ELSEVIER

Energy Policy 35 (2007) 5370–5383

ENERGY POLICY

www.elsevier.com/locate/enpol

Global economic effects of changes in crops, pasture, and forests due to changing climate, carbon dioxide, and ozone

J. Reilly[a,*], S. Paltsev[a], B. Felzer[b], X. Wang[a], D. Kicklighter[b], J. Melillo[b], R. Prinn[a], M. Sarofim[a], A. Sokolov[a], C. Wang[a]

[a]*MIT Joint Program on Science and Policy of Global Change, Massachusetts Institute of Technology, Cambridge, MA 02139, USA*
[b]*Ecosystems Center, Marine Biological Laboratory, Woods Hole, MA 02543, USA*

Received 15 September 2005; received in revised form 31 December 2005; accepted 1 January 2006
Available online 19 July 2007

Abstract

Multiple environmental changes will have consequences for global vegetation. To the extent that crop yields and pasture and forest productivity are affected, there can be important economic consequences. We examine the combined effects of changes in climate, increases in carbon dioxide (CO_2), and changes in tropospheric ozone on crop, pasture, and forest lands and the consequences for the global and regional economies. We examine scenarios where there is limited or little effort to control these substances, and policy scenarios that limit emissions of CO_2 and ozone precursors. We find the effects of climate and CO_2 to be generally positive, and the effects of ozone to be very detrimental. Unless ozone is strongly controlled, damage could offset CO_2 and climate benefits. We find that resource allocation among sectors in the economy, and trade among countries, can strongly affect the estimate of economic effect in a country.

Keywords: Climate change; Ozone damage; Agriculture

1. Introduction

Multiple environmental changes will have consequences for global vegetation. To the extent that crop yields and pasture and forest productivity are affected, there can be important economic consequences. We examine the combined effects of changes in climate, increases in carbon dioxide (CO_2), and changes in tropospheric ozone on crop, pasture, and forest land productivity and the consequences for the global and regional economies. We consider scenarios where there is limited or little effort to control CO_2 and ozone precursors, and policy scenarios that limit emissions of these substances. Much analysis and research on the economic impacts of climate change and/or higher ambient levels of CO_2 on agriculture have been conducted. Our study is unique in several ways, including the focus on multiple environmental changes, use of transient climate scenarios, comprehensive assessment of crops, pasture and forests, and evaluation of effects in both a reference and in pollution mitigation scenarios.

We apply the MIT Integrated Global Systems Model (IGSM) (Prinn et al., 1999), here updated to focus on the vegetation and economic effects of climate and ozone. In particular, the Terrestrial Ecosystem Model (TEM) component is a biogeochemical model that has been updated to include vegetation response to ozone as described in Felzer et al. (2004). We have also altered the Emissions Prediction and Policy Analysis (EPPA) model (Paltsev et al., 2005), a computable general equilibrium (CGE) model of the world economy, to better represent crops, livestock, and forest sectors. In Section 2, we review key previous agricultural impact studies, identifying how our approach advances methods in this field of research. Section 3 reviews briefly the model components used in the study. Section 4 describes the reference and pollution mitigation scenarios. Section 5 describes the results. Section 6 offers some caveats and Section 7 summarizes key results.

*Corresponding author.
E-mail address: jreilly@mit.edu (J. Reilly).

0301-4215/$ - see front matter
doi:10.1016/j.enpol.2006.01.040

2. Modeling global agricultural economic response to environmental change

Key previous studies of climate and CO_2 effects, focusing on those that are global or pioneer new methods, include Parry et al. (1988a, b, 1999, 2004), Adams et al. (1990), Tobey et al. (1992), Reilly and Hohmann (1993), Rosenberg (1993); Rosenzweig and Parry (1994), Mendelsohn et al. (1994), Darwin et al. (1996), Reilly et al. (2003), Izauralde et al. (2003), and Alig et al. (2003). There have been no global estimates of the potential economic impact of ozone damage on crops. The most comprehensive economic study focused on current estimates of ozone damage was for the US (Adams et al., 1986). More recent work has examined crop production effects in the eastern US (Westenbarger and Frisvold, 1994, 1995) and Asia (Wang and Mauzerall, 2004), with very limited evaluation of economic effects. There has been much experimental work on both ozone and CO_2 effects and a large number of crop site studies, and farm or regional level studies for climate and CO_2, as reviewed in Gitay et al. (2001) and Reilly and Schimmelpfennig (1999). The methods pioneered in the literature cited above have also been applied in other studies, and using different climate scenarios. A recent review of these major agricultural assessment exercises is provided in Reilly (2002) and Gitay et al. (2001).

This study is unique in several ways. (1) We include the combined effects of climate, CO_2, and tropospheric ozone, whereas previous work has mostly examined climate and CO_2 or climate effects only. (2) The climate and yield effects are from fully transient climate scenarios where gradual increases in greenhouse gases (GHGs) gradually force the climate. Much previous work is based on equilibrium-doubled CO_2 climate scenarios, and so it is unclear in what year such a climate would be obs erved. Some previous work has simulated economic effects through time but have only estimated yield effects for a circa 2030, 2070, or 2100 climate scenario, interpolating yield effects for earlier years. Most previous work has used static economic models examining the impacts of climate change as if it occurred on the agricultural economy as it exists today. (3) The scenarios of climate, CO_2, and ozone concentrations are from consistent economic scenarios; most previous work is based on doubled CO_2 equilibrium climate scenarios, requiring assumptions about when such a climate would be realized as well as the extent to which the forcing was all CO_2 or partly due to other GHGs. (4) We consider effects in no-policy and in policy scenarios, thus making it possible to assess the "benefits" of the prescribed policy; previous work has simply examined different climate scenarios. (5) The terrestrial biogeochemical model we use simulates the relatively immediate response of vegetation to climate and atmospheric change as well as the longer-term soil dynamics and its impact on productivity. Previous work takes soil characteristics as unchanging.

There are important advances represented in previous work, and our approach follows closely the state-of-the-art in this regard. (1) We simulate the economic effects using a global CGE model that is recursive dynamic, thus capturing the interactions among agriculture, forestry, and livestock sectors, and with the rest of the economy, as well as international trade effects as economies develop over time. Rosenzweig and Parry (1994) and Parry et al. (1999, 2004) use a forward-looking dynamic CGE model capturing such effects as well. Darwin et al. (1996) use a static CGE model, and so capture interactions with the rest of the economy, but an economy of circa 1995. Other work uses partial equilibrium market models and so fails to capture interactions with the rest of the economy, or econometric approaches that do not consider market price effects at all. Much work considers a single country or smaller region and is thus unable to correctly account for international trade and changes in international prices. (2) We assess effects on a $0.5^\circ \times 0.5^\circ$ latitude–longitude grid level, of which there are about 62,000 globally, allowing for a fairly complete assessment of existing spatial variation. Darwin et al. (1996) use a $0.5^\circ \times 0.5^\circ$ latitude–longitude grid but with a static CGE model, and without a process-model representation of effects on vegetation. Izauralde et al. (2003) approach this coverage by modeling 204 separate hydrologic unit areas, but their application is for the US only. Mendelsohn et al. (1994) use county-level data for the US (of which there are on the order of 3000 counties) to estimate a statistical model of climate impacts on vegetation, but there are no market feedbacks and no assessment of trade effects. Most previous work has used crop models applied at relatively sparsely located sites—as many as 40–50 for the US, but sometimes just a few to represent, for example, the entire African continent, and thus one can question whether these relatively few sites are representative of spatially varying conditions. (3) We evaluate the combined effects on crops, pasture, and forests, activities that all compete for land use. Most studies consider only crops, and often a limited set of crops. Reilly et al. (2003) considered impacts on crops and pasture and Alig et al. (2003) included crops, pasture, and forests, but both studies were limited to the US.

To achieve these methodological advances, we have had to simplify other aspects of the models so that they remained computationally feasible. The biogeochemical model runs on a monthly time step, and simulates a generic crop, thus making simulation for the large number of grid cells feasible. More detailed crop models run on an hourly or quarter-day time step, with specific model parameters for each crop. We gain by representing the spatial diversity of cropping more completely, but we cannot represent the details of the phenological development of different crops and response to diurnal weather variability. We represent crops, livestock, and forestry sectors in a relatively aggregate fashion, assuming that the yield effects simulated by TEM are reflected as productivity impacts to land in the economic model. We gain by representing all three of these large land-using sectors in a single model, and by treating the interaction of these sectors with other sectors of the economy but we are not able to represent individual crop and livestock sectors, or the details of optimal forest rotation, harvesting and regrowth. The climate model is a zonal land–ocean resolving model, and we therefore must use a fixed longitudinal pattern of climate that is adjusted by changes in the zonal average simulated by the 2-D model. We also use a fixed spatial pattern of ozone driven by modeled zonal mean ozone levels as projected by the 2-D model. This makes simulation of multiple climate scenarios numerically feasible, but does not adequately capture finer details of the changing spatial pattern of climate, or possible changes in transport of ozone as climate changes. We return to these issues Section 6, where we discuss caveats and implications for future research. Climate impact research remains subject to many caveats because the accurate prediction of fine-scale changes in weather patterns, even in the most highly resolved general circulation models (GSMs), remains elusive.

3. Model descriptions

We briefly describe the MIT IGSM, and then focus attention on the TEM and EPPA components as modified for this work. The MIT IGSM includes sub-models of the relevant aspects of the natural earth system coupled to a model of the human component as it interacts with climate processes. A description of the system components used in Version 1, along with a sensitivity test of key aspects of its behavior, is reported in Prinn et al. (1999).

