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Global crop yield reductions due to surface ozone exposure: 1. Year 2000 crop production losses and economic damage

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ABSTRACT

Exposure to elevated concentrations of surface ozone (O_3) causes substantial reductions in the agricultural yields of many crops. As emissions of O_3 precursors rise in many parts of the world over the next few decades, yield reductions from O_3 exposure appear likely to increase the challenges of feeding a global population projected to grow from 6 to 9 billion between 2000 and 2050. This study estimates year 2000 global yield reductions of three key staple crops (soybean, maize, and wheat) due to surface ozone exposure using hourly O_3 concentrations simulated by the Model for Ozone and Related Chemical Tracers version 2.4 (MOZART-2). We calculate crop losses according to two metrics of ozone exposure – seasonal daytime (08:00–19:59) mean O_3 (M12) and accumulated O_3 above a threshold of 40 ppbv (AOT40) – and predict crop yield losses using crop-specific O_3 concentration:response functions established by field studies. Our results indicate that year 2000 O_3-induced global yield reductions ranged, depending on the metric used, from 8.5–14% for soybean, 3.9–15% for wheat, and 2.2–5.5% for maize. Global crop production losses totaled 79–121 million metric tons, worth $11–18 billion annually ($USD_{2000}$). Our calculated yield reductions agree well with previous estimates, providing further evidence that yields of major crops across the globe are already being substantially reduced by exposure to surface ozone – a risk that will grow unless O_3-precursor emissions are curbed in the future or crop cultivars are developed and utilized that are resistant to O_3.

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1. Introduction

Surface ozone (O_3) is a major component of smog, produced in the troposphere by the catalytic reactions of nitrogen oxides ($NO_x = NO + NO_2$) with carbon monoxide (CO), methane (CH_4), and non-methane volatile organic compounds (NMVOCs) in the presence of sunlight. In addition to having a detrimental effect on human health, field experiments in the United States, Europe, and Asia demonstrate that surface ozone causes substantial damage to many plants and agricultural crops, including increased susceptibility to disease, reduced growth and reproductive capacity, increased senescence, and reductions in crop yields (Mauzerall & Wang, 2001). O_3 penetrates leaves through the stomata, where it reacts with various compounds to yield reactive odd-oxygen species that oxidize plant tissue and result in altered gene expression, impaired photosynthesis, protein and chlorophyll degradation, and changes in metabolic activity (Booker et al., 2009; Fuhrer, 2009). Based on the large-scale experimental studies of the National Crop Loss Assessment Network (NCLAN) conducted in the United States in the 1980s (Heagle, 1989; Heck, 1989), the U.S. Environmental Protection Agency (EPA) estimated that the yields of about one third of U.S. crops were reduced by 10% due to ambient O_3 concentrations during this time (EPA, 1996). Results from the European Open-Top Chamber Programme (EOTC) in the 1990s (Krupa et al., 1998) similarly suggest that the European Union (EU) may be losing more than 5% of their wheat yield due to O_3 exposure (Mauzerall & Wang, 2001). Although comparable large-scale studies have not been conducted in developing countries, the potential risk of ambient O_3 exposure to agricultural production has been documented through both small-scale field studies and modeling efforts in East Asia (Chameides et al., 1999; Aunan et al., 2000; Wang & Mauzerall, 2004; Huixiang et al., 2005), the Indian subcontinent (Agrawal, 2003; Wahid, 2003;

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Emberson et al., 2009; Debaje et al., 2010), Egypt (Abdel-Latif, 2003), and South Africa (Van Tienhoven & Scholes, 2003).

With over one billion people in the world currently estimated to be undernourished (FAO, 2009), the impact of O_3 pollution on present-day and future global food production deserves attention. This is especially true as both population and O_3-precursor emissions are projected to increase in most developing nations over the next few decades (Nakićenović et al., 2000; Dentener et al., 2005; Riahi et al., 2007). Rising emissions of O_3-precursors in these countries pose a risk to not only their national and regional food security but also to global food production as O_3 and some of its precursors are sufficiently long-lived to be transported between continents (Fiore et al., 2009).

To our knowledge, only one study has calculated O_3-induced crop yield reductions in the present and the near future on a global scale. Van Dingenen et al. (2009) (hereafter VD2009) use concentration:response (CR) functions derived from field studies, simulated datasets of global crop distributions, O_3 precursor emissions for the year 2000 and 2030 as projected under the optimistic "current legislation (CLE) scenario" (which assumes that presently approved air quality legislation will be fully implemented by 2030), and simulated global hourly ozone concentrations by the TM5 atmospheric chemical transport model (CTM). VD2009 calculate that present-day global crop yield losses are significant for wheat and soybean (up to 12 and 16%, respectively) but smaller for the more O_3-tolerant rice and maize crops (between 3% and 5%), with total production losses worth \$14–26 billion (USD_{2000}) annually. VD2009 additionally find that global crop yield reductions increase only marginally under the 2030 CLE scenario, with the most significant additional losses primarily occurring in developing nations where emission regulations do not exist or are particularly lenient and/or unenforced.

The VD2009 study is an important step towards assessing O_3 risk to agricultural production globally, but further work is necessary to reduce uncertainties and to verify crop yield loss estimates under both current day and potential future levels of O_3. In this first part of our two-paper series, we provide an estimate of global crop yield reductions and economic losses due to ozone exposure in the year 2000 using simulated O_3 concentrations, field-based CR relationships, and crop distributions of three key staple crops: soybean, maize, and wheat. In part two of the series (Avnery et al., 2011), we compare these present-day crop yield reductions and their associated costs with future estimates of O_3-induced crop losses in 2030 calculated with simulated O_3 distributions according to two different emission scenarios: the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES) B1 and A2 storylines (Nakićenović et al., 2000). These scenarios represent optimistic and pessimistic trajectories of ozone precursor emissions in order to illustrate a range of possible future crop losses and the importance of O_3 mitigation.

We use a similar methodology to VD2009, which is modeled on the analyses of Aunan et al. (2000) and Wang and Mauzerall (2004) (hereafter WM2004). However, our study differs from and compliments VD2009 in a number of important ways. Most significantly, we use the global chemical transport Model for Ozone and Related Chemical Tracers version 2.4 (MOZART-2) to simulate hourly O_3 concentrations at a $2.8^\circ \times 2.8^\circ$ horizontal resolution. This resolution is higher than the $6^\circ \times 4^\circ$ resolution used by VD2009 over South America, Africa, and other parts of the Southern Hemisphere. We also perform a detailed spatial evaluation of simulated surface O_3 concentrations over the U.S. and Europe, as well as at surface observation sites in Asia, Africa, South America, and the Pacific where data are available. Additionally, the crop distribution maps used in this study to calculate production losses are globally-gridded, satellite datasets merged with national yield statistics (Monfreda et al., 2008; Ramankutty et al., 2008), thereby removing some of the uncertainty associated with modeling crop distributions based on suitability indices (as used by VD2009).

2. Methodology

To estimate global crop yield losses due to O_3 exposure we use: (1) observation-based global crop production maps; (2) simulated surface ozone concentrations from which we calculate O_3 exposure over crop growing seasons; and (3) CR functions that relate a given level of ozone exposure to a predicted yield reduction. Here we discuss the sources of each of these datasets and the methodologies used to evaluate resulting global crop yield reductions due to O_3 exposure and their associated costs.

2.1. Distribution of selected grain crops

The global crop distribution datasets, including both crop areas and yields, were compiled by Monfreda et al. (2008) and Ramankutty et al. (2008) using a data fusion technique in which two different satellite-derived products (Boston University's MODIS-based land cover product and the GLC2000 data set obtained from the VEGETATION sensor aboard SPOT4) were merged with national-, state-, and county-level census yield statistics. Area harvested and yields of 175 distinct crops were compiled at 5 min $\times$ 5 min latitude–longitude resolution for the years 1997–2003 and subsequently averaged to produce a single representative value for each country circa year 2000 (see Monfreda et al. (2008) for further details). These crop distribution maps for soybean, maize, and wheat have been regridded to match the $2.8^\circ \times 2.8^\circ$ resolution of MOZART-2 (Fig. 1) for our calculations of O_3-induced yield reductions.

2.2. Plant exposure to O_3

2.2.1. MOZART-2 model simulation

MOZART-2 (Horowitz et al., 2003) is a global chemical transport model (CTM) that contains a detailed representation of tropospheric ozone–nitrogen oxide–hydrocarbon chemistry, accounting for surface emissions, emissions from lightning and aircraft, advective and convective transport, boundary layer exchange, and wet and dry deposition. Surface emission sources include fossil fuel combustion, biomass burning, vegetation, soils, and oceans. MOZART-2 simulates the concentrations and distributions of 63 gas-phase species and 11 aerosol and aerosol precursor species (including sulfate, nitrate, ammonium, black carbon, organic carbon, and mineral dust of 5 size bins with diameters ranging from 0.2 to 20.0 μm). The model, driven here by the National Center for Atmospheric Research (NCAR) Community Climate Model (MACCM3) (Kiehl et al., 1998), has a $2.8^\circ \times 2.8^\circ$ horizontal resolution with 34 hybrid sigma-pressure levels up to 4 hPa, and a 20-min time step for chemistry and transport.

