Ecological Economics, 8 (1993) 157–175
Elsevier Science Publishers B.V., Amsterdam

From ecology to economics: the case against CO_2 fertilization

Jon D. Erickson
Department of Agricultural Economics, Cornell University, Ithaca, NY, USA

(Accepted 18 November 1992)

ABSTRACT

Erickson, J.D., 1993. From ecology to economics: the case against CO_2 fertilization. *Ecol. Econ.*, 8: 157–175.

The effects of increasing concentrations of atmospheric carbon dioxide (CO_2) on agricultural yields are analyzed. It is argued that any positive effects on yields from CO_2 fertilization, demonstrated in controlled experiments, would be weak in farm conditions given water and nutrient limits. Furthermore, possible benefits would be more than offset by predicted consequences of climate change, ozone depletion, and additional gases created from fossil fuel combustion. The impact of including CO_2 fertilization on crop yield and economic welfare predictions is evaluated. The policy-distorting potential of fragile claims is stressed.

INTRODUCTION

Climate change issues have touched the minds, polls, and pens of an increasingly international community. The realization of potential physical and social impacts as a result of increasing atmospheric levels of greenhouse gases (GHGs) has both the scientific and political community scrambling for predictions, solutions, and commitments. The Framework Convention on Climate Change, signed by 154 nations in June 1992 at the United Nations Conference on Environment and Development (the Earth Summit) in Rio de Janeiro, forces issues concerning the global environment into domestic policy decisions and mandates continued climate negotiations. Crucial stages in climate policy development involve modeling the

---

Correspondence to: J.D. Erickson, 115 Warren Hall, Department of Agricultural Economics, Cornell University, Ithaca, NY 14850, USA.

planet's reaction to the disruption of pre-industrial GHG concentrations, followed by assessing the economy's response to the predicted impacts of global warming, specifically in regard to agriculture, water, forestry, and other natural resources. In these processes, the uncertainties often outweigh the certainties, and the distinction between science-based predictions and ecological reality is often ambiguous.

Nevertheless, much policy is based on prediction, prediction relies on modeling, and models must be accountable to accurate interpretations of the available information. The present thesis evaluates the modeling of agricultural yield in light of climate-change predictions, increasing concentrations of carbon dioxide (the chief GHG), and the future mix of agricultural stresses. A larger, often overlooked, ecological picture is argued for, and the inclusion of ad hoc physiological effects of increased CO_2 concentration on agricultural yield forecasts is deemed inappropriate based on a more complete scientific framework and the physical and moral policy implications.

CLIMATE, CROP AND ECONOMIC MODELING

The first step in modeling the physiological and economic reactions of the agricultural sector to climate change is predicting future weather conditions. One of three methods is typically used: general circulation models (GCMs), paleoclimatic reconstruction, or analog climates of historical data. The most popular method of prediction is using GCMs – elaborate mathematical computer simulations of planetary physics. The GHG equivalence of a CO_2 doubling ($2 \times CO_2$) is often evaluated with estimates of global mean warming ranging from 2.5°C to 5.5°C, with greater-than-average warming in high latitude regions and, at times, summer drying of soil moisture in mid-continental regions (Rosenzweig, 1989). The most frequently cited models are from the National Aeronautics and Space Administration's (NASA) Goddard Institute of Space Science (GISS) and the Princeton Geophysical Fluid Dynamics Laboratory (GFDL), and are typically both reported due to their opposing degree of prediction extremity (with the GFDL usually more extreme). Although GCMs are in their infancy and many unknowns still exist, especially in predicting regional variables, they are relied on regularly. (The GCM method is used in Parry et al., 1988a,b; Smith and Tirpak, 1988; Adams, 1989).

The use of paleoclimatic reconstruction and analog climates are part of the evolution of climate studies. The MINK study (Missouri, Iowa, Nebraska, Kansas) uses climate data from the 1930s – a period hotter and dryer than the base climate (1951–1980) in the region – to study the impacts of global warming (Easterling et al., 1992). Menzhulin (1992) uses paleoclimatic data to estimate the future evolution of agroclimatic schemes. The study by Kaiser et al. (1992) uses an alternative GCM method in which a stochastic weather generator based on historical weather data is incorporated to study GCM scenarios. The last two approaches have the advantage of avoiding static $2 \times CO_2$ predictions, with a more dynamic ability to investigate intermediate effects of climate change and adaptation.

In the second step of agricultural modeling, regional weather data from one of the above methods is used as an input into crop yield models. Examples of crop models currently used include: CERES-Maize (Jones and Kiniry, 1986), CERES-Wheat (Ritchie and Otter, 1985), SOYGRO (Wilkerson et al., 1985), and EPIC (Williams et al., 1984). With the exception of EPIC, these models were originally developed to explore the relationships between plant growth conditions and crop yield. The EPIC model (Erosion-Productivity Impact Calculator), originally a soil erosion model, has been adapted to a crop yield model. The range of models include a range of variables such as weather, hydrology, erosion, nutrients, pests, solar radiation, evapotranspiration, farming practices, and economic factors.

A third and final model is used to determine the economic consequences of changes in yields, water supply and demand, acreage, crop mix, input costs, product prices, import/export mix, world trade, population, technology, multiplier effects, and in general, degrees of food security or scarcity. Models range in technique and vary in their completeness. For example, Adams' (1989) national study adjusts the parameters of a U.S. agricultural sector economic model (see Cheng and McCarl, 1989) to reflect physical effects of climate change. Kane et al. (1992) examine global agricultural market effects using the Static World Policy Simulation Model (SWOPSIM; see Roningen, 1986). This is a partial-equilibrium model based on a system of supply and demand equations specified by matrices of own-and cross-price elasticities. Kaiser et al. (1992) use a mathematical programming technique known as discrete stochastic sequential programming (DSSP) that models the farmer's decision-making process as multistage and sequential.

The focus of this paper is on the second step of the modeling process, crop yield models, and the sensitivity of the third step, economic modeling, to yield results. In particular, the inclusion of the so-called "CO_2 fertilizer effect" is evaluated.

