (1994), Liverman and O'Brien (1991) and Liverman *et al.* (1994) uniformly find wheat and maize yield losses, after adaptation, in Brazil and Mexico, although soybean yields increase. Downing (1992) has mixed results for Norte Chico, Chile, an area with a wide range of climates due to altitude changes, which makes assessment difficult. Sala and Paruel (1994) find maize yield losses in Argentina, after adaptation.

In China, the studies predict minor to substantial losses for agriculture resulting from mean global temperature increases of 1–1.5°C. While these are large temperature changes relative to the last 10 000 years, they are small temperature changes relative to the next 200 to 400 years. Tao (1993) finds wheat, rice, cotton, fruits, oil crops, potatoes and corn yield losses, with agricultural productivity losses greater than 5 per cent for a 1°C increase. Zhang (1993) and Jin *et al.* (1994) find substantial losses for rainfed rice in Southern China, but the possibility of increases in rice production for irrigated areas.

All of this work suffers the defect of considering a mere doubling, or less, of greenhouse gases. Reilly *et al.* (1996) report upper temperature bounds for wheat (C3) at 30–35°C, rice (C3) at 35–38°C, potatoes (C3) at 25°C, soybeans (C3) at 35°C and maize (C4) at 32–37°C, with optimum temperatures considerably below the upper ranges. For comparison, in the three scenarios considered in this paper, mean global temperature reaches a maximum at 19.4°C (Manne-Richels), 25.6°C (Reilly-Edmonds *et al.*) and 35.5°C (Nordhaus-Yohe). Of course, the mean global temperature will be considerably lower than the average temperature in the tropics, which are 10–15°C warmer. So the mid-range scenario results in tropical temperatures at or above the upper ranges for agricultural production. In this sense, the results presented here for the United States are rosy indeed, relative to worldwide prospects.

We can deny these possibilities, or simply use a 5 per cent discount rate and claim it is rational to ignore disaster, as long as it is far enough away. Or we can believe that we have enough time to make changes later, if we find out that climate change is not benign.

Consider the path dependence of technological change (Goodstein, 1995). It took 10 to 20 years for infant industries in solar and wind energy to emerge, and as long for institutions to learn how to develop policies which nurture them cost-effectively, rather than wastefully (Hall, 1996a). Power plants last for 30 to 50 years, and they will not be easily replaced, as long as variable costs of existing plants are less than long-run marginal costs of replacement plants. The electric car was scheduled to help replace the use of oil for transport, but that policy initiative has been delayed. We have considerable institutional, physical and economic barriers to clear before the market will replace coal and other fossil fuels, barriers that will delay any meaningful replacement for decades.

Reality exists independently of our world view. Like an ostrich, if reality is inconsistent with that view, we can bury our heads in the sand, refuse to believe the physical science, just consider the next 100 years, discount the future or believe we can always avoid disaster by waiting until later to invent and substitute alternatives to fossil fuel technologies. If we persist in ignoring reality because it requires actions inconsistent with our world view, we run the risk of condemning future *Homo sapiens sapiens* to the miseries of forced migration and malnutrition.

REFERENCES

Adams, R.M. (1986), 'Agriculture, Forestry and Related Benefits of Air Pollution Control: A Review and Some Observations', *American Journal of Agricultural Economics*, **68**, 464–72.

Adams, R.M., McCarl, B.A., Dudek, K.J. and Glyer, J.D. (1988), 'Implications of Global Climate for Western Agriculture', *Western Journal of Agricultural Economics*, **13**, 348–56.

Adams, R.M., Fleming, R.A., Chang, C-C., McCarl, B.A. and Rosenzweig, C. (1995a), 'A Reassessment of the Economic Effects of Global Climate Change on U.S. Agriculture', *Climate Change*, **30**, 147–67.

Adams, R.M., McCarl, B.A., Segerson, K., Rosenzweig, C., Bryant, K.J., Dixon, B.L., Conner, R., Evenson, R.E. and Ojima, D. (1995b), *The Economic Effects of Climate Change on U.S. Agriculture*, Palo Alto: Electric Power Research Institute.

Adams, R.M., Rosenzweig, C., Peart, R.M., Ritchie, J.T., McCarl, B.A., Glyer, J.D., Curry, R.B., Jones, J.W., Boote, K.J. and Allen, L. Hartewell Jr. (1990), 'Global Climate Change and US Agriculture', *Nature*, **345**, 17 May, 219–24.

