FUTURE EFFECTS OF OZONE ON CARBON SEQUESTRATION AND CLIMATE CHANGE POLICY USING A GLOBAL BIOGEOCHEMICAL MODEL

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Abstract. Exposure of plants to ozone inhibits photosynthesis and therefore reduces vegetation production and carbon sequestration. The reduced carbon storage would then require further reductions in fossil fuel emissions to meet a given CO_2 concentration target, thereby increasing the cost of meeting the target. Simulations with the Terrestrial Ecosystem Model (TEM) for the historical period (1860–1995) show the largest damages occur in the Southeast and Midwestern regions of the United States, eastern Europe, and eastern China. The largest reductions in carbon storage for the period 1950–1995, 41%, occur in eastern Europe. Scenarios for the 21st century developed with the MIT Integrated Global Systems Model (IGSM) lead to even greater negative effects on carbon storage in the future. In some regions, current land carbon sinks become carbon sources, and this change leads to carbon sequestration decreases of up to 0.4 Pg C yr^{-1} due to damage in some regional ozone hot spots. With a climate policy, failing to consider the effects of ozone damage on carbon sequestration would raise the global costs over the next century of stabilizing atmospheric concentrations of CO_2 equivalents at 550 ppm by 6 to 21%. Because stabilization at 550 ppm will reduce emission of other gases that cause ozone, these additional benefits are estimated to be between 5 and 25% of the cost of the climate policy. Tropospheric ozone effects on terrestrial ecosystems thus produce a surprisingly large feedback in estimating climate policy costs that, heretofore, has not been included in cost estimates.

1. Introduction

Exposure of plants to ozone inhibits photosynthesis (Reich, 1987; Mauzerall and Wang, 2001) and thereby reduces vegetation production and carbon sequestration. The reduced carbon storage would then require further fossil fuel emission reductions to meet a given CO_2 concentration target, and increase the cost of meeting that target. We use an integrated global systems model that includes coupled models of the oceans, atmosphere, and the land systems with an economic model to evaluate the magnitude of this effect.

This integrated modeling system is the MIT Integrated Global Systems Model (MIT-IGSM, Prinn et al., 1999; Reilly et al., 1999). It simulates the emissions of greenhouse gases and other pollutants including ozone precursors as affected by economic activity, their effects on climate and atmospheric composition, and the

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follow-on effects on vegetation. To evaluate the effects of ozone on vegetation, we use the Terrestrial Ecosystem Model (TEM 4.3). This version of TEM has been used to examine the consequences of ozone damage on terrestrial carbon dynamics in the conterminous United States (Felzer et al., 2004). Here, we evaluate the magnitude of ozone damage for the terrestrial biosphere generally and for those hotspot regions where additional economic costs may be required to reduce CO_2 emissions that would otherwise be sequestered by terrestrial ecosystems.

First we provide background information on our previous research and on the nature and extent of the ozone effect. In the methods section, we describe the models, experimental design, and how global ozone datasets are constructed. We then describe how the present day ozone is used as a method of calibrating and validating our future ozone projections. Scenarios of the future are then considered, with an emphasis on how ozone exposure could reduce carbon sequestration over particular "hot spot" regions (regions where the effect of ozone on carbon sequestration is significant). Finally, we present an economic analysis using these carbon sequestration values to drive the economics model. We conclude with a discussion of policy implications of these results.

2. Background

Regional measurements of tropospheric ozone show a number of ozone peaks in highly industrialized regions across the globe as well as in places where biomass burning is a major land clearing and management tool. On the global-scale, central Europe and eastern China, along with the eastern U.S., are the regions with the highest levels of ozone pollution. Measurements from the European Monitoring and Evaluation Program (Hjellbrekke, 1998; Hjellbrekke and Solberg, 1999) indicate that the highest ozone levels in Europe occur in Central and Southern Europe, including Spain, Italy, and Germany. Although ozone measurements in China described in the literature are limited to only a few sites (Luo et al., 2000), Aunan et al. (2000) estimate, using an atmospheric chemistry-transport model, that the highest ozone levels in China occur in eastern, coastal regions. In the U.S., measurements of ozone by the Environmental Protection Agency's (EPA) Clean Air Status and Trends Network (CASTNET) are highest in the Southeast and Southern California, although the effect on vegetation is largest in the eastern U.S. because of higher vegetation productivity and concentration of croplands in this region (Felzer et al., 2004). High ozone levels also exist in the tropical rainforests of Brazil (Kirchoff and Rasmussen, 1990) and Africa (Cros et al., 1988) due to biomass burning.

The effects of ozone on vegetation have been studied both within the laboratory and in field experiments, using controlled greenhouses or growth chambers, open-top chambers, and field plots (see Krupa and Manning, 1988; Mauzerall and Wang, 2001; or Felzer et al., 2004 for literature review). Ozone affects vegetation by direct cellular damage once it enters the leaf through the stomata (Mauzerall and

Wang, 2001). A secondary response to ozone is possibly a reduction in stomatal conductance (Reich, 1987), which has implications for further ozone uptake and moisture availability. Ozone uptake is therefore a function of both ambient ozone levels and stomatal conductance. Reich (1987) concluded that crops are more sensitive to ozone exposure than deciduous trees, which are, in turn, more sensitive than coniferous trees. For a more thorough review of the effects of ozone on vegetation, see Felzer et al. (2004).

Reduced vegetation productivity and carbon sequestration from ozone damage will have important consequences on both our use of natural resources and the economic implications of climate and carbon policy. Ozone damage to forests will affect forestry products, such as wood for construction, paper, fuel and fiber, as well as secondary factors including water quantity and quality from watersheds, nutrient cycling, and recreational opportunities (IPCC: Gitay et al., 2001). A variety of studies have focused on crop and forest product effects (e.g. Adams et al., 1986; Westenbarger and Frisvold, 1995). We focus in this paper on the effects on carbon storage and climate policy. We define ozone "hotspots" as regions where high ozone levels coincide with high plant productivity to cause substantial ozone damage, such as the eastern U.S. (Felzer et al., 2004). If terrestrial carbon uptake is reduced, or if terrestrial systems become a source of carbon due to ozone damage, further efforts will be required to reduce carbon emissions, and it could undermine efforts to manage forest and croplands to enhance carbon sequestration.

This effect and its consequences on terrestrial carbon dynamics in the conterminous United States (U.S.) was recently demonstrated by using the Terrestrial Ecosystems Model, Version 4.3 (TEM 4.3) (Felzer et al., 2004). Net Primary Production (NPP) was calculated to be reduced by up to 7% for the conterminous U.S. during the late 1980s-early 1990s, and carbon sequestration (Net Carbon Exchange, NCE) since the 1950s by 18–38 Tg C yr^{-1} with the presence of ozone.

3. Methods

We use the MIT-IGSM to estimate the potential impact of tropospheric ozone on NCE and the economic consequences for meeting a target of stabilizing atmospheric greenhouse gases. The IGSM (described in Prinn et al., 1999) includes: a chemistry and climate component that includes a two-dimensional (2D) land–ocean (LO) resolving climate model (Sokolov and Stone, 1998), coupled to a 2D model of atmospheric chemistry (Wang et al., 1998; Wang and Prinn, 1999; Mayer et al., 2000a); an ocean component that includes a 2D model of ocean circulations (Kamenkovich et al., 2002); a terrestrial component to simulate carbon and nitrogen dynamics of terrestrial ecosystems (Xiao et al., 1997, 1998); and an economic component designed to project emissions of greenhouse-relevant gases (Jacoby et al., 1997; Babiker et al., 2001) and the economic consequences of policies to limit them (e.g., Babiker et al., 2000, 2002; Jacoby and Sue Wing, 1999; Reilly et al., 1999). Applications of the full system have focused on understanding uncertainty in future forecasts of climate change (Prinn et al., 1999; Webster et al., 2003). We describe the terrestrial and economic components in somewhat greater detail here as they are key components in the model simulations we conduct.

3.1. THE TERRESTRIAL MODEL

For the terrestrial component, we use the Terrestrial Ecosystem Model (TEM, Melillo et al., 1993; Tian et al., 1999, 2003; Felzer et al., 2004), which is a process-based biogeochemistry model that simulates the cycling of carbon, nitrogen, and water among vegetation, soils, and the atmosphere. Version 4.3 of this model (TEM 4.3) includes modeling of the pathways by which ozone influences the productivity and carbon storage of terrestrial ecosystems (Felzer et al., 2004). We incorporate the effects of ozone on productivity by modifying the calculation of Gross Primary Production (GPP) in TEM (Felzer et al., 2004). The effect of ozone is to linearly reduce GPP above a threshold ozone level according to the Reich (1987) and Ollinger et al. (1997) models. We calculate separate coefficients of linearity for hardwoods, conifers, and crops. Although different species of trees and types of crops respond differently to ozone, we have made this simplifying assumption based on the Reich (1987) model.

