# *MIT Joint Program on the Science and Policy of Global Change*

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# Past and Future Effects of Ozone on Net Primary Production and Carbon Sequestration Using a Global Biogeochemical Model

Benjamin S. Felzer[†], John M. Reilly[*], Jerry M. Melillo[†], David W. Kicklighter[†], Chien Wang[*], Ronald G. Prinn[*], Marcus Sarofim[*] and Qianlai Zhuang[†]

**Abstract**

*Exposure of plants to ozone inhibits photosynthesis and therefore reduces vegetation production and carbon sequestration. Simulations with the Terrestrial Ecosystem Model (TEM) for the historical period (1860-1995) show the largest damages occur in the eastern U.S., Europe, and eastern China, with reductions in Net Primary Production (NPP) of over 70% for some locations. Scenarios through the year 2100 using the MIT Integrated Global Systems Model (IGSM) show potentially greater negative effects in the future. In the worst-case scenario, the current land carbon sink in China could become a carbon source. Reduced crop yields resulting from ozone damage are potentially large but can be mitigated by controlling emissions of ozone precursors. Failure to consider ozone damages to vegetation would by itself raise the costs over the next century of stabilizing atmospheric concentrations of* $CO_2$ *by 3 to 18%. But, climate policy would also reduce ozone precursor emissions, and ozone, and these additional benefits are estimated to be between 4 and 21% 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.*

**Contents**



## 1. INTRODUCTION

Ozone pollution near the Earth's surface inhibits photosynthesis in vegetation (*e.g.*, Reich, 1987; Mauzerall and Wang, 2001). We recently demonstrated the consequences of this effect on terrestrial carbon dynamics in the conterminous United States (U.S.) by using the Terrestrial Ecosystems Model, Version 4.3 (TEM4.3) (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

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1990s, and carbon sequestration (Net Carbon Exchange, NCE) since the 1950s has been reduced by 18 to 38 Tg C $yr^{-1}$ with the presence of ozone. 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.

Regional measurements of tropospheric ozone have identified 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. 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 primarily in the eastern U.S. (Felzer *et al.*, 2004). 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), using an atmospheric chemistry-transport model, show that the highest ozone levels in China occur in eastern, coastal regions using an atmospheric chemistry-transport model. 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.

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: Antle, 2001). We define ozone "hotspots" as regions where high ozone levels coincide with high plant productivity to cause substantial ozone damage. Because the ozone hotspots in the midlatitudes occur in major agricultural regions of the world, ozone pollution will have a significant negative effect on future crop yield and make it more difficult to feed the world's growing population. Current levels of tropospheric ozone have already been shown to have significant effects on the economics of crop production in the U.S., as indicated by estimates of the potential benefits of ozone reduction standards (Adams *et al.*, 1986; Westenbarger and Frisvold, 1995). 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.

To evaluate the effects of ozone across the globe, we use the Terrestrial Ecosystem Model (TEM4.3). 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). Our investigation of historical ozone damage is based on transient ozone datasets that we have developed from both observational and modeling data. Our investigation of future scenarios makes use of the MIT Integrated Global Systems Model (MIT-IGSM, Prinn *et al.*, 1999; Reilly *et al.*, 1999) that includes a model of the world economy coupled to an AOGCM with explicit urban and rural atmospheric chemistry, as well as TEM4.3 (Prinn *et al.*, 1999; Webster *et al.*, 2003). The MIT IGSM is thus able to simulate the emissions of greenhouse gases and other pollutants including ozone precursors as affected by economic activity, their effects on climate and atmospheric composition, and, through TEM, the follow-on effects on vegetation. Here we evaluate the magnitude of ozone damage for both the terrestrial biosphere 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. We make particular use of the economic component, the Emissions Prediction and Policy Analysis (EPPA) model (Babiker *et al.*, 2001) of the MIT-IGSM, for both emissions scenarios and to evaluate the cost of increased mitigation efforts required to offset lost carbon sequestration.

## 2. METHODS

### 2.1 Model Description

The Terrestrial Ecosystem Model is a process-based biogeochemistry model that simulates the cycling of carbon, nitrogen, and water among vegetation, soils, and the atmosphere. Details of TEM4.3 are described in Felzer *et al.* (2004). Here, we briefly review how ozone influences the productivity and carbon storage of terrestrial ecosystems in our simulations. We incorporate the effects of ozone on productivity by modifying the calculation of Gross Primary Production (GPP) in TEM. The effect of ozone is to linearly reduce GPP above a threshold ozone level according to the Reich (1987) and Ollinger (1997) models. We calculate separate coefficients for hardwoods, conifers, and crops.

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

$$NPP = GPP - R_A \tag{1}$$

where $R_A$ is autotrophic respiration. To estimate carbon sequestration by the ecosystem, we calculate net carbon exchange (NCE) as follows:

$$NCE = NPP - R_H - Ec - Ep \tag{2}$$

where $R_H$ is heterotrophic respiration, *Ec* is the carbon emission during the conversion of natural ecosystems to agriculture, and *Ep* is the sum of carbon emission from the decomposition of products (McGuire *et al.*, 2001). For natural vegetation, *Ec* and *Ep* are equal to 0, so *NCE* is equal to net ecosystem production (*NEP*). Thus, the reduction of GPP by ozone will also reduce both NPP and NCE.

### 2.2 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 three independent datasets (1860-1995) based upon ozone distribution maps developed by several researchers to provide a way of bounding the large uncertainties represented among these maps. For each dataset (HARL, HARJ, and MIT), we perform two sets of simulations to examine how land management might modify the effects of ozone damage, one with and one without nitrogen fertilization (F). There are two additional control experiments (CTL, one with and one without nitrogen fertilization) that do not include ozone. There are therefore a total of 8 model experiments (**Table I**) designed to study the historical effects of ozone.

Ozone levels in the future will be limited both by potential climate policies designed to reduce the levels of greenhouse gases (GHG) ($CO_2$, $CH_4$, $N_2O$, CFCs) and by environmental policies designed to reduce the level of pollutant gases (CO, VOC, NOx, $SO_2$), both sets of which include precursors to ozone formation. We therefore run TEM4.3 with four scenarios of the future developed from the MIT EPPA and 2 dimensional land ocean (2D-LO) atmospheric chemistry models (Sokolov and Stone, 1998; Wang *et al.*, 1998), mapping the 2D ozone predictions to 3D using a mapping procedure described in the Appendix. These scenarios form a matrix of GHG reductions by urban gas controls. 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), whereas for other pollutants emissions are somewhat higher because existing clean air standards, where they exist, are not necessarily enforced in this scenario. Instead, the POL scenario can be compared 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 at 1995 values in the Annex 1 nations (USA, Japan, Europe, the former Soviet Union, and other developed countries)[1] to account for current pollution controls. A third scenario (GSTAB) is a GHG policy case (3´ from Reilly *et al.*, 1999) that assumes significant reduction in GHG emissions by 2100, but no caps on pollutant gases. In particular, Kyoto controls for both $CO_2$ and other GHGs are imposed on Annex 1 nations in 2010 and on all nations in 2025, such that allowable emissions quotas decrease by 5% every 15 years from the 2010 or 2025 baseline. This scenario leads to stabilization of atmospheric $CO_2$ at about 550 ppm by 2100. A fourth scenario

**Table I**. Historical Simulations

| Simulations | irrigation/fertilization | ozone |
|---|---|---|
| HARL | no | HARVARD-L |
| HARLF | yes | HARVARD-L |
| HARJ | no | GEOS-CHEM |
| HARJF | yes | GEOS-CHEM |
| MIT | no | MIT |
| MITF | yes | MIT |
| CTL | no | no |
| CTLF | yes | no |

[1] Annex 1 refers to those nations listed in Annex 1 of the Framework Convention on Climate Change as approximated given the regional aggregation of the EPPA model, which includes parts of the former Soviet Union that was not identified in Annex 1.

(GSTABCAP) applies pollution caps to the GSTAB scenario. Note that China is not an Annex 1 nations and so has different policies than the U.S. and Europe under each of these scenarios. Each of the four scenarios is run assuming ozone effects or no ozone effects to evaluate the relative role of ozone on terrestrial carbon dynamics. In addition, each of the four scenarios is run with and without optimal nitrogen fertilization to assess the influence of management on the response of crops to ozone damage. A total of 16 simulations (**Table II**) are conducted to evaluate the potential consequences of future climate and environmental policies.

For each simulation, 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 spinup 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 spinup 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.