CO_2 FERTILIZATION

Anthropogenic processes such as fossil fuel burning and deforestation have disrupted the pre-industrial age balance of long-term carbon sources and sinks. Increasing atmospheric concentrations of CO_2 have been well documented for a number of decades (see Hansen et al., 1988). With respect to plants, surplus CO_2 plays an indirect and a direct role.

Indirectly, CO_2 is recognized as the chief greenhouse gas contributing to global warming. Climate change in turn influences temperature, precipitation, frequency and severity of climatic events, soil moisture and erosion, insect and weed pests, plant pathogens, and cloud cover - all of which affect agriculture.

Directly, CO_2 is an essential compound in the process of photosynthesis. Its concentration can also affect water-use efficiency (WUE) in plants. All green plants depend on photosynthesis for growth and maintenance. Carbon from CO_2, hydrogen from water, and energy from the sun are utilized to form carbohydrates. Intake of CO_2 occurs through the stomata in the leaves. While open, the stomata lose water vapor. With increased concentrations of CO_2, stomata are less open (increased resistance) and consequently less water vapor loss (transpiration) occurs (see Rosenberg et al., 1990, for physiological details). In this manner, CO_2 is often viewed as a limiting factor in crop yield, with increasing atmospheric concentrations having obvious advantages.

In fact, CO_2 enrichment of greenhouse crops has been utilized since the late 1800s (Wittwer, 1986). Marketable yield responses have been well documented for a variety of crops. Response to enrichment varies with plant species, and in particular with differing carbon metabolism pathways (see Tolbert and Zelitch, 1983). Kimball (1986a) reviewed over 140 reports and assembled over 770 observations gathered under ideal greenhouse conditions on the economic yield or biomass production of 38 agricultural crops and 18 other species. Table 1 lists the average greenhouse crop yield responses to various CO_2 enrichment levels for the major crop categories. Kimball utilizes this data as a basis for predicting crop yield responses to a doubling (660 $\mu l\ l^{-1}$) of atmospheric CO_2 in the next century (also in Table 1).

Data from CO_2 fertilization experiments is typically used in modifying existing crop growth models. The MINK study adopts the concept of radiation-use efficiency (RUE) to adapt the Erosion-Productivity Impact Calculator (EPIC) model (as reported in Stockle et al., 1992a). Radiation-use efficiency equals the ratio of the amount of crop dry matter produced per unit of intercepted photosynthetically active radiation (g MJ^{-1}), and is modeled as being dependent on atmospheric CO_2 concentration (ppm):

$$\mathrm{RUE} = (100)(\mathrm{CO_2})/[\mathrm{CO_2} + b_1 \exp(-b_2\mathrm{CO_2})]$$

The parameters b_1 and b_2 are solved given two known points from a crop-specific response curve generated by controlled experiments. In addi-

TABLE 1

Percent yield response of greenhouse crops to CO_2 enrichment and predicted response to a doubling of atmospheric CO_2 (source: Kimball, 1986a)

Crop category	Mean yield percentage increase	
	Experimental data	Predicted, CO_2 doubling
Fiber crops (cotton)	106	118
Fruit crops	29	31
Grain crops (C3)	30	31
Leaf crops	41	25
Legume seed crops	37	31
Herbaceous, nonag. (C3)	50	34
Woody plants	31	34
C4 plants (i.e., corn)	30	14
All species	31	32

tion, RUE values are adjusted for ambient vapor pressure deficit (VPD). Given a doubling of CO_2 (660 ppm), the RUE is calculated and multiplied by the daily intercepted radiation to estimate potential biomass accumulation. Thus, photosynthetic enhancement from CO_2 simply becomes a multiplier dependent on data from controlled experiments. In addition, the RUE formulation makes no distinction between crop dry matter and marketable yield changes. Economic yield, however, is entirely dependent on changes in marketable yield, not simply plant growth.

In modeling improved water-use efficiency, the MINK study models the effects of CO_2 concentration and VPD on leaf conductance (the inverse of resistance; also reported in Stockle et al., 1992a). Again, data from controlled experiments are utilized and generalized into a single linear relationship demonstrating a reduction of conductance by about 60% given a doubling of CO_2. Values of daily average leaf conductance were converted into daily leaf resistance and included in the commonly used Penman–Monteith model (Monteith, 1965) for estimating evapotranspiration (total water transfer into the atmosphere). Given hourly VPD estimates, a doubling of atmospheric CO_2 concentration increases leaf resistance, increasing canopy resistance, which decreases evapotranspiration, and thus increases water-use efficiency.

While the logic and experimental data behind radiation- and water-use efficiency improvements seem intuitively appealing, the magnitude of feedback mechanisms are unclear (Wilks, pers. commun., 1992). For instance, much of the atmospheric vapor content comes from transpiration, thus increasing stomatal resistance should increase VPD. Similarly, increasing stomatal resistance will increase leaf temperature, which may affect radiation use efficiency, particularly above optimal temperatures. Advocating strong CO_2 effects while ignoring at least the possibility of such feedback mechanisms seems unjustified.

Although not as thorough as the MINK study, similar inclusions of the CO_2 effect based on controlled experiments are utilized in Environmental Protection Agency (EPA) studies (Smith and Tirpak, 1988) including Adams' national study (Adams, 1989). These influential climate-change studies have relied rather heavily on CO_2 effects in modeling agricultural response. All mentioned studies run their models both with and without CO_2 effects included. However, conclusions are generally based on the CO_2 effect scenarios which substantially affect the results.

For instance, in the MINK study (Easterling et al., 1992), when current adaptation techniques to climate change are assumed available, the inclusion of the CO_2 effect alleviates estimated value of production declines by $983.1 million for the four crops analyzed. The CO_2 effect alone is responsible for a 58% increase in value of production over the worst case scenario (no CO_2 effect and no on-farm adjustments). Ignoring adjustments, including CO_2 fertilization lowers irrigation demand 4–12% for irrigated farms and lowers total consumption use for irrigation by about 6%. When future adaptation technology is assumed available, the inclusion of the CO_2 effect has the strong implication of changing total *losses* of $2.029 billion into total *gains* of $645 million.

