AE International – Asia

Atmospheric Environment 38 (2004) 4383–4402

ATMOSPHERIC ENVIRONMENT

www.elsevier.com/locate/atmosenv

Characterizing distributions of surface ozone and its impact on grain production in China, Japan and South Korea: 1990 and 2020

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Received 9 November 2003; accepted 10 March 2004

Abstract

Using an integrated assessment approach, we evaluate the impact that surface O_3 in East Asia had on agricultural production in 1990 and is projected to have in 2020. We also examine the effect that emission controls and the enforcement of environmental standards could have in increasing grain production in China. We find that given projected increases in O_3 concentrations in the region, East Asian countries are presently on the cusp of substantial reductions in grain production. Our conservative estimates, based on 7- and 12-h mean (M7 or M12) exposure indices, show that due to O_3 concentrations in 1990 China, Japan and South Korea lost 1–9% of their yield of wheat, rice and corn and 23–27% of their yield of soybeans, with an associated value of 1990US$ 3.5, 1.2 and 0.24 billion, respectively. In 2020, assuming no change in agricultural production practices and again using M7 and M12 exposure indices, grain loss due to increased levels of O_3 pollution is projected to increase to 2–16% for wheat, rice and corn and 28–35% for soybeans; the associated economic costs are expected to increase by 82%, 33%, and 67% in 2020 over 1990 for China, Japan and South Korea, respectively. For most crops, the yield losses in 1990 based on SUM06 or W126 exposure indices are lower than yield losses estimated using M7 or M12 exposure indices in China and Japan but higher in South Korea; in 2020, the yield losses based on SUM06 or W126 exposure indices are substantially higher for all crops in all three countries. This is primarily due to the nature of the cumulative indices which weight elevated values of O_3 more heavily than lower values. Chinese compliance with its ambient O_3 standard in 1990 would have had a limited effect in reducing the grain yield loss caused by O_3 exposure, resulting in only US$ 0.2 billion of additional grain revenues, but in 2020 compliance could reduce the yield loss by one third and lead to an increase of US$ 2.6 (M7 or M12) –27 (SUM06) billion in grain revenues. We conclude that East Asian countries may have tremendous losses of crop yields in the near future due to projected increases in O_3 concentrations. They likely could achieve substantial increases in future agricultural production through reduction of surface O_3 concentrations and/or use of O_3 resistant crop cultivars.

Keywords: Air pollution impacts; Ozone; Agriculture; East Asia; Integrated assessment

1. Introduction

In this paper, we examine the impact of surface ozone (O_3) on grain production in East Asia for 1990 and 2020. We also estimate the economic damage associated with yield reductions, and examine the effectiveness of

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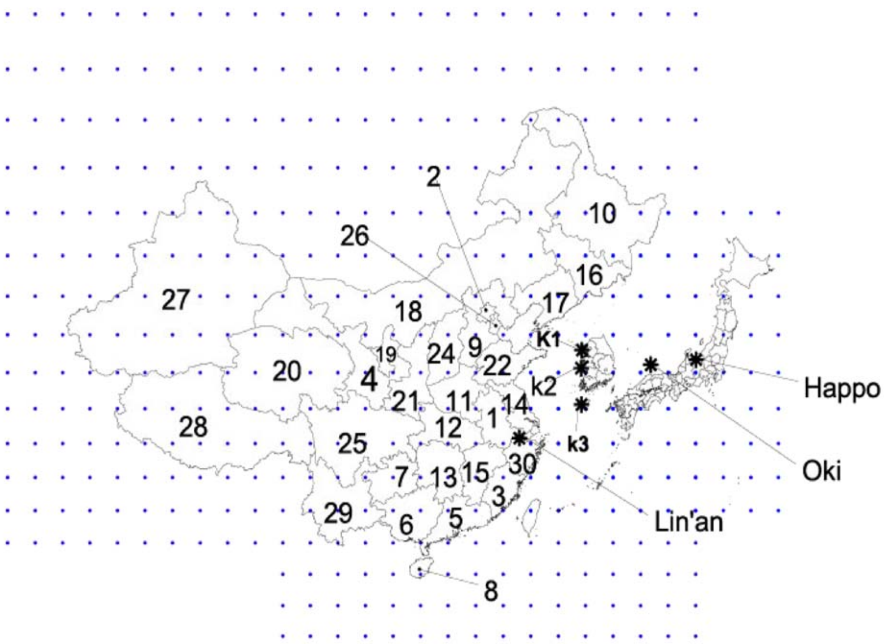
1352-2310/$ - see front matter
doi:10.1016/j.atmosenv.2004.03.067

possible pollution control policies in reducing the O_3 impact on China's grain production. The study includes three countries: China, Japan and South Korea (Fig. 1), with an emphasis on China.

East Asia is one of the most dynamic regions in the world. It hosts 25% of the world's population, consumes 19% of its total energy and produces 21% of its total cereals (Food and Agricultural Organization, 2003; International Energy Agency, 1999). Agriculture is an important sector in the Chinese economy, accounting for 27% of its total GDP in 1990, although its share has been decreasing. China has 7% of the world's arable land yet feeds over 20% of the world's population (Wang et al., 1996).