**Table II**. Simulations of Future Scenarios

| Scenario | Irrigation/ Fertilization[a] | Ozone Damage Included[b] | Pollutant Controls[c] | $CO_2$/GHG Controls[d] |
|---|---|---|---|---|
| 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 |

[a] Nitrogen fertilization (F) column: "yes" means optimal F turned on, "no" means no F

[b] Ozone Damage Included: "yes" indicates that ozone concentrations influence terrestrial carbon dynamics, "no" indicates that ozone concentrations had no influence on terrestrial carbon dynamics

[c] Pollutant Controls: "yes" means pollutant caps applied to Annex 1 nations, "no" means no pollutant caps applied

[d] $CO_2$/GHG Controls: "yes" indicates greenhouse gases controlled to achieve stabilization at 550 ppm by 2100, "no" assumes no explicit climate policy

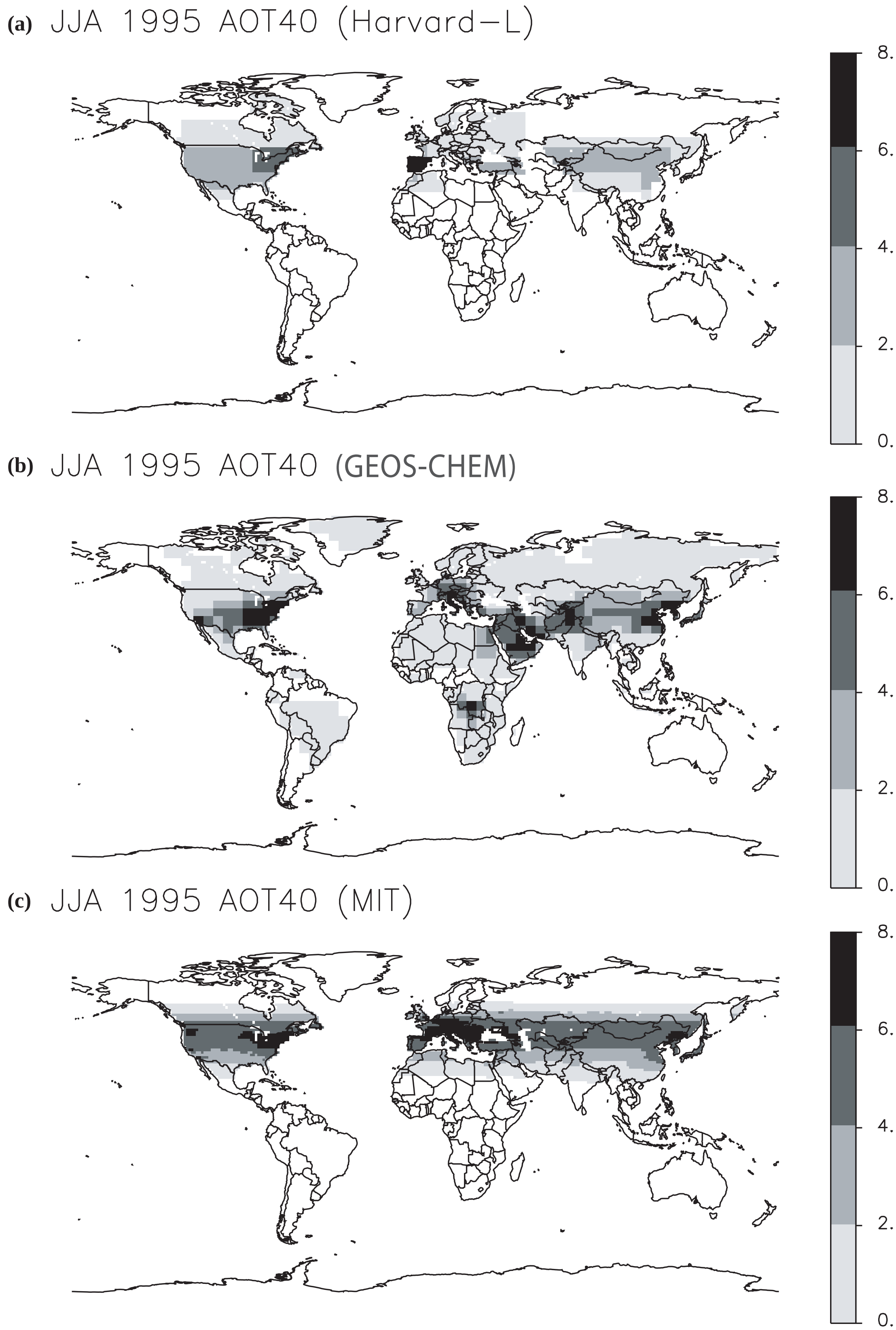


**Figure 1**. Mean of AOT40 (ppm-hr) for June-July-August using: (a) HARVARD-L method, (b) GEOS-CHEM method, and (c) MIT method.

### 2.3 Dataset Development

The ozone effect within TEM4.3 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 develop other methods of constructing the three global AOT40 maps, referred to as HARVARD-L, GEOS-CHEM, and MIT (**Figure 1**). The mapping methods are described in the Appendix. Both the HARVARD-L and GEOS-CHEM methods are used to develop a single monthly climatological ozone dataset for the present. The MIT method, on the other hand, is used to develop transient datasets for the present and future. Because TEM is run in a transient mode, we also develop historical datasets based on the present ozone dataset from each of the three methods.

The historical simulations (1860-1995) use one of the present-day climatological AOT40 datasets (1995 for the MIT data) to develop historical AOT40 data. The present-day datasets are assumed to represent ozone distributions during 1995. No trends in interannual ozone levels are assumed to occur between 1976 and 1995. Before 1976, ozone levels are assumed to increase by 1.6% per year (Marenco *et al.*, 1994). Seasonal variations are determined in a similar manner described in Felzer *et al.* (2004) for all three datasets (Harvard-L, GEOS-CHEM, MIT).

The future simulations (1976-2100) use the AOT40 datasets generated from the MIT-IGSM, along with the MIT-IGSM predicted climatology. For our scenarios, we use the MIT IGSM to produce NOx emissions from 1995-2100 and latitudinal band ozone from 1977-2100. Prior to 1995, we assume that NOx emission patterns remain similar to present.

In addition to ozone levels, other driving variables include $CO_2$, climate, and land use. For the historical mode, $CO_2$ fertilization is calculated from historical atmospheric $CO_2$ concentrations (Keeling *et al.*, 1995; Etheridge *et al.*, 1996), climate variability is taken from surface temperature, precipitation, and climatological cloud datasets (Jones, 1994; Hulme, 1995), and 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 data sets 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 (Xiao *et al.*, 1998). These values are derived from a reference simulation for the historical period and then from each of the individual future scenarios for the future.

## 3. RESULTS

### 3.1 Historical

Ozone has a negative effect on NPP, because it decreases GPP. All three historical ozone mapping methods (Harvard-L, GEOS-CHEM, MIT) show that the largest decrease in NPP between 1989 and 1993 (**Figure 2**) occurs in the eastern U.S., Europe, and eastern China and Japan. While only the maps of the simulations with optimal nitrogen fertilization are shown, the