Similarly, the results in Adams' (1989) national study are extremely sensitive to inclusion of the CO_2 effect. Using climate-change forecasts from the GISS model, the change in economic surplus without the CO_2 fertilizer effect is *negative* $6.5 billion, and with the CO_2 fertilizer effect is *positive* $9.9 billion. Using the GFDL climate model, the change is from negative $35.9 to negative $10.5 billion, without and with the CO_2 effect, respectively.

At the global level, the preliminary findings of Rosenzweig et al. (1992) note the optimism of fully realizing the laboratory benefits of CO_2 fertilization, yet evaluate future world food trade based on strong fertilization assumptions. Without the direct effects of CO_2, the forecasted crop yield changes are negative in all the countries and GCM scenarios investigated. With the direct effects of CO_2, many of the crop yield changes turn positive, and all significantly improve.

The large magnitude of differences between scenarios with and without the CO_2 fertilizer effect included is unquestionable. The influence of the agricultural sector on public policy lies deep in tradition and national security interests, and strong claims such as CO_2 fertilization need to be brought under careful scrutiny. Future climate and agriculture rely on current resource policy decisions. Relying on a fragile assessment could be devastating to future national and world food security.

LIMITING FACTORS AND FEEDBACKS

Given the current knowledge of CO_2 and plant physiology interactions, recognizing the *possibility* of a *limited* CO_2 effect is justifiable. However, relying on yield response data from controlled experiments in the laboratory and present day growing conditions to completely offset other climate-change factors is unrealistic.

In controlled experiments all crucial growth factors such as water, nitrogen, phosphorus, soil, pests, temperature, solar radiation, atmospheric turbulence, and management can be regulated so they are no longer limiting to plant growth. The CO_2 concentration may then act as the single limiting factor, with enrichment having obvious advantages. However, in actual farm settings CO_2 is rarely the limiting factor. A complex mixture of stresses can limit crop yields. Interpreting these limits when a doubling of CO_2 occurs is essential for an accurate assessment.

Water supply is widely recognized as the chief limiting factor in crop production worldwide. Plants depend on water in nearly every physiological process. Reduction in plant size and yield is the most common effect of water deficit. This occurs through reducing photosynthesis by a reduction in leaf area, closure of stomata, and a decrease in the efficiency of the carbon fixation process. Even after water stress is relieved, limits on photosynthesis, and thus crop yields, persist due to reduced photosynthetic surface (Kramer, 1983). Although increased CO_2 concentration may improve water-use efficiency and reduce water stress, future water shortages could easily reduce yields relative to present day conditions. In fact, the studies that incorporate the CO_2 effect also predict future water shortages and often outline the need to meet water demands in order to capture the yield advantages of increased CO_2.

Lowering water demand by improving crop water-use efficiency can be quite different from meeting non-limiting watering conditions needed to take advantage of photosynthesis enhancement, especially for currently non-irrigated crops. In addition, irrigation shortages arise from both natural drought and societal conflict over water uses. Increasing world population at a rate of more than 250000 people a day, particularly in developing countries, intensifies the battle between water for domestic use and water for agriculture. Furthermore, a warmer climate could translate into a more erratic hydrologic cycle. Using GCMs, greater evaporation is predicted to be balanced by greater precipitation with net soil moisture expected to fall in many regions (i.e., the MINK region) (Mearns et al., 1990). Statistical evidence also suggests that small changes in averages can cause shocking changes in the frequency of extremes – more hot spells, more droughts, or more floods – adding to future water stress (Waggoner and Revelle, 1990). In addition, Cline (1992) points out the absence of "memory" of water depletion in current crop models, thus avoiding the strong effects of possible successive drought years.

The probability of frequent swings between droughts and floods, average dryer soils, and increasing demand for domestic water leaves little hope for stable water availability worldwide. Kimball (1986b) reviewed the results of several CO_2 enrichment experiments in which a water-stress variable was included. The overall conclusion was that as long as the water stress was not too great, enrichment will stimulate the growth of the water-stressed plants as much or more than it stimulates well-watered plants. In fact, Rosenberg et al. (1990) concludes that "the opposing effects of CO_2 enrichment and mild water stress approximately compensated one another."

Extending these conclusions to future climate scenarios is flawed in a number of ways. First, the reference to *mild* water stress is an inaccurate interpretation of climate predictions. General circulation models (GCM) predict higher globally-averaged precipitation rates, but fail to assure where the extra precipitation will fall (i.e., the ocean?). On average, the stress may indeed be mild in some regions, but the concern with crop yields should focus on the extremes and their frequency. Carbon dioxide enrichment has no effect on flood damage, and whether stomata are closed due to drought or CO_2 concentration, additional CO_2 needed for photosynthesis will not enter the plant. In addition, water stress occurring in crucial stages of plant development can limit marketable yield later when harvest occurs. Although higher CO_2 permitted grain to develop in wheat under severely limiting dry conditions (Pearcy and Bjorkman, 1983), the focus of crop models is a comparison of future yields and current yields, and given the predicted frequency of extremes related to water availability, a positive *absolute* yield change in many regions seems unlikely.

Furthermore, with the possibility of more hot spells in the future, theoretically, a plant beyond its optimal growing temperature would be forced to open its stomata to regulate leaf temperature and therefore may lose the advantages of water-use efficiency from greater CO_2. No studies have been found that include higher CO_2 concentrations, water-stress, *and* higher temperatures as variables – all of which are included in climate models, but not in ad hoc CO_2 effect estimates. In step with this paper's overall thesis, the magnitude of the CO_2 effect must be examined only in light of all future plant stresses.