Food security is a long-standing concern of China. China has long stressed its food self-sufficiency policy and rebutted the claim of its potential dependence on food imports (Brown, 1995). However, this self-sufficiency policy has been relaxed over the last decade as China negotiated to join the World Trade Organization (WTO). China became a net grain importer in 1999 (Chadha, 2000) and is expected to import about 10% of its wheat in 2004 from the United States alone (Tuan and Hsu, 2001). Despite the lower-priced imports, the



Province indices and names in China

Index	Name	Index	Name	Index	Name
1	Anhui	11	Henan	21	Shaanxi
2	Beijing	12	Hubei	22	Shandong
3	Fujian	13	Hunan	23	Shanghai
4	Gansu	14	Jiangsu	24	Shanxi
5	Guangdong	15	Jiangxi	25	Sichuan
6	Guangxi	16	Jilin	26	Tianjin
7	Guizhou	17	Liaoning	27	Tibet
8	Hainan	18	Inner Mongolia	28	Xinjiang
9	Hebei	19	Ningxia	29	Yunnan
10	Heilongjiang	20	Qinghai	30	Zhejiang

Fig. 1. The map shows the central point of the MOZART-2 grid cells (dots), provincial boundaries of China, Japan and South Korea (black curves), and monitoring stations (stars and labeled station names) where observations are compared with model results. Numbers on the maps are provincial indices for China with corresponding province names listed below.

Chinese government aims to maintain 95% grain self sufficiency to protect the livelihood of the two-thirds of its population residing in the countryside (Chadha, 2000). In shaping China's agricultural policy or the prognosticative debate, little consideration has been given to the potential impact of increasing air pollution on agricultural production.

Due to population growth and increased fossil fuel consumption, East Asia is experiencing serious air pollution. Particulate concentrations are above the average of most developed countries and the World Health Organization (WHO) standard. Increasing nitrogen oxide ($NO_x = NO + NO_2$) emissions contribute to acid deposition and are a primary precursor for O_3 and particulate formation. Emissions of major pollutants are expected to increase substantially in the next 20 years (Streets and Waldhoff, 2000). As a result, in this paper we predict substantial increases in summer O_3 levels by 2020. Trans-boundary air pollution has also become an increasing concern for this region. Back-trajectory analyses have suggested that anthropogenic emissions in continental East Asia contribute significantly to O_3 concentrations observed in Japan (Pochanart et al., 2002, 2004). There is also evidence that outflow from the Asian continent elevates pollutant levels over the Pacific Ocean (Jacob et al., 2003; Mauzerall et al., 2000; Wild and Akimoto, 2001), and reach as far as the west coast of the United States (Jaffe et al., 2003).

Field experiments, notably the National Crop Loss Assessment Network (NCLAN) experimental studies in the US in the early 1980s and the European Open-Top Chamber (EOTC) study in 1987–1991, found that elevated surface O_3 concentrations can substantially reduce grain yield (EEA, 1999; EPA, 1996). Based on the NCLAN results, the US EPA estimated that due to ambient O_3 concentrations, the yields of about one third of US crops decreased by 10%. In some areas such as California, the losses were likely higher (EPA, 1996). Much of the European Union could be losing more than 5% of their crop yield due to exposure to O_3 (Mauzerall and Wang, 2001).

Few studies have been conducted in East Asia examining the impact of air pollution on agriculture (Ashmore and Marshall, 1999; Mauzerall and Wang, 2001). Measurements of O_3 concentrations at five locations in China suggest that impacts on Chinese wheat may be sufficiently high to affect China's crop yield in the 1990s (Chameides et al., 1999; Li et al., 1999). Field experiments conducted in the UK to investigate the sensitivity of Chinese crops to typical O_3 levels in central China found that rice cultivars grown in China may be more sensitive to O_3 than cultivars grown in Pakistan, Japan, and the US (Zheng et al., 1998). Kobayashi et al. (1995) found that the effect of O_3 on rice yield reduction in Japan was comparable to that reported for rice cultivars in California. Using an integrated assessment approach but a lower resolution atmospheric model than we use (Aunan et al., 2000) estimated that reductions in crop yields in 1990 in China were $<3\%$ for most crops (except soybeans) but that crop losses for soybeans and spring wheat might reach 20% and 30% by 2020.

Section 2 of this paper describes the integrated assessment approach we use which includes atmospheric modeling, assessment of crop yield reduction due to O_3 exposure and economic valuation of the grain yield lost. Section 3 presents our analysis of the impact of surface O_3 concentrations on grain yields for 1990 and 2020, including O_3 distributions, crop exposures, crop production losses and the associated economic costs. It also shows the effect that compliance with the current Chinese O_3 standard would have on improving grain yields for the two case years. In Section 4, we discuss the uncertainty and limitations of this undertaking and policy implications. Section 5 is a summary.

2. Methodology

2.1. Distribution of selected grain crops in East Asia

Four major grain crops are selected in this study for China and South Korea: rice, wheat, corn and soybeans. Only rice, wheat and soybeans are included in the analysis of Japanese yield losses because corn is a minor crop in Japan. In 1990, these crops accounted for 82%, 92% and 87% of the total sown area for grain production, and 63%, 46% and 61% of the total area sown for agricultural production in China, Japan and South Korea, respectively (China State Statistics Administration, 1992; Japan Statistical Bureau, 1992; The Korean Statistical Association, 1991). In China, most of the four crops are grown in the eastern part of the country (see http://www.iiasa.ac.at/Research/LUC/ChinaFood/data/maps/crops/all_m.htm for details). Rice and soybeans in Japan and South Korea and corn in South Korea are evenly distributed within each country. Wheat in Japan is grown primarily in Hokkaido, the most northern province. Wheat is a minor crop in South Korea which is primarily grown in the eastern part of the country.