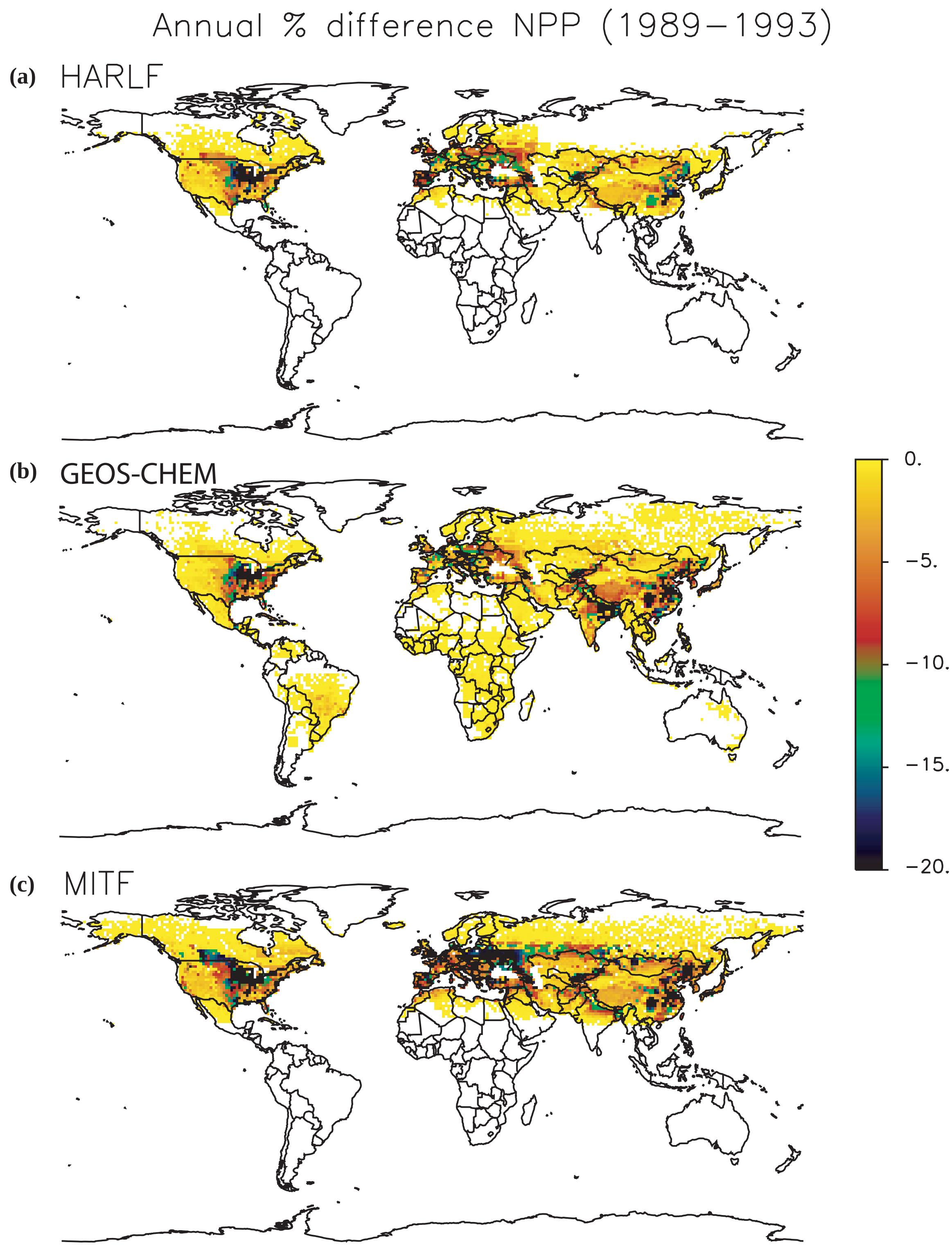


**Figure 2**. Maps of mean annual NPP percent difference between the ozone and control simulations (with nitrogen fertilization, F) for the years 1989-1993 for: (a) HARVARD-L method, (b) GEOS-CHEM method, and (c) MIT method. Largest decrease is 73.1% and largest increase is 9.6%, which occurs for only 4.1% of grids. Most significant decreases in NPP occur in the eastern half of the U.S., Europe, and eastern China.

simulations without fertilization show a similar pattern, but reduced magnitude and extent throughout agricultural regions. The maximum magnitude of the decreases, however, remains about the same. The maximum NPP reductions are 73.1% using the MIT method, 70.3% using the GEOS-CHEM method, and 43.4% using the HARVARD-L method. The GEOS-CHEM method is the only one to show changes in the tropical regions (*e.g.*, India) and southern hemisphere, which is a pattern consistent with the different estimated ozone levels. In the HARVARD-L method, we ignore the few ozone values greater than the AOT40 threshold in the southern hemisphere because of the limited availability of diurnal datasets. Also, the regional compartmentalization of the diurnal cycles in this method results in no ozone effect on NPP in northern Eurasia.

The major agricultural regions of the world (**Figure 3**) correspond closely to the ozone hotspots. We find an interaction between fertilization and ozone damage, and this interaction shows up strongly because the ozone hotspots are heavily agricultural. Ozone damage is greater because fertilization increases plant growth, photosynthesis, and stomatal conductance: there is both more biomass to damage and the increase in stomatal conductance, the pathway through which ozone damages the plant, creates greater damage per unit of leaf area. As a result, in all three hotspot regions, the NPP reductions are greater in agricultural regions when they are fertilized. The GEOS-CHEM method also shows an additional sensitive region in India, which corresponds to one of the major agricultural regions of the world (Figure 3).

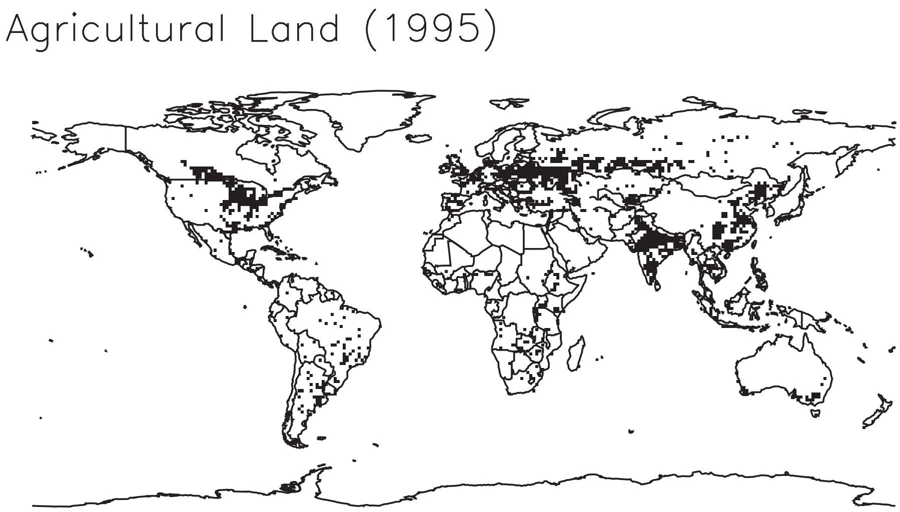


**Figure 3**. Map of TEM grids designated as croplands in 1995 and from 1995-2100.

Carbon sequestration is also reduced by ozone, consistent with the reduction in NPP (**Figure 4**). While the effect of ozone is to reduce NCE, the actual NCE is sometimes positive and sometimes negative, depending upon 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,

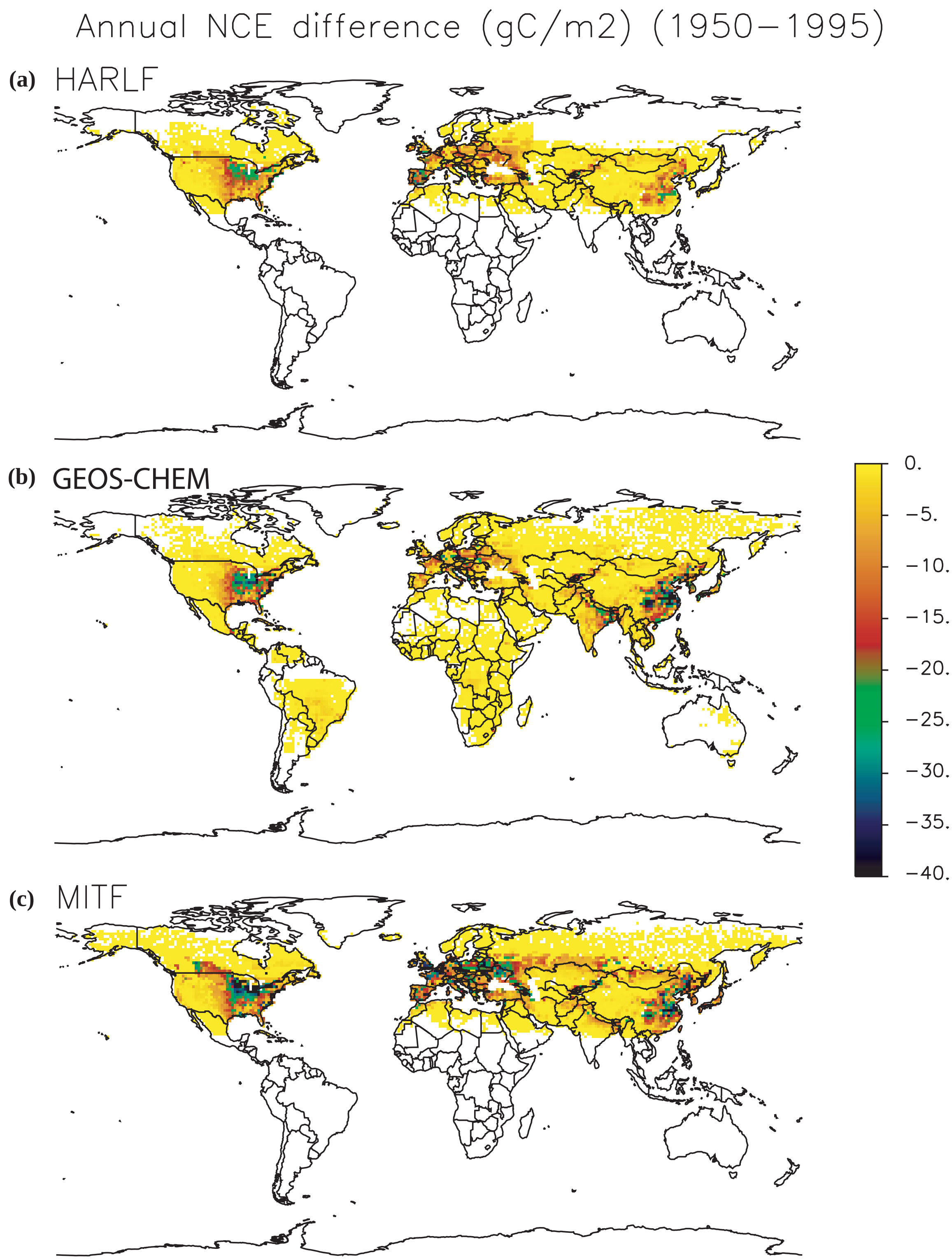


**Figure 4**. Maps of annual NCE difference between the ozone and control simulations (with nitrogen fertilization) for the years 1950-1995 in g C $m^{-2}$ $yr^{-1}$ for: (a) HARVARD-L method, (b) GEOS-CHEM method, and (c) MIT method. Largest decrease is 115.5 g C $m^{-2}$ $yr^{-1}$. NCE decreases occur in similar locations as the NPP decreases.