The major model components of the IGSM are:

- A model of human activity and emissions (the emission prediction and policy analysis, or EPPA model).
- An atmospheric dynamics, physics, and chemistry model, which includes a sub-model of urban chemistry.
- An ocean model with carbon cycle and sea-ice sub-models.
- A terrestrial ecosystem model (TEM) that represents terrestrial ecosystem processes and a natural emissions model (NEM) that represents methane and N_2O cycles.

For this work, we use Version 1 of the IGSM because we are interested in retaining the $0.5^\circ \times 0.5^\circ$ degree resolution of the original TEM. The $0.5^\circ \times 0.5^\circ$ TEM is forced off-line by the IGSM climate scenario.[1] In addition, the version of EPPA model applied here—EPPA-AGRI—is also run off-line, forced by changes in crop, pasture, and forest productivity as determined by TEM. The economic changes and ozone damages that result imply changes in emissions of GHGs but we do not feed these back into the climate system. Thus, we are using the output of the 2-D land–ocean resolving GCM of the MIT IGSM as an exogenous scenario to drive the impact models. The MIT IGSM is a flexible model in the sense that parameters controlling climate sensitivity, response to aerosols, and ocean heat uptake can be set such that the model replicates results of other GCMs. The standard settings for the model, and those used here, are the median values from a climate detection and attribution study, with expert priors, of Forest et al. (2002) as applied in Webster et al. (2003).

TEM (Melillo et al., 1993; Tian et al., 1999, 2003; Felzer et al., 2004) is a process-based biogeochemistry model that simulates the cycling of carbon, nitrogen (N), and water among vegetation, soils, and the atmosphere. Version 4.3 (TEM 4.3) includes modeling of the pathways by which ozone influences the productivity and carbon storage of terrestrial ecosystems (Felzer et al., 2004). The effects of ozone on productivity were incorporated 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. Separate coefficients of linearity are calculated 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:

$$\mathrm{NPP} = \mathrm{GPP} - R_{\mathrm{A}}, \quad (1)$$

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

$$\mathrm{NCE} = \mathrm{NPP} - R_{\mathrm{H}} - E_{\mathrm{c}} - E_{\mathrm{p}}, \quad (2)$$

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 Eqs. (1) and (2), the reduction of GPP by ozone will also reduce both NPP and NCE.

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, the Model for Atmospheric Transport and Chemistry (MATCH) (Lawrence et al., 1999; Mahowald et al., 1997; Rasch et al., 1997; von Kuhlmann et al., 2003) has been used, run at $2.8^\circ \times 2.8^\circ$ or T42 horizontal resolution, to construct global AOT40

[1]Version 2 of the model includes an improved land system component (more closely linking the TEM, NEM, and community land model that represents energy and water balance of the land surface with the atmosphere), but is resolved at zonal bands of 4° matching the resolution of the atmospheric model, inadequate for capturing the spatial variation in ozone concentrations. Because of flexibility of the model, the overall behavior of Versions 1 and 2 of the IGSM is very close when key climate parameters are set to identical values as shown in Sokolov et al. (2005).

maps for each hour utilizing the zonal and 3-h mean surface ozone concentration provided by the IGSM. MATCH is a three-dimensional (3-D) global chemical transport model driven by reanalysis meteorological fields. 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. Greater detail on these procedures is provided in Felzer et al. (2005).

The EPPA model is a CGE model of the world economy that has been extensively used to examine climate and environmental issues (Table 1). The main advantage of CGE models is their ability to capture the influence of a sector-specific (e.g., energy, fiscal, or agricultural) policy or forces on other industry sectors, consumption, and on international trade. A traditional limitation of CGE models has been linkage of economic variables to physical variables such as land use, emissions, population, and energy use. The EPPA model overcomes this limitation by developing extensive supplementary tables on physical data as described in Paltsev et al. (2005) and is thus able to simulate and project growth and change in the economy, its implications for pollutant emissions, demands for natural resources, and feedback effects of environmental change on the economy. We designate the version of EPPA used here as EPPA-AGRI because of the further disaggregation of the agricultural sector as described in Wang (2005).

For this work, we examine the economic impacts of changes in climate, CO_2, and ozone as they affect crops, pasture, and forestry using the combined modeling system. Temporal and spatial scales, as discussed above, are resolved at different levels requiring interpolation or aggregation as data are passed from one modeling component to another. A complete description of the model is provided in Prinn et al. (1999). Here we briefly describe how key linkages are handled. The TEM model operates at a $0.5^\circ \times 0.5^\circ$ latitude by longitude spatial and monthly time scale. It includes the current monthly climatology resolved at that spatial scale. Ozone levels were resolved at the resolution of the MATCH model (T-42, approximately $2.8^\circ \times 2.8^\circ$) and interpolated to the TEM resolution as described in Felzer et al. (2005).

The 2-D land–ocean resolving GSM is resolved at 20 min time steps and for 24 latitudinal bands. CO_2 concentrations are assumed to be well-mixed globally. The changes in temperature and precipitation as predicted by the climate model for land in each latitude zone were used to scale the $0.5^\circ \times 0.5^\circ$ climatology of TEM (see Xiao et al., 1997).

The EPPA CGE model is resolved at 5-year time steps and for the 17 geopolitical regions shown in Table 1. Projected emissions of GHGs and other pollutants from EPPA drive the atmosphere ocean model. Emissions are distributed to the zonal resolution of the model and resolved for urban (high pollution) and non-urban (background pollution level) conditions.

Table 1
The Emissions Prediction and Policy Analysis (EPPA) model is a recursive-dynamic multi-regional CGE model of the world economy (Babiker et al., 2001; Paltsev et al., 2005), which is built on the economic and energy data from the GTAP dataset (Dimaranan and McDougall, 2002) and additional data for the greenhouse gas (CO_2, CH4, N_2O, HFCs, PFCs and SF_6) and urban gas emissions (CO, VOC, NO_x, SO_2, BC, OC, NH_4)

Countries/regions, sectors, and factors in the EPPA-AGRI model

Country or region	Sectors	Factors
Developed	**Non-energy**	**Economy-wide**
United States (USA)	Services	Capital
Canada (CAN)	Energy-intensive products	Labor
Japan (JPN)	Other industries products	**Energy**
European Union+[a] (EUR)	Transportation	Crude oil resources
Australia/New Zealand (ANZ)	*Food processing*	Shale oil resources
Former Soviet Union[b] (FSU)	**Energy**	Coal resources
Eastern Europe[c] (EET)	Coal	Natural gas resources
Developing	Crude oil	Nuclear resources
India (IND)	Shale oil	Hydro resources
China (CHN)	Refined oil products	Wind/solar resources
Higher income East Asia[d] (ASI)	Natural gas, coal gasification	**Land use**
Indonesia (IDZ)	Electric: Fossil, Hydro, Nuclear,	*Crop land*
Rest of World[e] (ROW)	Solar and wind, biomass, natural gas	*Pasture/grazing land*
Mexico (MEX)	Combined cycle, integrated coal	*Forest land*
Africa (AFR)	Gasification with sequestration	
Central and South America (LAM)	**Agriculture**	
Middle East (MES)	*Crops*	
	Livestock	
	Forestry	

It has been used extensively for the study of climate policy (Jacoby et al., 1997; Babiker et al., 2002, 2004; Paltsev et al., 2003; Reilly et al., 2002; McFarland et al., 2004), climate interactions (Reilly et al., 1999; Felzer et al., 2005), and to study uncertainty in emissions and climate projections for climate models Webster et al., 2002, 2003). It has been modified for this analysis to include greater disaggregation of the food and agriculture sectors, as shown in italics.

[a]The European Union (EU-15) plus countries of the European Free Trade Area (Norway, Switzerland, Iceland).

[b]Russia, Ukraine, Latvia, Lithuania, Estonia, Azerbaijan, Armenia, Belarus, Georgia, Kyrgyzstan, Kazakhstan, Moldova, Tajikistan, Turkmenistan, and Uzbekistan.

[c]Hungary, Poland, Bulgaria, Czech Republic, Romania, Slovakia, Slovenia.

[d]South Korea, Malaysia, Phillipines, Singapore, Taiwan, Thailand.

[e]All countries not included elsewhere: Turkey, and mostly Asian countries.

The growth of crops, pasture, and forests is simulated on a monthly basis at $0.5^\circ \times 0.5^\circ$ including spatial variation in soils, current climatology, and ozone levels, although simulated changes are only resolved at the latitudinal band level of the climate model. This follows a widely used methodology in impact assessment, where simulated changes from a more coarsely resolved climate model are combined with actual weather/climate data that are more finely resolved. Retaining the current climatology at the spatial scale of the more detailed impact model retains the spatial variation in weather/climate that *currently exists*, but cannot capture *changes* in spatial variation that are finer than the climate model. To simulate the economic effects of these changes through the EPPA CGE model, the yield and net primary productivity (NPP) effects estimated by TEM are related to each land use type (crops, pasture, forest) based on the TEM vegetation types (Table 2). These results are then aggregated from the $0.5^\circ \times 0.5^\circ$ level to the EPPA geopolitical regions. The productivity changes driving the EPPA model are thus an average for each region that is based on spatial variation simulated at $0.5^\circ \times 0.5^\circ$.