The year 2000 model simulation used in this study (Horowitz, 2006) is based on the 1990 simulation from Horowitz et al. (2003) with year 1990 anthropogenic emissions scaled by the ratio of 2000:1990 emissions in four geopolitical regions as specified by the IPCC SRES (Nakićenović et al., 2000). As emission changes from 1990 to 2000 are the same in all scenarios, we used the same scaling factors to obtain year 2000 B1 and A2 emissions (Table 1). The 1990 anthropogenic emissions are based on the Emission Database for Global Atmospheric Research (EDGAR) version 2.0 (Olivier et al., 1996) with some modifications (Horowitz et al., 2003). Biomass burning and biogenic emission inventories for the 1990 simulation are also included, described in detail in Horowitz et al. (2003) and Horowitz (2006). The biomass burning

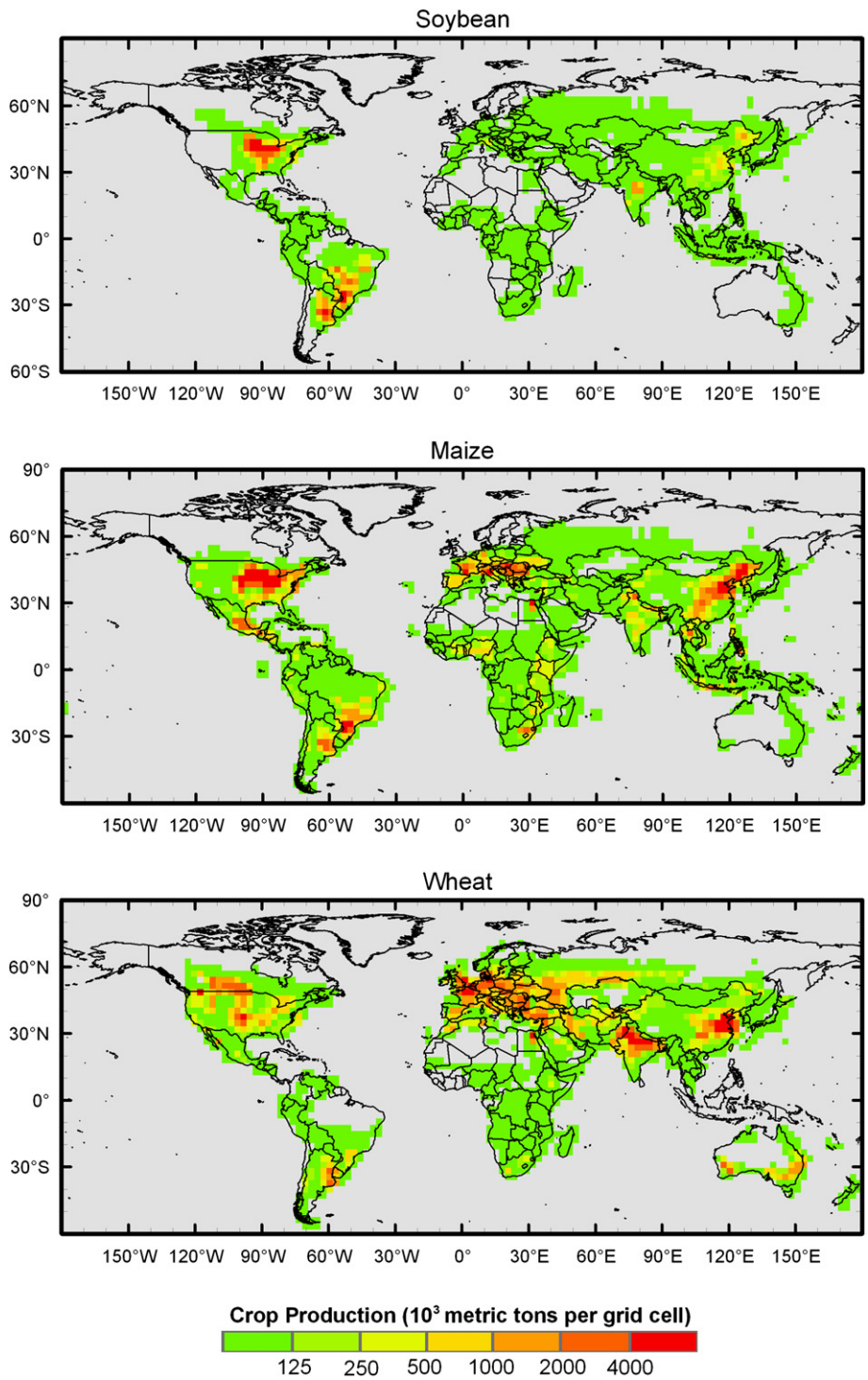

Fig. 1. Global distributions of soybean, maize, and wheat in the year 2000. Data are from Ramankutty et al. (2008) and Monfreda et al. (2008), regridded to MOZART-2 resolution (2.8° latitude × 2.8° longitude).

inventory is "climatological" and thus does not vary annually to reflect actual biomass burning episodes. Two-year simulations were performed, with the first year used as spin-up and results from the second year analyzed.

2.2.2. Metrics of O_3 exposure and CR relationships

In order to assess the present and potential future impacts of O_3 on agriculture, open-top chamber (OTC) field studies primarily in North America and Europe have established crop-specific CR functions that predict the yield response of a crop to a given level of ozone exposure (Heagle, 1989; Heck, 1989; Krupa et al., 1998). These CR functions require a statistical index to summarize the pattern of O_3 exposure during the crop growing season. We use two exposure-based metrics, M12 and AOT40, and their CR relationships to calculate crop yield losses globally:

Table 1
Scaling factors derived from the IPCC SRES scenarios used with the 1990 base emissions in MOZART-2 to obtain year 2000 anthropogenic emissions. The scaling factors to obtain 2000 from 1990 emissions are the same for all SRES scenarios.

	OECD[a]	REF[b]	Asia[c]	ALM[d]
CH_4	1.008	0.825	1.111	1.110
CO	0.900	0.599	1.149	1.022
NMVOC	0.850	0.823	1.139	1.143
NO_x	0.950	0.626	1.296	1.215
N_2O	0.998	0.934	1.118	1.099
SO_x	0.749	0.647	1.429	1.212

[a] 'OECD' refers to countries of the Organization for Economic Cooperation and Development as of 1990, including the US, Canada, western Europe, Japan and Australia.
[b] 'REF' represents countries undergoing economic reform, including countries of eastern European and the newly independent states of the former Soviet Union.
[c] 'Asia' refers to all developing countries in Asia, excluding the Middle East.
[d] 'ALM' represents all developing countries in Africa, Latin America and the Middle East.

$$\text{M12 (ppbv)} = \frac{1}{n}\sum_{i=1}^{n}[Co_3]_i$$

$$\text{AOT40 (ppmh)} = \sum_{i=1}^{n}\left([Co_3]_i - 0.04\right) \text{ for } Co_3 \geq 0.04 \text{ ppmv}$$

where: $[Co_3]_i$ is the hourly mean O_3 concentration during local daylight hours (8:00–19:59); and n is the number of hours in the 3-month growing season.

We define the "growing season" like VD2009 as the 3 months prior to the start of the harvest period according to crop calendar data from the United States Department of Agriculture (USDA) (USDA, 1994, 2008). While we could not obtain growing season data for every country, crop calendars for the top producing countries of each crop (representing greater than 95% of global production) were available and compiled. Global maps showing the start of the growing season (as defined here) for each crop are available in the Supplementary material.

Of the two types of exposure-based metrics used here (mean and cumulative), cumulative indices (e.g. AOT40) that ascribe greater weight to higher O_3 concentrations are believed to be more accurate predictors of crop yield losses than mean metrics (e.g. M12) (Lefohn & Runeckles, 1988). The AOT40 index is favored in Europe and is currently used to define air quality guidelines to protect vegetation (Fuhrer et al., 1997). We include the M12 metric (and substitute the highly correlated M7 metric when M12 parameter values have not been defined for certain crops) in order to facilitate intercomparisons among previous studies, and because this metric is the most robust in terms of replicating observed O_3 exposure values (see Section 3). The M7 metric is defined like M12 except using daylight hours from 9:00–15:59. Although stomatal flux metrics (which aim to quantify the effective flux of O_3 into plant stomata after accounting for temperature, water availability and plant defenses) have been shown to more accurately predict the yield response of some crops, flux-based indices are not yet suitable for large-scale impact analyses due to a lack of relevant data and the need to reduce remaining uncertainties (Musselman et al., 2006; Paoletti et al., 2008; Booker et al., 2009; Fuhrer, 2009). Furthermore, flux metric parameterizations are currently only available for wheat and potato.