Due to the heterogeneous climate throughout China, some crops are grown more than once a year in some provinces. As ambient O_3 levels have strong diurnal and seasonal cycles, the same crops grown in different seasons experience different O_3 exposure and resulting yield reductions. Thus we conduct separate analyses for the following crops: winter wheat, spring wheat, single-cropping rice, double-cropping early rice, double-cropping late rice, as well as spring and summer corn. Some areas of China grow three-cropping rice, but we do not include this category because the practice is limited. All crops are grown once a year in South Korea and Japan. Based on the growing seasons, wheat, rice and corn in South Korea and Japan generally correspond to winter wheat, single rice and summer corn in China.

2.2. Integrated assessment

In this analysis, we use an integrated approach that incorporates atmospheric modeling, plant exposure–yield response studies and economic assessment to estimate the value of the yields lost due to O_3 exposure. A similar approach has been used to evaluate reductions in agricultural yields caused by anthropogenic air pollution in the United States (Adams et al., 1989) and in China (Aunan et al., 2000). The steps for our approach are explained in Table 1.

2.2.1. MOZART-2 model simulation

We use MOZART-2 (Model of Ozone and Related Chemical Tracers, Version 2) to simulate ambient O_3 concentrations for 1990 and 2020. The model is fully described and evaluated in Horowitz et al. (2003). MOZART-2 contains a detailed representation of tropospheric ozone-nitrogen oxide-hydrocarbon chemistry, accounts for surface emissions and emissions from lightning and aircraft, advective and convective transport, boundary layer exchange, and wet and dry deposition. It simulates the concentration distributions of 63 chemical species. The model has a horizontal resolution of 2.8° latitude $\times$ 2.8° longitude and includes 34 hybrid vertical levels extending from the surface to approximately 40 km. The model runs at a time step of 20 min for all processes, and is driven by meteorological inputs from the Middle Atmosphere Community Climate Model Version 3 (MACCM3), a general circulation model.

Surface emissions used in MOZART-2 include those from fossil fuel combustion, biomass burning, biogenic emissions from vegetation and soils, and oceanic emissions. The 1990 anthropogenic emissions are based on the EDGAR v2.0 inventory (Olivier et al., 1996) with modifications. Biomass burning and biogenic emissions are also included and are described in Horowitz et al. (2003). 2020 emissions are obtained by scaling the spatially and temporally varying global 1990 anthropogenic emissions by the ratio of 2020/1990 total regional emissions specified in the Intergovernmental Panel on Climate Change (IPCC) B2-Message scenario (IPCC, 2000). The emission scaling factors are listed in Table 2. The IPCC-B2-Message scenario was chosen to represent a world in which there is moderate population growth, intermediate levels of economic development, increased concern for environmental and social sustainability, and less rapid technological development than in the A1 and B1 storylines. Projections of global anthropogenic emissions of reactive trace gases in 2020 range from highest to lowest from A2, to A1, B2 and finally B1 marker storylines (IPCC, 2000). Hence, the simulation conducted here using the B2 storyline is using global emissions that are substantially lower than a 'worst case' scenario for most species. One exception is that NO_x emissions from Asia in the B2 storyline are higher than in the A2 storyline. However, the resulting Asian NO_x scaling factor of 2.5 is supported by Streets and Waldhoff (2000). The 2020 methane concentrations and emissions used in MOZART-2 are scaled globally by the 2020-to-1990 ratio of 1.117 (IPCC, 2000).

Table 2
2020/1990 Scaling factors derived from the IPCC B2-Message scenario for reactive pollutants

	Asia[a]	ALM[b]	OECD90[c]	REF[d]
NO_x	2.516	1.392	1.25	0.927
CO	1.527	1.170	1.101	1.06
VOCs	1.575	1.365	1.064	1.153

[a] 'Asia' represents all developing countries in Asia, excluding the Middle East.

[b] 'ALM' represents all developing countries in Africa, Latin America and the Middle East.

[c] 'OECD' groups together all member countries of the Organization for Economic Cooperation and Development as of 1990 which include the US, Canada, western Europe, Japan and Australia.

[d] 'REF' represents countries undergoing economic reform and groups together the eastern European countries and the newly independent states of the former Soviet Union.

Table 1
Structure of integrated assessment

Intermediate outcome	Method
(1) Surface O_3 concentrations	Simulated using the 3-D global chemical tracer model MOZART-2 for 1990 and 2020
(2) Plant exposures to O_3	Calculated M7, M12, SUM06 and W126 (see Section 2.2.3 below for their definitions)
(3) Yield loss	Estimated for 1990 and 2020 based on exposure—response functions obtained from the US NCLAN study
(4) Economic values	Estimated value of lost grain yield based on the producer prices for 1990
(5) Policy implications	Estimated the potential yield gains if current ambient air quality standards for O_3 were met in 1990 and/or 2020

The simulated 1990 global distributions of O_3 and its precursors were evaluated extensively by comparison with observational data (Horowitz et al., 2003). The simulated seasonality, horizontal and vertical gradients of O_3 above the surface are generally in good agreement with observations. In Section 3, we compare simulated O_3 concentrations with surface observations from 6 stations in China, Japan and South Korea, which were not included in Horowitz et al. (2003).

For the agricultural impact analysis, we use hourly O_3 concentrations from the bottom layer of the model (extending from the surface to approximately 120 m). As agricultural data is usually available by administrative regions—in our case, by province, we convert O_3 concentrations within grid cells to concentrations within provinces. The provincial boundaries often partially overlap one or more MOZART-2 grid cells (Fig. 1). To capture this feature, we divide each MOZART-2 grid cell evenly into 36 smaller ones, each with the same O_3 concentration as the original grid, and then average the concentrations of all the smaller cells that fall into a province to obtain a provincial concentration.