**Table III**. Mean annual NPP (1989-1993) and NCE (1950-1995 and 1990-1994) in Pg C yr$^{-1}$

| Scenario | NPP | NCE (50-95) | NCE (90-94) | NPP % | difNCE (50-95) | difNPP (90-94) |
|---|---|---|---|---|---|---|
| CTL | 43.4 | –0.4 | 0.2 | - | - | - |
| CTLF | 55.0 | 1.3 | 0.9 | - | - | - |
| MIT | 43.0 | –0.5 | 0.02 | –1.1 | –0.1 | –0.1 |
| MITF | 52.8 | 0.9 | 0.6 | –4.0 | –0.4 | –0.3 |
| HARJ | 43.1 | –0.5 | 0.07 | –0.8 | –0.1 | –0.1 |
| HARJF | 53.2 | 1.0 | 0.7 | –3.2 | –0.3 | –0.2 |
| HARL | 43.2 | –0.4 | 0.1 | –0.5 | –0.06 | –0.06 |
| HARLF | 54.0 | 1.2 | 0.7 | –1.8 | –0.2 | –0.2 |

though much more strongly positive if nitrogen fertilization is assumed. After 1950, when the widespread use of fertilizers is assumed to occur, the effect of nitrogen fertilization is to initially increase carbon storage. However, NCE eventually returns to its original value because increased decomposition counteracts the increase in productivity. As a result of this temporary enhancement of carbon sequestration, the accumulated carbon storage with optimal agricultural management is greater than without nitrogen fertilization. While 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).

Decreases in NCE are largest in the same regions where the largest decreases in NPP occur, namely the eastern U.S., Europe, and eastern China. With agricultural management (Figure 4) the reductions in NCE are greater throughout the hotspot regions, , as well as India in the GEOS-CHEM case. The maximum magnitude of the reduction in carbon sequestration due to ozone is 0.06 PgCm$^{-2}$ with the HARVARD-L method, 0.1 PgCm$^{-2}$ with the MIT method, and 0.1 PgCm$^{-2}$ with the GEOS-CHEM method.

To put these differences into context, a global summary enables us to compare the means of the results from all three ozone mapping methods and the controls. Table III shows that NPP decreases are close to 1% with the MIT and GEOS-CHEM method without agricultural management and closer to 4.0% with agricultural management. The NCE reduction from 1950-1995 is about 0.5 PgCyr$^{-1}$ with the MIT and GEOS-CHEM method without agricultural management and about 1.0 PgCyr$^{-1}$ with agricultural management. The HARVARD-L method produces lower reductions in NPP and NCE than either of the other two methods.

From the mapped patterns it is clear that the ozone effect is largely a regional phenomenon due to the spatial inhomogeneity of ozone concentrations throughout the globe. For that reason, we concentrate on the three regions that receive maximum ozone damage, the U.S., Europe, and China, for examining the impacts of possible future ozone concentrations. Also, while the GEOS-CHEM method provides the most internally-consistent method of modeling ozone concentrations, the MIT method is remarkably close and therefore provides a useful method for assessing future scenarios using the MIT IGSM.

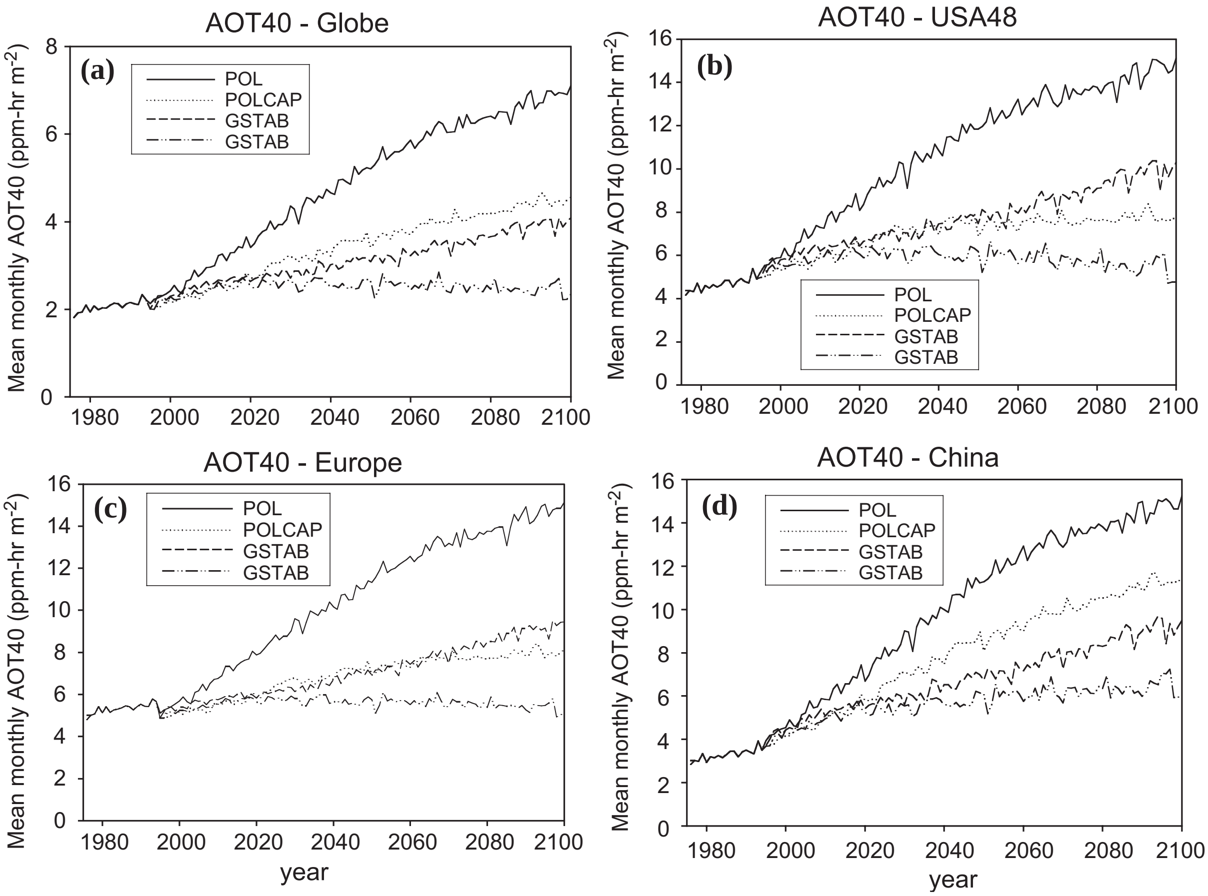


**Figure 5**. Time series of mean monthly AOT40 for each of the scenarios in ppm-hr $m^{-2}$ for: (a) globe, (b) U. S., (c) Europe, and (d) China.

### 3.2 Future

The ozone scenarios (**Figure 5**) to 2100 for the globe and each of the three maximum-impact regions all show, as expected, the POL scenario with the largest increase in ozone and the GSTABCAP scenario with the smallest increase because both GHG and pollution control policies directly or indirectly control ozone precursors. For both the U.S. and Europe, controls on greenhouse gases (GSTAB) result in higher ozone levels by 2100 than controls on pollutant gases (POLCAP), whereas the reverse occurs in China and for the globe. Because the pollution controls are only applied to the developed world, NOx and other pollutants continue to increase in China and throughout most of the world in the POLCAP scenario, resulting in these regional differences. Note that all three regions show similar levels in 2100 even though current Chinese AOT40 levels are much lower than in the other two regions. The year-to-year variability is the result of climate variability, which controls the atmospheric chemistry in the IGSM.

The future NPP reductions for each region follow the same trends as the ozone scenarios (**Figure 6**). For simplicity, we only 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. As we saw for the