Table 2
TEM vegetation types and land use classification

TEM VEG	Description of vegetation type	Land use classification
1	Ice	
2	Alpine tundra and polar desert	
3	Moist and wet tundra	
4	Boreal forest	Forestry
5	Forested boreal wetlands	Forestry
6	Boreal woodlands	Forestry
7	Non-forested boreal wetlands	
8	Mixed temperate forests	Forestry
9	Temperate coniferous forests	Forestry
10	Temperate deciduous Forests	Forestry
11	Temperate forested wetlands	Forestry
12	Tall grasslands	Pasture
13	Short grasslands	Pasture
14	Tropical savanna	Pasture
15	Arid shrublands	Pasture
16	Tropical evergreen forests	Forestry
17	Tropical forested wetlands	Forestry
18	Tropical deciduous forests	Forestry
19	Xeromorphic forests and woodlands	Pasture
20	Tropical forested floodplains	Forestry
21	Deserts	
22	Tropical non-forested wetlands	
23	Tropical non-forested floodplains	
24	Temperate non-forested wetlands	
25	Temperate forested floodplains	Forestry
26	Temperate non-forested floodplains	
27	Wet savannas	
28	Salt marsh	
29	Mangroves	
30	Tidal freshwater marshes	
31	Temperate savannas	Pasture
32	Cultivation	Cropland
33	Temperate broadleaved evergreen	Forestry
34	Reserved	
35	Mediterranean shrublands	Pasture

Note: Vegetation changes for ice, tundra, desert, and wetlands are excluded from any of the uses as indicated by blank space in the use column.

4. Scenarios

We consider the following scenarios.

- ***High pollution*** (*POLF*): There are no efforts to control emissions of GHGs. Emissions coefficients per unit of combustion for other pollutants decline in different regions as incomes increase based on cross-section estimates of the relationship between per capita income and these coefficients in the base year as estimated in Mayer et al. (2000). The decline is estimated separately for each pollutant, and for different combustion sources including large point source, small sources, and for households. In principle, this would tend to create an environmental Kuznets' curve relationship, but the exhibited decline in emissions per unit of fuel combustion is insufficient to offset increases in use of fuels, and so pollution levels rise substantially.
- ***Climate and GHGs only*** (*POLFCTL*): The same climate and pollution scenario as the ***High pollution*** case but with the ozone damage mechanism in TEM turned off so that we can observe the climate and CO_2 effects alone without the effect of ozone damage.
- ***Capped pollution*** (*POLCAPF*): Conventional pollutants (CO, VOC, NO_x, SO_2, NH_3, black carbon, and organic carbon) are capped at 2005 levels, but GHG emissions remain uncontrolled. The major effect of capping these pollutants is to reduce ozone levels because many of these are important ozone precursors, and thus ozone damage to vegetation is reduced. The climate effects of reducing these pollutants are small because of the offsetting effects from different pollutants (Prinn et al., 2007). Sulfates are cooling substances so reducing them tends to increase the temperature but ozone is a warming substance and, so reducing ozone precursors leads to less warming.
- ***GHGs capped*** (*GSTABF*): GHGs are controlled along a path that starts with the Kyoto Protocol, deepening the cuts in developed countries and expanding to include developing countries on a pathway that keeps CO_2 concentrations below 550 ppm by 2100 and with continued emissions reduction that could be consistent with stabilization of concentrations at 550 ppm. This scenario is described in Reilly et al. (1999). Because combustion of fossil fuels is affected, this scenario also leads to significant reduction from reference of other pollutants including ozone precursors.
- ***GHGs capped-no ozone*** (*GSTABFCTL*): The same climate and GHG levels as in the *GHGs capped* scenario, but with the ozone-damage mechanism in the TEM model again turned off so that we can observe the climate and CO_2 effects alone without the effect of ozone damage.

- ***GHGs and pollution capped*** (*GSTABCAPF*): GHGs controlled as in the ***GHGs capped*** scenario and conventional pollutants capped as in the ***Capped pollution*** scenario.

For expositional purposes, we have adopted as labels in this paper the terms above in bold italics. For ease of comparison, we include in parentheses labels that were used in Felzer et al. (2005) and Prinn et al. (2007), who report carbon storage and climate impacts, respectively, of these same emissions scenarios.

The temperature change, CO_2, and ozone concentrations resulting from these emissions are shown in Fig. 1. Unrestricted GHG emissions lead to a projected increase in average global temperature by 2.75 °C over a century. The temperature is increased even in GHG capped scenarios by approximately 1 °C. Over the century, CO_2 concentrations are rising from 375 to around 810 ppm in unrestricted GHG cases, and to around 515 ppm in the GHG capped cases. Ozone stays at its current levels in the GHG and pollution capped scenarios. Pollution-only control scenario affects ozone stabilization relatively more than the GHGs-only control scenario.

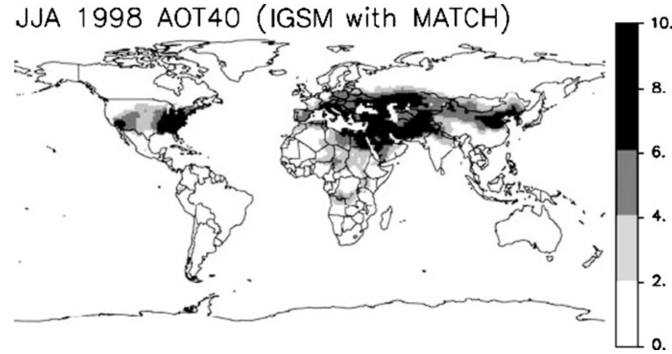

Fig. 2. Geographical distribution of ozone (AOT40, ppm-h), mean monthly levels for June–August of 1998.

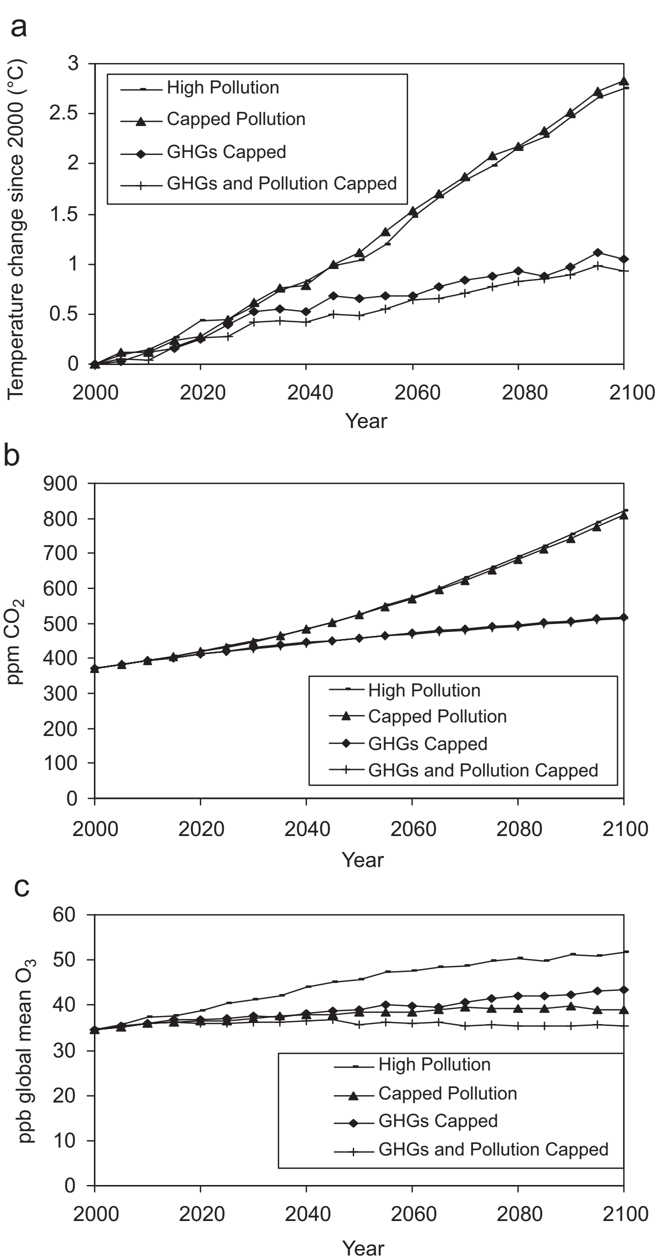

Fig. 1. Global changes in temperature, CO_2 concentrations and ozone levels: (a) temperature change; (b) CO_2 concentration; and (c) ozone level.

As noted, the spatial pattern of ozone is constructed for the present from the MATCH model and the result is shown in Fig. 2. For illustrative purposes, we show a map for June–August (JJA), the Northern Hemisphere summer. Ozone levels are highest in the mid-latitude temperate areas, where the largest emissions occur. However, the JJA period is the Southern Hemisphere winter, conditions that do not favor ozone formation, and thus the very low levels of ozone in the Southern Hemisphere partly reflect this choice of period. Fig. 3 shows the yearly levels of AOT40 for 2000–2100 for the 4 relevant scenarios[2] for key vegetation types, chosen to illustrate the differences between tropics, temperate, and boreal areas. Notably, the temperate regions, dominated by Northern temperate areas including the US, Europe, and China, have relatively high levels of AOT40. Also, note that levels of AOT40 increase much more rapidly than the levels of ozone itself as shown in Fig. 1(c). Whereas, the global increase in ozone levels is less than 50% in the ***High pollution*** case and less than 20% in the cases where pollution and/or GHGs are controlled, AOT40 increases by as much as six times in the ***High pollution*** case and doubles or triples in ***Capped pollution*** and ***GHGs capped*** cases, respectively. The large increase in AOT40 despite much smaller increases in ozone levels themselves is because the AOT40 is a threshold measure. Any increase in ozone in areas near or above this threshold will add to AOT40, whereas much of the current

[2]Those without any ozone damage (***Climate and GHGs only*** and ***GHGs capped, no ozone***) were constructed by leaving out the ozone damage mechanism in the TEM, and so the actual ozone levels are no different than in the comparable cases with ozone damage (***High Pollution*** and ***GHGs capped***, respectively).