To estimate the net assimilation of CO_2 into plant tissues (i.e. plant growth), we calculate net primary production (NPP) as follows:

$$\mathrm{NPP} = \mathrm{GPP} - R_{\mathrm{A}} \tag{1}$$

where R_{A} is autotrophic respiration. To estimate carbon sequestration by the ecosystem, we calculate net carbon exchange (NCE) as follows:

$$\mathrm{NCE} = \mathrm{NPP} - R_{\mathrm{H}} - E_{\mathrm{c}} - E_{\mathrm{p}} \tag{2}$$

where R_{H} is heterotrophic respiration, E_{c} is the carbon emission during the conversion of natural ecosystems to agriculture, and E_{p} is the sum of carbon emission from the decomposition of agricultural products (McGuire et al., 2001). For natural vegetation, E_{c} and E_{p} are equal to 0, so NCE is equal to net ecosystem production (NEP). As indicated by Equations (1) and (2), the reduction of GPP by ozone will also reduce both NPP and NCE.

3.2. THE ECONOMIC MODEL

For the economic component, we use the Emissions Prediction and Policy Analysis (EPPA) model (Babiker et al., 2001), which is a recursive-dynamic multi-regional general equilibrium model of the world economy developed for analysis

TABLE I
Countries, regions, and sectors in the general equilibrium model

Country or region	Sectors
Annex B	Non-energy
United States	Agriculture
Japan	Energy intensive products
European Union	Other industries products
Other OECD	Energy
Former Soviet Union	Coal
Eastern Europe	Crude oil
Non-Annex B	Natural gas
India	Refined oil,
Brazil	Synthetic gas from coal
Energy exporting economies	Oil from shale
Dynamic Asian economies	Electric: Fossil, nuclear, hydro Solar and wind, biomass, natural gas Combined cycle (NGCC), NGCC w/sequestration. Integrated Coal Gasification (IGCC) w/sequestration
Rest of world	
China	

of climate change policy. The version of EPPA used here is built on a comprehensive energy–economy dataset (GTAP4-E, Hertel, 1997) that accommodates a consistent representation of energy markets in physical units as well as detailed accounts of regional production and bilateral trade flows. The base year for the model is 1995, and it is solved recursively at 5-year intervals. The model is stratified into 12 regions across the globe and 10 economic sectors (Table I). It projects emissions of CO_2, methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons, perfluorocarbons, sulfur hexafluoride, sulfur dioxide (SO_2), black carbon and organic carbon, nitrogen oxides (NO_x), carbon monoxide (CO), ammonia and non-methane volatile organic compounds from coal, oil, and gas combustion; agricultural activities and biomass burning; and from industrial sources (Webster et al., 2003a; Mayer et al., 2000b). Because fossil fuel burning is often the source of ozone precursors, policies that limit fossil fuel emissions by reducing fossil fuel burning will also affect emissions of other pollutants as modeled in EPPA.

As with other models of this type, a carbon constraint can be specified, and the model algorithm searches for reductions across the economy such that the marginal cost of reduction is the same in each sector and, with international emissions trading, the same across regions. With the recursive dynamic structure of EPPA, banking and borrowing across time are not allowed, and so the global constraint specified for each period is met exactly in each period. EPPA also represents emissions of other greenhouse gases and pollutants, with the potential for emissions trading among the greenhouse gases (Hyman et al., 2002).

3.3. EXPERIMENTAL DESIGN

We explore the effects on the terrestrial biosphere of both historical ozone levels and future ozone levels as projected by the MIT-IGSM. Because there are no detailed, accurate historical surface ozone datasets for the globe, we develop an independent dataset (1860–1995) based on ozone distribution maps derived from the Multiscale Atmospheric Transport and Chemistry (MATCH) model (Lawrence et al., 1999; Mahowald et al., 1997; Rasch et al., 1997; von Kuhlmann et al., 2003), which is a three-dimensional (3D) global chemical transport model driven by reanalysis meteorological fields. We then perform two sets of simulations to examine how land management might modify the effects of ozone damage, one with and one without optimal nitrogen fertilization (F). In addition, two sets of control simulations (CTL, with and without optimal nitrogen fertilization) are conducted that do not include ozone effects. There are therefore a total of four model simulations designed to study the historical effects of ozone on terrestrial carbon sequestration.

Ozone levels in the future will be influenced both by potential climate policies designed to reduce the levels of greenhouse gases (GHG, i.e. CO_2, CH_4, N_2O, CFCs) and by environmental policies designed to reduce the level of pollutant gases (CO, VOC, NO_x, SO_2). Both sets of gases include precursors to ozone formation. We therefore run TEM 4.3 with four scenarios of the future developed from EPPA: a pollution scenario, a pollution cap scenario, a greenhouse gas stabilization scenario, and a scenario that combines a pollution cap with greenhouse gas stabilization. For each scenario, emissions from EPPA are used as inputs by the 2 dimensional land ocean (2D-LO) atmospheric chemistry model (Mayer et al., 2000a, b; Sokolov and Stone, 1998; Wang et al., 1998), which then transports the gases across the globe and simulates the appropriate chemical reactions of the gases in the atmosphere to update atmospheric concentrations of the gases. The 2D ozone predictions from the 2D-LO model are mapped to 3D using a procedure described in Section 3.4 below. Details of the four future scenarios are described below.

A pollution case (POL) allows GHG and pollutant gas emissions to continue increasing unabated. In terms of GHG emissions this scenario is roughly in the middle of the range of emissions projected by the IPCC in its Special Report on Emissions Scenarios (SRES, 2000). For the pollutants gases, emissions are somewhat higher because existing clean air standards, where they exist, are not necessarily enforced in this scenario. We compare the POL scenario with, for example, a pollution cap (POLCAP) scenario, to provide the basis for estimating the potential benefits of pollution control. The POLCAP scenario assumes no regulation of GHG emissions, but involves capping the pollutant gases everywhere at 1995 levels.

A third scenario (GSTAB) is a GHG policy case (i.e. case $3'$ in Reilly et al., 1999) that assumes significant reduction in GHG emissions by 2100. There are no specific caps on pollutant gases but their emissions are affected by the climate policy. Controls for both CO_2 and other GHGs are imposed on the U.S.A., Japan, Europe, the former Soviet Union, and other developed countries beginning in 2010

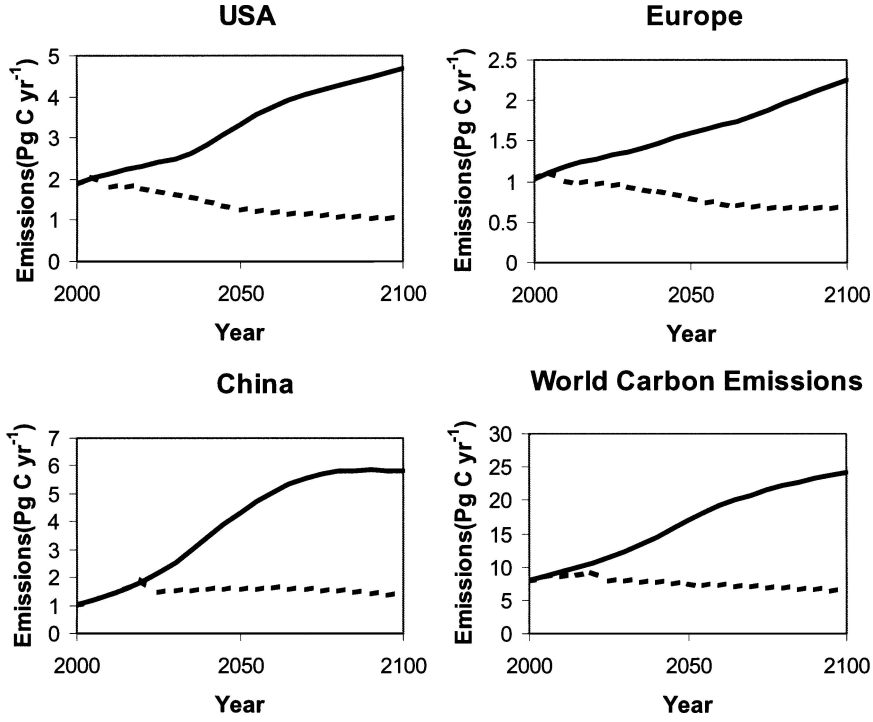

Figure 1. EPPA reference CO_2 emissions and caps. Solid line is EPPA POL CO_2 emissions and dashed line is EPPA GSTAB CO_2 emissions.

with emissions capped at 5% below 1990 levels for the group,* and declining by 5 percentage points every 15 years. All other nations take on a GHG cap in 2025 at 5% below their 2010 emissions, and then this declines by 5 percentage points every 15 years. For example, Figure 1 shows the EPPA reference carbon dioxide emissions and the cap for the world, and for the 3 regions on which we focus. The policy scenario leads to stabilization of atmospheric CO_2 at about 550 ppm by 2100. This scenario was chosen because the target of 550 ppm is often discussed as a goal for climate policy, and the MIT IGSM results of running this scenario are available in the literature (Reilly et al., 1999).