2.2.2. Plant exposure

No large-scale field experiments have been conducted in Asia to investigate plant exposure to O_3 and the subsequent exposure–yield loss relationship for crops. As mentioned in the introduction, two comprehensive, large-scale field studies have been carried out in Europe and in the US. The EOTC studies conducted in Europe mainly focused on wheat, but the US NCLAN studies included, among others, wheat, corn and soybeans that are also of interest to this study. Therefore, we use exposure indices and corresponding exposure–response relationships obtained in the US NCLAN studies for wheat, corn and soybeans. Rice is not a major crop in the US or Europe, and was not included in the NCLAN or EOTC studies. Kats et al. (1985) carried out an independent regional rice study in the San Joaquin Valley of California exploring the impact of O_3 on rice yields. Adams et al. (1989) fitted the experimental data obtained under this study with a Weibull function and derived a M7-based exposure–yield relationship for rice. Individual field studies for rice have also been carried out in Japan (Kobayashi et al., 1995) and Pakistan (Kobayashi et al., 1995; Wahid et al., 1995a,b). Rice yield loss due to O_3 exposure in Japan was found to be similar to that in the US, but in Pakistan it was higher. We choose to use the Adams et al. (1989) result for rice in our analysis as a conservative estimate.

Four exposure indices have been used most in the US NCLAN studies. During the NCLAN field experiments, 7-h (900–1559 hours) seasonal mean O_3 concentrations (M7) were initially used to characterize crop exposure, and at a later stage 12-h (800–1959 hours) seasonal means (M12) were introduced in order to include more of the elevated O_3 concentrations (Hogsett et al., 1988). However, in the post-experimental data analysis, cumulative indices (e.g. SUM06 and W126) were found to be a better fit to the yield loss data (EPA, 1996; Mauzerall and Wang, 2001; Tingey et al., 1991). SUM06 emphasizes both exposure duration and peak O_3 concentrations. It is defined as:

$$\text{SUM06 (ppmh)} = \sum_{i=1}^{n} [C_{O_3}]_i \quad \text{for } C_{O_3} \geqslant 0.06 \text{ ppm}, \tag{1}$$

where C_{O_3} is the hourly mean O_3 concentration (ppm), i is the index and n is the total number of hours in three consecutive months of a growing season for which the SUM06 value is highest. The definition of W126 is similar to that of SUM06 except that it does not rely on a threshold value. Rather, it gives lower weight to lower concentrations and higher weight to higher concentrations based on a weighting function. The weighting factor w_i for the ith hour is defined as:

$$w_i = 1/\{1 + 4403 \exp[-0.126\ (C_{O_3})_i]\}. \tag{2}$$

The general form of W126 is:

$$\text{W126 (ppm)} = \sum_{i=1}^{n} w_i\ [C_{O_3}]_i. \tag{3}$$

While the current knowledge of the physiology of plant response to O_3 exposure is not sufficient to fully explain the difference in the yield responses obtained with different indices, the use of cumulative O_3 exposure indices is favored by most experts (e.g. Lee and Hogsett, 1999; Lefohn and Foley, 1992; Lefohn et al., 1989; Tingey et al., 1991). Europe has adopted a cumulative exposure index, AOT40, for its ambient O_3 standard (EEA, 1999). (AOT40 is defined as the sum of the difference between hourly O_3 concentrations above 40 ppb during daylight hours when clear sky radiation is above 50 W m^{-2} for 3 months —usually May–July.) However, the ambient O_3 standards in the US and East Asia are still based on 8-h average or 1-h maximum concentrations. To illustrate the range of uncertainty of the results associated with the use of different exposure indices, we include both the mean and cumulative exposure indices in our analysis.

The growing season typically spans from planting to ripening and is species and location dependent. However, until emerging from the ground, the plant is thought to be unaffected by O_3. Hence in our analysis the growing season is defined by an emerging date (a transplanting date for rice) and a ripening date, and varies by crop and province (Fig. 2). For the study region, O_3 measurements and model simulations indicate that O_3 levels appear to peak in the spring, decrease in the summer and then increase in the fall (Ghim and Chang, 2000; Mauzerall et al., 2000; Wang et al., 2001). Since higher O_3 levels usually occur in the late stage of the growing season (spring for wheat and

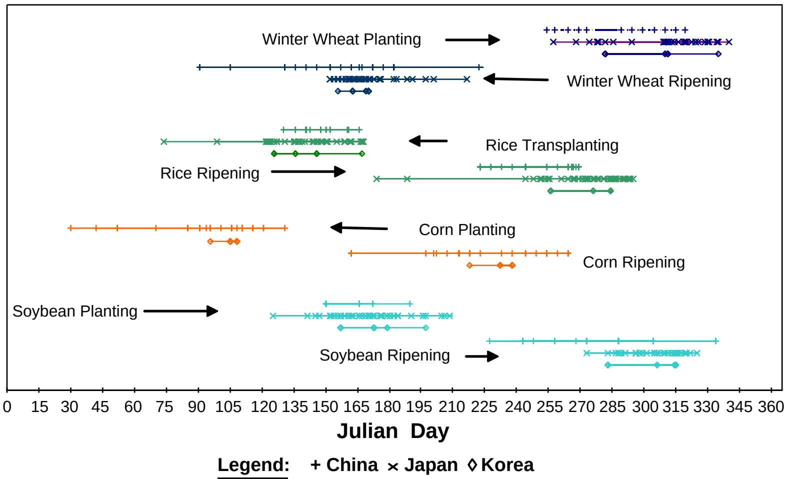


Fig. 2. Growing seasons for crops grown in China, Japan and Korea. The data points in a line correspond to the planting or ripening dates in individual provinces in each country. For a cluster of three lines, from top to bottom, are China, Japan and South Korea; for a cluster of two lines, the top line is for China, and the bottom line is for South Korea.

fall for rice, corn and soybeans), we expect the highest three consecutive months for SUM06 and W126 to mostly occur during the last 3 months of a crops growing season, and consequently calculate SUM06 and W126 during those periods. The growing season dates were obtained from Gui and Liu (1984) for China, from Kobayashi (2001) for Japan and from Ryou (2001) for South Korea.