Akong'a, J., Downing, T.E., Konijn, N.T., Mungai, D.N., Muturi, H.R. and Potter, H.L. (1988), 'The Effects of Climatic Variations on Agriculture in Central and Eastern Kenya', in M.L. Parry, T.R. Carter and N.T. Konijn (eds), *The Impact of Climatic Variations on Agriculture, Vol. 2, Assessments in Semi-Arid Regions*, Dordrecht: Kluwer Academic Press.

Arrow, K.J., Cline, W.R., Maler, K-G., Munasinghe, M., Squitieri, R. and Stiglitz, J.E. (1996), 'Intertemporal Equity, Discounting and Economic Efficiency', in IPCC, *Climate Change 1995: Economic and Social Dimensions of Climate Change, Contribution of Working Group III to the Second Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge: Cambridge University Press.

Baethgen, W.E. (1994), 'Impact of Climate Change on Barley in Uruguay: Yield Changes and Analysis of Nitrogen Management Systems', in C. Rosenzweig and A. Iglesias (eds), *Implications of Climate Change for International Agriculture: Crop Modeling Study*, Washington, DC: U.S. Environmental Protection Agency.

Cline, W.R. (1992), *Global Warming: The Economic Stakes*, Washington, DC: Institute for International Economics.

Cline, W.R. (1996), 'The Impact of Global Warming on Agriculture: Comment', *American Economic Review*, **86**, 1309–11.

Crowley, T.J. (1996), 'Remembrance of Things Past: Greenhouse Lessons from the Geologic Record', *Consequences: The Nature and Implications of Environmental Change*, **2**, 2–12.

Downing, T.E. (1992), *Climate Change and Vulnerable Places: Global Food Security and Country Studies in Zimbabwe, Kenya, Senegal and Chile*, Research Report No. 1, Environmental Change Unit, University of Oxford.

Edmonds, J. and Reilly, J. (1985), *Global Energy: Assessing the Future*, New York: Oxford University Press.

Eid, H.M. (1994), 'Impact of Climate Change on Simulated Wheat and Maize Yields in Egypt', in