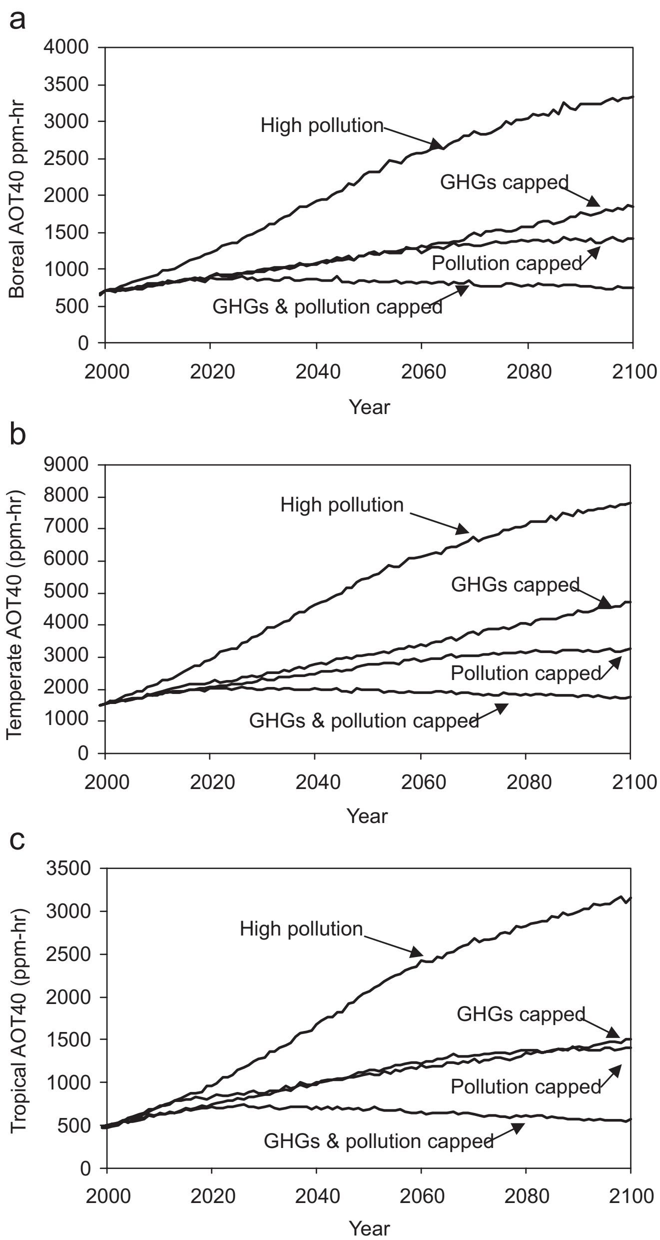

Fig. 3. Annual ozone levels (AOT40) by vegetation type, 2000–2100: (a) boreal vegetation types; (b) temperate vegetation types; and (c) tropical vegetation types.

ozone contributes to levels that are below this threshold and thus contribute nothing to the AOT40 index. Much of the industrial activity leading to emissions is in the temperate regions in the Northern hemisphere and ozone levels are highest over temperate vegetation, although ozone levels increase substantially over both boreal and tropical vegetation.

5. Agriculture, pasture, and forestry results

Yields on croplands are taken from TEM estimates of changes in yield for a "generic" C3 crop (Felzer et al., 2004). This crop is grown on areas identified as cropland by McGuire et al. (2001), which has been derived from the historical fractional cropland dataset of Ramankutty and Foley (1998, 1999), for the period of the early 1990s. For pasture and forestry, the change in NPP is used as a measure of yield effects. Fig. 4 shows the results for the six scenarios mapped at the $0.5^{\circ} \times 0.5^{\circ}$ resolution of TEM, with absolute yield changes in $gC/m^2/year$ between 2090 and 2100 and the present (1995–2005). The average yield/NPP is calculated for each of these decades. Also shown is the average percentage yield change for crops, pasture, and forestry for each of the 16 EPPA regions over the same period.

The ***High pollution*** and ***Climate and GHGs only*** were constructed to show the separate effects of ozone damage and climate and CO_2 in a scenario where there was no explicit climate policy and where emissions per unit of combustion of conventional pollutants fell as a function of rising per capita income, but insufficiently to prevent pollution levels from rising significantly. Comparing results for these scenarios in Fig. 4 shows climate and CO_2 effects to be beneficial almost everywhere; however, when ozone damage is included, many areas experience severely negative effects. These negative effects are especially strong in cropland areas, in the Northern Hemisphere. This is evident by examining the percentage change results for cropland as compared with pasture and forestry. The strong effects of ozone on cropland are the result of four effects as discussed in Felzer et al. (2005): (1) inherent higher sensitivity of crops than forests/natural vegetation to ozone as represented in response functions of Reich (1987); (2) spatial variation in ozone levels that often lead to higher ozone concentrations over cropland; (3) spatial variation in GPP, with fertilized croplands tending to have higher levels, since stomatal conductance and, thus ozone damage, is proportional to GPP; and (4) the interaction of ozone damage with applications of N fertilizer.

Comparing the map of ozone damage in Fig. 4 with the spatial pattern of high ozone (Fig. 2 and zonal increases in Fig. 3), there is a general correlation between areas where higher ozone damage occurs and higher ozone levels. The areas of high ozone damage occur mainly in Northern mid-latitudes where industrial activity and emissions of ozone precursors are high. With regard to (3), higher absolute effects (damage and benefit) occur where there are higher rates of vegetation growth. The arid areas of the western US, northern and Southern Africa, Central Asia, and much of Australia and the very cold areas of far northern Canada, Europe, and Asia all show lower absolute increases in productivity due to climate and CO_2 than relatively moist and warmer climates. Thus, some areas of high ozone levels such as southwest US, the Middle East, and central Asia do not show large decreases in productivity due to ozone exposure. However, as pointed out previously, Fig. 2 represents JJA only and significant damage can occur in other months. For a more complete comparison of these effects, see Felzer et al. (2004, 2005). With regard to (4), Felzer et al. (2004) also identify a strong interaction effect between ozone damage and N

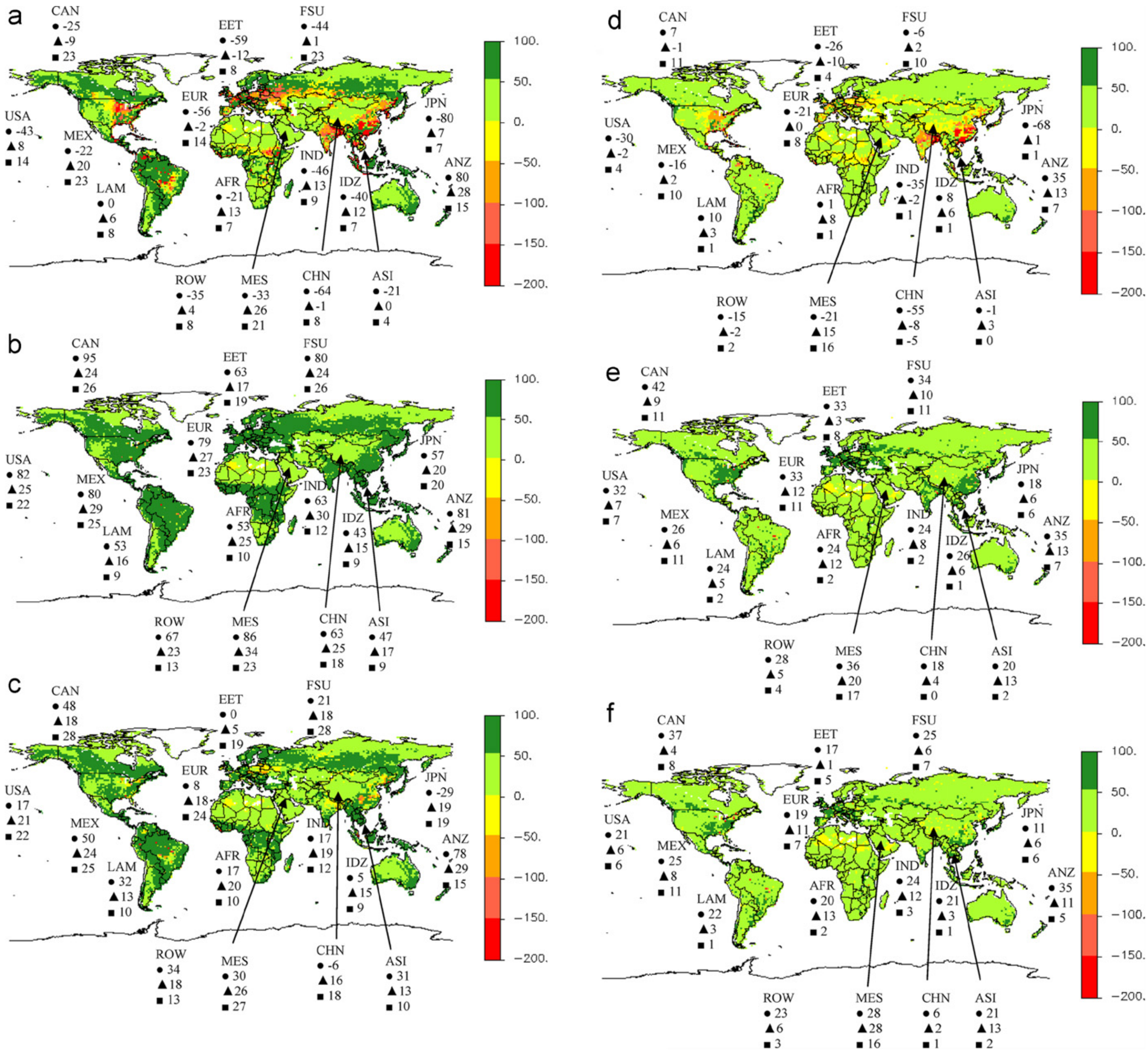

Fig. 4. Change in yield between 2000 and 2100 (gC/m^2/year). Regional level percent changes in yield (crops) and NPP (pasture, forestry): ●—crops, ▲—pasture, ■—forestry. (a) ***High Pollution*** scenario. (b) ***Climate and GHGs only*** scenario. (c) ***Capped pollution*** scenario. (d) ***GHGs capped*** scenario. (e) ***GHGs capped-no ozone*** scenario. (f) ***GHGs and pollution capped*** scenario.

fertilization, beyond what one would expect simply because N fertilizer increases the productivity of plants. In these scenarios, optimum N fertilization is applied on all cropland, and thus the largest absolute losses of yield occur on cropland areas exposed to high ozone. This combination—stronger response of crops, use of N fertilizer, high productivity, and the spatial pattern of high ozone concentrations—strongly biases high ozone damage toward crops, relative to pasture or forest land. By comparison, pasture and forest land is not subject to N fertilization in the model (reflecting predominant practice) and these lands are often more remote from industrial regions where ozone concentrations are lower and productivity is lower. All these factors contribute to less ozone damage.