Additional natural limits include nitrogen and phosphorus availability. The nitrogen content of a plant's leaves limits its maximum potential rate of photosynthesis and thus its CO_2 assimilative ability (Pitelka, 1992). Evidence exists that some growth response to CO_2 exists under nitrogen shortage; probably due to improved nitrogen uptake and increased nitrogen-use efficiency (Goudriaan and de Ruiter, 1983). However, the magnitude of the CO_2 effect typically used in climate-change studies is very dependent upon *non-limiting* nitrogen availability.

The efficiency of phosphorus use, a critical element in the molecules that transfer energy during photosynthesis, is not expected to rise in response to increased CO_2 concentration. Thus the amount of phosphorus demanded by plants rises in direct proportion to the reaction rate and the CO_2 uptake (Pitelka, 1992). In CO_2 enrichment experiments with phosphorus shortage, the consistent response was no CO_2 effect at all (Goudriaan and de Ruiter, 1983).

Current trends in soil depletion and future possibilities of frequent flooding place natural limits on essential soil nutrients. Kimball (1985) concludes that nutrient fertilization must increase in proportion to CO_2 yield enhancement to obtain maximum benefit from higher CO_2 concentrations. The production of fertilizers is highly dependent on burning fossil fuels, further aggravating the greenhouse effect. Optimal fertilization occurs where the value of marginal product of fertilizer equals the price of fertilizer. Future levels of fertilizers will be determined by how the marginal product of fertilizer, crop price, and fertilizer price change, not solely by potential benefits from higher CO_2 concentrations. Furthermore, applying fertilizers is of little consolation to poorer farms with limits on both natural soils and funds for fertilizers. The MINK study (Stockle et al., 1992b) and EPA studies (Smith and Tirpak, 1988) assumed nutrients to be non-limiting, a useful simplification, but an unrealistic one considering the dependency of the CO_2 effect on phosphorus and nitrogen, and the probability of future nutrient constraints.

Thus increased CO_2 concentrations do not necessarily result in increased crop yields. Cline (1992, p. 91) concludes, "it would seem risky to count on agriculture in general experiencing the same degree of benefits from carbon fertilization as has been observed in the laboratory experiments, especially in developing countries where the complementary water and fertilizers may be lacking." Korner and Arnone III (1992) studied the carbon, nutrient, and water balance of a tropical ecosystem and found no significant growth response to CO_2 enhancement. They emphasize the "inadequacy" of fertilization modeling and stress the "urgent need for whole-system experimental approaches in global-change research." Indeed, CO_2 fertilization is highly contingent upon ideal conditions in a non-ideal world. Its magnitude demonstrated in controlled settings with professional plant scientists at hand would not be realized in actual fields with actual managerial ability, actual farm-level funds, and current trends in soil depletion and water scarcity.

OFFSETTING THE CO_2 EFFECT

Attention is now turned to additional factors often or entirely ignored, and with their inclusion, any weak CO_2 effect remaining is most likely offset. These factors are all linked to the global warming hypothesis and demand serious consideration in future climate-change studies.

Timing of $2 \times CO_2$

A mistake in climate-change studies using GCM output is to predict climatic variables at the time that $2 \times CO_2$ occurs and then evaluate the physiological effects of a doubling of CO_2 on agriculture at the same time. "$2 \times CO_2$" and "a doubling of CO_2" are not the same and will occur at different times. There are a number of GHGs, each with its own global warming potential, and it is common practice to weight each gas by its radiative forcing properties and atmospheric lifetime relative to CO_2. "$2 \times CO_2$" is typically viewed, and entered as GCM input, as an estimate for the doubling of the CO_2 equivalence of all GHGs, not CO_2 alone.

Using a Global Warming Potential index, the Intergovernmental Panel on Climate Change (IPCC) estimates that CO_2 presently accounts for approximately 61% of human-related radiative forcing to date. Methane (CH_4), chlorofluorocarbons (CFCs), nitrous oxide (N_2O), carbon monoxide (CO), nitrogen oxides (NO_x), and other gases account for the remaining 39% (Houghton et al., 1990). Thus, over one-third of the radiative forcing at "$2 \times CO_2$" may result from non-CO_2 GHGs. Using IPCC methods, Cline (1992) estimates a CO_2 concentration of 442 ppm when $2 \times CO_2$ occurs, only two-thirds of the amount typically used in CO_2 enrichment experiments (i.e., 660 ppm). The EPA studies (Smith and Tirpak, 1988, ch. 10, p. 4), in fact, recognize this inconsistency in timing as a limitation, yet accept it as a shortcoming of the available data. Evaluating agricultural response in a climate when a doubling of CO_2 *equivalence* occurs, while using a doubling of CO_2 *alone* to calculate a fertilizer effect, explicitly overstates the benefits of CO_2 fertilization.

Ultraviolet radiation

According to the Global Warming Potential index, halocarbons (particularly CFC-11 and CFC-12) account for 11.7% of human-related radiative forcing to date (Houghton et al., 1990). The accuracy of this share is questionable because CFC caused stratospheric ozone depletion has an offsetting effect in the global greenhouse since ozone itself is a GHG. In fact, the decrease in radiative forcing resulting from depletion of ozone in the lower stratosphere in the middle and high latitudes is thought "to be comparable in magnitude to the radiative forcing contribution of CFCs (globally-averaged) over the last decade or so" (IPCC, 1992). Nevertheless, the ozone layer protects living things from harmful ultraviolet (UV-B) radiation, thus CFCs have an added indirect impact on agriculture. A 2% ozone depletion translates into a 4% increase in biologically active UV-B flux at the surface (Oppenheimer, 1989). Plant reaction to UV-B radiation varies by species, cultivar, and environmental conditions (Terramura and Sullivan, 1989). However, crop response to UV-B is yet another variable to consider in climate-change studies.