2.2.3. Yield loss

The Weibull function is widely used to express the relationship between O_3 exposure and crop yield reduction. Its general form is (Lesser et al., 1990):

$$Y = A\exp[-(X/B)^C], \tag{4}$$

where Y is the estimated mean yield, X the O_3 exposure index (M7, M12, SUM06 or W126 here), A the theoretical yield at zero O_3 concentration, B the scale parameter for O_3 exposure which reflects the dose at which the expected response is reduced to $0.37A$, and C the shape parameter affecting the change in the predicted rate of loss.

Relative yield losses (RYL) are defined as:

$$\mathrm{RYL} = 1 - Y/Y_{\mathrm{base}}, \tag{5}$$

where Y_{base} is the estimated mean yield at the reference exposure index. We rely on the original sources of the exposure–response functions for the reference levels for different indices. The reference level is 25 ppb for M7, 20 ppb for M12, and 0 ppmh for SUM06 and 0 ppm for W126 (EPA, 1996).

Because the response of crop yield to O_3 exposure in the NCLAN study varied by cultivar and experimental location Lesser et al. (1990) used a regression model to combine all field experimental data for different cultivars of a crop in order to characterize the average response of the crop to O_3 concentrations. Weibull functions based on 7- or 12-h seasonal means were then derived for winter wheat, corn and soybeans; we use these functions in our analysis. No single Weibull function based on SUM06 or W126 has been developed for an entire crop. Individual SUM06 and W126 exposure–response functions were fit for each crop cultivar included in each of the 54 NCLAN case studies (EPA, 1996). For the same crop, the Weibull parameters A, B and C were found to differ across experimental sites, up to an order of magnitude for soybeans. We plotted all of the exposure–response functions from individual case studies and found that the function with median Weibull parameter values best represents the characteristic exposure–response function for a given crop species. Hence, we use median Weibull parameter values to calculate SUM06 and W126 for each crop category in our analysis.

Exposure–response functions used in this analysis are shown in Table 3 and graphed in Fig. 3. At a given M7 or M12 value, the RYL is largest for soybeans, and least for spring wheat and rice, with corn and winter wheat in the middle. However, at a given SUM06/W126 value, the RYL is largest for wheat, followed by soybeans and corn. The ordering of RYL for the four crops when the seasonal mean indices are used differs from the ordering with the cumulative indices. This suggests that some crops (e.g. soybeans) are more sensitive to long-term exposure to modest O_3 levels (characterized by seasonal means) than frequent exposure to high O_3 levels (which are best captured by cumulative indices). Different ordering could also be due to the different statistical

Table 3
O_3 exposure–yield response equations for rice, wheat, corn and soybeans based on 7-h and 12-h means, SUM06 and W126 indices

Crop	Exposure–relative yield (RY) relationship	Reference
Rice	$RY = \exp[-(M7/202)^{2.47}]/\exp[-(25/202)^{2.47}]$	Adams et al. (1989)
Wheat	$RY = \exp[-(M7/137)^{2.34}]/\exp[-(25/137)^{2.34}]$ (Winter wheat)	Lesser et al. (1990)
	$RY = \exp[-(M7/186)^{3.2}]/\exp[-(25/186)^{3.2}]$ (Spring wheat)	Adams et al. (1989)
	$RY = \exp[-(SUM06/52.32)^{2.176}]$	Adapted from EPA (1996)[a]
	$RY = \exp[-(W126/51.2)^{1.747}]$	Adapted from EPA (1996)[a]
Corn	$RY = \exp[-(M12/124)^{2.83}]/\exp[-(20/124)^{2.83}]$	Lesser et al. (1990)
	$RY = \exp[-(SUM06/93.485)^{3.5695}]$	Adapted from EPA (1996)[a]
	$RY = \exp[-(W126/93.7)^{3.392}]$	Adapted from EPA (1996)[a]
Soybean	$RY = \exp[-(M12/107)^{1.58}]/\exp[-(20/107)^{1.58}]$	Lesser et al. (1990)
	$RY = \exp[-(SUM06/101.505)^{1.452}]$	Adapted from EPA (1996)[a]
	$RY = \exp[-(W126/109.75)^{1.2315}]$	Adapted from EPA (1996)[a]

[a] Weibull parameters are given for each studied cultivars of a particular crop under NCLAN. We construct a single exposure–response function for a crop by using the median Weibull parameters of all studied cultivars.