For each metric, CR functions have been obtained by fitting linear, quadratic, or Weibull functions to the yield responses of crops at different levels of O_3 exposure. The CR relationships for the M7 and M12 metrics have a Weibull functional form while the AOT40 CR relationships are linear. We use median parameter values of pooled CR relationships from a variety of cultivars grown in the U.S. (Heagle, 1989; Heck, 1989) adapted from WM2004 for the M7/M12 metrics. For the AOT40 index, we use CR functions based on field studies in both the U.S. and Europe defined in Mills et al. (2007). Because robust CR data are lacking for Asia, Africa, and South America, we apply the U.S. and European CR functions globally. Table 2 lists the CR equations used to calculate the relative yields (RY) of soybean, maize, and wheat as a function of each metric.

2.3. Yield reductions and associated costs

2.3.1. Integrated assessment

We follow the integrated assessment approach outlined by WM2004 and VD2009 and combine crop distribution maps, O_3 exposure, and CR relationships to calculate relative yield lost (RYL) (i.e. yield lost compared to a theoretical yield without O_3 damage), crop production losses (CPL), and economic losses (EL). We first calculate O_3 exposure (according to M12 and AOT40) using simulated hourly O_3 concentrations over the appropriate growing season for soybean, maize, and wheat in each $2.8^\circ \times 2.8^\circ$ grid cell. We then calculate RYL_i (according to the CR functions defined in Table 2) for every grid cell and each crop. We next calculate CPL in each grid cell (CPL_i) from RYL_i and the actual crop production in the year 2000 (CP_i) (Monfreda et al., 2008; Ramankutty et al., 2008) according to:

$$CPL_i = \frac{RYL_i}{1 - RYL_i} \times CP_i \quad (1)$$

We sum the crop production loss in all grid cells within each country to obtain national CPL. Finally, we define national RYL as national CPL divided by the theoretical total crop production without O_3 injury (the sum of crop production loss and actual crop production in the year 2000).

Following the approach of WM2004 and VD2009, CPL is translated into economic loss by multiplying national CPL by producer prices for each crop in the year 2000 as given by the FAO Food Statistics Division (FAOSTAT, http://faostat.fao.org/), which are used

Table 2
Concentration:response equations used to calculate relative yield losses of soybean, maize, and wheat. RY = relative yield as compared to theoretical yield without O_3-induced losses. Relative yield loss (RYL) is calculated by subtracting the RY from unity, which represents the theoretical yield without O_3 damage (i.e. 100% yield). Adams et al. (1989) and Lesser et al. (1990) CR functions are based on the U.S. NCLAN studies, while the relationships from Mills et al. (2007) are derived from both U.S. NCLAN data and the EOTC field experiments. See Section 2.2.2 for definitions of M7, M12 and AOT40. We calculate yield reductions for winter and spring wheat varieties separately and sum them together for our estimates of total O_3-induced wheat yield and crop production losses.

Crop	Exposure – Relative Yield Relationship	Reference
Soybean	$RY = \exp[-(M12/107)^{1.58}]/\exp[-(20/107)^{1.58}]$	Adams et al. (1989)
	$RY = -0.0116 \times AOT40 + 1.02$	Mills et al. (2007)
Maize	$RY = \exp[-(M12/124)^{2.83}]/\exp[-(20/124)^{2.83}]$	Lesser et al. (1990)
	$RY = -0.0036 \times AOT40 + 1.02$	Mills et al. (2007)
Wheat	$RY = \exp[-(M7/137)^{2.34}]/\exp[-(25/137)^{2.34}]$ (Winter)	Lesser et al. (1990)
	$RY = \exp[-(M7/186)^{3.2}]/\exp[-(25/186)^{3.2}]$ (Spring)	Adams et al. (1989)
	$RY = -0.0161 \times AOT40 + 0.99$	Mills et al. (2007)

as a surrogate for domestic market prices due to insufficient information on actual crop prices. Where producer prices are unavailable for minor producing countries, we apply the international median crop price for the year 2000. This simple revenue approach to calculate economic loss takes the market price as given and ignores the feedbacks of reduced grain output on price, planting acreage, or farmers' input decisions. Westenbarger and Frisvold (1995) reviewed several studies involving use of a general equilibrium model with factor feedbacks and found that economic damage estimates derived from a simple revenue approach are within 20% of those derived using a general equilibrium model.

3. Model evaluation

We evaluate the performance of MOZART-2 in simulating regional monthly M12 (where hourly observation data are available) and M24 (24-h average) O_3 elsewhere in Fig. 2. In Table 3, we provide regional averages of the ratio of modeled:measured M12 and AOT40 (where data are available) and M24 elsewhere during representative crop

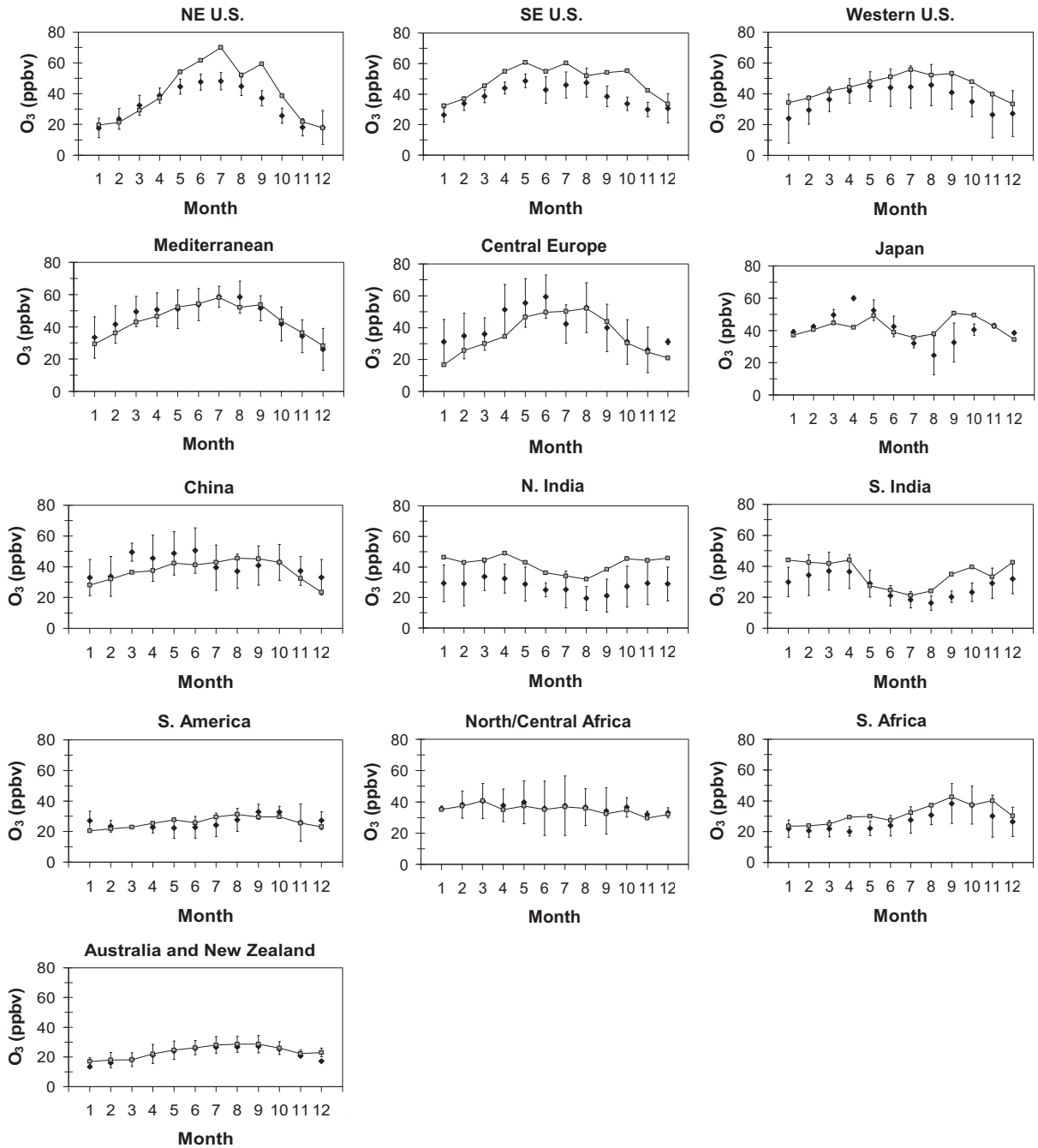

Fig. 2. Comparison of regionally-averaged monthly mean surface ozone concentrations from monitoring sites (black diamonds) and MOZART-2 (grey squares). Monthly simulated values are averaged over grid boxes containing the observation sites in each region and monthly observed values are averaged over all sites within every region. Error bars on observed values indicate ± one standard deviation from the monthly mean station data in each region. Data sources for observation sites and regional boundaries are listed in Table 3. M12 values are calculated and displayed for regions where hourly data exist that meet quality control requirements (U.S., Europe, and Japan; first 6 panels); M24 is illustrated for the rest of the world.