UV-B and crop yield studies are fairly limited, especially in non-controlled settings. Of the 10 crop field studies reviewed by Terramura and Sullivan (1989), about half demonstrated effects on overall yield from UV-B radiation. At the sensitive end of the spectrum, with a simulated 20% ozone depletion, the Essex soybean experienced a 25% yield reduction (Terramura and Sullivan, 1989). In general, the photosynthetic process has been shown to be sensitive to UV-B radiation (Sission, 1986). Crop ability to acclimate to future UV-B levels, and the magnitude of UV-B induced yield reductions in future climates, are difficult to evaluate. However, any study currently relying on the unknown magnitude of CO_2 fertilization would only be appropriate if the potential of UV-B damage was assessed as well.

Perhaps ignoring UV-B as a variable in climate studies was assumed warranted given the timetables for CFC reduction mandated by the 'Montreal Protocol on Substances That Deplete The Ozone Layer' and the subsequent London Amendments. The 1990 London Amendments call for a complete phase out of most CFCs by the year 2000 for developed countries, and likewise by 2010 for developing countries (Drennen, 1992). However, a critical distinction must be made between consumption and atmospheric concentration of CFCs. While worldwide consumption may cease by the year 2010, atmospheric concentrations will continue to increase due to the long life times of CFCs (ranging from decades to centuries) and their continued disposal – primarily as refrigerants in a wide range of products. Given worldwide compliance with the London Amendments, initial CFC consumption increases in developing countries, and atmospheric lifetimes, Drennen (1992) estimates that atmospheric concentrations of CFCs will continue increasing for nearly 20 years before falling, and that it will take over 50 years for atmospheric levels of CFC-12 to be reduced below current levels. With these estimates, ozone depletion seems far from over.

Furthering the threat to agriculture, recent evidence suggests that stratospheric ozone depletion is not limited to the polar regions. The IPCC reports ozone decreases in the range of 3.4% to 5.1% between 30° and 64° north latitude for the winter months between 1969 and 1988 (Houghton et al., 1990). NASA researchers feel that the ozone-depleting ingredients of extreme cold, sunshine, and chlorine will be in full force in the coming decades in the Northern Hemisphere and that widespread ozone destruction seems likely (Kerr, 1992). Global warming is thought to aggravate the process even further as the warming of the troposphere may lead to cooling of the stratosphere, enabling the conditions for rapid ozone loss to spread beyond the polar regions (Oppenheimer, 1989). Needless to say, ignoring the future yield effects of UV-B radiation is entirely premature.

Tropospheric ozone, sulfur dioxide, and nitrogen oxides

Carbon dioxide is by no stretch of the imagination a "lonely gas." Industrial and transportation sources of CO_2 are also sources of sulfur dioxide (SO_2), nitrogen oxides (NO_x), and volatile organic hydrocarbons (VOCs). Sulfur dioxide and NO_x affect plants directly as gases and indirectly as components of acid rain and deposition. Nitrogen oxides and VOCs both contribute to the photochemical creation of tropospheric ozone (O_3), an oxidant well documented for its detrimental effects on plant life. Nitrogen oxides and O_3 are also part of the GHG list while sulphur aerosols are thought to reflect incoming solar radiation, creating a cooling effect (IPCC, 1992; Lelieveld and Heintzenberg, 1992).

The transportation sector is the primary source of NO_x and VOC emissions, and consequently, O_3 creation (see Treshow and Anderson, 1989). Although industrial sources are also responsible for the precursors to O_3, they are almost entirely responsible for SO_2 emissions. Modern power plants are equipped to remove about 90% of SO_2; however, many older plants still operate and much of the developing world has little if any pollution abatement in place.

Tropospheric O_3 has by far the most convincing, definitive effects on agricultural yield. As a reactive oxidant, O_3 is toxic to numerous plant metabolic processes, and the most consistent response to increasing O_3 concentrations is a reduction in growth or yield (Chevone et al., 1990). As with CO_2, O_3 enters the plant through the stomata. In fact, due to stomatal closure, water-stressed plants are generally less sensitive to O_3 than non-stressed plants. However, O_3 and moisture stress together have a greater effect on stomatal function than either stress alone (Chevone et al., 1990), limiting CO_2 sequestering even further.

Concern for O_3 crop damage prompted the EPA to initiate the National Crop Loss Assessment Network (NCLAN) in 1980. Predicted relative yield losses at a seasonal 7-h/day mean O_3 concentration of 0.09 ppm (a level in compliance with the current U.S. National Ambient Air Quality Standard (NAAQS) of 0.12 ppm (maximum daily 1-h average)) were evaluated using the Weibull function (Heck et al., 1984). The common response of cultivars of corn, sorghum, soybean, and wheat were yield losses of 12.5%, 6.5%, 30.7%, and 27.4%, respectively. Using the Weibull model, yield response to O_3 can be estimated with species and cultivar data, given various exposure statistics. The typical response function in adequately watered plants is a near linear decline in yield or biomass accumulation as ozone concentration increases (Chevone et al., 1990).

Estimates of U.S. financial losses due to O_3 induced yield reduction range from $1 billion to $5 billion per year (Fishman and Kalish, 1990). Some data suffers from the controlled experiment dilemma, but the bold inclusion of CO_2 fertilization deserves the overwhelming evidence of O_3 damage. If an ozone variable was added to current crop yield models, given O_3 transport, exposure rates, and concentrations in the regions of interest, even strong CO_2 effects would be partially, if not totally, offset. For instance, Kimball's (1986a) mean prediction of a 17% *increase* in soybean marketable yield with a doubling of CO_2 is more than offset given Heck et al.'s (1984) estimate of a 30.7% *decrease* in soybean yield at 0.09 ppm exposure to O_3. Surprisingly, the EPA studies (Smith and Tirpak, 1988) did not utilize their past knowledge of O_3 damage modeling in their current modeling of CO_2 fertilization.