The ***Capped pollution*** scenario is intermediate between the ***High pollution*** and ***Climate and GHGs only*** scenarios. Even capping the conventional pollutants at current levels does not entirely prevent increases in ozone levels. CH_4 is uncontrolled in these scenarios and it is an ozone precursor. Further, there are non-linear interactions in chemistry that depend on relative levels of these pollutants and whether they are emitted into a relatively clean or highly polluted environment, in addition to temperature and humidity effects on various atmospheric reaction pathways. Prinn et al. (2007) provide a more in-depth evaluation of these scenarios in terms of the implications of capping these pollutants. In general, yield of forests, pasture, and cropland are relatively positive.

The ***GHGs capped***, ***GHGs capped-no ozone***, and ***GHGs and pollution capped*** scenarios show generally less increase in yields in areas where the yield changes were dominated by the positive effects of CO_2 and climate and less ozone damage. In the ***GHGs capped*** scenario, less ozone damage occurs because the GHG policy results in less combustion of fossil fuels and therefore a side effect is less emissions of ozone precursors as well as less CH_4. Ozone damage remains significant enough, however, to turn what would be a large increase in yield in eastern US, Europe, India, and eastern China from CO_2 and climate into significant negative effects on yields. This can be seen from comparing the ***GHGs capped*** and ***GHGs capped-no ozone*** scenarios. The ***GHGs and pollution capped*** scenario also keeps other ozone precursors from increasing and these two factors together mean that there is very little increase in ozone from current levels, as can be seen from Fig. 3. The result is that the yield change map for the ***GHGs and pollution capped*** scenario is very similar to that for the scenario where the ozone damage mechanism was simply turned off in TEM (i.e., ***GHGs capped-no ozone***).

The percentage yield effects at 5-year intervals (the EPPA temporal resolution) were introduced as changes in the productivity of land from the reference level in each of the sectors (agriculture, livestock, forestry) in the EPPA model for each of the 16 regions.[3] In general, land productivity is modeled as increasing in EPPA in the reference due to improving technology, and thus a positive effect of environmental change is a further increase in land productivity, whereas a negative environmental effect reduces the productivity increase and may cause an absolute decline in yields (relative to current) if the environmental impact is large enough. Our principal interest is in how changes in the environment (climate, CO_2, and ozone) affect agricultural production and the economy relative to the reference. Thus, for example, land productivity increasing at a compounded rate of 1 percent per year would imply a 64 percent increase by 2050, or, with year $2000 = 1.00$, an index value of 1.64 in 2050. If the TEM yield change estimate is for an increase of 10 percent, the new productivity index value in 2050 for that sector/region would by $1.10 \times 1.64 = 1.81$, or if environmental change caused average yield to fall to 0.9 percent, then the new productivity index for EPPA is $0.90 \times 1.64 = 1.48$.

We focus first on global effects on production of these yield changes. To effectively compare the global production effects with the yield changes, we construct a measure of global yield change for crops, pasture, and forestry derived from TEM to compare with estimated production change once we simulate the effect of these changes in EPPA. The global yield changes are derived by summing the total level of agroecosystem productivity (gC/year) for the globe and calculating the difference from 2000, as we did for each of the regions. Thus, the percentage change is weighted by the absolute productivity in different regions. The global sector production (crop, livestock, forestry) is measured by the total value of production in real terms in 1997 US dollars and at 1997 market exchange rates as reported in EPPA. We calculate the difference from the reference projection (without environmental effects) to measure the effect on production of each of the environmental changes in terms of sector production levels. These are plotted in Figs. 5–7. For exposition, we have not plotted the ***GHGs capped-no ozone*** scenario because it is very similar to ***GHGs and pollution capped*** scenario.

Fig. 5 reports the results for crops. As expected, positive (negative) yield effects of environmental change lead to positive (negative) production effects. However, note that the production effects are far smaller than the yield effects. The global yield effects range from an increase of over 60 percent (***Climate and GHGs only***) to a decline of nearly 40 percent (***High pollution***), while the crop production effects

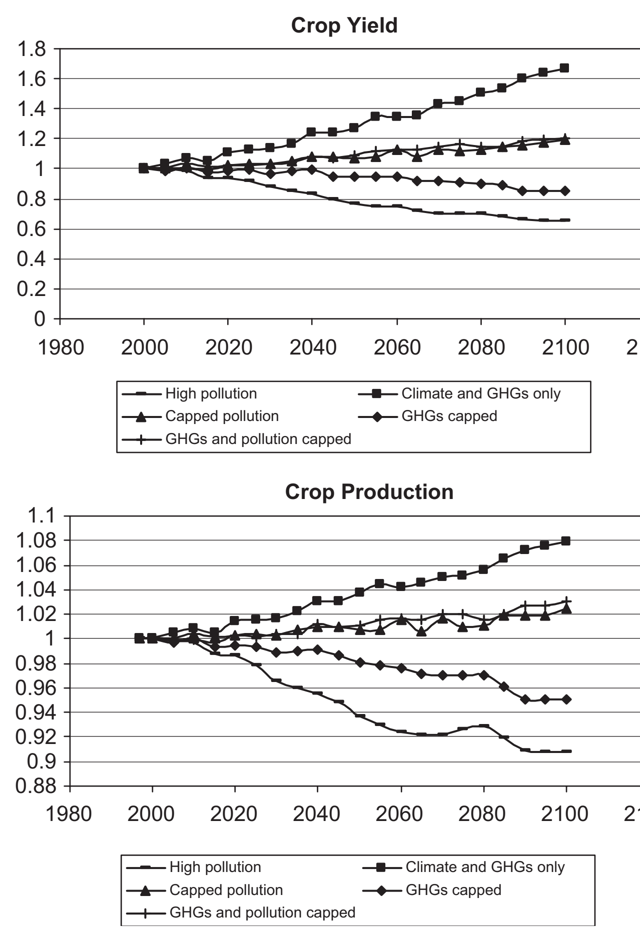

Fig. 5. Index for crop yield and production.

[3]We use the term "yield" to refer to estimates derived from TEM. "Land productivity" multiplier for land in the constant elasticity of substitution (CES) production functions for crops, forestry, and livestock used in EPPA. Actual "yield" as modeled by EPPA depends on the exogenous time trend on land productivity in combination with parameters that govern substitution between land and other inputs as their prices change.

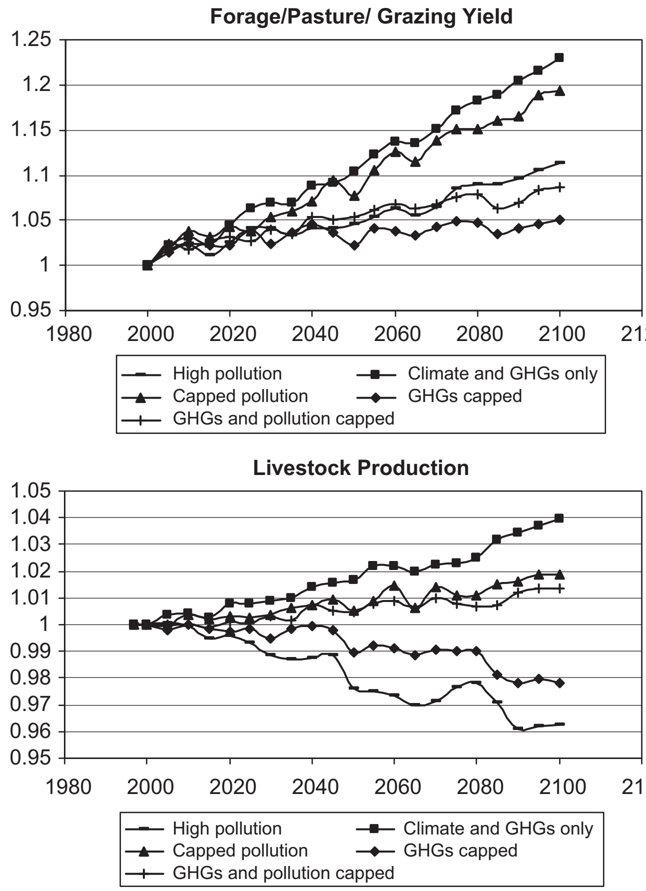

Fig. 6. Index for pasture yield and livestock production.