Table 3
Regionally-averaged ratios of modeled:observed M12, M24, and AOT40 (depending on data availability) during the representative Northern Hemisphere summer growing season (May–July) and Southern Hemisphere summer/dry season (Aug–Oct in South America and southern Africa; Dec–Feb in Australia and New Zealand). Data sources for observed O_3, regional boundaries, and the number of observation stations per region are also listed. In order for U.S. and European data to be included in the analysis of M12 and AOT40, each site was required to have hourly O_3 concentrations for at least 75% of the hours needed to compute the exposure metrics (which are then compared to 12-h MOZART-2 metric calculations). For the U.S. observation data, metric values were computed for each three-month growing season every year within a 5-year period (1998–2002) and subsequently averaged in order to produce a 5-yr seasonal average O_3 exposure value, as O_3 levels were anomalously low over some parts of the U.S. in the year 2000. Metrics were calculated only for monitoring sites with at least four years (80%) of sufficient hourly O_3 data over the 1998–2002 period. O_3 data outside of the U.S. and Europe are from the year 2000 whenever possible, but generally fall within the range of 1995–2005 according to data availability. Requirements for these data can be found in the listed references. Observed AOT40 in China and northern India are from monitoring sites listed in Huixiang et al. (2005) and Ghude et al. (2008), respectively. The AOT40 comparison for China is based on April–Jun and for India Mar–May based on the available data.

Region	M12 (M24)	AOT40	Minimum Lon, Lat	Maximum Lon, Lat	Number of Stations	Data Source
Northeast U.S.	1.33	2.45	−90, 37	−64, 50	390	EPA Air Quality System (AQS), (http://www.epa.gov/ttn/airs/airsaqs/)
Southeast U.S.	1.28	1.58	−90, 18	−64, 36	193	AQS
Western U.S.	1.16	1.69	−155, 18	−91, 63	337	AQS
Central Mediterranean	1.01	1.17	0, 35	30, 45	8	European Monitoring and Evaluation Programme (EMEP) (http://www.nilu.no/projects/CCC/onlinedata/ozone/index.html)
Central Europe	0.93	0.89	7, 46	17, 54	41	EMEP
Japan	1.12	1.23	126, 26	146, 46	4	World Data Centre for Greenhouse Gases (WDCGG) (http://gaw.kishou.go.jp/wdcgg/), Li et al. (2007)
China	(0.91)	0.87	74, 15	137, 56	12	WDCGG, Carmichael et al. (2003); Huixiang et al. (2005); Li et al. (2007)
Northern India	(1.43)	1.49	68, 21	90, 35	5	Mittal et al. (2007); Ghude (2008)
Southern India	(1.07)	–	68, 5	90, 20	7	Naja and Lal (2002); Naja et al. (2003); Debaje et al. (2003); Ahammed et al. (2006); Beig et al. (2007); Mittal et al. (2007); Debaje et al. (2010)
North/Central Africa	(1.09)	–	19, 4	61, 38	3	WDCGG, Carmichael et al. (2003)
Southern Africa	(1.10)	–	3, −35	7, 54	9	Zunckel et al. (2004)
South America	(0.97)	–	−94, −58	−30, 14	4	WDCGG, Teixeira et al. (2009)
Australia and New Zealand	(1.24)	–	110, −50	180, −11	2	WDCGG

growing seasons. Regional boundaries and sources for the observation data are listed in Table 3. Monthly simulated values are averaged over grid boxes containing the observation sites in each region and monthly observed values are averaged over all sites within every region. We provide detailed, regionally-disaggregated maps of evaluated M12 and AOT40 during the growing season (where data are available) in the Supplementary material.

In general, M12 and M24 is well-simulated by MOZART-2 in most regions of the world, reproducing seasonal trends and falling within one standard deviation of observations. O_3 is particularly well-simulated over Europe and Japan during the growing season, with a model:observed ratio for M12 (AOT40) of 0.93–1.01 (0.89–1.17) and 1.12 (1.23), respectively (Table 3). However, MOZART-2 misses some of the seasonal trend in Japan, underpredicting O_3 in April by up to ~20 ppbv and overpredicting O_3 in fall by up to ~15 ppbv. The model also underestimates O_3 in central Europe by ~5–17 ppbv during the first half of the year (Fig. 2). Based on the available data, MOZART-2 appears to perform well in China, southern India, north/central Africa, southern Africa, and South America where modeled:observed M24 ranges from 0.91–1.10 during the growing season. MOZART-2 seems to overpredict O_3 in Australia and New Zealand during the dry season (modeled:observed ratio of 1.24), but simulates observed values extremely well throughout the rest of the year. The model also appears to significantly overestimate O_3 in northern India (by ~10–18 ppbv throughout the year), a similar bias seen in TM5 CTM used by VD2009. As noted by VD2009 however, observation data in this region may not reflect regional-scale O_3 concentrations, as most monitoring sites are situated in densely-populated urban areas where local O_3 may be inhibited by NO_x titration.

Unfortunately, MOZART-2 systematically overestimates O_3 exposure in the U.S, particularly in the north- and south-eastern parts of the country by up to 22 ppbv. The bias is present to some extent throughout the year in the southeastern and western U.S., but is particularly problematic in the northeastern U.S. during the summer growing season (Table 3). This type of bias is common in global models which, on average, appear to overpredict surface O_3 in the eastern U.S. by 10–20 ppbv in summer (Reidmiller et al., 2009). Although the reasons for this bias remain somewhat unclear, possible explanations include the coarse resolution of global CTMs, as well as potential issues related to heterogeneous chemistry, isoprene emissions and oxidation pathways, and the discharge of elevated emission point sources into the model surface layer (Horowitz et al., 2007; Reidmiller et al., 2009). Furthermore, as MOZART-2 returns O_3 concentrations from the midpoint of the surface layer (~992 hPa, approximately 175 m), surface ozone concentrations may be biased high in regions where vertical mixing in the boundary layer is suppressed. For example, Aunan et al. (2000) found that O_3 concentrations at the surface were ~17% lower than at the 250-m layer midpoint height of the CTM used in their study of ozone impacts on crops in China. Based on a linear approximation from these results, a first order estimate of the potential ground-level bias caused by the presence of a vertical O_3 gradient within our surface layer of thickness ~175 m is approximately +12%.

Because the U.S. is a major producer of all three crops examined here, and because the most significant overestimation of O_3 unfortunately occurs in areas of intense crop cultivation (Supplementary material Figs. 2–3), we use observations to bias-correct values of simulated O_3 exposure (both M12 and AOT40) in the U.S. in order to constrain a major source of uncertainty in our estimates of U.S. crop yield losses. Our corrected values are calculated by dividing the simulated value of O_3 exposure in each U.S. grid cell by the ratio of modeled:observed O_3 in the same grid cell where data exist for each crop growing season (we use regional ratio averages where observations are unavailable). Our U.S. O_3 exposure values, relative yield loss, crop production loss, and economic damage estimates presented in the following sections are based on these bias-corrected values of O_3 exposure.

4. Results

4.1. Distribution of crop exposure to O_3

Fig. 3 illustrates the global distribution of crop exposure to O_3 according to the M12 and AOT40 metrics. The highest exposure levels generally occur in the Northern Hemisphere and Brazil due to greater O_3-precursor emissions and concentrations during the growing season. M12 ranges from 10 ppbv in the far north to over 80 ppbv in parts of the U.S., China and Brazil while AOT40 ranges from zero to over 40 ppmh in some locations. As evident from Fig. 3, AOT40 values in many regions of the world are above the 3 ppmh "critical level" established in Europe for the protection of crops (Karenlampi & Skarby, 1996). O_3 exposure during the soybean and maize growing seasons is high in the Northern Hemisphere, as these crops' growing seasons overlap periods of peak summer O_3 in North America and the EU; O_3 peaks during spring and fall in China and India preceding and following the annual monsoon. In the Southern Hemisphere, the high O_3 exposure levels in the Democratic Republic of the Congo (DRC) during the maize growing season and in Brazil during the wheat growing season are due to the coincidence of the relevant crop growing seasons (August–October) with the biomass burning season in each country. Both Brazil and the DRC are biomass burning hotspots in South America and Africa (Christopher et al., 1998; Roberts & Wooster, 2007) that are spatially well-simulated by MOZART-2, with observation data from Brazilian cerrado indicating that O_3 reaches 80 ppbv during biomass burning events (Kirchoff et al., 1996). Overall, the highest levels of O_3 exposure during the soybean growing season occur in the U.S., China, South Korea, and Italy (Fig. 3a), while these nations plus the DRC also endure the highest O_3 exposures during the maize growing season (Fig. 3b). O_3 exposure during the wheat growing season is greatest in central Brazil, Bangladesh, eastern India, and the Middle East (Fig. 3c).