As with CFCs, perhaps ignoring the effects of O_3 in the future when $2 \times CO_2$ occurs was deemed appropriate due to existing legislation (i.e., the Clean Air Act Amendments of 1990). Again this is an erroneous exclusion. As previously mentioned, current NAAQSs for ozone, set for human (not plant) health concern, are well above crop damaging levels. Furthermore, even with relatively stringent U.S. ozone standards, the national composite average of O_3 (measured as second highest daily maximum 1-h concentration at 471 sites) remained above the NAAQS throughout the 1980s and only recently crossed the 0.12 ppm mark with 98 areas still designated nonattainment as of October 1991 (U.S. EPA, 1991). Present O_3 concentrations are certainly conducive to plant damage and future outlooks are not expected to improve.

Ozone not only contributes to global warming as a GHG, but global warming is expected to enhance O_3 formation, aggravating the greenhouse effect and O_3 induced plant damage even further. The photochemistry behind O_3 formation is significantly tied to levels of both temperature and UV-B radiation (Crutzen and Andreae, 1985). In fact, spikes in O_3 data correspond with spikes in temperature data. The relatively high O_3 concentrations in 1983 and 1988 were attributable to relatively hotter, dryer, and more stagnant meteorological conditions (U.S. EPA, 1991). With continued stratospheric O_3 depletion and a stronger greenhouse effect, trends in tropospheric O_3 may respond positively. Assuming a 3K temperature rise, UV-B enhancement corresponding to 10% ozone depletion, and projected increases in NO_x and VOC emissions, Oppenheimer (1989) projects an increase in rural ozone levels by about a factor of two in the U.S. by the year 2030.

The threat of O_3 to future agriculture is an inclusion worthy of the evidence and its partnership with CO_2 emissions. The effects of SO_2, NO_x, and resulting acid rain and dry deposition on crop yields are far less definitive and can have both positive and negative impacts. On the positive side, sulfur and nitrogen are essential elements in crop nutrition and their availability in soil may be supplemented by atmospheric deposition from the air as gases, fine particles, aerosols (dry deposition), or precipitation (wet deposition) (NAPAP, 1991). In addition, aerosols from sulphur emissions reflect incoming solar radiation, creating a cooling effect and possibly offsetting a portion of the greenhouse warming to date (IPCC, 1992), thus indirectly affecting crop yields. The negative effects include soil acidification, calcium removal, aluminum and manganese solubilization, crop quality reduction, elimination of useful microorganisms, reduced resistance to pathogens, and accelerated erosion of waxes on leaf surfaces (Canter, 1986). Often the opposing physiological effects seem to balance the scale. The recent National Acid Precipitation Assessment Program (NAPAP, 1991) report concludes there is no evidence of *consistent* crop responses to ambient acidic deposition, but that regional forest damage is apparent and of greater concern.

Interestingly, low levels of SO_2 seem to induce stomatal opening, possibly offsetting water-use efficiency gains from increased CO_2. In addition, evidence does exist of additive negative effects of NO_x, SO_2, and O_3 on crop yields, and various descriptive and process models of the effects of SO_2 on plant growth are available (see Winner et al., 1985). Most data again suffer from the controlled experiment dilemma. Given present knowledge, perhaps NAPAP's conclusions are warranted, at least on a general level, and atmospheric deposition of sulfur and nitrogen should be recognized as a potential stress, but not quantified in crop models. Modelers should be aware, however, of possible lagged effects due to factors such as changing soil chemistry. The future quantifying of any cooling effect of sulphur aerosols will also require attention.

Pests

Insects, weeds, and diseases together pose yet another factor directly linked to climate change. Insects thrive in warmer climates and weeds withstand arid conditions and compete with crops for water and nutrients. Not only may various pests become more prolific, but their geographic distribution may expand in a warmer world. Mild winters and longer growing seasons will most likely contribute to increases in pest survival and regeneration, while dryer conditions may work in favor of disease prevention. Given global warming, Pimentel et al. (1992) estimate an increase in average losses of 32% to 34% in North America and 45% to 46% in Africa due to pests for five major crops. Pests are often included in crop yield models, but only at their present level of impact. Their potential livelihood in a warmer climate has yet to be evaluated.

CONCLUSION

Funding from the U.S. Environmental Protection Agency, Department of Agriculture, and Department of Energy has clearly pushed for modeling the maximum benefits from CO_2 fertilization (Smith and Tirpak, 1988; Adams, 1989; Easterling et al., 1992; Rosenzweig et al., 1992). Undoubtedly, the inclusion of CO_2 fertilization pushed by the Bush administration weighed heavily into justifying their "wait and see" approach to GHG reduction commitments. After all, this one variable causes crop yield predictions to dramatically change from disastrous to favorable, and thus delays firm policy decisions in the present to the future.

Perhaps the ecology of agricultural yield will never fully be understood, but the present ecological picture is far from conducive to benefit from additional CO_2. Relying on CO_2 from industrialization to fertilize the world's agriculture is analogous to relying on your car's exhaust to fertilize your home garden. The future mix of agricultural stresses from air pollution, UV-B enhancement, and pest proliferation, as well as the constraints of water and nutrient availability, all work against the realization of benefits from higher CO_2 levels.

Concluding on a moral note, CO_2 fertilization is more of a justification for fossil fuel dependence than an interpretation of ecological reality. The profile of this dependence reveals one-fourth of the world's population consuming three-fourths of the world's energy (Chapman and Drennen, 1990). The fires of fossil fuels have left the few with the riches of industrialization, and the many with the externalities of their use. Glorifying the emissions of CO_2 as benefiting the world's agriculture supports the status quo of vast inequalities between nations, avoids pertinent policy decisions on mitigation and adaptation, and hampers efforts for global commitment to preservation and sustainability. Misinterpreting the risks of tomorrow can only devalue the prevention efforts of today.

ACKNOWLEDGEMENTS

The author thanks Professor Duane Chapman for his patience, comments, and original insight into the complexities involved. Thanks also for critical and constructive comments from Harry Kaiser, Tom Drennen, Dan Wilks, Eleanor Smith, Susan Riha, David Pimentel, John Duxbury, and three reviewers. As always, love and gratitude to Pat, Louis, and Jon.