A fourth scenario (GSTABCAP) applies the pollution caps from the POLCAP scenario to the GSTAB scenario. For each of the four scenarios, four sets of simulations are conducted to evaluate the relative role of ozone on terrestrial carbon dynamics and to assess the influence of management on the response of crops to

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*The country-specific caps are those agreed to in the Kyoto Protocol, with the US at 7% below 1990 and the EU at 8% below 1990 levels. Under the Protocol, developing countries did not take on reduction targets in the first commitment period. The policy described here goes beyond the Kyoto targets in a fashion that brings the world on a path toward stabilization at 550 ppm. It is for illustrative purposes, and is not intended as a prediction of the likely or best policy path.

TABLE II
Simulations of future scenarios

Scenario	Irrigation/ Fertilization*	Ozone damage included**	Pollutant controls***	CO_2/GHG controls****
POL	No	Yes	No	No
POLF	Yes	Yes	No	No
POLCAP	No	Yes	Yes	No
POLCAPF	Yes	Yes	Yes	No
GSTAB	No	Yes	No	Yes
GSTABF	Yes	Yes	No	Yes
GSTABCAP	No	Yes	Yes	Yes
GSTABCAPF	Yes	Yes	Yes	Yes
POLCTL	No	No	No	No
POLFCTL	Yes	No	No	No
POLCAPCTL	No	No	Yes	No
POLCAPFCTL	Yes	No	Yes	No
GSTABCTL	No	No	No	Yes
GSTABFCTL	Yes	No	No	Yes
GSTABCAPCTL	No	No	Yes	Yes
GSTABCAPFCTL	Yes	No	Yes	Yes

*Nitrogen fertilization (F) column: “yes” means optimal F turned on, “no” means no F.

**Ozone Damage Included: “yes” indicates that ozone concentrations influence terrestrial carbon dynamics, “no” indicates that ozone concentrations had no influence on terrestrial carbon dynamics.

***Pollutant Controls: “yes” means pollutant caps applied everywhere at 1995 levels.

****CO_2/GHG Controls: “yes” indicates greenhouse gases controlled to achieve stabilization at 550 ppm by 2100, “no” assumes no explicit climate policy.

ozone damage: 1) no ozone effects and no fertilization; 2) ozone effects and no fertilization; 3) no ozone effects and fertilization; and 4) ozone effects and fertilization. As a result, a total of 16 simulations (Table II) are conducted to evaluate the potential consequences of future climate and environmental policies.

To focus on how carbon uptake by ecosystems affect policy we do not utilize the EPPA feature that allows emissions trading across GHGs, but we do allow trading of carbon emissions across regions. The representation of the non-GHG air pollutants in EPPA is simplified such that it is not possible to realistically estimate the cost of the policy constraint on them (Mayer et al., 2000b). This remains a limit of EPPA and other similar models to the extent they represent both other pollutants and GHGs. In cases where we represent caps on these pollutants, we impose an exogenous scenario for these emissions. Issues that arise in considering pollution and carbon policy together, where explicit costs of controlling both are represented in EPPA, were considered in de Masin (2003) for the case of particulate matter.

For each simulation of TEM, carbon and nitrogen dynamics of terrestrial ecosystems are initialized to equilibrium conditions assuming the land is covered with the original natural vegetation. The model is then run in a transient spin-up mode for 120 years using the historical climate data during the initial 40 years three times. If a grid cell is cultivated in 1860, the grid cell is converted during the first year of this spin-up period, and terrestrial carbon and nitrogen dynamics are allowed to come back into a dynamic equilibrium state before starting our historical analysis from 1860 to 1995. The future scenarios are then run from 1977–2100, based on the state of terrestrial ecosystems resulting from the MIT ozone historical runs.

3.4. DATASET DEVELOPMENT

The ozone effect within TEM 4.3 is based on the AOT40 index. This index is a measure of the accumulated hourly ozone levels above a threshold of 40 ppb. Since hourly datasets of surface ozone do not exist at the spatial extent and resolution of TEM, we have used the MATCH model (run at 2.8 ×2.8 degree or T42 horizontal resolution) to construct global AOT40 maps for each hour. The average monthly boundary layer MATCH ozone values for 1998 are scaled by the ratio of the zonal average ozone from the IGSM (which are 3-hourly values that have been linearly interpolated to hourly values) to the zonal ozone from the monthly MATCH to maintain the zonal ozone values from the IGSM. This procedure is done for the period 1977–2100. From 1860–1976, we assume the zonal ozone values increase by 1.6%/year based on Marenco et al. (1994). In both cases, the AOT40 values are then calculated from the hourly ozone. The resulting pattern (Figure 2) shows large ozone levels in the southeastern U.S., Italy, parts of the Middle East, and eastern China. These AOT40 distributions are not claimed to be exact, but do provide feasible geographically and temporally varying patterns to illustrate ozone effects on vegetation.

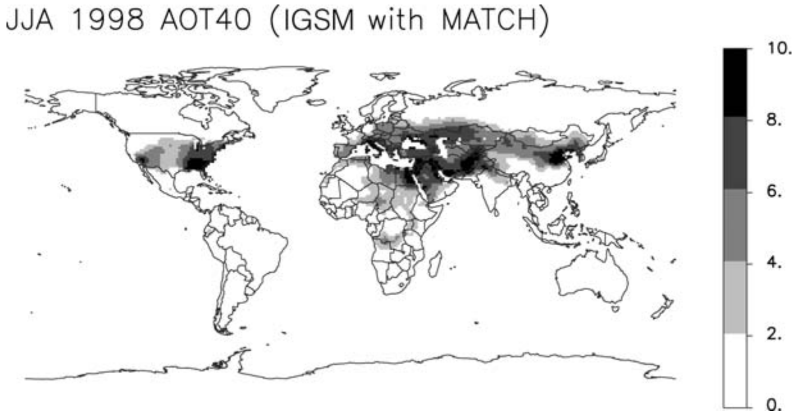


Figure 2. Mean AOT40 (ppm-h) for June–July–August of 1998.

In addition to ozone levels, other driving variables for TEM include CO_2, climate, and land use. CO_2 fertilization from 1860–1976 and climate variability (surface temperature, precipitation, top-of-the-atmosphere and surface radiation) from 1860–1927 are derived from a reference simulation for the historical period and from each of the individual future scenarios for the future. Land use is prescribed by agricultural land datasets until 1993 (McGuire et al., 2001). After 1993, no land use change is assumed to occur so that the distribution of croplands remains constant. The model also uses spatially-explicit datasets of soil texture, elevation, and potential vegetation (McGuire et al., 2001), which is used to represent original natural vegetation. For simulations of future conditions, TEM derives monthly climate data (surface temperature, precipitation, surface and top of the atmosphere short wave radiation) and annual CO_2 concentrations from the MIT-IGSM using procedures described by Xiao et al. (1998). The EPPA model requires the GTAP4-E dataset as input, as described in Section 3.2.