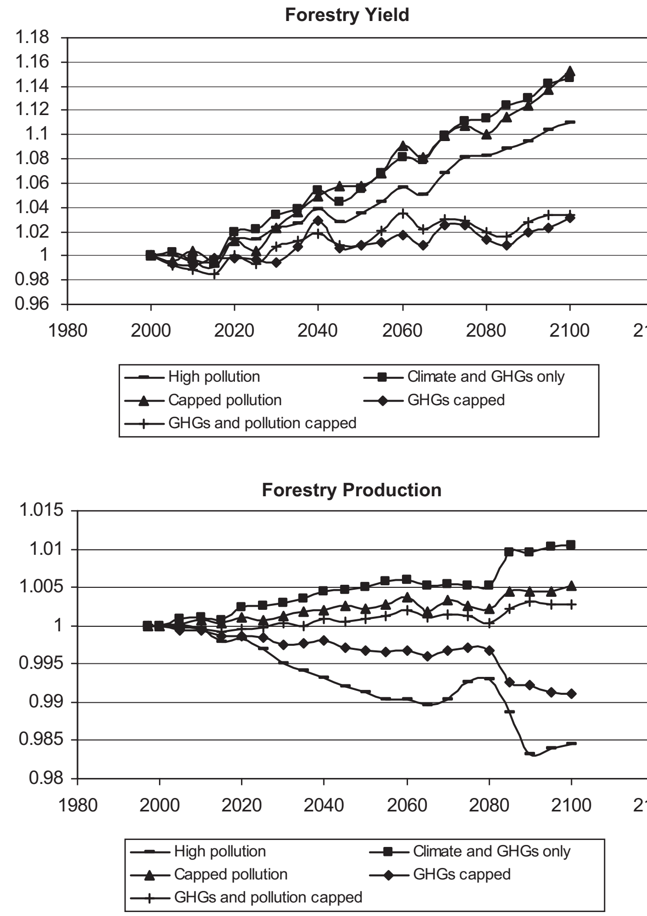

Fig. 7. Index for forestry yield and production.

are no larger than ± 8 percent. This reflects the relative inelastic demand for crops because of a relatively inelastic demand for food, the ability to substitute other inputs for land (adapt), and the ability to shift land into or out of crops.

Fig. 6 reports the results for livestock. Here the livestock production results bear little relationship to the yield effects for pasture. The pasture results are all positive, whereas several of the scenarios show reductions in livestock production. In fact, the scenarios mirror closely the production effects on crops. This reflects the fact that feedgrains and other crops are important inputs into livestock production, relatively more important than pasture. A reduction (increase) in crop production is reflected in higher (lower) prices for feedgrains and other crops used in livestock, and this tends to lead to reduced (increased) production of livestock. Again, the percentage differences in livestock production are relatively small compared with the crop production changes, even in cases where production increases are driven both by an increase in crop production and by an increase in pasture productivity.

Fig. 7 reports results for forestry. The general result is that the production effects are very small—less than 1 percent compared with yield effects of 3–15 percent. Notably, however, despite small positive yield effects for forestry in all cases, the production effects are slightly negative in the ***High pollution*** and ***GHGs capped*** cases. One result of the strong negative crop yield effect is to use more land for crop production at the expense of forestry and pasture, and thus the negative forestry production effect is driven by reduction in land used for forestry. The livestock production effect is also partly driven by a reduction in pasture/grazing land, but in that case the more important effect is the increase in feedgrain prices.

An important result of the general equilibrium modeling of these impacts is that effects can be felt beyond the agricultural sector. We can investigate the general equilibrium effects stemming from agricultural impacts because we are simulating only the climate/CO_2/ozone effects on agriculture (including crops, pasture, and forestry) and include no other impact shocks in other sectors. Thus, any economic effects occurring elsewhere in the economy are due to the initial agricultural shock. We show this in Fig. 8, where we have plotted macroeconomic consumption change and the change in food consumption, both as a percent of food consumption, in a reference case where there is no environmental feedback on the economy. To illustrate this effect, we present the results for two scenarios—***High pollution*** and ***Climate and GHGs only***—because those are the ones that show the biggest change.

This shows that, in general, the aggregate consumption effect is bigger in absolute terms than the agricultural production effect. Thus, adaptation in the agricultural sector, which was seen most clearly in the crop sector results, but with the general result that the production effects were much smaller than the yield effects, is partly the result of shifting of resources into or out of these sectors, thereby affecting the rest of the economy. Thus, we see in our results the frequently expressed view that the adaptation potential of the agricultural sector is considerable—most yield effects are offset, leaving very little change in food consumption. But, we also see that this comes about through resource reallocation from or to the rest of the economy, and focusing only on the changes in the agricultural sector/food consumption underestimates the damages (or benefits) of the environmental change. Thus, while yield change alone overestimates the economic effect, focusing on agricultural production or food consumption underestimates the full economic effect. Fully measuring the economic effect requires a general equilibrium approach that evaluates the impact on resource reallocation beyond the agricultural sector.

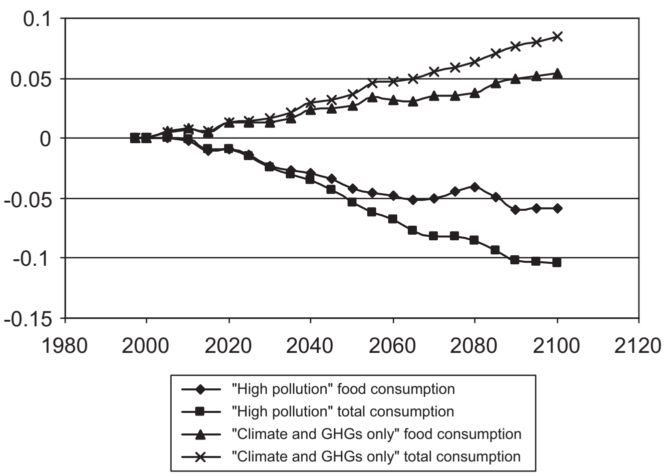

Fig. 8. Change in global food consumption and total global macroeconomic consumption as a share of agriculture production.

Finally, we focus on the regional economic effects for the ***High pollution*** and ***Climate and GHGs only*** scenarios for selected countries in Fig. 9. These illustrate several important results. First, the impact as a percentage of the economy differs because of the different importance of these sectors in the economy. Food consumption is generally income inelastic, a feature we have approximated in EPPA, and this means agriculture is generally falling as a share of all economies over time. However, for developing country regions, agriculture is currently a relatively large share of the economy, as much as 20%, compared with as little as 1 or 2 percent in developed countries. Second, trade effects can be important. In the ***High pollution*** case,

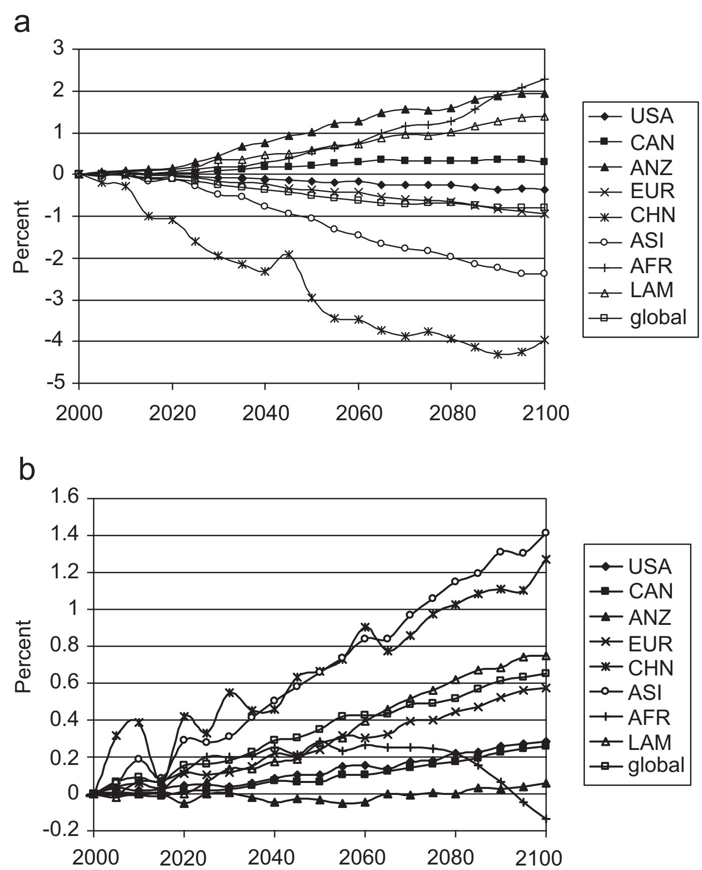

Fig. 9. Percent change in macroeconomic consumption, selected regions. (a) ***High pollution*** scenario. (b) ***Climate and GHGs only*** scenario.

tropical, Southern Hemisphere, and far northern regions (AFR, LAM, ANZ, CAN) benefit economically even though they suffer crop yield losses (or no change in the case of LAM). Economic gains result because they export agricultural products to other regions where crop yields are severely reduced due to ozone. The trade effects in the ***Climate and GHGs only*** scenario are less obvious from the total economic impact, but ANZ, a major agricultural exporter, suffers economic loss from lower export prices even though crop yields are estimated to rise by over 80 percent. Thus, the net economic effect due to changes in agriculture, pasture, and forestry productivity are a complex combination of a changing pattern of trade among regions and resource reallocation between the agriculture sectors and other sectors of the economy.