REFERENCES

Adams, R.M., 1989. Global climate change and agriculture: an economic perspective. Am. J. Agric. Econ., 71: 1272–1279.

Canter, L.W., 1986. Acid Rain and Dry Deposition. Lewis Publishers, Chelsea, MI.

Chapman, D. and Drennen, T., 1990. Equity and effectiveness of possible CO_2 treaty proposals. Contemp. Policy Issues, 8(3): 16–28.

Cheng, C.C. and McCarl, B.A., 1989. The Agricultural Sector Model. Dep. Agr. Econ. Texas A&M University, College Station, TX.

Chevone, B.I., Seiler, J.R., Melkonian, J. and Amundson, R.G., 1990. Ozone–water stress interactions. In: R.G. Alscher and J.R. Cumming (Editors), Stress Responses in Plants: Adaptation and Acclimation Mechanisms. Wiley-Liss, New York, NY, pp. 311–328.

Cline, W.R., 1992. The Economics of Global Warming. Institute for International Economics, Washington, DC.

Crutzen, P.J. and Andreae, M.O., 1985. Atmospheric chemistry. In: T.F. Malone and J.G. Roederer (Editors), Global Change. Cambridge University Press, UK, pp. 75–113.

Drennen, T., 1992. Economic development and climate change: analyzing the international response. Ph.D. Dissertation, Dept. Agric. Econ., Cornell University, Ithaca, NY.

Easterling, W.E., Crosson, P.R., Rosenburg, N.J., McKenney, M.S. and Frederick, K.D., 1992. Methodology for assessing regional economic impacts of and responses to climate change: the MINK study. In: J.M. Reilly and M. Anderson (Editors), Economic Issues in Global Climate Change. Westview Press, Boulder, CO, pp. 168–199.

Fishman, J. and Kalish, R., 1990. Global Alert: The Ozone Pollution Crisis. Plenum Press, New York/London.

Goudriaan, J. and de Ruiter, H.E., 1983. Plant growth in response to CO_2 enrichment, at two levels of nitrogen and phosphorus supply. 1. Dry matter, leaf area and development. Neth. J. Agric. Sci., 31: 157–169.

Hansen, J., Fung, I., Lacis, A., Lebedeff, S., Rind, D., Ruedy, R. and Russell, G., 1988. Prediction of near-term climate evolution: what can we tell decision-makers now? In: J. Topping (Editor), Preparing for Climate Change. Proceedings of the First North American Conference on Preparing for Climate Change, 27–29 Oct. 1987, Climate Institute, Washington, DC. Government Institutes, Inc., Rockville, MD.

Heck, W.W., Cure, W.W., Rawlings, J.O., Zaragoza, L.J., Heagle, A.S., Heggestad, H.E., Kohut, R.J., Kress, L.W. and Temple, P.J., 1984. Assessing impacts of ozone on agricultural crops: II. Crop yield functions and alternative exposure statistics. J. Air Pollut. Control Assoc., 34: 810–817.

Houghton, J.T., Jenkins, G.J. and Ephraums, J.J. (Editors), 1990. Climate Change: The IPPC Scientific Assessment, Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge.

Intergovernmental Panel on Climate Change, 1992. 1992 IPCC Supplement, February.

Jones, C.A. and Kiniry, J.R., 1986. CERES-Maize: A Simulation Model of Maize Growth and Development. Texas A&M Press, College Station, TX.

Kaiser, H.M., Riha, S.J., Rossiter, D.G. and Wilks, D.S., 1992. Agronomic and economic impacts of gradual global warming: a preliminary analysis of midwestern crop farming. In: J.M. Reilly and M. Anderson (Editors), Economic Issues in Global Climate Change. Westview Press, Boulder, CO, pp. 91–116.

Kane, S.M., Reilly, J.M. and Tobey, J., 1992. A sensitivity analysis of the implications of climate change for world agriculture. In: J.M. Reilly and M. Anderson (Editors), Economic Issues in Global Climate Change. Westview Press, Boulder, CO, pp. 117–131.

Kerr, R.A., 1992. Not over the arctic – for now. Science, 256: 734.

Kimball, B.A., 1985. Adaptation of vegetation and management practices to a higher carbon dioxide world. In: B.R. Strain and J.D. Cure (Editors), Direct Effects of Increasing Carbon Dioxide on Vegetation. U.S. Dept. of Energy, Carbon Dioxide Research Division, Washington, DC, pp. 185–204.

Kimball, B.A., 1986a. Influence of elevated CO_2 on crop yield. In: H.Z. Enoch and B.A. Kimball (Editors), Carbon Dioxide Enrichment of Greenhouse Crops, Vol. 2. CRC Press, Boca Raton, FL, pp. 105–115.

Kimball, B.A., 1986b. CO_2 stimulation of growth and yield under environmental restraints. In: H.Z. Enoch and B.A. Kimball (Editors), Carbon Dioxide Enrichment of Greenhouse Crops, Vol. 2. CRC Press, Boca Raton, FL, pp. 53–67.

Korner, C. and Arnone III, J.A., 1992. Responses to elevated carbon dioxide in artificial tropical ecosystems. Science, 257: 1672–1675.

Kramer, P.J., 1983. Water Relations of Plants. Academic Press, New York, NY.

Lelieveld, J. and Heintzenberg, J., 1992. Sulfate cooling effect on climate through in-cloud oxidation of anthropogenic SO_2. Science, 258: 117–120.

Mearns, L.O., Gleick, P.H. and Schneider, S.H., 1990. Climate forecasting. In: P.E. Waggoner (Editor), Climate Change and U.S. Water Resources. John Wiley & Sons, New York, NY, pp. 87–137.

Menzhulin, G.V., 1992. The impact of expected changes on crop yields: estimates for europe, the USSR, and North America based on paleoanalogue scenarios. In: J.M. Reilly and M. Anderson (Editors), Economic Issues in Global Climate Change. Westview Press, Boulder, CO, pp. 353–381.