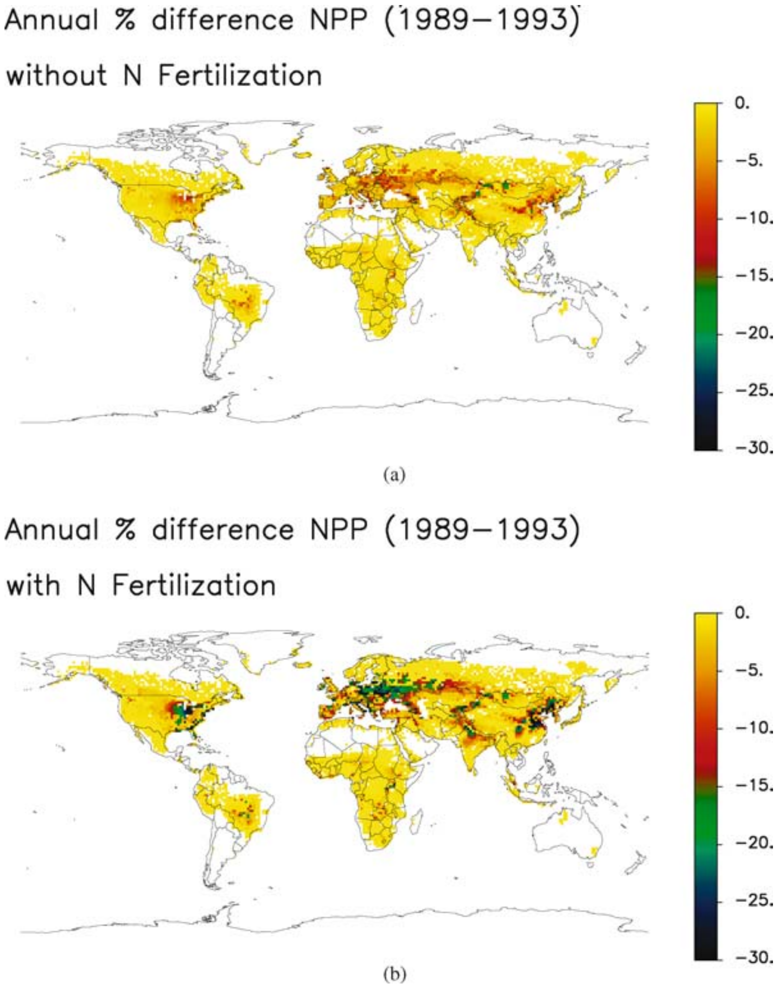
4. Results

4.1. CURRENT CONDITIONS

Ozone reduces NPP (Figure 3) because it decreases GPP. The largest reductions occur in the midWestern U.S., eastern Europe, and eastern China. Because of the larger vegetation productivity in the southeastern U.S., the percent difference reduces the apparent magnitude of the ozone effect in this region relative to the midWestern U.S. The magnitude of the reductions is larger when optimal N fertilization is used on cropland, though the patterns remain similar. The NPP reductions in the hot spot regions are in the 15–20% range with optimal N fertilization and 10–15% without N fertilization.

The major agricultural regions of the world (Figure 4) correspond to the ozone hotspots because of the large sensitivity of crops to ozone. Ozone damage to NPP is more intense when agricultural regions are fertilized because of the dependency of the ozone effect on stomatal conductance and the relation between stomatal conductance and photosynthesis. In all three hotspot regions, the NPP reductions are greater in agricultural regions when they are fertilized.

Carbon sequestration is also reduced by ozone (Figure 5), because of the reduced NPP. The NCE decreases occur in similar locations to the NPP decreases, i.e. the southeastern U.S., eastern Europe, and eastern China, though all continents suffer some ozone damage. The simulations without N fertilization show a similar pattern to the simulations with fertilization, but reduced magnitude and extent throughout agricultural regions. Also the midWestern U.S. has a more pronounced ozone effect than the southeastern U.S. when fertilization is used due to the enhanced sensitivity of fertilized agricultural regions. The maximum magnitude of the reduction in carbon sequestration due to ozone is



Annual % difference NPP (1989–1993) without N Fertilization

(a)

Annual % difference NPP (1989–1993) with N Fertilization

(b)

Figure 3. Maps of mean annual NPP percent difference between the ozone and control simulations for the years 1989–1993 for: (a) no nitrogen fertilization and (b) with optimal nitrogen fertilization. Largest decrease is 60% and largest increase is 8%, which occurs for only 2.6% of grids. Most significant decreases in NPP occur in the southeastern half of the U.S., eastern Europe, and eastern China.

0.1 Pg C m^{-2} yr^{-1} with optimal N fertilization and 0.06 Pg C m^{-2} yr^{-1} without N fertilization.

Although the effect of ozone is to reduce NCE, the actual NCE is sometimes positive and sometimes negative, depending on the time period. During 1950–1995, the TEM results show that NCE for the world as a whole is negative (i.e. carbon source) if agricultural management (nitrogen fertilization) is not considered and positive (i.e. carbon sink) if it is considered (Table III). On the other hand, from 1990–1994, NCE is positive in both cases, though much more strongly positive if optimal nitrogen fertilization is assumed. After 1950, when the widespread use

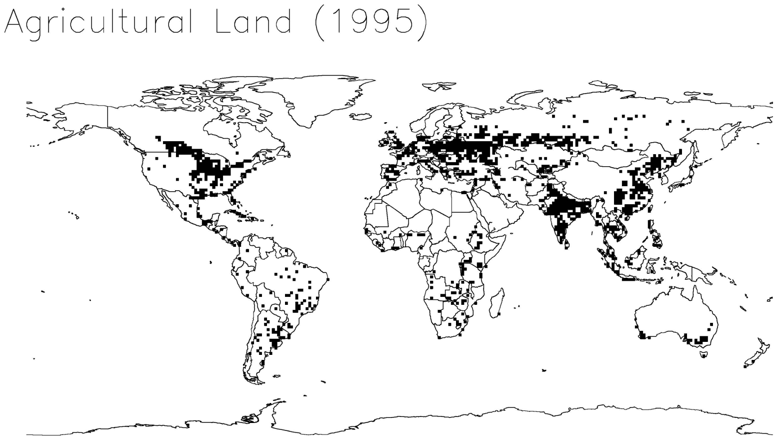


Figure 4. Map of TEM grids designated as croplands in 1995 and from 1995–2100.

of fertilizers is assumed to occur, the effect of optimal nitrogen fertilization is to initially increase carbon storage in croplands. However, as 60% of crop biomass is assumed to remain in fields as stubble, NCE is reduced over time because decomposition of the additional organic matter counteracts the increase in productivity (NPP). As a result of this temporary enhancement of carbon sequestration, the accumulated carbon storage with optimal agricultural management is greater than without nitrogen fertilization. Although the ozone effect is greater when agricultural management is used, the actual carbon storage is still much greater with agricultural management than without (Table III).

The global effects of ozone on NPP are a decrease of 0.8% without agricultural management and a decrease of 2.9% with optimal agricultural management (Table III). The NCE from 1950–1995 is reduced by 0.1 Pg C yr^{-1} without agricultural management and reduced by 0.3 Pg C yr^{-1} with optimal agricultural management. During 1990–1994, the short-term reductions in NCE are nearly similar to the longer-term reductions (1950–1995). For the U.S., ozone reduces NPP (1989–1993) by 2.3% without optimal N fertilization and 7.2% with optimal N fertilization, which

TABLE III

Mean annual net primary production (NPP) from 1989 to 1993 and the change in mean net carbon exchange (NCE) from 1950 to 1995 and from 1990 to 1994 in Pg C yr^{-1}

Scenario	NPP	NCE (50–95)	NCE (90–94)
No ozone, no fertilization	44.8	−0.5	0.3
No ozone, with fertilization	57.4	1.4	1.1
Ozone with no fertilization	44.4	−0.6	0.1
Ozone with fertilization	55.8	1.1	0.7