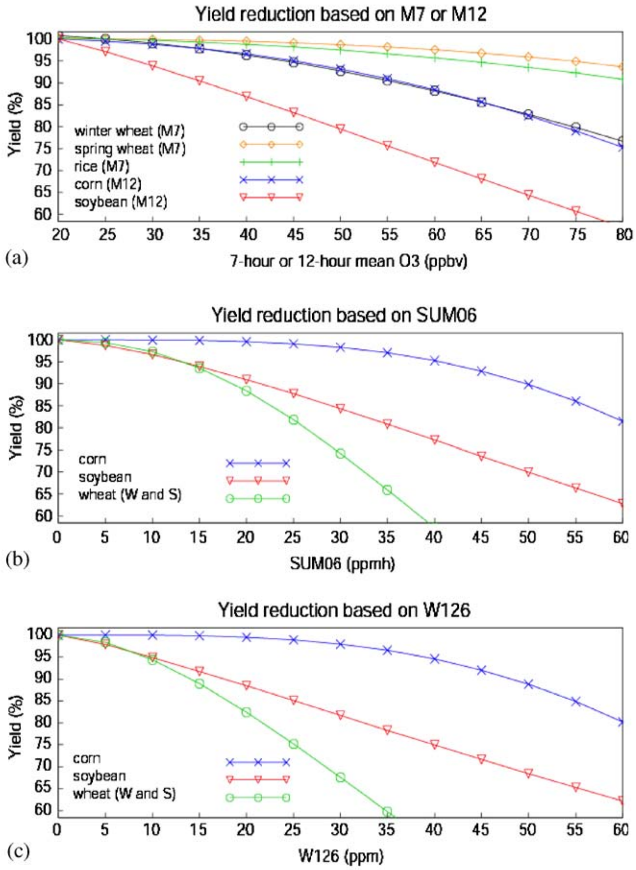


Fig. 3. O_3 exposure–yield response functions used in this analysis for (a) 7-h (M7) or 12-h. (M12) seasonal O_3 means, and cumulative indices (b) SUM06, and (c) W126. The equations for these functions are shown in Table 3.

methods used to derive the average exposure–response function for individual crops. In addition, at high O_3 concentrations, the cumulative indices predict larger losses than do the mean indices. This is due largely to the fact that higher concentrations are weighted much more heavily with the cumulative than with the mean indices. For example, for SUM06, O_3 concentrations of 59 ppb would be counted as zero (and hence would not result in

Table 4
Producer prices of grains in 1990 (Food and Agricultural Organization, 2003)

	China		Japan		South Korea	
	Yuan ton^{-1}	US$ ton^{-1}	yen ton^{-1}	US$ ton^{-1}	won ton^{-1}	US$ ton^{-1}
Wheat	636	133	161,733	1117	354,000	500
Rice	708	148	334,333	2309	817,254	1155
Corn	479	100			261,900	370
Soybeans	1073	224	241,667	1669	917,825	1297

a yield reduction) while concentrations of 62 ppb would be counted as 2 ppbh for each hour the concentration was 2 ppb above 60 ppb. With the mean indices, concentrations that differ by only 3 ppb would result in very similar estimates of yield losses.

Crop production loss (CPL) is calculated based on RYL and actual output, that is:

$$\mathrm{CPL} = \frac{\mathrm{RYL}}{1\text{-}\mathrm{RYL}} \times \mathrm{Output}, \tag{6}$$

where output means the actual annual yield of each crop in 1990 and is obtained from the country statistical yearbooks (China State Statistics Administration, 1992; Japan Statistical Bureau, 1992; The Korean Statistical Association, 1991). The national average RYL for each crop is calculated as:

$$\text{National Average RYL} = \frac{\sum_{i=1}^{n}[\mathrm{CPL}]_i}{\sum_{i=1}^{n}([\mathrm{CPL}]_i + [\mathrm{Output}]_i)}, \tag{7}$$

where n is the number of provinces included for each country (30 for China, 47 for Japan and 15 for South Korea).

2.2.4. Economic analysis

We translate the crop production loss into economic costs (EC) based on the commodity price, i.e. economic costs = market price × crop production loss. This simple revenue approach for economic analysis takes the market price as given and ignores the feedback of reduced grain output on the 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 the benefit measures derived from such a revenue approach are within 20% of those derived from a general equilibrium model. Due to lack of information on domestic market prices in 1990 for the three countries, we use the producer prices as surrogates for market prices. The producer prices for different grains in the three countries are presented in Table 4 (Food and Agricultural Organization, 2003).

2.3. The effect of compliance

Ambient air quality standards in China include three classes of standards that apply to different functional zones. The Class I standard for O_3 is an hourly average concentration of $0.12\,\mathrm{mg\,m^{-3}}$ (56 ppb) not to be exceeded at any hour in nature reserves, scenic sites and protected areas; the Class II standard is an hourly average of $0.16\,\mathrm{mg\,m^{-3}}$ (75 ppb) not to be exceeded at any hour in designated residential, commercial, cultural, general industrial and rural areas; the Class III O_3 standard is an hourly average of $0.20\,\mathrm{mg\,m^{-3}}$ (93 ppb) not to be exceeded at any hour in special industrial areas (State Environmental Protection Agency of China, 1996). We examine the possible gain in crop yield that would be achieved if the Class II standard were met throughout China by substituting all the hourly provincial averages above 75 with 75 ppb, and then calculating the potential yield loss. The potential gain in grain yield is calculated as the difference between yields achieved with assumed compliance and the actual yield loss. As we neglect the downward shift in all O_3 concentrations that would occur if compliance with the standard were actually achieved, we potentially underestimate the benefits of compliance.

3. Results

In this section, we first compare 1990 model calculated O_3 concentrations with the limited observations of O_3 concentrations available in China, Japan and South Korea. We then present model-simulated O_3 distributions, crop exposures to O_3, yield losses as well as the resulting economic damage in East Asia for 1990 and 2020. Finally, we examine the effect on grain production if China had attained its Class II O_3 standard in 1990 and 2020.