6. Caveats and comparison with previous work

There have been no similar studies of the combined effects of climate, CO_2, and ozone on global crops, pasture, and forestry. There has been considerable work on climate/ CO_2 effects on crops. Our estimates (***Climate and GHGs only*** scenario) are relatively positive compared with previous work. The broad conclusion of past studies is that mid- and high-latitude areas could see substantial yield gains from climate or climate and CO_2 effects, but that yield losses are likely in tropical regions (Gitay et al., 2001; Reilly and Schimmelpfennig, 1999). In contrast, in this study, we see less yield gains in all regions when only climate and CO_2 changes are considered, albeit the yield gains are smaller in the tropics than in temperate or boreal regions. Several factors likely contribute to this more positive result:

- TEM grows the "generic" crop as soon as the weather is suitable and automatically grows additional crops if the season is lengthened, or, in subtropical regions, may find that winter cropping improves even if summer cropping fails. This full adaptation to changes in seasons has generally not been considered in previous studies.
- The "generic" TEM crop is a C3 crop that responds relatively strongly to CO_2 fertilization.[4] In reality, agriculture includes C4 crops which are less responsive to CO_2, and so the average response including C4 crops is likely to be lower than we estimate.
- The TEM estimates assume an optimum N fertilization of crops, so that CO_2 fertilization is not N-limited as it would be for natural vegetation (Kicklighter et al., 1999) or under conditions with where fertilizer application is not optimal. Thus, neither spatial nor temporal variations in the amount, timing, and the effectiveness of fertilizer applications have been considered, which may also contribute to the positive effect. On the other hand, the TEM simulations also do not consider the influence of irrigation so that crop productivity may be underestimated in arid regions.
- The CO_2 response modeled in TEM is similar to that used to parameterize crop models and so does not explain a major difference with studies that have included a CO_2 fertilization effect. Some comparisons of free air carbon exchange (FACE) results have suggested much lower CO_2 response than conventionally assumed (Long, et al., 2006); however, further evaluation shows the response of mainstream crop models to be generally consistent with the FACE results (Tubiello et al., 2006). Nevertheless, inclusion of the CO_2 fertilization effect contributes a strong positive effect on yield.
- The climate scenarios are for a relatively mild increase in global temperature (2.7 °C by 2100 from the present, less when GHGs are controlled), reflecting work that has tried to estimate climate sensitivity and other climate model parameters (Forest et al., 2002; Webster et al., 2003). More negative results in some studies have resulted from climate scenarios with a mean surface temperature increase of 4–5 °C. There is considerable uncertainty in future temperature projections and so an increase of 4–5 °C cannot be ruled out if GHGs are uncontrolled (Webster et al., 2003). An update of the Forest et al. (2002) analysis (Forest et al., 2006) likely implies considerably higher temperatures by 2100 because they find it likely that less heat is being taken up by the oceans and so higher temperatures will be realized sooner.
- Apart from the global mean temperature change, the 2-D climate scenarios used to force the TEM model may tend to produce milder climate changes. While the IGSM is a land–ocean resolving model, it cannot project phenomena such as mid-continental drying, a result often shown in 3-D models. The zonal climate changes may thus under-represent local extremes that are possible, particularly in precipitation. Precipitation changes remain uncertain in even highly resolved GCMs and the 3-D pattern need not create more negative crop effects, but it seems likely that it could.
- TEM models vegetation on a monthly basis for a generic crop. Crop yield for specific crops can be severely affected by short periods of heat or drought during key developmental phases. TEM results can be seen as a case where crop breeders/changes in crop type are able to overcome these limitations as climate changes.

7. Conclusions

Multiple environmental changes will have consequences for global vegetation. To the extent that crop yields and pasture and forest productivity are affected, there can be important economic consequences. We examine the combined effects of changes in climate, increases in CO_2, and

[4]C3 and C4 crops refer to the photosynthetic carbon pathway of the crop. The main C4 crops are maize and sorghum. Most grains, legumes, and vegetables are C3 crops.

changes in tropospheric ozone on crop, pasture, and forests, and the consequences for the global and regional economies. We find that climate and CO_2 effects are generally positive for crop, livestock, and forestry yields over most of the world. However, we find potentially highly detrimental effects of ozone damage unless ozone precursors are strongly controlled. Because climate and CO_2 effects are generally beneficial, controlling GHG emissions tends to reduce these beneficial effects. However, controlling GHGs also limits emissions of ozone precursors because CH_4 is an ozone precursor and control of CO_2 implies less combustion of fossil fuels and lower emissions of NO_x, VOCs, and other ozone precursors that are also generated during combustion.

Simulating the effects on vegetation demonstrated some important economic results. (1) Agriculture can successfully adapt to yield changes if adaptation is measured as change in production relative to change in the initial yield effect of environmental change. The production effect after adaptation is 1/5–1/6 of the initial yield effect. (2) However, evaluating the impact terms of agricultural consumption/production underestimates the economic effects because adaptation involves shifting resources into or out of the agricultural sector. The full effect of these changes can only be observed in looking at the overall measures of economic well-being, such as macroeconomic consumption change. (3) National and regional economic effects are strongly influenced by trade effects such that yield effects that are positive for a region, may lead to negative economic effects if the other countries gain more. Or, countries can gain through trade even if yield effects are negative if other regions are more severely affected, as we find for the case with high ozone levels. Thus, analysis that purports to estimate economic effects for a nation or region, where a consideration of the effects on global markets or interaction with the rest of the economy is absent, may be in error not only in the magnitude of the effect but also in its direction.

Acknowledgements

This research was supported by the US Department of Energy, US Environmental Protection Agency, US National Science Foundation, US National Aeronautics and Space Administration, US National Oceanographic and Atmospheric Administration; and the Industry and Foundation Sponsors of the MIT Joint Program on the Science and Policy of Global Change.

References

Adams, R.M., Hamilton, S.A., McCarl, B.A., 1986. The benefits of pollution control: the case of ozone and US agriculture. American Journal of Agricultural Economics 68, 886–893.

Adams, R.M., Rosenzweig, C., Peart, R.M., Richie, J.T., McCarl, B.A., Glyer, J.D., Curry, R.B., Jones, J.W., Boote, K.J., Allen, L.H., 1990. Global climate change and US agriculture. Nature 345, 219–224.

Alig, R.J., Adams, D.M., McCarl, B.A., 2003. Projecting impacts of global climate change on the US forest and agriculture sectors and carbon budgets. Forest Ecology and Management 169, 3–14.

Babiker, M., Reilly, J., Mayer, M., Eckaus, R., Sue Wing, I., Hyman, R., 2001. The MIT Emissions Prediction and Policy Analysis Model: Revisions, Sensitivities, and Comparisons of Results. MIT Joint Program on the Science and Policy of Global Change, Report 71, Cambridge, MA.

Babiker, M., Jacoby, H., Reilly, J., Reiner, D., 2002. The evolution of a climate regime: Kyoto to Marrakech. Environmental Science and Policy 5 (3), 195–206.

Babiker, M., Reilly, J., Viguier, L., 2004. Is emissions trading always beneficial? Energy Journal 25 (2), 33–56.

Darwin, R., Tsigas, M., Lewandrowski, J., Raneses, A., 1996. Land use and cover in ecological economics. Ecological Economics 17, 157–181.

Dimaranan, B., McDougall, R., 2002. Global Trade, Assistance, and Production: The GTAP 5 Data Base. Center for Global Trade Analysis, Purdue University, West Lafayette, IN.

Felzer, B.S.F., Kicklighter, D.W., Melillo, J.M., Wang, C., Zhuang, Q., Prinn, R.G., 2004. Ozone effects on net primary production and carbon sequestration in the conterminous United States using a biogeochemistry model. Tellus 56B, 230–248.

Felzer, B., Reilly, J., Melillo, J., Kicklighter, D., Sarofim, M., Wang, C., Prinn, R., Zhuang, Q., 2005. Future effects of ozone on carbon sequestration and climate change policy using a global biogeochemical model. Climatic Change 73, 345–373.

Forest, C.E., Stone, P.H., Sokolov, A.P., Allen, M.R., Webster, M., 2002. Quantifying uncertainties in climate system properties with the use of recent climate observations. Science 295, 113–117.

Forest, C.E., Stone, P.H., Sokolov, A.P., 2006. Estimated PDFs of climate system properties including natural and anthropogenic forcings. Geophysical Research Letters 33, L01705.

Gitay, H., Brown, S., Easterling, W., Jallow, B., 2001. Ecosystems and their goods and services. In: McCarthy, J., Canziani, O., Leary, N., Dokken, D., White, K. (Eds.), Climate Change 2001: Impacts, Adaptation, and Vulnerability. Cambridge University Press, Cambridge, UK (Chapter 5).

Izauralde, C., Rosenberg, N.J., Brown, R.A., Thomson, A.M., 2003. Integrated assessment of Hadley Center (HadCM2) climate-change impacts on agricultural productivity and irrigation water supply in the conterminous United States. Part II. Regional agriculture production in 2030 and 2095. Agricultural and Forest Meteorology 117, 97–122.

Jacoby, H., Eckaus, R., Ellermann, A.D., Prinn, R., Reiner, D., Yang, Z., 1997. CO_2 emissions limits: economic adjustments and the distribution of burdens. Energy Journal 18, 31–58.

Kicklighter, D.W., Bruno, M., Dönges, S., Esser, G., Heimann, M., Helfrich, J., Ift, F., Joos, F., Kaduk, J., Kohlmaier, G.H., McGuire, A.D., Melillo, J.M., Meyer, R., Moore III, B., Nadler, A., Prentice, I.C., Sauf, W., Schloss, A.L., Sitch, S., Wittenberg, U., Würth, G., 1999. A first-order analysis of the potential role of CO_2 fertilization to affect the global carbon budget: a comparison study of four terrestrial biosphere models. Tellus 51B, 343–366.

Lawrence, M.G., Crutzen, P.J., Rasch, P.J., Eaton, B.E., Mahowald, N.M., 1999. A model for studies of tropospheric photochemistry: description, global distributions, and evaluation. Journal of Geophysical Research 104, 26245–26277.

Long, S.P., Ainsworth, E.A., Leakey, A.D.B., Nösefberger, J., Ort, D.R., 2006. Food for thought: lower-than-expected crop yield stimulation with rising CO_2 concentration. Science 312, 1918–1921.

Mahowald, N.M., Rasch, P.J., Eaton, B.E., Whittlestone, S., Prinn, R.G., 1997. Transport of 222 radon to the remote troposphere using the model of atmospheric transport and chemistry and assimilated winds from ECMWF and the National Center for Environmental Prediction/NCAR. Journal of Geophysical Research 102, 28139–28152.