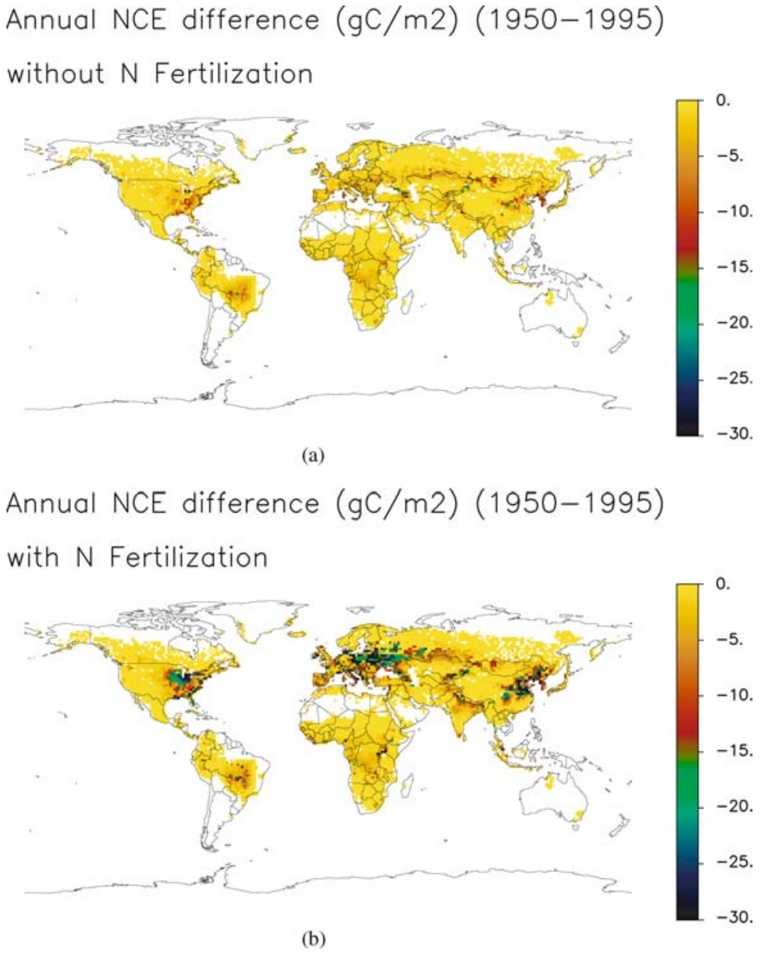


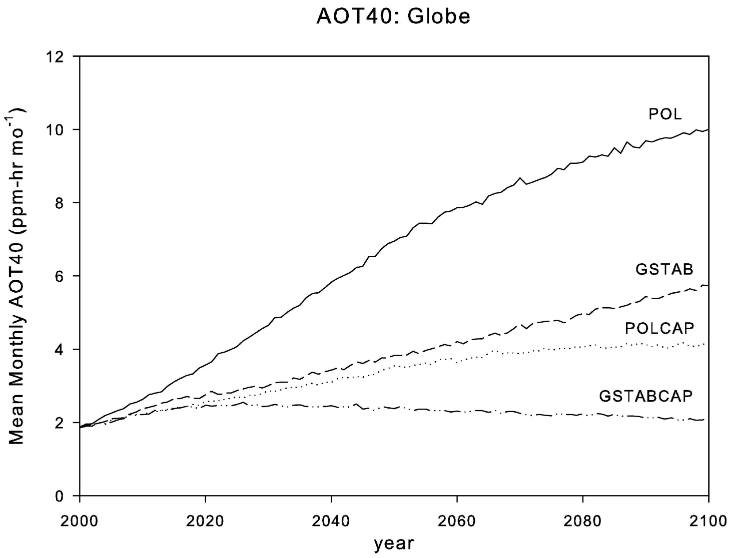
Figure 5. Maps of annual NCE difference between the ozone and control simulations (with nitrogen fertilization) for the years 1950–1995 in g C m^{-2} yr^{-1} for: (a) no nitrogen fertilization, (b) with optimal nitrogen fertilization. Largest decrease is 99 g C m^{-2} yr^{-1}. NCE decreases occur in similar locations as the NPP decreases.

are very close to the values of 2.6 and 6.8%, respectively, from the Felzer et al. (2004) results that were obtained using an observationally-based AOT40 dataset. This model-based AOT40 mapping method therefore provides a similar ecosystem response to the observationally-based ozone data for the present for the U.S.

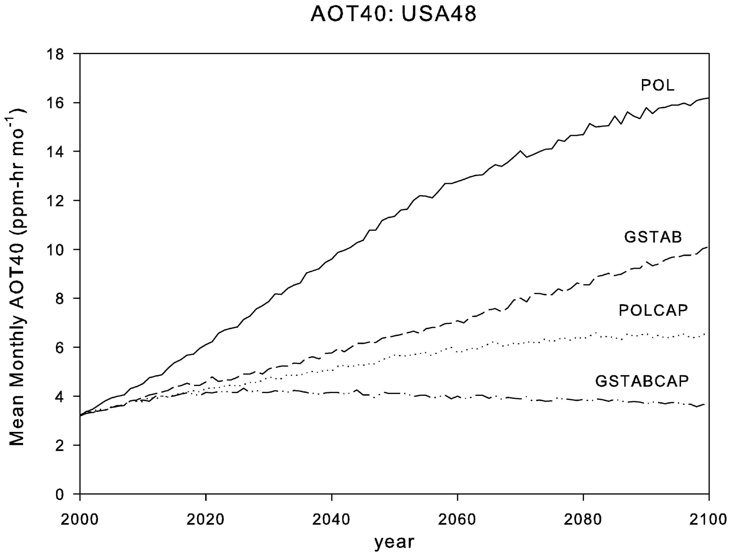
From the mapped patterns it is clear that the ozone effect is largely a regional phenomenon due to the spatial heterogeneity of ozone concentrations throughout the globe. For that reason, we concentrate on the three regions (i.e. “hot spots”) that experience the maximum ozone damage, the U.S., Europe, and China, for examining the impacts of possible future ozone concentrations associated with various pollution control and greenhouse gas control policies.

4.2. FUTURE

Between the years 2005 and 2100 the AOT40 ozone index (Figure 6) for the globe and each of the three maximum-impact regions increase for all the policy scenarios. As expected, the POL scenario shows the largest increase in AOT40

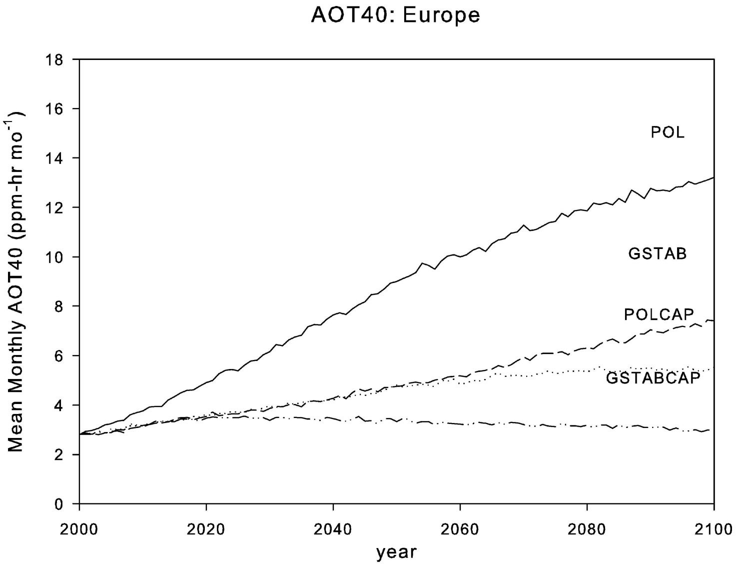


(a)

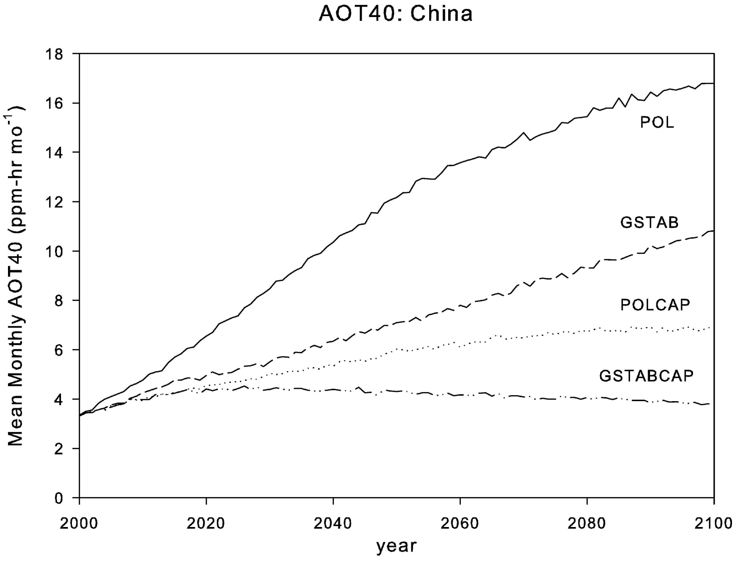


(b)

Figure 6. Time series of mean monthly AOT40 for each of the scenarios in ppm-hr month^{-1} for: (a) globe, (b) U. S., (c) Europe, and d) China. (*Continued on next page*)



(c)

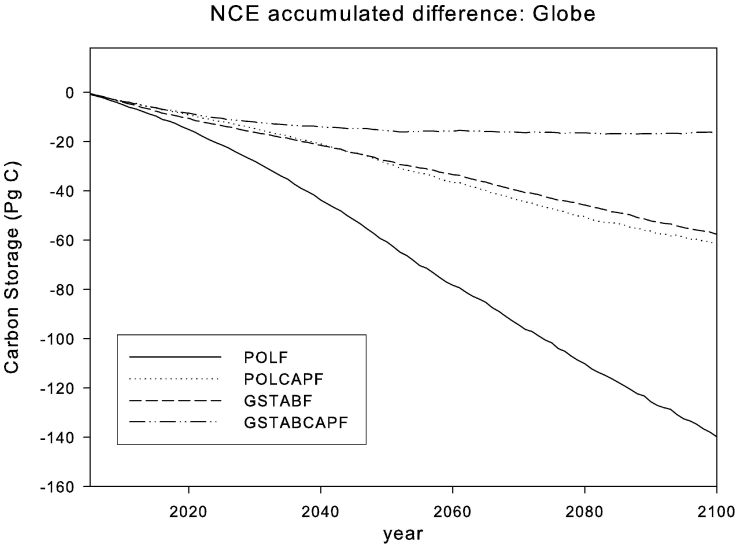


(d)