3.1. Comparison of modeling results with surface observations

We compare simulated monthly averages of O_3 concentrations with surface observations available for

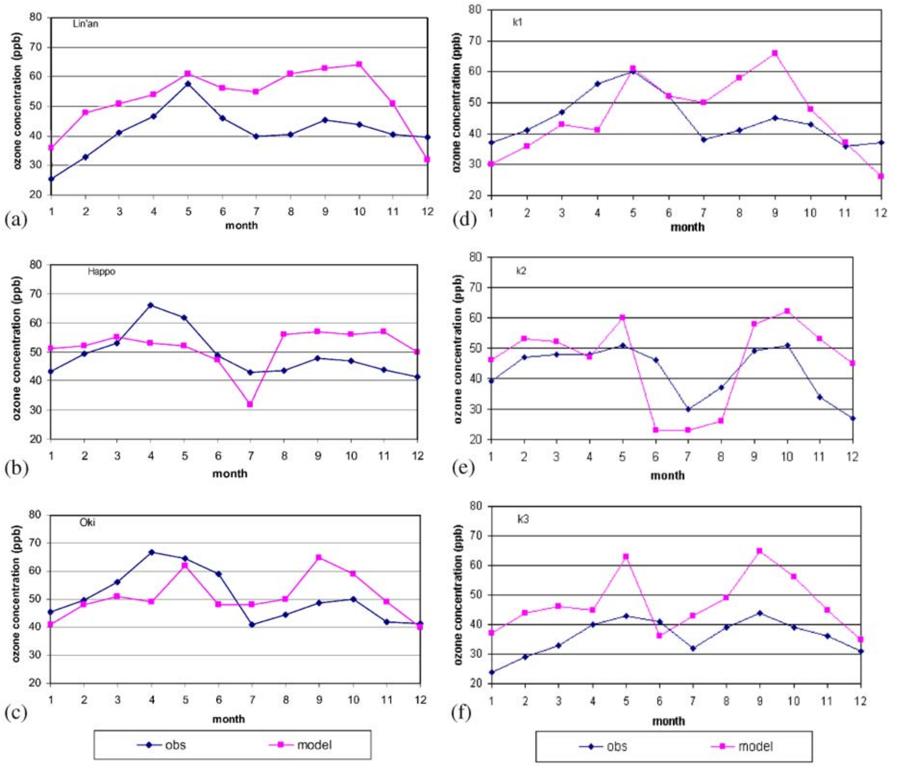


Fig. 4. Comparison of observed (closed diamonds) and simulated (open squares) monthly mean 12-h daily average (8 a.m.–8 p.m.) O_3 concentrations (ppb) in Lin'an (30°25′N, 119°44′E, 132 m), Oki (36°17′N, 133°11′E, 90 m), Happo (36°41′N, 137°48′E, 1840 m), and three Korean sites—k1 (37°25′N, 126°10′E), k2 (33°9′N, 126°7′E), and k3 (36°26′N, 126°5′E). The observations for Lin'an were made from August 1999 to July 2000 (Wang et al., 2001). The measurements for Happo and Oki were made continuously in 1996 and 1997 (Mauzerall et al., 2000). The observations at the three Korean sites were made in 2001 and 2002 (Kim, 2003). Monthly averages based on the 2-years of observations in Japan and Korea are used for comparison.

six stations in this region (see Fig. 1 for station locations); results are shown in Fig. 4. MOZART-2 generally reproduces O_3 concentrations reasonably well at all six sites. At Lin'an and at the third Korean site (k3), the model over predicts the O_3 concentrations for all but 1 month by several to 20 ppb. At the other four sites, the model tends to overestimate O_3 concentrations in the fall months. The over-estimate in model calculated autumn O_3 concentrations will result in an over-estimate of O_3 impacts on yields, particularly for soybeans that are harvested in late autumn. Other than the model weaknesses discussed in Horowitz et al. (2003), these discrepancies could result from the fact that the climatological winds used in MOZART-2 are likely to be different from the conditions prevailing during the measurement periods and that emissions from biomass burning in the model may be overestimated at high northern latitudes in autumn and hence contribute excess O_3 precursors.

3.2. Distribution of O_3 concentrations and crop exposures

Monthly means of daily 12-h average O_3 concentrations simulated by MOZART-2 for 1990, 2020 and the difference between 1990 and 2020 for East Asia are shown in Fig. 5 for April, July and October. While O_3 concentrations are projected to increase substantially in July for all three countries in 2020 over 1990, the increase is largest in China and smallest in Japan. In July 2020, surface O_3 concentrations in central China are predicted to exceed 65 ppb, an average increase of approximately 15 ppb over 1990 levels. Average concentrations in Japan and South Korea are predicted to be <60 ppb in July 2020 with an increase of approximately 5 ppb from 1990 levels. Increases in O_3 concentrations in April and October are predicted to largely be in southern China and southeast Asia with decreases predicted for north-eastern China and Korea. These decreases occur where NO_x emissions are largest