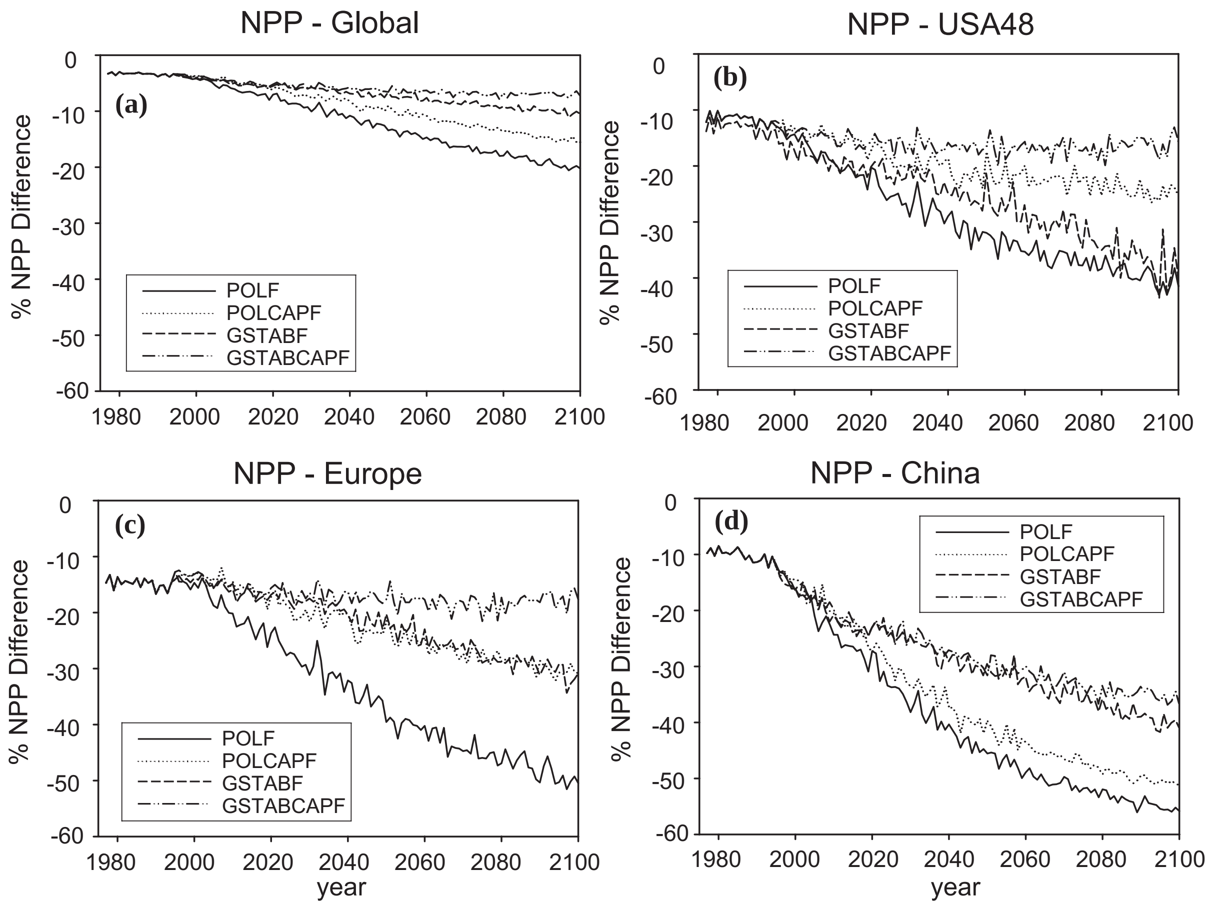


**Figure 6**. Time series of mean annual NPP percent difference between the ozone and control simulations for each of the scenarios with F, for: (a) globe, (b) U.S., (c) Europe, and (d) China.

historical cases, the use of nitrogen fertilization significantly increases the magnitude of the ozone effect for each scenario in each region, specifically because overall productivity is greater. In all cases, the POL scenario results in the largest NPP reductions, with the largest percentage reductions occurring in China (over to 55% by 2100 with F). Since pollutant gases are never limited in China in these simulations, every scenario results in a significant ozone effect, including the GSTABCAP scenario. In the U.S. and Europe, the two scenarios in which pollutants are controlled, POLCAP and GSTABCAP, only produce a significant reduction on NPP when optimal agricultural management is used.

Because increasing ozone may result in the most ozone damage relative to the current situation in China, we focus the following discussion there. Without accounting for ozone effects, NPP increases substantially in the POL and POLCAP scenarios when agricultural management is used (**Figure 7**a). However, with ozone, NPP levels actually decrease in both scenarios (Figure 7b). In these scenarios ozone acts to counteract the benefits of agricultural management entirely. The stabilization scenarios also change from an increase in NPP to a decrease when ozone is present. Even without agricultural management (not shown), small increases in NPP in both the POL and POLCAP scenarios are reversed due to ozone effects.

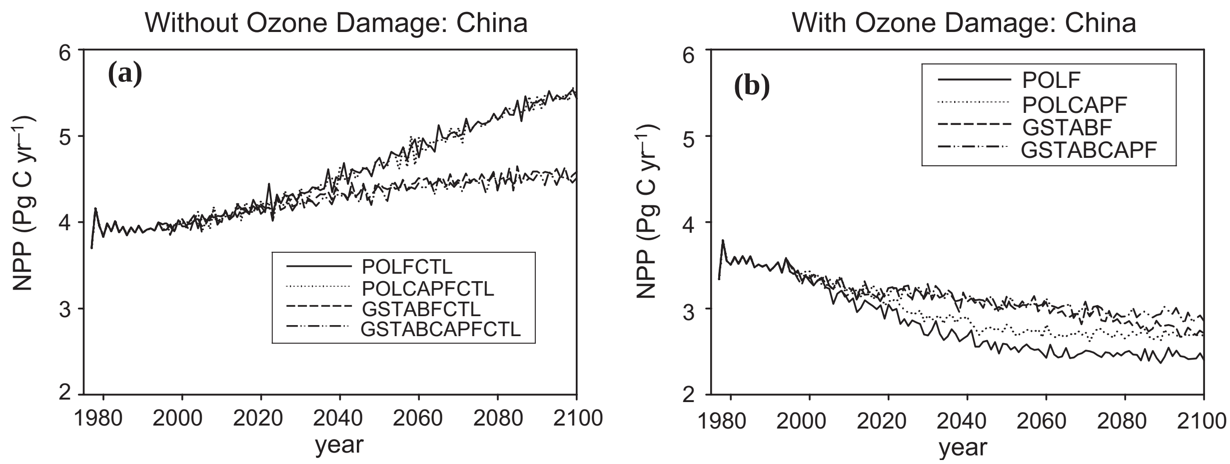


**Figure 7.** Time series of mean annual NPP (Pg C yr$^{-1}$) for China for each of the scenarios with F for: (a) control simulations, and (b) ozone simulations.

The relative effect of ozone on agricultural versus natural ecosystems in China depends on management practices. The POL scenario is shown, but the following conclusions hold for the other scenarios as well. The ozone effect is larger in crops than natural vegetation, consistent with the larger crop sensitivity to ozone, and even larger when the crops are fertilized (**Figure 8**a). Without ozone present (Figure 8b), natural vegetation is more productive than unfertilized crops but less productive than fertilized crops.

The reduced carbon sequestration resulting from ozone, shown for simulations with F (**Figure 9**), follows similar trends to that of the NPP reductions, except for the U.S. where POLCAP and GSTAB are fairly similar. In each case, the POL scenario results in the largest decrease in NCE, while the GSTABCAP scenario results in the least (Figures 5b,d). 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 initial increase (as discussed above).

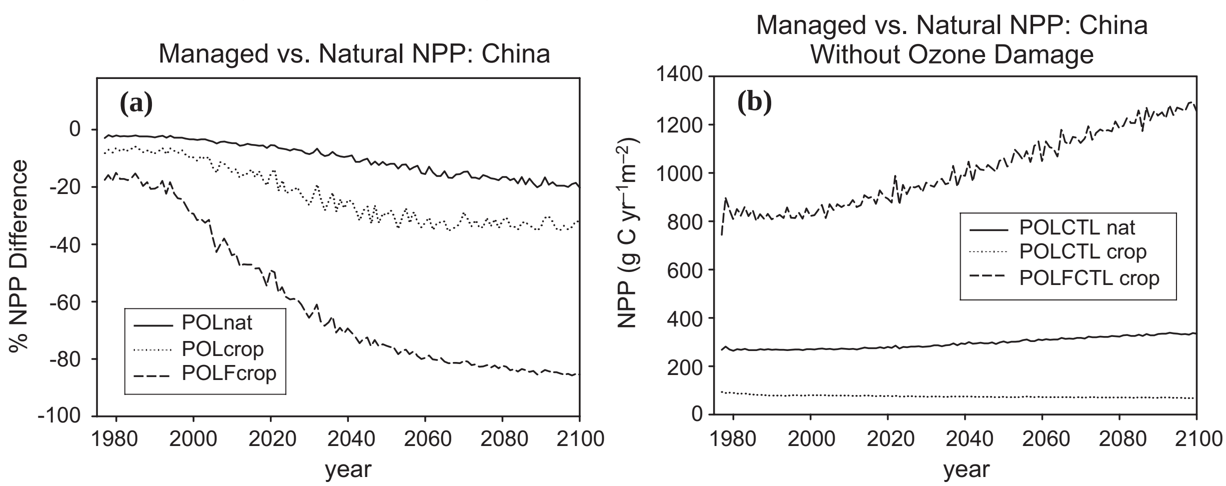


**Figure 8**. Natural vs. crop NPP for China with the POL scenario (both with and without F) showing (a) mean annual NPP percent difference, and (b) control mean annual NPP (Pg C yr$^{-1}$).