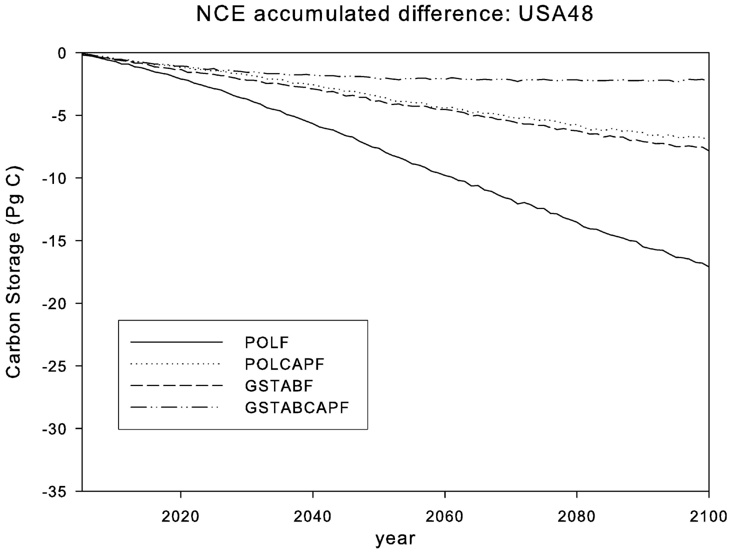
Figure 6. (*Continued*)

whereas the GSTABCAP scenario shows the smallest increase because both GHG and pollution control policies directly or indirectly control ozone precursors. Controls on pollutant gases (POLCAP) are more effective at reducing future ozone levels than controls on greenhouse gases (GSTAB). Note that all the scenarios produces higher ozone levels by 2100 in the U.S. and China than in Europe. The year-to-year variability is the result of climate variability, which is one of the controls on the atmospheric chemistry in the IGSM.

The future NCE reductions for each region are shown in Figure 7. Table IV shows the cumulative NCE values at the year 2100. For simplicity, we only



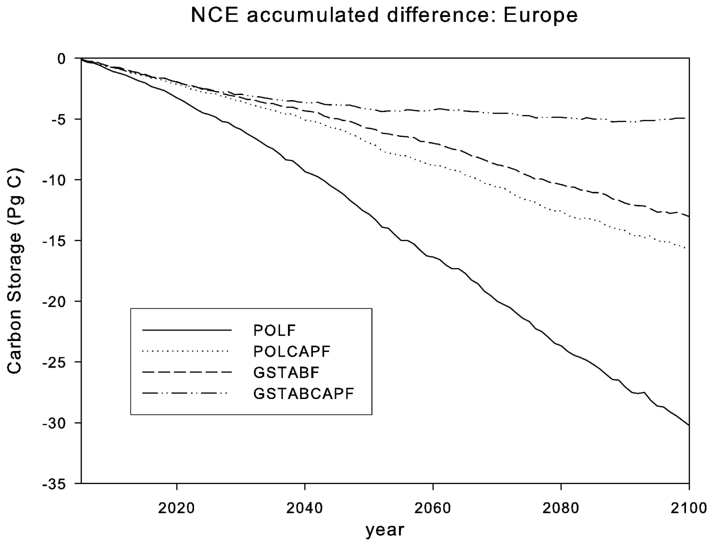
(a)



(b)

Figure 7. Time series of accumulated NCE difference (Pg C) between the ozone and control simulations for each of the scenarios with optimal nitrogen fertilization for: (a) Globe, (b) U.S., (c) Europe, and (d) China.

(*Continued on next page*)



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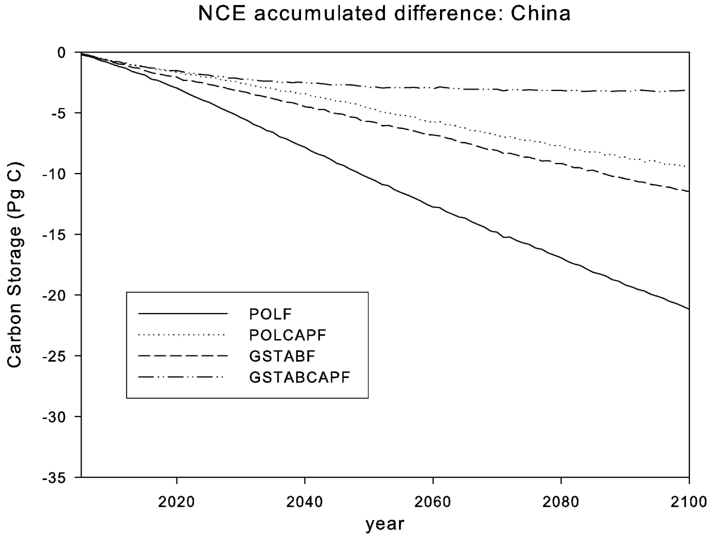


(d)

Figure 7. (*Continued*)

show results from simulations with optimal nitrogen fertilization, and these are more relevant for our focus regions where croplands are already intensively managed and likely to become much more so in the future. The linear response of carbon sequestration to ozone is a result of the linear Reich (1987) model used within TEM to model the effects of ozone on GPP. Like the ozone trends (Figure 6), the POL case produces the most significant reductions in NCE, while the GSTABCAP case produces the least. The carbon sequestration response of the

TABLE IV

Difference in the accumulated net carbon exchange (NCE) at 2100 between simulations with ozone and without ozone in Pg C

	U.S.	Europe	China	Globe
POL	−6.99	−7.06	−9.39	−55.29
POLF	−17.10	−30.24	−21.17	−139.72
POLCAP	−1.82	−2.44	−3.04	−18.41
POLCAPF	−6.95	−15.79	−9.53	−61.70
GSTAB	−2.70	−2.37	−4.10	−18.77
GSTABF	−7.84	−13.05	−11.51	−57.64
GSTABCAP	−0.59	−0.73	−1.09	−4.11
GSTABCAPF	−2.23	−5.01	−3.23	−16.38

other two scenarios (POLCAP and GSTAB) are more similar than indicated by the corresponding ozone levels, which implies that the ecosystem sensitivity is similar when controlling pollutant gases or greenhouse gases. For each scenario, the effect of ozone is greater with agricultural management than without, even though the total amount of carbon stored in the soils is greater with agricultural management because of the enhanced productivity. Both Europe and China show a larger response than the U.S. for all scenarios because of the way ozone is distributed within each of these regions. Although overall ozone levels for each scenario are higher in the U.S. and China, ozone levels within the U.S. are largest in the southeast and northwest, which are not the major agricultural regions, whereas the highest ozone levels in China and Europe occur within the agricultural regions.

Because increasing ozone in China may result in this region having the most ozone damage in the future relative to the current situation, we focus our discussion on this region. Carbon accumulation in the simulations without ozone increases for all scenarios (Figure 8a). The responses are similar between the POL and POLCAP scenarios and between the GSTAB and GSTABCAP scenarios and are primarily the result of increased CO_2 fertilization. The GSTAB and GSTABCAP scenarios produce less atmospheric CO_2 concentrations than the POL and POLCAP scenarios. Ozone reduces the benefits of CO_2 fertilization (Figure 8b) and, in some cases, such as in the POL and GSTAB scenarios with optimal fertilization, ozone may switch China from being a sink of atmospheric CO_2 to being a source.

The relative effect of ozone on cropland versus non-crop ecosystems depends on the management practices adopted. Without considering ozone effects, CO_2 fertilization and climate change alone result in a substantial increase in stored carbon in non-crop vegetation of all scenarios, but especially for the POL (Figure 9a) scenario. In croplands, however, carbon storage decreases slightly unless agricultural management is considered. The response of agricultural lands without nitrogen fertilization to ozone associated with the POL scenario is negligible (Figure 9b); the