4.2. Relative yield loss

Fig. 4 illustrates the global distribution of national RYL for each crop due to O_3 exposure. Estimates of soybean and maize (wheat) yield losses are generally larger (smaller) when the M12 rather than AOT40 metric is used. Using both metrics, O_3-induced RYL of wheat is highest in Bangladesh (15–49%), Iraq (9–30%), India (9–30%), Jordan (9–27%), and Syria (8–25%). Although O_3 is elevated during the wheat growing season over much of central Brazil, most of this nation's wheat is grown in the south where O_3 exposure is significantly lower (Figs. 1 and 3c). Soybean RYL is estimated to be

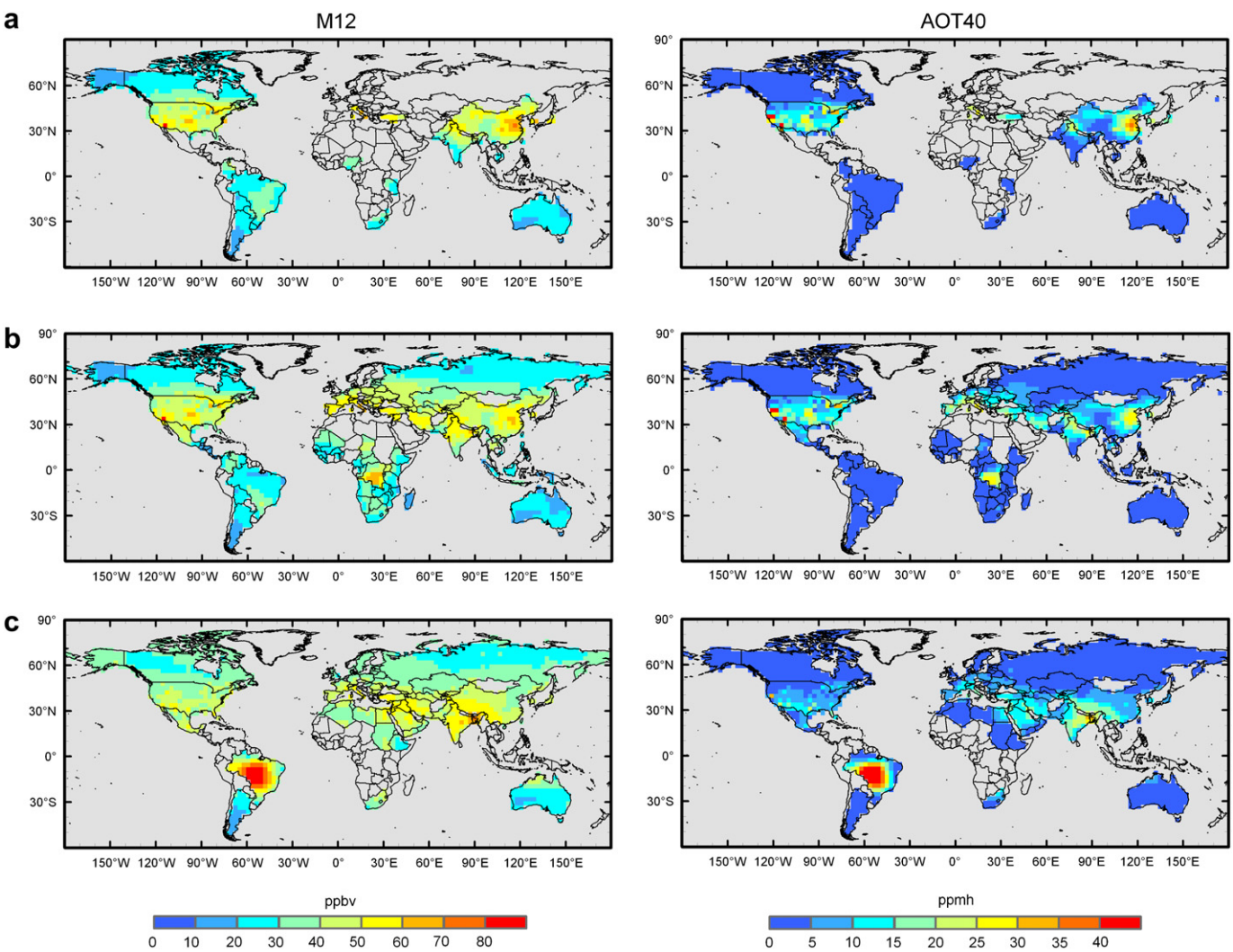

Fig. 3. Global distribution of O_3 exposure according to the M12 (left panels) and AOT40 (right panels) metrics during the respective growing seasons in each country (where crop calendar data are available) of (a) soybean, (b) maize, and (c) wheat. Values in the U.S. have been corrected using observation data as described in Section 3.

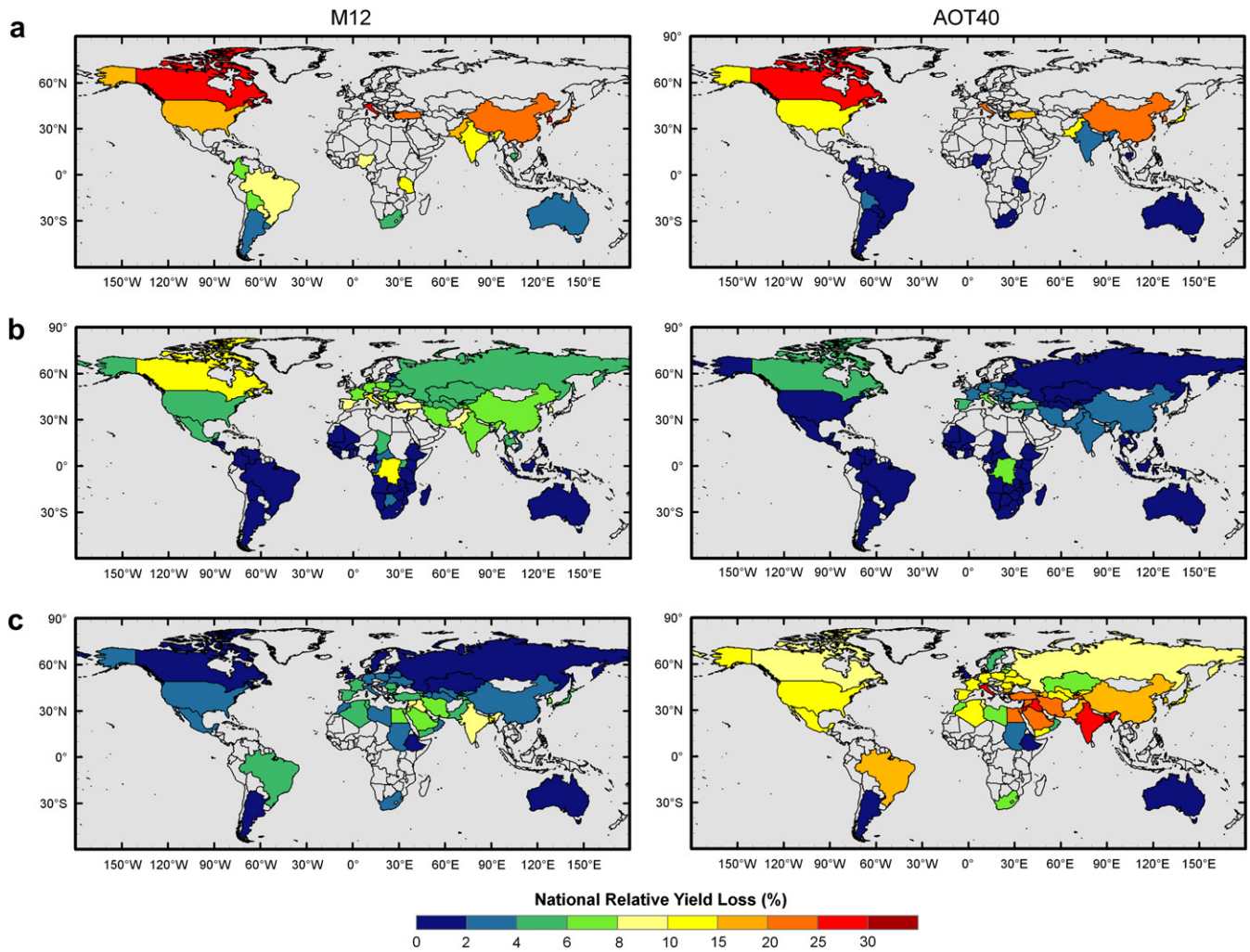

Fig. 4. National relative yield loss according to the M12 (left panels) and AOT40 (right panels) metrics for (a) soybean, (b) maize, and (c) wheat.