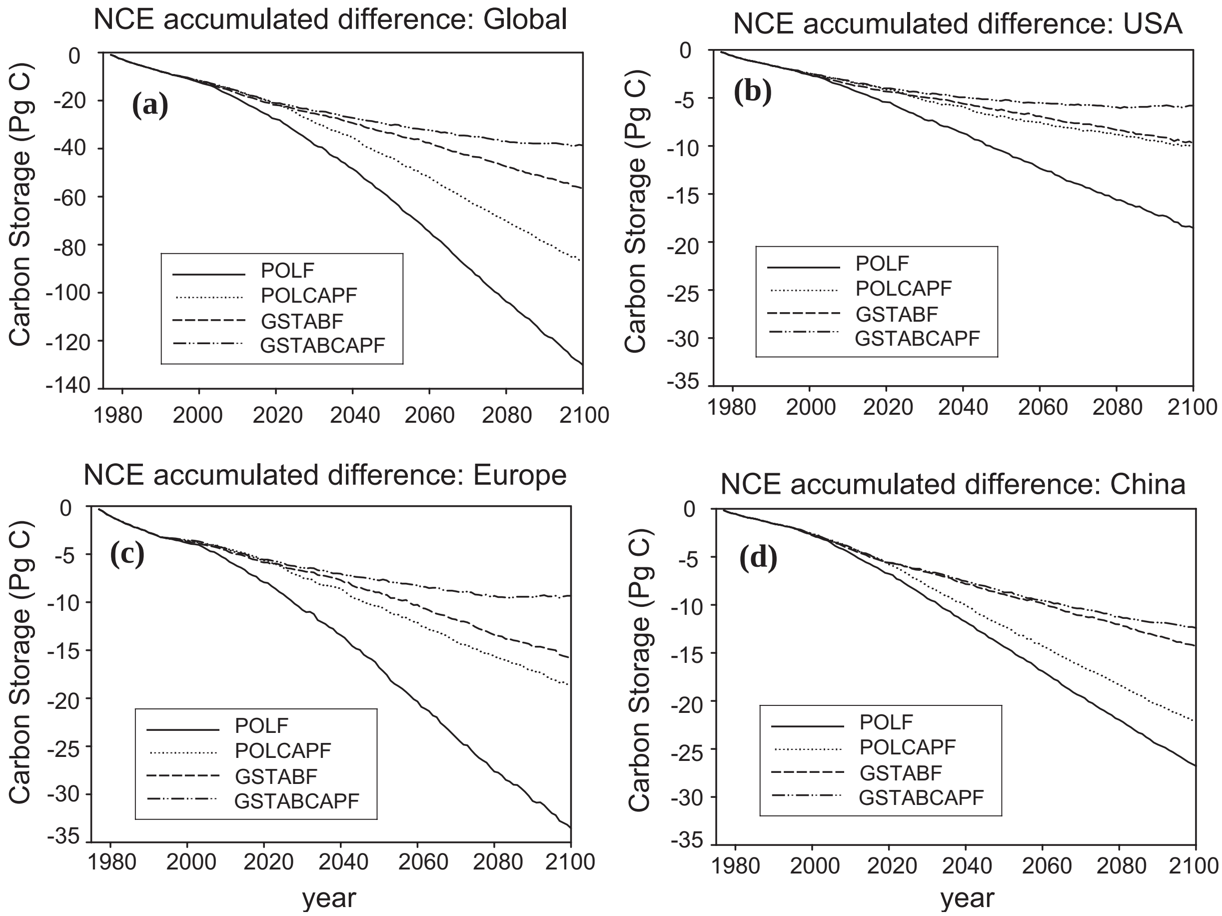


**Figure 9**. Time series of accumulated NCE difference (Pg C) between the ozone and control simulations for each of the scenarios with F for: (a) globe, (b) U.S., (c) Europe, and (d) China.

To illustrate the causes of this NCE behavior, we show the control and ozone NCE of China for each scenario with optimal nitrogen fertilization (**Figure 10**). Carbon accumulation for the control increases for all scenarios, with increasing rates evident in the POL and POLCAP scenarios (which have similar effects). This increase is primarily the result of increased $CO_2$ fertilization. Ozone has a dramatic effect on carbon sequestration, and actually switches China from a sink to a source in the POL scenario, and reduces levels in the other scenarios. The increasing carbon storage in all the scenarios is stopped as a result of ozone pollution.

Similar to the NPP results, the relative effect of ozone on agricultural versus natural ecosystems depends on management practices. However, without nitrogen fertilization (using the POL scenario as an example), the ozone effect is negligible in agricultural lands (**Figure 11**a) and the response is almost completely attributable to natural ecosystems. With nitrogen fertilization, the reduction in NCE is much greater than either unfertilized croplands or natural vegetation (Figure 11 a). Without considering ozone effects, $CO_2$ fertilization and climate change alone result in a substantial increase in stored carbon in natural vegetation of all scenarios, but especially for the POL (Figure 11b) and POLCAP (not shown) scenarios. In croplands, however, carbon storage decreases slightly unless agricultural management is considered. The effect of

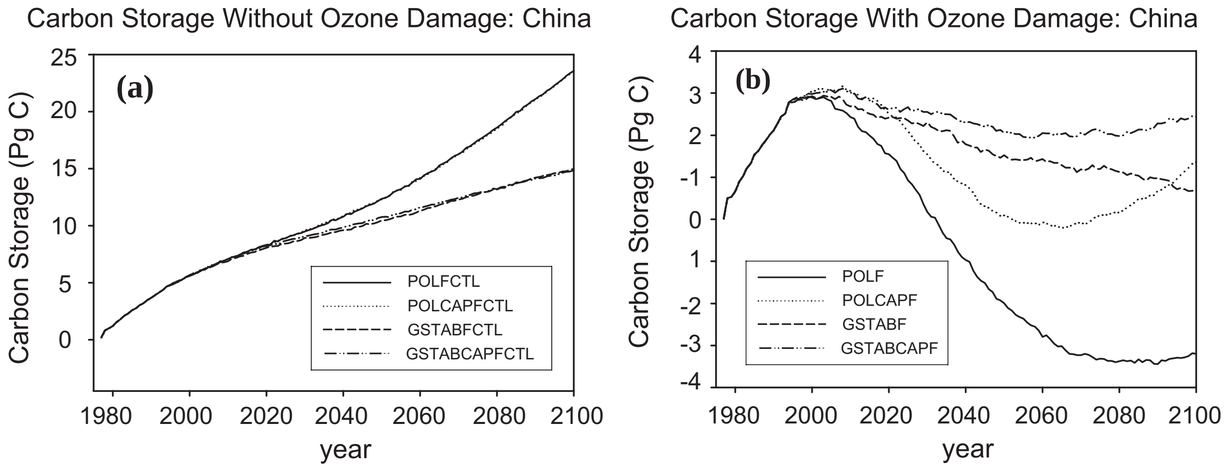


**Figure 10**. Time series of accumulated NCE (Pg C) for China for each of the scenarios (with F) for: (a) control simulations, and (b) ozone simulations.

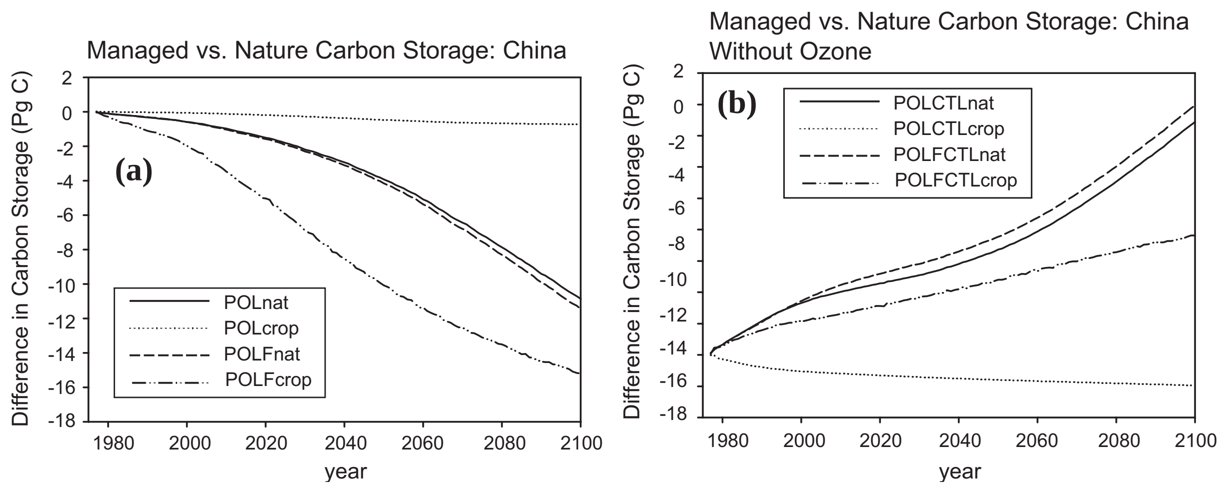


**Figure 11**. Natural vs. crop carbon storage for China with the POL scenario (both with and without F) showing (a) accumulated NCE difference (Pg C), and (b) control accumulated NCE (Pg C).

ozone is therefore so large when nitrogen fertilizer is applied, that the rate of carbon storage loss surpasses that when no fertilizer is used. This effect is possible because, with fertilization, the stock of carbon in the soil is much higher than without fertilization. With severe ozone damage biomass additions to the soil are inadequate to sustain this higher stock, and it is released with respiration. Without fertilization the soil carbon stock is never as large, and therefore the loss due to respiration is less. Even with the greater loss with fertilization, the net amount of carbon stored in the soils remains larger.