Monteith, J.L., 1965. Evaporation and environment. Symp. Soc. Exp. Biol., 19: 205–34.

NAPAP, 1991. 1990 Integrated Assessment Report. The National Acid Precipitation Assessment Program Office of the Director, Washington, DC.

Oppenheimer, M., 1989. Climate change and environmental pollution: physical and biological interactions. Clim. Change, 15: 255–270.

Parry, M.L., Carter, T.R. and Konijn, N.T. (Editors), 1988a. The Impact of Climatic Variations on Agriculture, Vol. 1: Assessments in Cool Temperate and Cold Regions. Kluwer Academic Publishers, The Netherlands.

Parry, M.L., Carter, T.R. and Konijn, N.T. (Editors), 1988b. The Impact of Climatic Variations on Agriculture, Vol. 2: Assessments in Semi-Arid Regions. Kluwer Academic Publishers, The Netherlands.

Pearcy, R.W. and Bjorkman, O., 1983. Physiological effects. In: E.R. Lemon (Editor), CO_2 and Plants – The Response of Plants to Rising Levels of Atmospheric Carbon Dioxide, AAAS Selected Symposia Series. Westview Press, Boulder, CO, pp. 65–105.

Pimentel, D., Brown, N., Vecchio, F., La Capra, V., Hausman, S., Lee, O., Diaz, A., Williams, J., Cooper, S. and Newburger, E., 1992. Ethical issues concerning potential global climate change on food production. J. Agric. Environ. Ethics, 5: 113–146.

Pitelka, L., 1992. Forest reponse to carbon dioxide. Electr. Power Res. Inst. J., Jan./Feb., pp. 38–41.

Ritchie, J.T. and Otter, S., 1985. Description and performance of CERES-Wheat: a user-oriented wheat yield model. In: W.O. Willis (Editor), ARS Wheat Yield Project. USDA-ARS, ARS-38: 159–175.

Roningen, V., 1986. A static world policy simulation (SWOPSIM) modeling framework. ERS Staff Report AGE860625. U.S. Dept. of Agric., Washington, DC.

Rosenberg, N.J., Kimball, B.A., Martin, P. and Cooper, C.F., 1990. From climate and CO_2 enrichment to evapotranspiration. In: P.E. Waggoner (Editor), Climate Change and U.S. Water Resources. John Wiley & Sons, New York, NY, pp. 151–175.

Rosenzweig, C., 1989. Global climate change: predictions and observations. Am. J. Agric. Econ., 71: 1265–1271.

Rosenzweig, C., Parry, M., Fischer, G. and Frohberg, K., 1992. Climate Change and World Food Supply: A Preliminary Report. Environmental Change Unit, University of Oxford, UK.

Sission, W.B., 1986. Effects of UV-B radiation on photosynthesis. In: R.C. Worrest and M.M. Caldwell (Editors), Stratospheric Ozone Reduction, Solar Ultraviolet Radiation and Plant Life. Springer-Verlag, Berlin, pp. 161–169.

Smith, J.B. and Tirpak, D.A. (Editors), 1988. The Potential Effects of Global Climate Change on the United States, Draft Report to Congress. U.S. Environmental Protection Agency, Office of Policy, Planning, and Evaluation, Office of Research and Development, Washington, DC.

Stockle, C.O., Williams, J.R., Rosenberg, N.J. and Jones, C.A., 1992a. A method for estimating the direct and climatic effects of rising atmospheric carbon dioxide on growth and yield of crops: part I – modification of the EPIC model for climate change analysis. Agric. Syst., 38: 225–238.

Stockle, C.O., Dyke, P.T., Williams, J.R., Jones, C.A. and Rosenberg, N.J., 1992b. A method for estimating the direct and climatic effects of rising atmospheric carbon dioxide on growth and yield of crops: part II – sensitivity analysis at three sites in the Midwestern USA. Agric. Syst., 38: 239–256.

Terramura, A.H. and Sullivan, J.H., 1989. How increased solar ultra-violet-B radiation may impact agricultural productivity. In: J. Topping (Editor), Coping With Climate Change. Proceedings of the Second North American Conference on Preparing for Climatic Change: A Cooperative Approach. The Climate Institute, Washington, DC, pp. 203–207.

Tolbert, N.E. and Zelitch, I., 1983. Carbon metabolism. In: E.R. Lemon (Editor), CO_2 and Plants – The Response of Plants to Rising Levels of Atmospheric Carbon Dioxide, AAAS Selected Symposia Series. Westview Press, Boulder, CO, pp. 21–64.

Treshow, M. and Anderson, F.K., 1989. Plant Stress from Air Pollution. John Wiley & Sons, Chichester, UK.

U.S. EPA, 1991. National Air Quality and Emissions Trends Report, 1990. Office of Air and Radiation, Office of Air Quality Planning and Standards, Research Triangle Park, NC.

Waggoner, P.E. and Revelle, R.R., 1990. Summary. In: P.E. Waggoner (Editor), Climate Change and U.S. Water Resources. John Wiley & Sons, New York, NY, pp. 447–477.

Wilkerson, G.G., Jones, J.W., Boote, K.J. and Mishoe, J.W., 1985. SOYGRO V5.0: Soybean Crop Growth and Yield Model, Technical Documentation. University of Florida, Gainesville, FL.

Williams, J.R., Jones, C.A. and Dyke, P.T., 1984. A modeling approach to determining the relationship between erosion and soil productivity. Trans. Am. Soc. Agric. Eng., 27: 129–144.

Winner, W.E., Mooney, H.A. and Goldstein, R.A. (Editors), 1985. Sulfur Dioxide and Vegetation: Physiology, Ecology, and Policy Issues. Stanford University Press, Stanford, CA.

Wittwer, S.H., 1986. Worldwide status and history of CO_2 enrichment – an overview. In: H.Z. Enoch and B.A. Kimball (Editors), Carbon Dioxide Enrichment of Greenhouse Crops, Vol. 1. CRC Press, Boca Raton, FL, pp. 3–15.