greatest in Canada (27–28%), followed by Italy (24–27%), South Korea (21–25%), China (21–25%), and Turkey (16–23%). Yield reductions of maize are smaller, with the highest losses occurring in the DRC (7–13%), Italy (7–12%), Canada (6–11%), South Korea (4–9%), and Turkey (4–9%). Table 4 lists regionally and globally aggregated RYL estimates (see Fig. 5 for regional definitions). On a global scale, O_3-induced RYL according to the M12 and AOT40 metrics ranges from 3.9–15% for wheat, 8.5–14% for soybean, and 2.2–5.5% for maize. Wheat yield reductions in South Asia are calculated to be the most significant (17% according to the average of metric estimates) followed by Africa and the Middle East (13%) and East Asia (10%). Large inter-regional differences exist for soybean yield losses, with North America, the EU-25, and East Asia calculated to suffer much larger reductions (14–26%, based on the average of metric estimates) than Latin America, South Asia, or Africa (<8%). RYL of maize is estimated to be more evenly distributed, with the greatest losses in East Asia (5.9%) followed closely by South Asia and the EU-25 (5.7% each).

4.3. Crop production loss (CPL) and associated economic losses (EL)

The combined global crop production and economic losses for soybean, maize, and wheat due to O_3 exposure are illustrated in Fig. 6. The distribution of CPL also accounts for production intensity, so some nations with high RYL do not have correspondingly high CPL if they are minor producers; likewise, major producers with relatively low RYL may have large CPL. We estimate CPL worldwide to be between 21–93 million metric tons (Mt) of wheat, 13–32 Mt of maize, and 15–26 Mt of soybean, depending on the metric used. The range of wheat CPL is particularly large due to the fact that this crop appears to be resistant to O_3 exposure according to the M12 metric, but extremely sensitive to ozone according to the AOT40

Table 4
Estimated regional relative yield loss (%) due to O_3 exposure according to the M7, M12 and AOT40 metrics and the metric average.

	World	EU-25	FUSSR & E. Europe	N. Am	L. Am.	Africa & M.E.	E. Asia	S. Asia	ASEAN & Australia
Wheat									
AOT40	15.4	12.1	11.4	11.0	5.9	20.1	16.3	26.7	1.0
M7	3.9	3.3	2.4	2.6	1.5	5.9	3.3	8.2	0
Mean	9.6	7.7	6.9	6.8	3.7	13.0	9.8	17.4	0.5
Maize									
AOT40	2.2	3.5	2.3	2.0	0	0.6	3.8	3.4	0.3
M12	5.5	7.9	6.5	5.1	2.1	2.5	8.0	8.0	2.4
Mean	3.9	5.7	4.4	3.6	1.2	1.6	5.9	5.7	1.4
Soybean									
AOT40	8.5	23.9	–	12.0	0.2	2.0	20.9	3.1	0
M12	13.9	27.4	–	16.9	6.3	9.8	24.7	13.2	3.7
Mean	11.2	25.6	–	14.4	3.3	5.9	22.8	8.2	1.9

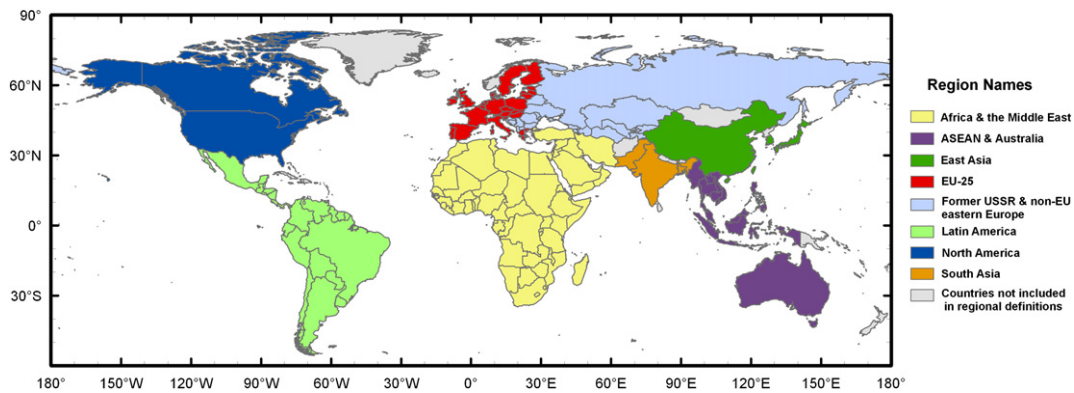

Fig. 5. Definitions used to calculate relative yield and crop production losses by region.

index. Global CPL for all three crops totals 79–121 Mt (from the M12 and AOT40 metrics, respectively). Table 2 of the Supplementary material contains regionally-averaged CPL results.

Fig. 7 depicts CPL for the ten countries with the highest estimated losses for each crop individually and combined ranked according to the mean of M12 and AOT40 values, while Fig. 8 illustrates the same for economic losses. Wheat CPL is highest in India and China (6.0–26 and 3.0–19 Mt, respectively), followed by the U.S. (2.1–7.6 Mt). CPL of soybean and maize is highest in the U.S. (9.2–14 and 4.6–13 Mt, respectively), followed by China (3.7–4.6 and 4.5–9.8 Mt, respectively). Total CPL is greatest in the U.S (21–29 Mt), followed by China (18–27 Mt) and India (8–25 Mt). We estimate that global present-day crop yield losses of all three crops range from \$11–18 billion (USD_{2000}), with soybean accounting for \$2.9–4.9 billion (27% of total losses based on the average of metric estimates), maize for \$2.6–5.5 billion (15%), and wheat for \$3.2–14 billion (58%). The greatest economic losses occur in the U.S (\$3.1 billion according to the metric average), followed by China (\$3.0 billion) and India (\$2.5 billion) (Fig. 8) – together these three countries comprise 59% of the global economic damage (21, 21, and 17%, respectively).

We provide an in-depth comparison of our results with those of VD2009 and WM2004, two studies that follow a similar methodology to calculate RYL, CPL, and EL, in the Supplementary material. Despite differences in the agricultural datasets and model scenarios, resolution, emissions inventories, and chemistry, our estimates agree very well with these two studies and provide further evidence that surface O_3 is already having a substantial detrimental impact on global agricultural production.

5. Discussion of uncertainties

While extremely useful for understanding the large-scale impacts of ozone on agricultural yields, integrated assessments such as the approach used here accumulate the uncertainties of each step of the analysis (WM2004, VD2009). One of the most