C. Rosenzweig and A. Iglesias (eds), *Implications of Climate Change for International Agriculture: Crop Modeling Study*, Washington, DC: U.S. Environmental Protection Agency.
Erickson, J.D. (1993), 'From Ecology to Economics: the Case Against CO_2 Fertilization', *Ecological Economics*, **8**, 157–75.
Goodstein, E. (1995), 'The Economic Roots of Environmental Decline: Property Rights or Path Dependence', *Journal of Economic Issues*, **24**, 1029–43.
Hall, Darwin C. (1996a), 'Geoeconomic Time and Global Warming: Limits to Economic Analysis', *International Journal of Social Economics*, **23**, 64–87.
Hall, Darwin C. (1996b), *Advances in the Economics of Environmental Resources: Marginal Cost Rate Design and Wholesale Water Markets*, Vol. 1, Greenwich, Connecticut: JAI Press.
Intergovernmental Panel on Climate Change (1990), *IPCC First Assessment Report, Volume I: Overview and Summaries, Scientific Assessment of Climate Change*, New York: World Meteorological Organization and United Nations Environment Programme.
Intergovernmental Panel on Climate Change (1996), *Climate Change 1995: The Science of Climate Change*, Cambridge: Cambridge University Press.
de Janvry, A. (1972), 'The Class of Generalized Power Production Functions', *American Journal of Agricultural Economics*, **54**, 234–7.
Jin, Z., Daokou, Ge, H.C. and Fang, J. (1994), 'Effects of Climate Change on Rice Production and Strategies for Adaptation in Southern China', in C. Rosenzweig and A. Iglesias (eds), *Implications of Climate Change for International Agriculture; Crop Modeling Study*, Washington, DC: U.S. Environmental Protection Agency.
Khanna, N. and Chapman, D. (1996), 'Time Preference, Abatement Costs and International Climate Policy: An Appraisal of IPCC 1995', *Contemporary Economic Policy*, **14**, 56–66.
Liverman, D. and O'Brien, K. (1991), 'Global Warming and Climate Change in Mexico', *Global Environmental Change*, **1** (4), 351–64.
Liverman, D., Dilley, M., O'Brien, K. and Menchaca, L. (1994), 'Possible Impacts of Climate Change on Maize Yields in Mexico', in C. Rosenzweig and A. Iglesias (eds), *Implications of Climate Change for International Agriculture: Crop Modeling Study*, Washington, DC: U.S. Environmental Protection Agency.
Manne, A. and Richels, R. (1990), 'CO_2 Emission Limits: An Economic Cost Analysis for the USA', *The Energy Journal*, **11**, 51–74.
McNeil, M. (1964), 'Lateritic Soils', *Scientific American*, **211**, 96–117.
Mendelsohn, Robert and Nordhaus, William (1996), 'The Impact of Global Warming on Agriculture: Reply', *American Economic Review*, **86**, 1312–15.
Mendelsohn, R., Nordhaus, W. and Shaw, D. (1994), 'The Impact of Global Warming on Agriculture: A Ricardian Analysis', *American Economic Review*, **84**, 753–71.
Muchena, P. (1994), 'Implications of Climate Change for Maize Yields in Zimbabwe', in C. Rosenzweig and A. Iglesias (eds), *Implications of Climate Change for International Agriculture: Crop Modeling Study*, Washington, DC: U.S. Environmental Protection Agency.
Nordhaus, W. and Yohe, G. (1983), 'Future Carbon Dioxide Emissions from Fossil Fuels', *Changing Climate*, Washington, DC: National Research Council, National Academy Press.
Reilly, J. (1996), 'Climate Change, Global Agriculture and Regional Vulnerability', in N. Nakićenović, W.D. Nordhaus, R. Richels and F.L. Toth (eds), *Climate Change: Integrating Science, Economics and Policy*, Laxenburg, Austria: International Institute for Applied Systems Analysis.
Reilly, J., Edmonds, J., Gardner, R. and Brenkert, A. (1987), 'Uncertainty Analysis of the IEA/ORAU CO_2 Emissions Model', *The Energy Journal*, **8**, 1–29.
Reilly, J. *et al.* (1996), 'Agriculture in a Changing Climate: Impacts and Adaptation', in IPPC, *Climate Change 1995: Impacts, Adaptations and Mitigation of Climate Change: Scientific–Technical Analyses, Contribution of Working Group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge: Cambridge University Press.
Rich, P. (1996), 'Photosynthesis', *Grolier's Multimedia Encyclopedia*, Danbury, Connecticut: Grolier Interactive.
Rosenzweig, C. and Hillel, D. (1995), 'Potential Impacts of Climate Change on Agriculture and Food Supply', *Consequences: The Nature and Implications of Environmental Change*, **1**, 22–32.
Rosenzweig, C. and Parry, M.L. (1994), 'Potential Impact of Climate Change on World Food Supply', *Nature*, **367**, 13 January, 33–138.

Sala, O.E. and Paruel, J.M. (1994), 'Impacts of Global Climate Change on Maize Production in Argentina', in C. Rosenzweig and A. Iglesias (eds), *Implications of Climate Change for International Agriculture: Crop Modeling Study*, Washington, DC: U.S. Environmental Protection Agency.

Schulze, R.E., Kiker, G.A. and Kunz, R.P. (1993), 'Global Climate Change and Agricultural Productivity in Southern Africa', *Global Environmental Change*, **4**, 329–49.

Shreeve, J. (1995), *The Neandertal Enigma*, New York: Avon Books.

de Siquera, O.E., Boucas Farias, J.R. and Aguiar Sans, L.M. (1994), 'Potential Effects of Global Climate Change for Brazilian Agriculture: Applied Simulation Studies for Wheat, Maize and Soybeans', in C. Rosenzweig and A. Iglesias (eds), *Implications of Climate Change for International Agriculture: Crop Modeling Study*, Washington, DC: U.S. Environmental Protection Agency.

Sivakumar, M.V.K. (1993), 'Global Climate Change and Crop Production in the Sundano-Sahelian Zone of West Africa', in Crop Science Society of America (ed.), *International Crop Science, Vol. I*, Madison: Crop Science Society of America.

Tao, Z. (1993), 'Influences of Global Climate Change on Agriculture of China', in R.G. Zepp (ed.), *Climate Biosphere Interactions*, New York: John Wiley and Sons.

Williams, L.J., Shaw, D. and Mendelsohn, R. (1996), *Evaluating GCM Output with Impact Models*, Palo Alto: Electric Power Research Institute.

Zhang, H. (1993), 'The Impact of Greenhouse Effect on Double Rice in China', *Climate Change and Its Impact*, Beijing: Meteorology Press.