## 4. OZONE EFFECTS ON CROP YIELD

Crop yield is significantly reduced when ozone levels are high enough. The relationship between crop yield and AOT40 is shown in **Figure 12** for the POLF scenario in the three focus regions. This scenario provides the largest range of ozone exposures from which to estimate a

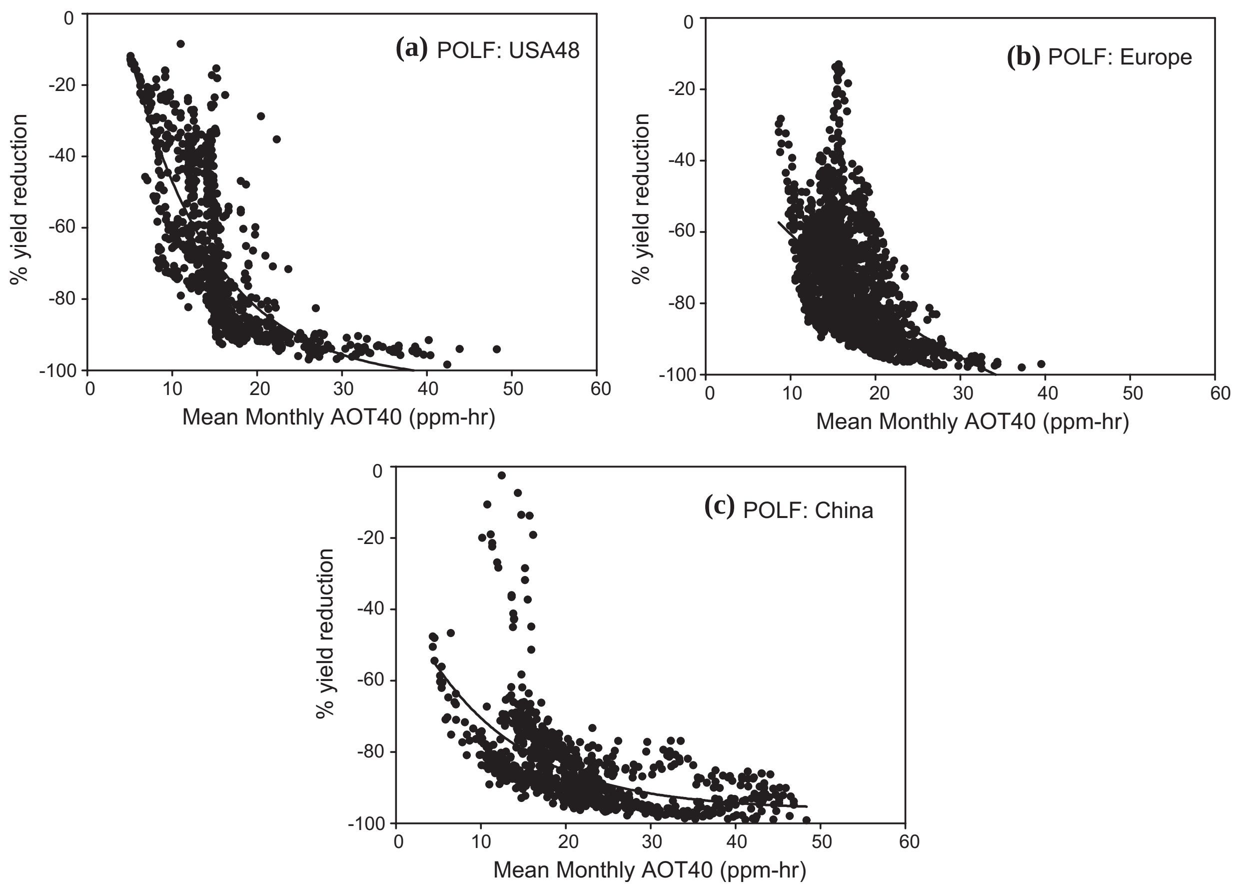


**Figure 12**. Exponential decay model of percent yield reduction as a function of mean monthly AOT40 in ppm-hr for: (a) U.S., (b) Europe, and (c) China.

more complete correlation. In order to obtain a wide range of ozone values, we have used the yield and ozone levels from the end period of the model simulations (2096-2100). In agricultural lands, the simulations with agricultural management significantly reduce crop yield, but as noted earlier these simulations are likely to be more realistic, especially in the future as a growing population will increase pressure to optimize management.

To define the relationship between the reduction in crop yield and ozone, we have fit an exponential decay equation:

$$\textit{\% yield reduction} = a \exp(-b \, AOT40) + y0 \qquad (3)$$

The values of *a* are 151.2, 103.0, and 60.9, *b* are 0.10, 0.03, 0.09, and *y0* are –103.4, –136.9, and –96.2, for the U.S., Europe, and China, respectively. While these correlations indicate that the U.S. is less sensitive to ozone damage at low ozone levels, both Europe and China also exhibit this potential (Figure 12).

All of these relationships show that the detrimental effects per unit increase in AOT40 on crop yield are much more severe at low AOT40 dosages than higher dosages. This distinction implies that we can achieve greater crop protection per unit decrease in AOT40 by acting early to control ozone levels before they get beyond the transition towards saturation. The inflexion point occurs around 17 ppm-hr. After this point, further increases in ozone levels have a smaller effect on yield reduction, eventually saturating towards very high ozone dosages. Regional differences are partly a function of where ozone occurs within each region. If high ozone levels occur in regions with high yield, then yield should be more sensitive to ozone changes. Other nonlinear factors such as climate variability within each region will also influence the sensitivity of the ozone effect in each region.

The exponential relationships developed here are similar to the Weibull model used by Heck *et al.* (1984) to develop relationships between yield reduction and ozone levels for the National Crop Loss Assessment Network (NCLAN) for the U.S. but the estimates cannot be directly compared. Their model is based on various measures of ozone concentration, rather than AOT40 or ozone dose. It is also important to note that each specific crop type has it's own "Weibull function" parameters, so that it is impossible to compare specific numbers with our results for a generic annual crop. For example, the Weibull function allows the exponential to be raised to a power other than 1.0, which alters the shape of the curve from exponential decay at values less than 1.0 to no sensitivity until a threshold ozone level for values greater than 1.0. Each major crop type (*e.g.*, corn, cotton, soybean, and wheat) has examples of both types of exponential relationships, illustrated here for wheat (**Figure 13**) (Heck *et al.*, 1984). By comparison, the TEM exponential curve for China lies between both empirical endmembers for medium ozone exposures and asymptotes at a value less than 100% yield reduction (Figure 13).

The effects of ozone on crop yield for China have been studied by Aunan *et al.* (2000), partly using ozone-response relationships from the NCLAN study. Using an atmospheric chemistry model to derive ozone concentrations for provinces within China, they calculate reductions of 1.7 to 9.1% in winter vs. spring wheat during 1990 and 13.4 to 29.3% reduction in 2020. The

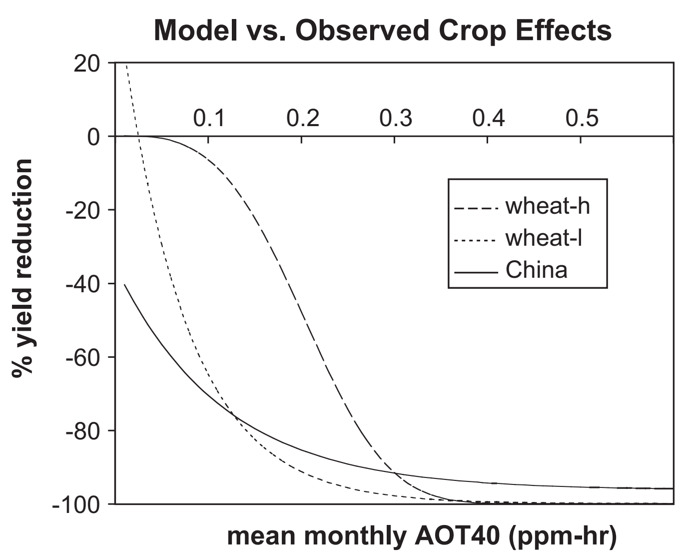


**Figure 13**. Weibull function for winter wheat from Heck *et al.* (1984), with TEM results for China. Each of these functions describes results from different crop samples. The same functional spread exists for corn, cotton, and soybean.

extent of this range is therefore highly dependent upon not just the crop type, but the actual variety of wheat. These values are also somewhat less than the sensitivity obtained in this study because they are based on Weibull functions with exponential powers greater than 1.0. Other assessments from Europe as part of the European OTC program (EOTC) show a 5% yield reduction under low AOT40 ozone exposures (1ppm-hr) (Mauzerall and Wang, 2001).

## 5. ECONOMIC IMPLICATIONS ON CARBON POLICY

While there are economic implications on agricultural markets from 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. 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 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 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. 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 (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 proposed Kyoto targets 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). The more robust result is not the absolute ozone damage cost, but this damage cost expressed as a percentage of the total cost of the carbon policy.