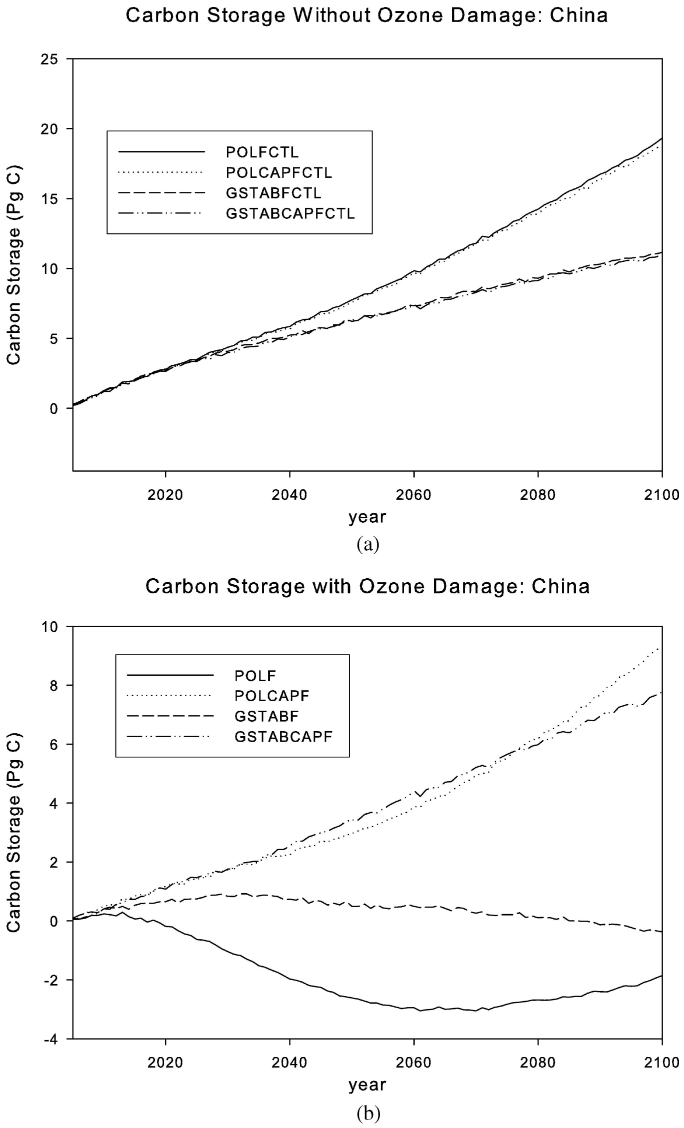
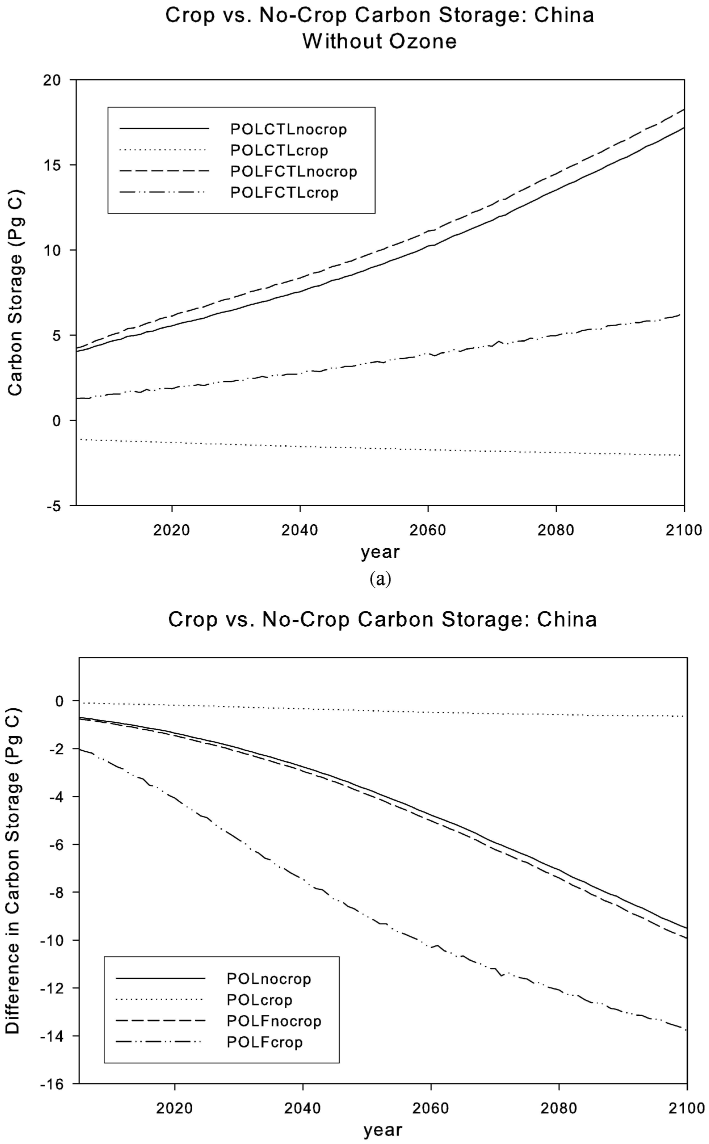


Figure 8. Time series of accumulated NCE (Pg C) for China for each of the scenarios (with optimal nitrogen fertilization) for: (a) control simulations and (b) ozone simulations.

response is almost completely attributable to non-crop ecosystems. With nitrogen fertilization, however, the reduction in NCE is much greater on croplands than if they are unfertilized croplands, and the reduction is greater even than that on other vegetation, which covers a much larger area (Figure 9b). The effect of ozone is therefore so large when nitrogen fertilizer is applied, that the rate of carbon storage loss surpasses that of non-crop vegetation. However, the net amount of carbon stored in the soils is still larger because of the earlier buildup of carbon in the fertilized soils.



(a)

(b)

Figure 9. Natural (non-crop) versus crop carbon storage for China with the POL scenario (both with and without optimal nitrogen fertilization) showing accumulated NCE difference (Pg C) for (a) control simulations and (b) ozone simulations.

5. Economic Implications on Carbon Policy

While there are economic implications on agricultural markets from the potential changes in yield and productivity discussed in Section 4, and further economic costs related to ecosystem damage, we focus here on the potential costs of ozone damage due to loss of carbon sequestration. The EPPA model experiment design is as follows. In the GSTAB cases, carbon emissions are reduced below reference emissions through an emissions cap and trade system as previously described in Section 3.2. The GHG policy limits cumulative emissions of CO_2 through 2100 to a level that would be consistent with CO_2 concentrations approaching 550 ppm stabilization sometime after 2100 (Reilly et al., 1999). GSTAB thus establishes a value for carbon that rises over time, with attendant costs on the economy measured in terms of lost welfare or equivalently, given the EPPA model design, of reduced final consumption of goods and services. The path of allowable carbon emissions from fossil energy combustion and other human activities depends on the level of uptake by terrestrial systems and the oceans.

The initial EPPA simulations (Figure 1) of required CO_2 emission reductions based on the MIT IGSM did not include the consideration of ozone damage. From the future scenarios with ozone damage simulated here we are able to calculate the year-by-year and region-by-region change in carbon sequestration (Figure 7, Table IV, but values are not accumulated when applied to EPPA). Further emissions reductions from fossil fuel combustion in each year and region were then made so that the carbon addition to the atmosphere (net of emissions and terrestrial uptake) from any constrained region and for each year is identical to the GSTAB case. This tighter cap on fossil fuel emissions necessarily increases the cost of the GHG policy. We then interpret the difference in cost as the cost of lost carbon sequestration due to ozone damage.

Before discussing the results, we note that our ozone damage cost estimates depend on the specifications of the EPPA model and the particular reference and policy scenarios. They also depend critically on how the policy is formulated. A least cost policy for stabilization at 550 ppm would start immediately, include participation by all countries, and would be optimally timed so that carbon prices rose gradually, and would include multiple GHGs and emissions trading among them (Wigley et al., 1996; Reilly et al., 1999). While optimal, the prospects for immediate implementation of such a policy are unlikely. Hence, the policy we consider is somewhat more pragmatic, building on the original targets proposed under the Kyoto Protocol, the climate treaty negotiated in 1997, for developed countries with developing countries joining later. Since we also wish to focus on carbon and to assure that the carbon addition to the atmosphere remains the same in all cases, we do not allow optimal trading among non-CO_2 GHGs and CO_2. As such, it is somewhat more costly than an optimal policy. Our estimates of costs of ozone damage thus depend on the specification of the carbon policy. Also, the regional costs depend on the specific regional targets. The costs assume emissions trading in carbon among the constrained regions (Kyoto Protocol Annex B countries through 2020, and globally thereafter; see Reilly et al. (1999) for Annex B definition). Marginal abatement costs (cost per ton of carbon emission reduction as a function of total reduction) needed in these calculations are computed endogenously in EPPA (e.g. Reilly et al., 1999). While the absolute ozone damage cost in dollars is

TABLE V
Net present value consumption loss (billions of 1997 dollars, 5% discount rate)

	United States	European Union	China	Global
GHG Stabilization GSTABCTL	2,888	4,238	6,396	20,781
	Additional costs from ozone damage			
Climate policy, W/O fertilization GSTAB-GSTABCTL	208	298	341	1,165
Climate policy and fertilization GSTABF-GSTABFCTL	622	1,769	1,181	4,461
Climate policy and pollution policy, W/O fertilization GSTABCAP-GSTABCAPCTL	121	100	36	349
Climate policy, pollution policy, and fertilization GSTABCAPF-GSTABCAPFCTL	335	921	171	1,819

highly dependent on the specific policy assumptions, this damage cost expressed as a percentage of the total cost of the carbon policy is much less sensitive.