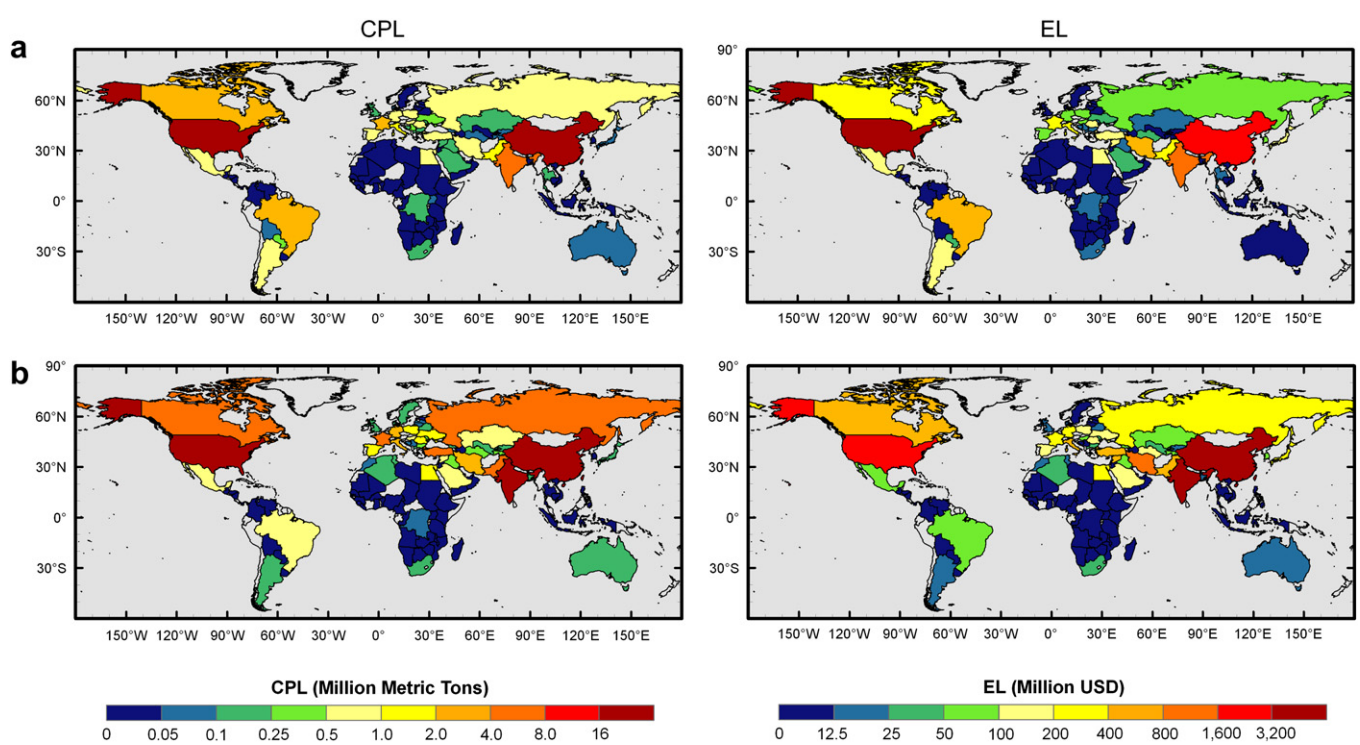

Fig. 6. Total crop production loss (CPL, left panels) and economic loss (EL, right panels) for all three crops derived from (a) M12 and (b) AOT40 estimates of O_3 exposure.

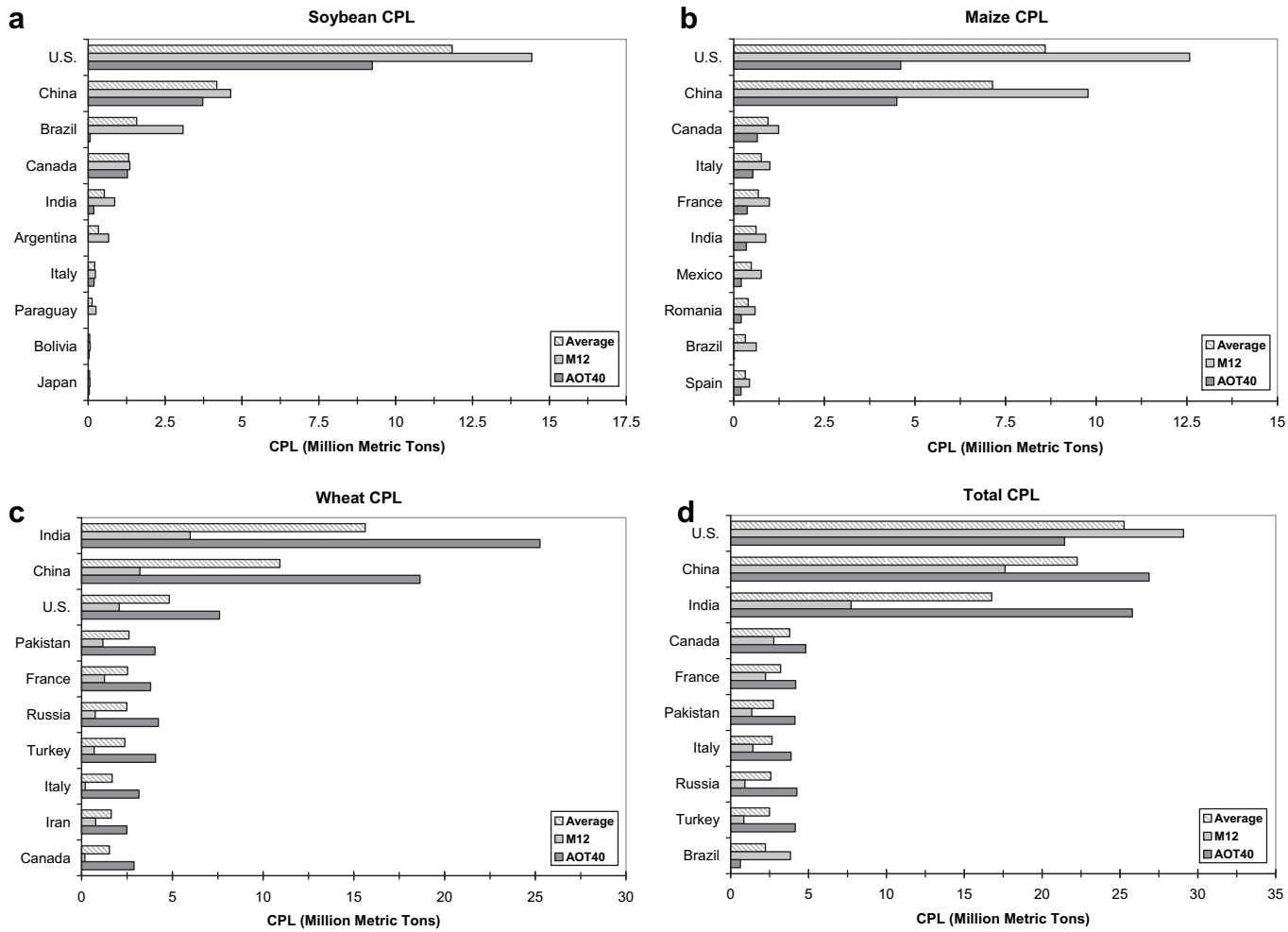

Fig. 7. Crop production loss (CPL, million metric tons) for the ten countries with highest estimated mean CPL using the M12 and AOT40 metrics for a) soybean, b) maize, c) wheat, and d) total CPL.

significant sources of uncertainty in this study is the use of a CTM with variable accuracy in predicting observed hourly surface O_3 concentrations to calculate crop losses (Fig. 2, Table 3, Supplementary material). The possible presence of a vertical gradient near the surface that is not resolved within the model's bottom layer may lead to overestimated O_3 exposure at the crop canopy height in locations and at times of day when vertical mixing in the boundary layer is weak. Due to the nature of the AOT40 metric, where small differences in O_3 concentrations near 40 ppbv can accumulate to a large discrepancy between modeled and observed exposure, the M12 metric is a more robust indicator of actual O_3 exposure during the growing season. However, as cumulative indices that ascribe greater weight to elevated O_3 are considered to be better predictors of crop response to O_3 than mean indices (Lefohn & Runeckles, 1988), significant uncertainties exist when calculating crop yield losses with either metric and should be considered when interpreting results. Our use of exposure-based indices rather than flux metrics, which account for climatic conditions and biological defenses that may affect crop sensitivity to O_3, introduces additional uncertainty in our results (Musselman et al., 2006). Particularly important climatic parameters include soil moisture and leaf-to-air vapor pressure deficits that moderate the flux of O_3 into the leaf stomata. Where crops are grown in arid climates without irrigation, yield losses may be less than predicted here due to water stress resulting in the closure of stomata and hence a relative reduction in O_3 exposure (Fuhrer et al., 1997; Fuhrer, 2009; Fiscus et al., 2005; Booker et al., 2009).

As evident from our results and observed in previous studies (Lefohn & Runeckles, 1988; Aunan et al., 2000; WM2004; VD2009), the same pattern of O_3 exposure may produce significantly different RYL estimates depending on the metric and CR relationship used. This discrepancy may be an artifact of the different statistical methods used to derive CR relationships across studies and to their different functional form (Lesser et al., 1990), or may be due to differences in crop sensitivities to various patterns of O_3 exposure: some crops may be more sensitive to long-term exposure at modest O_3 concentrations (better captured by seasonal mean metrics), while others may be more sensitive to frequent exposure to elevated O_3 (better characterized by cumulative indices) (WM2004; VD2009). The difference in calculated RYL will be particularly large when O_3 concentrations above the threshold values of cumulative metrics are prevalent during crop growing seasons, as cumulative indices weigh elevated O_3 much more heavily than mean metrics (WM2004).