**Table IV** provides the estimates of the net present value (NPV) cost of the climate policy using a 5% discount rate and reported in 1997 constant dollars and how it would change when considering ozone damage. The results, particularly the absolute dollar amounts, are highly sensitive to the assumed discount rate. To illustrate that sensitivity we report in parenthesis here the results + or –, respectively, 2 percentage points. The total cost of the policy is about $21 ($9; $60) trillion or approximately 2 (1.4; 3) % of the NPV of total consumption in the reference over the 100-year period. The bounding cases for ozone damage with and without nitrogen fertilization (GSTAB minus GSTABCTL and GSTABF minus GSTABFCTL) increase global costs by $1.0 ($0.6; $2.3) to $3.7 ($2.1; $8.5) trillion (5 (7;4) to 18 (23;14)%). Under the pollution cap case ozone damages are reduced so that the global cost is $0.6 ($0.4; $1.0) to $2.5 ($1.6;$4.8) trillion (3 (4; 2) to 12(18; 8) % 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 $1.0 – $0.6=$0.4 trillion to $3.7 – $2.5=$1.2 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, and the additional costs to the region due to ozone damage also do not depend on the 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

**Table IV**. Net Present Value Consumption Loss (billions of 1997 dollars, 5% discount rate)

| Scenario | United States | European Union | China | Global |
|---|---|---|---|---|
| GSTABCTL | 2,888 | 4,238 | 6,396 | 20,781 |
| ***Additional Costs from Ozone Damage*** | | | | |
| GSTAB-GSTABCTL | 188 | 269 | 308 | 1,011 |
| GSTABF-GSTABFCTL | 520 | 1,530 | 1,028 | 3,748 |
| GSTABCAP-GSTABCAPCTL | 129 | 141 | 171 | 580 |
| GSTABCAPF-GSTABCAPFCTL | 354 | 1,002 | 704 | 2,540 |

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. Whether these regions bear this extra cost themselves will depend on how the extra burden of reduction is allocated in future climate policies.

Examining the regional estimates in Table IV, we see that ozone damage costs in the three maximum-impacted regions listed is 76 to 82% of the total damage cost for the world. And 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., particularly in the cases 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 NOx, CO and nonmethane hydrocarbons (NMHC), as well as $CH_4$. Second, many of these other ozone production precursors (NMHC, CO, NOx) 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 production precursors such as biomass burning in agricultural 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 models 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 ancilliary benefit. To examine the magnitude of this effect we compared the carbon sequestration with ozone damage in four POL cases (no climate policy) and the carbon sequestration in four GSTAB cases. We expected and found that ozone levels and ozone damage in terms of carbon sequestration was less with the GSTAB climate policies than without (POL cases. We valued these differences by relaxing the carbon constraint over time and in each region to account for this ancillary benefit of the climate policy.

**Table V** reports our estimates. The range is a climate policy savings of about \$0.9 to \$4.3 trillion or between 4 and 21% 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 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 exists or not to

**Table V**. Benefits of Avoided Ozone Damage from a Climate Policy (billions of 1997 dollars, 5% discount rate).

| | U.S. | EU | China | Global |
|---|---|---|---|---|
| (POL-POLCTL) – (GSTAB-GSTABCTL) | 151 | 505 | 629 | 1,853 |
| (POLF-POLFCTL) – (GSTABF-GSTABFCTL) | 100 | 1,577 | 1,185 | 4,336 |
| (POLCAP-POLCAPCTL) – (GSTABCAP-GSTABCAPCTL) | 15 | 171 | 375 | 874 |
| (POLCAPF-POLCAPFCTL) – (GSTABCAPF–GSTABCAPFCTL) | 99 | 806 | 989 | 2952 |

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 should be taken as only indicative of the potential magnitude of this 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 and developing world, including the U.S., Europe, and China. The other major ozone hotspot is 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), we have shown 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. While 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 management practices in these non-agricultural regions, such as timber harvesting. In considering the economic implications of ozone damage for climate policy we have considered only a part of ozone damages. 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, 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.

Agricultural production in these hotspots is particularly important because the U.S., Europe, and China include some of the world's most productive agricultural areas. The fact that ozone reduces crop yield in these most important crop producing and consuming regions is significant. We have used the process-based TEM model to show that ozone reductions at lower ozone exposure levels are more effective in improving crop yield than ozone reductions at higher exposures due to saturation. However, empirical data have also shown different types of correlations between ozone levels and crop yield for different types of crop. The next step in this analysis is to improve the relatively simple crop model used here by parameterizing different crop types. Our assumption of optimal nitrogen fertilization, while providing an upper bounds on both crop yields and the ozone effect, can be refined if we have transient datasets of both irrigation and fertilization for each grid cell. Although the use of agricultural management improves crop yield considerably, the more severe ozone damage under these conditions further necessitates the need to address this issue.

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 $yr^{-1}$. 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 1.4 to 15.0 % of the total range, or 5.3% of the means. The effect of ozone on carbon sequestration is therefore considerable on the global scale. It 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.

## Acknowledgments

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## APPENDIX: OZONE DATASETS

**1. HARVARD-L:** The HARVARD-L method involves our addition of diurnal variability cycles to the Logan (1999) monthly mean ozone maps at resolution 4$^o$ latitude by 5$^o$ longitude developed using surface observations from 1977-1995. This dataset assigns latitudinal band ozone concentrations based on concentrations at a single site within each latitude band (a total of 31 sites), so it is only a very rough estimate of ozone levels around the globe. We then use hourly data from the EPA CASTNET for the U.S., EMEP for Europe, several remote sites including Bermuda, Iceland, and Hawaii (Oltmans and Levy II, 1994), China (Luo *et al.*, 2000), and Japan (Sunwoo *et al.*, 1994) in order to understand regional diurnal variability cycles. The maximum amplitude of the diurnal variability and the times of the occurrence of minimum and maximum ozone levels are then added regionally to the mean monthly ozone patterns to develop monthly AOT40 maps (Figure 1a). Highest ozone levels occur on the Iberian Peninsula, with high levels also throughout the U.S. and eastern China. We specifically limit this method to the northern hemisphere.

**2. GEOS-CHEM:** The second method (GEOS-CHEM) of developing global AOT40 maps (Figure 1b) relies on the 3-D GEOS-CHEM atmospheric chemistry model (Fiore *et al.*, 2003) to describe the distribution of ozone across the globe. The GEOS-CHEM model has horizontal resolution of 4$^o$ latitude x 5$^o$ longitude with 20 vertical levels and is driven by assimilated meteorological observations. The values used here are driven by emissions of NOx, nonmethane hydrocarbon, and CO during the year 2001 and also includes biomass burning emissions and isoprene emissions from vegetation. The model uses 24 chemical tracers to develop the tropospheric $O_3$-NOx-hydrocarbon chemistry. We then use this model to directly compute the monthly AOT40 index from hourly ozone values for the globe. While this method provides the most internally-consistent ozone maps for the present, the low resolution distorts some of the observed ozone patterns, especially in regions of high topography. Highest ozone levels (Figure 1b) occur in the eastern U.S., southern Europe (Italy), the Arabian Peninsula, and eastern China. This model also shows the effects of biomass burning in central Africa and Brazil.

**3. MIT:** The third method (MIT) of developing global AOT40 maps relies on combining latitudinal band ozone concentration data with gridded (1$^o$ latitude x 1$^o$ longitude) NOx emissions data from the MIT IGSM (Prinn *et al.*, 1999). The EPPA submodel in the IGSM uses economic and policy assumptions to compute annual emissions of atmospheric gases ($CO_2$, $CH_4$, $N_2O$, CFC, $SO_x$, CO, and NOx). The NOx and other emissions are then used as input to a 2-D (7.8$^o$ latitude x 9 vertical levels) coupled atmospheric chemistry (Wang *et al.*, 1998; Mayer *et al.*, 2000) and land-ocean (LO) climate model. The atmospheric chemistry model has 25 chemical species, including ozone. The temporal resolution is 3 hours for photochemical species like ozone, which we use to estimate mean hourly ozone values for each month. In order to incorporate the changing NOx geographic emission patterns over time predicted by EPPA, we develop a method of mapping the ozone using these emissions, which first requires converting the emissions to concentrations (Felzer *et al.*, 2002). We then apply a wide log-normal smoother (60 TEM $0.5^{o}$ grids), appropriately skewed towards the west in the mid-high latitudes and towards the east in the tropics, to provide a proxy for the zonal atmospheric circulation. The resulting patterns are also normalized to ensure that the mean ozone level of the latitudinal band remains unchanged when the normalized value is multiplied by the hourly latitudinal ozone. Note that since the NOx values are annual and ozone 3 hourly, the seasonal signature is entirely within the ozone signal. The AOT40 index (Figure 1c) is then calculated from the resulting mean hourly ozone data for each month. Ozone levels are highest in the eastern U.S. and central and southern Europe, with a secondary high in northeastern China. Although biomass burning is a part of the EPPA model, neither the ozone nor NOx resolution is sufficient to allow for a positive AOT40 value to register in central Africa or Brazil.

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