Table V provides the estimates of the net present value (NPV) cost of the climate policy using a 5% discount rate and how it would change when considering ozone damage. These estimates are reported in 1997 constant dollars. The results, particularly the absolute dollar amounts, are also sensitive to the assumed discount rate. To illustrate that sensitivity, we report in parentheses here the results respectively of + or −2 percentage points. The total cost of the policy is about \$21 (\$9; \$60) trillion or approximately 2 (1.4; 3) percentage of the NPV of total consumption in the reference over the 100-year period. The bounding cases for ozone damage without and with nitrogen fertilization (GSTAB minus GSTABCTL and GSTABF minus GSTABFCTL) increase global costs by \$1.2 (\$0.6; 2.7\$) to \$4.5 (\$2.5; \$10) trillion (6 (7; 5) to 21 (27; 17)%). Under the pollution cap case ozone damages are reduced so that the global cost is \$0.3 (\$0.3; \$0.4) to \$1.8 (\$1.4; \$2.5) trillion (2 (3; 1) to 9 (15; 4) % of the total cost). We can also observe from this table that the value of the pollution cap in terms of increased carbon sequestration is the difference between the corresponding cases, that is a \$1.2 − \$0.3 = \$0.9 trillion to \$4.5 − \$1.8 = \$2.7 trillion global benefit of the pollution cap.

The regional costs of the climate policy itself depend on the specific targets, and given the disparity in costs among the regions shown, the allocation of the large burden of reduction to China, for example, might be considered unreasonable. Given emissions trading, the global costs are largely unaffected by that allocation. If the burden of reduction were reallocated so that China could sell carbon permits, allowing other countries to pay for some of its reductions, then the ozone losses can be interpreted as potentially lost revenue from permit sales if China were forced to fully account for its net contribution of carbon to the atmosphere from both fossil and land use. The Kyoto Protocol, the current international climate agreement, does not include total land use accounting of carbon, although the U.S., before withdrawing from this agreement, argued that it should. Whether or not total carbon accounting is an explicit part of international policy agreements, the extra costs must be borne somewhere, if the world is to meet the same atmospheric target. In short, the more important aspect of the regional estimates is the ozone damage costs rather than the climate policy cost in these regions. And who actually bears those extra costs will depend on how the extra burden of reduction is allocated in future climate policies.

The three maximum-impacted regions (i.e. the United States, European Union, and China) represent 73 to 80% of the total ozone damage cost for the world (Table V). The damage in each of these regions is of roughly equal order of magnitude, although damage costs in Europe and China are somewhat higher than the U.S. in some cases (i.e., with nitrogen fertilization).

In addition to an effect of ozone damage on climate policy, climate policy will itself affect the level of tropospheric ozone, and thus damage due to ozone. There are several ways in which this will happen. First, methane is itself an ozone precursor: a climate policy that reduces methane will thus also affect tropospheric ozone, although the atmospheric chemistry of ozone formation is quite complex and non-linear, involving NO_x, CO and nonmethane hydrocarbons (NMHC), as well as CH_4. Second, many of these other ozone production precursors (NMHC, CO, NO_x) are products of fossil fuel combustion. Climate policy that reduces fossil fuel use will reduce emissions of these substances as well. Third, to the extent climate policy reduces overall economic activity or causes a shift among sectors, it can affect other activities that emit ozone producing precursors such as biomass burning in agriculture or industrial process emissions of pollutants. Fourth, ozone formation is in part dependent on climate and may therefore be affected by climate change. Fifth, there are climate interactions with vegetation and ozone damage. The economic, atmospheric chemistry, and vegetation components of the MIT IGSM simulate these interactions explicitly. Finally, our assumption of a dependency between stomatal conductance and photosynthesis means that with stabilization, less CO_2 fertilization results in reduced GPP and therefore reduced stomatal conductance. This relationship is a byproduct of the empirical estimates we use for stomatal conductance and may lead to an overestimate of this ancillary benefit. To examine the magnitude of this effect we have compared the carbon sequestration with ozone damage in four POL cases (no climate policy) and the carbon sequestration in four GSTAB cases. We have found, as expected, that ozone levels and ozone damage in terms of carbon sequestration is less with the GSTAB climate policies than without (POL cases). These differences have been valued by relaxing the carbon constraint over time and in each region to account for this ancillary benefit of the climate policy.

Table VI reports our estimates. The range is a climate policy savings of about 1.0 to 5.2 trillion or between 5 and 25% of the total climate policy cost when we properly account for the fact that the policy, by indirectly reducing ozone damage and thereby increasing carbon sequestration, will not need to be as stringent to

TABLE VI
Benefits of avoided ozone damage from a climate policy in terms of reduced climate policy costs (billions of 1997 dollars, 5% discount rate)

	U.S.	EU	China	Global
Climate policy, W/O fertilization (POL-POLCTL) – (GSTAB-GSTABCTL)	\$132	\$617	\$696	\$2704
Climate policy and fertilization (POLF-POLFCTL) – (GSTABF-GSTABFCTL)	\$24	\$1564	\$1201	\$5220
Climate policy, Pollution policy, W/O fertilization (POLCAP-POLCAPCTL) – (GSTABCAP-GSTABCAPCTL)	\$22	\$204	\$271	\$990
Climate policy, Pollution policy, and fertilization (POLCAPF- POLCAPFCTL)- (GSTABCAPF – GSTABCAPFCTL)	\$84	\$859	\$824	\$2904

meet the same atmospheric CO_2 goals. As expected, the savings are much less in the pollution cap case than without the pollution cap, particularly in the U.S. and the EU where the pollution cap is applied. These differences reflect one of the problems in estimation of the so-called ancillary benefits of climate policy. Specifically, the calculation depends on whether one assumes that a policy does or does not exist to control the non-climate pollution problem. And, it can further depend on how the pollution policy is formulated. For example, if the policy is an ambient air quality standard for ozone, a climate policy that made it easier to meet that standard might result in a relaxation of efforts to control other emissions so that the standard is just met, rather than ozone levels being reduced below the standard. The benefits might thus best be measured as a reduced cost of the combined policies (de Masin, 2003). In any case, these considerations should be taken as only indicative of the potential magnitude of this secondary effect for the various reasons already discussed.

6. Policy and Future Directions

Ozone pollution is detrimental to vegetation and therefore affects forest and crop productivity, particularly in regions where high ozone levels occur (hotspots) over forest and crop land. These hotspots primarily occur in the industrialized world, including the U.S., Europe, and China. Other less intense hotspots occur in tropical regions where biomass burning is a natural ecosystem process and important agrarian management tool. While in Brazil and central Africa, relatively high ozone levels coincide with very large productivity (Cros et al., 1988; Kirchoff and Rasmussen, 1990), our study indicates that the above three industrialized regions are the primary contributors to reduced global carbon sequestration due to ozone pollution.

The U.S. has an especially large amount of forest still intact. Although we have used the TEM model to show that there are also significant NPP reductions in naturally-vegetated regions, we have not yet accounted for the effects of management practices in these non-agricultural regions, such as timber harvesting on terrestrial carbon sequestration. In our estimation of the economic implications of ozone damage for climate policy, we have considered only a part of the potential ozone damages to society. The physical impacts on crop yield and forest productivity will also affect agriculture and timber markets, as well as other ecosystem services. Clearly a future research goal is to include an evaluation of these costs. As we have shown, however, the evaluation of future effects will depend on a complex interaction of economic forces and the particular design of both climate and air pollution policy. Thus, there is not a simple answer to the question of how big these effects might be, or how climate policy affects air pollution damages and vice versa. Our results clearly show that these interactive effects are substantial.

One of the major uncertainties is the relative importance of CO_2 fertilization to terrestrial carbon sequestration. While TEM estimates of CO_2 fertilization in the absence of ozone pollution are consistent with the results of inverse modeling studies (Kicklighter et al., 1999; McGuire et al., 2001) and forest inventory studies (Joos et al., 2002) and their uncertainties, there is still considerable disagreement over the magnitude of this effect. The current study, similar to Ollinger et al. (2002), suggests that some of the potential benefits of CO_2 fertilization or nitrogen deposition may have been offset by the effects of ozone damage in regions with high ozone levels.

The reduced carbon storage caused by ozone has both regional and global implications. The reduction of carbon sequestration caused by ozone pollution during the early 1990s ranges from 0.1 to 0.3 Pg C yr^{-1}, which is a 45% (without fertilization) to 30% (with fertilization) reduction. The estimated total global carbon sequestration for this time period from inverse modeling estimates is 1.7 to 4.3 Pg C yr^{-1} (note that TEM also computes a carbon sink during this time period, but with lower values than this range), with a mean of 2.8 Pg C yr^{-1} (Schimel et al., 2001). The ozone effect therefore accounts for about 0.8–1.3 Pg C yr^{-1}. The effect of ozone on carbon sequestration is even more substantial on the regional scale. In the U.S., Europe, and China, the reduced carbon storage resulting from ozone exposure could have a significant effect on allowable carbon credits under future policy directives.

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