Uncertainty in our results also arises from the uniform application of experimentally-derived CR functions developed for Western cultivars popular in the 1980s/90s to crops across the globe today. Despite the possibility that crop cultivars currently under cultivation may have different sensitivities to O_3 than those used in the NCLAN and EOTC studies, and that experimental methods (such as the use of OTCs) may have influenced yield loss

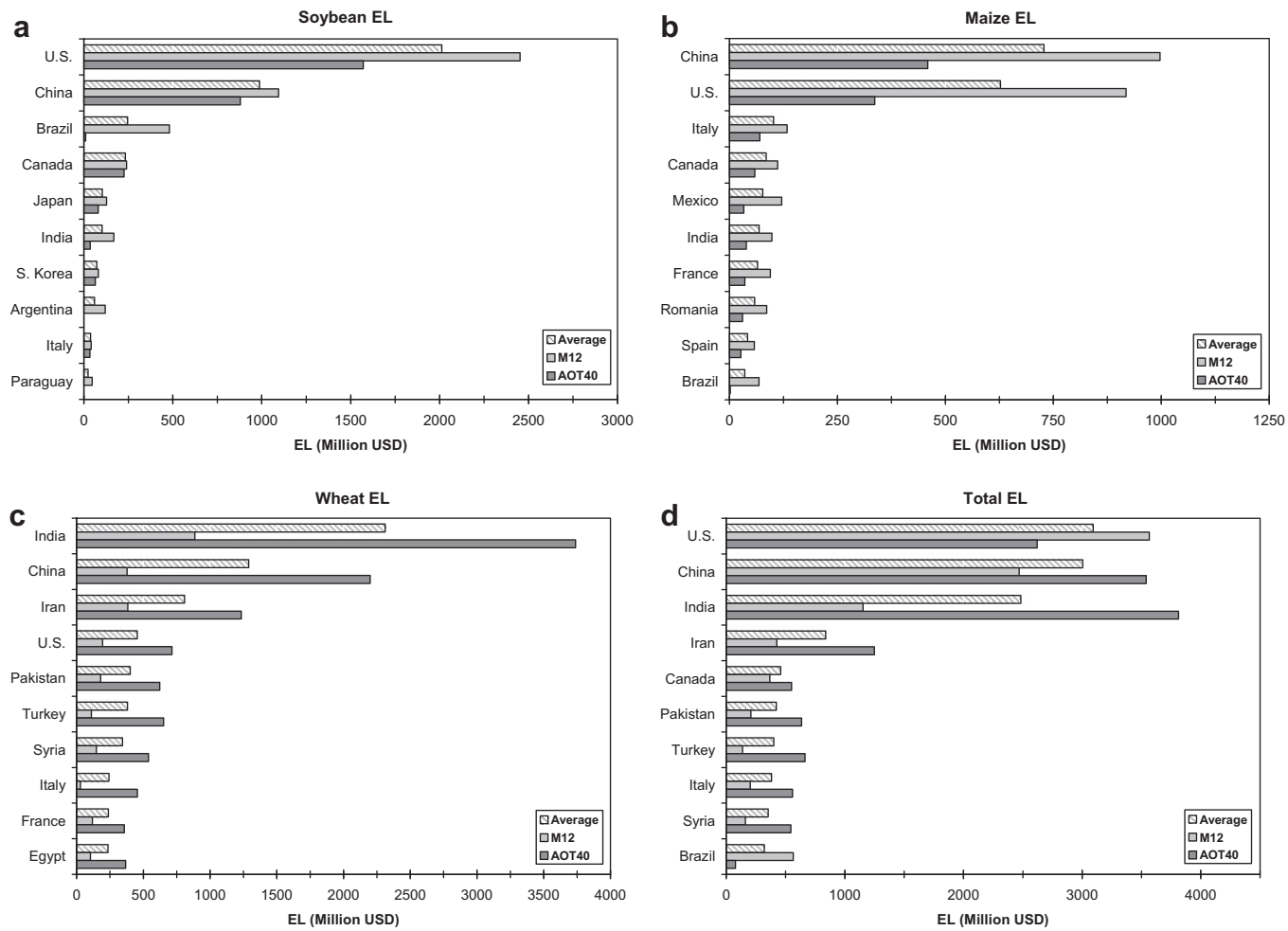

Fig. 8. Economic loss (EL, million USD_{2000}) for the ten countries with the largest estimated mean EL using the M12 and AOT40 metrics for a) soybean, b) maize, c) wheat, and d) total EL.

results, new research indicates that current crop sensitivity is at least as great as that found in these earlier studies. Specifically, the Free Air O_3 Concentration Enrichment (FACE) soybean experiment in Illinois found yield losses that were tantamount to or greater than losses reported in earlier chamber studies (Long et al., 2005; Morgan et al., 2006). Furthermore, in a recent comparison of North American and Asian CR relationships, Emberson et al. (2009) found that CR functions derived in North America underestimate the effects of O_3 on crop yields in Asia. Thus, our use of Western CR relationships may lead to an underestimation of yield reductions resulting from O_3 exposure.

Our choice to implement CR functions representing median cultivar ozone sensitivity for each crop means that our RYL and CPL calculations could be biased high or low (as predicted by each metric) depending on the relative sensitivity of the local cultivar grown. Feng and Kobayashi (2009) conduct a meta-analysis of field/experimental data that assesses the impact of O_3 on crops and find that the mean yield loss of soybean and wheat was ~8% and 10%, respectively, at average O_3 levels of ~40 ppbv, but with a 95% confidence interval of ~±4% RYL depending on the cultivar. Mills et al. (2007) find that for wheat, RYL at AOT40 of ~23 ppmh could range from ~30–50% depending on the crop cultivar. Given the large intra-crop sensitivity to ozone exposure, choosing crop cultivars with O_3-resistance, or breeding new cultivars with this trait, may be an important opportunity to reduce O_3-induced agricultural losses.

Although a detailed analysis of uncertainty propagation is beyond the scope of this paper, we have the greatest confidence in our European and U.S. crop loss calculations given model performance in these regions (after a bias-correction in the U.S.), and because the CR relationships implemented here were derived from crop cultivars grown in the U.S. and Europe. We have less confidence in our results in Asia: in particular, the overprediction of O_3 by MOZART-2 in northern India may lead to an overestimate of agricultural losses in this region, especially for wheat (which is largely grown in the north, Fig. 1) and according to the threshold-sensitive AOT40 metric. However, we are less confident about the data used to evaluate MOZART-2 in this part of the world. Furthermore, as Asian (including Indian) cultivars may be more sensitive to O_3 than predicted by western CR functions (Emberson et al., 2009), the potential high bias caused by model overprediction of surface ozone may be somewhat counteracted. Because MOZART-2 performs well in southern India during the growing season, the use of western CR relationships may lead to an underprediction of crop losses in this region. The same may be true in China, where O_3 is slightly underestimated by MOZART-2 and where regional crop cultivars also exhibit greater sensitivity to O_3 exposure (Emberson et al., 2009). By contrast, because the model appears to somewhat overestimate surface ozone in southern Africa, agricultural losses here may be biased high. Unfortunately we do not have enough monitoring data to evaluate model performance in South America, northern/central Africa, and

Australia/New Zealand beyond the stations used in this analysis, nor do we know the relative sensitivity of local cultivars to O_3 in these regions compared to those of the U.S. and Europe. As such, crop loss results in the Southern Hemisphere are considered particularly uncertain.

6. Conclusions and policy implications

In this study we estimated the global risk to three key staple crops (soybean, maize, and wheat) of surface ozone pollution using simulated O_3 concentrations and two metrics of O_3 exposure (M12 and AOT40), field-based CR relationships, and global maps of agricultural production compiled from satellite data and census yield statistics. We find that year 2000 global yield losses range between 3.9–15% for wheat, 8.5–14% for soybean, and 2.2–5.5% for maize depending on the metric used. Our findings agree well with previous studies (see Supplementary material), providing further evidence that O_3 already has a significant impact on global agricultural production.

The results presented here suggest that O_3 abatement may be one way to feed a growing population without the negative environmental impacts associated with many farming practices aimed at improving crop yields, including increased fertilizer application, water consumption, and/or greater land cultivation. The U.S. EPA recently proposed a new rule (on January 19th, 2010) to strengthen the U.S. national ambient air quality standards for ground-level O_3, including the establishment of a secondary standard to protect crops and other sensitive vegetation (EPA, 2010). Our study highlights the need for such a secondary O_3 standard, with O_3-induced agricultural losses already estimated to cost an annual $11–18 billion globally and over $3 billion in the U.S. alone. For context, these damages are 2–3 times larger than estimated global crop losses due to climate change since the 1980s ($5 billion annually) (Lobell & Field, 2007). While the selection and development of crop cultivars with O_3-resistance is therefore a worthwhile addition to efforts to increase crop resilience to climatic stresses, strategies aimed at mitigating global O_3 concentrations would provide additional co-benefits for human health and climate change (Naik et al., 2005; West et al., 2007; Fiore et al., 2008). Ozone is a noxious air pollutant in the troposphere and the third most potent greenhouse gas after carbon dioxide and methane (Forster et al., 2007). Reductions in CH_4 in particular have been shown to decrease surface ozone concentrations globally with significant health benefits (West et al., 2006; Fiore et al., 2008) while also generating the largest net reduction in radiative forcing of all the O_3-precursor species (West et al., 2007).

Given the significant present-day impact of O_3 on crops worldwide and the uncertainty of future mitigation efforts, our companion paper (Avnery et al., 2011) will explore the O_3-induced yield reductions and their associated costs expected under a range of policy scenarios with different levels of O_3-precursor abatement in the future. Further work will examine the possible benefits to agriculture of methane mitigation policies that also have demonstrated climate change and public health benefits.

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Appendix. Supplementary material

Supplemental material related to this article can be found online at doi:10.1016/j.atmosenv.2010.11.045.

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