Mayer, M., Hyman, R., Harnisch, J., Reilly, J., 2000. Emissions inventories and time trends for greenhouse gases and other pollutants, MIT Joint Program on the Science and Policy of Global Change, Technical Note 1, Cambridge, MA.

McFarland, J.R., Reilly, J.M., Herzog, H.J., 2004. Representing energy technologies in top-down economic models using bottom-up information. Energy Economics 26 (4), 685–707.

McGuire, A.D., Sitch, S., Clein, J.S., Dargaville, R., Esser, G., Foley, J., Heimann, M., Joos, F., Kaplan, J., Kicklighter, D.W., Meier, R.A., Melillo, J.M., Moore III, B., Prentice, I.C., Ramankutty, N., Reichenau, T., Schloss, A., Tian, H., Williams, L.J., Wittenberg, U., 2001. Carbon balance of the terrestrial biosphere in the twentieth century: analyses of CO_2, climate and land-use effects with four process-based ecosystem models. Global Biogeochemical Cycles 15 (1), 183–206.

Melillo, J.M., McGuire, A.D., Kicklighter, D.W., Moore III, B., Vorosmarty, C.J., Schloss, A.L., 1993. Global climate change and terrestrial net primary production. Nature 363, 234–240.

Mendelsohn, R., Nordhaus, W.D., Shaw, D., 1994. The impact of global warming on agriculture: a Ricardian analysis. American Economic Review 84 (4), 753–771.

Ollinger, S.V., Aber, J., Reich, P., 1997. Simulating ozone effects on forest productivity: interactions among leaf-, canopy-, and stand-level processes. Ecological Applications 7 (4), 1237–1251.

Paltsev, S., Reilly, J.M., Jacoby, H.D., Ellerman, A.D., Tay, K.H., 2003. Emissions Trading to Reduce Greenhouse Gas Emissions in the United States: The McCain-Lieberman Proposal. MIT Joint Program on the Science and Policy of Global Change. Report 97, Cambridge, MA.

Paltsev, S., Reilly, J.M., Jacoby, H.D., Eckaus, R.S., McFarland, J., Sarofim, M., Asadoorian, M., Babiker, M., 2005. The MIT Emissions Prediction and Policy Analysis (EPPA) Model: Version 4, MIT Joint Program on the Science and Policy of Global Change. Report 125, Cambridge, MA.

Parry, M.L., Carter, T.R., Konijn, N.T. (Eds.), 1988a. The Impact of Climate Variations on Agriculture: Volume 1: Assessments in Cool Temperate and Cold Regions. Kluwer Academic Press, Dordrecht, The Netherlands.

Parry, M.L., Carter, T.R., Konijn, N.T. (Eds.), 1988b. The Impact of Climatic Variations on Agriculture: Volume 2 Assessment in Semi-arid Regions. Kluwer Academic Press, Dordrecht, The Netherlands.

Parry, M., Rosenzweig, C., Iglesis, A., Fischer, G., Livermore, M., 1999. Climate change and world food security: a new assessment. Global Environmental Change 9, S51–S67.

Parry, M.L., Rosenzweig, C., Iglesias, A., Livermore, M., Fischer, G., 2004. Effects of climate change on global food production under SRES emissions and socio-economic scenarios. Global Environmental Change 14, 53–67.

Prinn, R., Jacoby, H., Sokolov, A., Wang, C., Xiao, X., Yang, Z., Eckaus, R., Stone, P., Ellerman, D., Melillo, J., Fitzmaurice, J., Kicklighter, D., Holian, G., Liu, Y., 1999. Integrated global system model for climate policy assessment: feedbacks and sensitivity studies. Climatic Change 41, 469–546.

Prinn, R., Reilly, J., Sarofim, M., Wang, C., Felzer, B., 2007. Effects of air pollution control on climate. In: Schlesinger, M. (Ed.), Integrated Assessment of Human-induced Climate Change. Cambridge University Press, Cambridge, UK (in press), and MIT Joint Program for the Science and Policy of Global Change. Report No. 118, January 2005, Cambridge, MA.

Ramankutty, N., Foley, J.A., 1998. Characterizing patterns of global land use: an analysis of global croplands data. Global Biogeochemical Cycles 12, 667–685.

Ramankutty, N., Foley, J.A., 1999. Estimating historical changes in global land cover: croplands from 1700 to 1992. Global Biogeochemical Cycles 13, 997–1027.

Rasch, P.J., Mahowald, N.M., Eaton, B.E., 1997. Representations of transport, convection, and the hydrologic cycle in chemical transport models: implications for the modeling of shortlived and soluble species. Journal of Geophysical Research 102, 28127–28138.

Reich, P.B., 1987. Quantifying plant response to ozone: a unifying theory. Tree Physiology 3, 63–91.

Reilly (Ed.), 2002. Agriculture: The Potential Consequences of Climate Variability and Change. Cambridge University Press, Cambridge, UK.

Reilly, J., Hohmann, N., 1993. Climate change and agriculture: the role of international trade. American Economic Review: Papers and Proceedings 83, 306–312.

Reilly, J., Schimmelpfennig, D., 1999. Agricultural impact assessment, vulnerability, and the scope for adaptation. Climatic Change 43 (4), 745–788.

Reilly, J., Prinn, R., Harnisch, J., Fitzmaurice, J., Jacoby, H.D., Kicklighter, D., Melillo, J., Stone, P., Sokolov, A., Wang, C., 1999. Multi-gas assessment of the Kyoto Protocol. Nature 401, 549–555.

Reilly, J., Mayer, M., Harnisch, J., 2002. The Kyoto protocol and non-CO_2 greenhouse gases and carbon sinks. Environmental Modeling and Assessment 7 (4), 217–229.

Reilly, J., Tubiello, F., McCarl, B., Abler, D., Darwin, R., Fuglie, K., Hollinger, S., Izaurralde, C., Jagtap, S., Jones, J., Mearns, L., Ojima, D., Paul, E., Paustian, K., Riha, S., Rosenberg, N., Rosenzweig, C., 2003. US agriculture and climate change: new results. Climatic Change 57, 43–69.

Rosenberg, N.J., 1993. Towards An Integrated Assessment of Climate Change: The MINK Study. Kluwer Academic Publishers, Boston, 173pp.

Rosenzweig, C., Parry, M.L., 1994. Potential impact of climate change on world food supply. Nature 367, 133–138.

Sokolov, A.P., Schlosser, C.A., Dutkiewicz, S., Paltsev, S., Kicklighter, D.W., Jacoby, H.D., Prinn, R.G., Forest, C.E., Reilly, J., Wang, C., Felzer, B., Sarofim, M.C., Scott, J., Stone, P.H., Melillo, J.M., Cohen, J., 2005. The MIT Integrated Global System Model (IGSM) Version 2: Model Description and Baseline Evaluation. MIT Joint Program for the Science and Policy of Global Change. Report 124, Cambridge, MA.

Tian, H., Melillo, J.M., Kicklighter, D.W., McGuire, A.D., Helfrich, J.V.K., 1999. The sensitivity of terrestrial carbon storage to historical climate variability and atmospheric CO_2 in the United States. Tellus 51B, 414–452.

Tian, H., Melillo, J.M., Kicklighter, D.W., Pan, S., Liu, J., McGuire, A.D., Moore, B., 2003. Regional carbon dynamics in monsoon Asia and its implications for the global carbon cycle. Global and Planetary Change 37, 201–217.

Tobey, J., Reilly, J., Kane, S., 1992. Economic implications of global climate change for world agriculture. Journal of Agricultural and Resource Economics 17, 195–204.

Tubiello, F.N., Amthor, J.S., Boote, K., Donatelli, M., Easterling, W., Gifford, R., Howden, M., Fischer, G., Reilly, J., Rosenzweig, C., 2006. Crop response to elevated CO_2 and world food supply: a comment on "Food for Thought…" by Long et al. Science 312, 1918–1921 European Journal of Agronomy, online version, 〈www.sciencedirect.com〉.

Von Kuhlmann, R., Lawrence, M., Crutzen, P., Rasch, P., 2003. A model for studies of tropospheric ozone and nonmethane hydrocarbons: model description and ozone results. Journal of Geophysical Reseach 108.

Wang, X., 2005. The economic impact of global climate and tropospheric ozone on world agricultural production. Master of Science Thesis, Engineering Systems Division, Massachusetts Institute of Technology, Cambridge, MA (May).

Wang, X., Mauzerall, D.L., 2004. Characterizing distributions of surface ozone and its impact on grain production in China, Japan and South Korea: 1990 and 2020. Atmospheric Environment 38, 4383–4402.

Webster, M.D., Babiker, M., Mayer, M., Reilly, J.M., Harnisch, J., Sarofim, M.C., Wang, C., 2002. Uncertainty in emissions projections for climate models. Atmospheric Environment 36 (22), 3659–3670.

Webster, M., Forest, C., Reilly, J., Babiker, M., Kicklighter, D., Mayer, M., Prinn, R., Sarofim, M., Sokolov, A., Stone, P., Wang, C., 2003. Uncertainty analysis of climate change and policy response. Climatic Change 62, 295–320.

Westenbarger, D., Frisvold, G., 1994. Agricultural exposure to ozone and acid precipitation. Atmospheric Environment 28, 2895–2907.

Westenbarger, D.V., Frisvold, G.B., 1995. Air pollution and farm-level crop yields: an empirical analysis of corn and soybeans. Agricultural and Resource Economics Review 24 (2), 156–165.

Xiao, X., Kicklighter, D.W., Melillo, J.M., McGuire, A.D., Stone, P.H., Sokolov, A.P., 1997. Linking a global terrestrial biogeochemical model and a 2-dimensional climate model: implications for the carbon budget. Tellus 49B, 18–37.