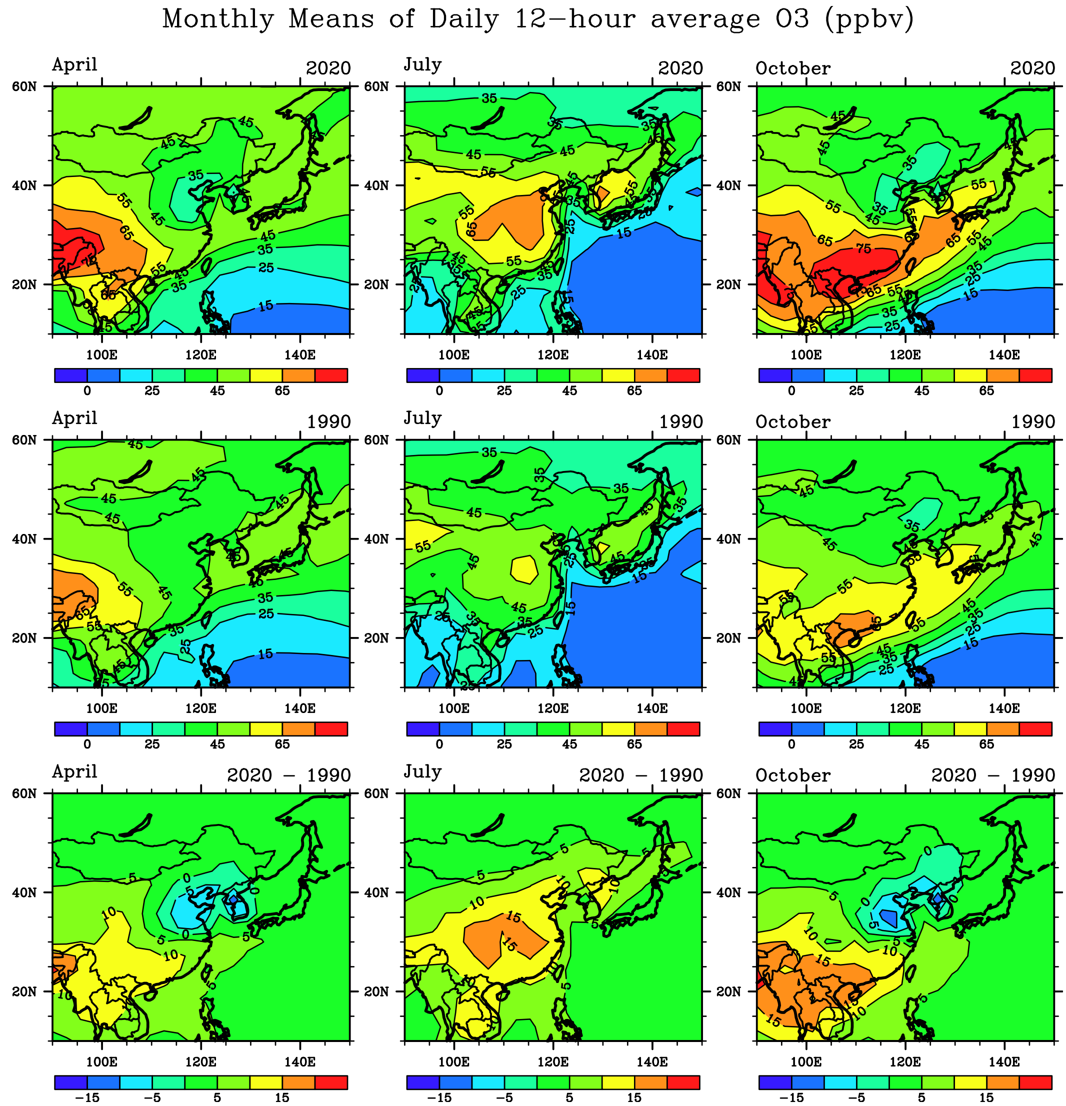


Fig. 5. MOZART-2 simulated monthly mean surface O_3 concentrations (ppb) derived from 12-h. daily averages over East Asia in 2020 (top panels) and 1990 (middle panels) and the difference between the 2 years (bottom panels) for April, July and October.

resulting in destruction of O_3 at the surface during the cooler months.

Fig. 6 shows the distribution of O_3 exposure over the last 90 days of a crop's growing season by province. For most provinces where the crops are grown, the M12 for soybeans is highest followed by M7 for single rice, M12 for corn, and M7 for winter wheat. This is consistent with the seasonal variations of O_3 concentrations since wheat is harvested in late spring or early summer while rice, corn and soybeans are harvested in late summer or autumn when O_3 concentrations are higher (see Fig. 2 for growing seasons). The M7 (or M12) for each crop are heterogeneously distributed across the provinces. For soybeans, M12 values in 1990 ranged from 29 ppb in the island provinces of Southern Japan to 70 ppb in central eastern China. SUM06 and W126 share a similar regional distribution pattern with M7 or M12. This suggests that those provinces with high 3-month mean concentrations also have more peak episodes of long duration. W126 values (not shown) are generally slightly lower than SUM06 values.

Almost all exposure indices increase dramatically from 1990 to 2020 except for M7 for winter wheat. The decrease of M7 for wheat in 2020 is because surface O_3 concentrations are predicted to decrease during the winter growing season due to elevated NO_x concentrations destroying surface O_3. M7 for rice is predicted to increase by 10–25 ppb in China, 4–10 ppb in Japan, and 6–15 ppb in South Korea, varying by province. SUM06 for soybeans increases by 6–70 ppmh in China, 8–32 ppmh in Japan, and 19–39 ppmh in Korea with variation occurring among provinces.

3.3. Relative yield loss

Calculated national average yield losses for China, South Korea and Japan in 1990 and 2020 are shown in Table 5. The O_3-induced RYL in 1990 was highest in South Korea and was comparable for China and Japan. The SUM06 and W126 RYLs in 1990 for winter wheat in Korea reached 43% and 39%, respectively. However, winter wheat is a minor crop in Korea, and thus the economic consequence is limited. The M7/M12 RYL for soybeans was as high as 23% in China and Japan and 27% in South Korea in 1990. The curvature of the

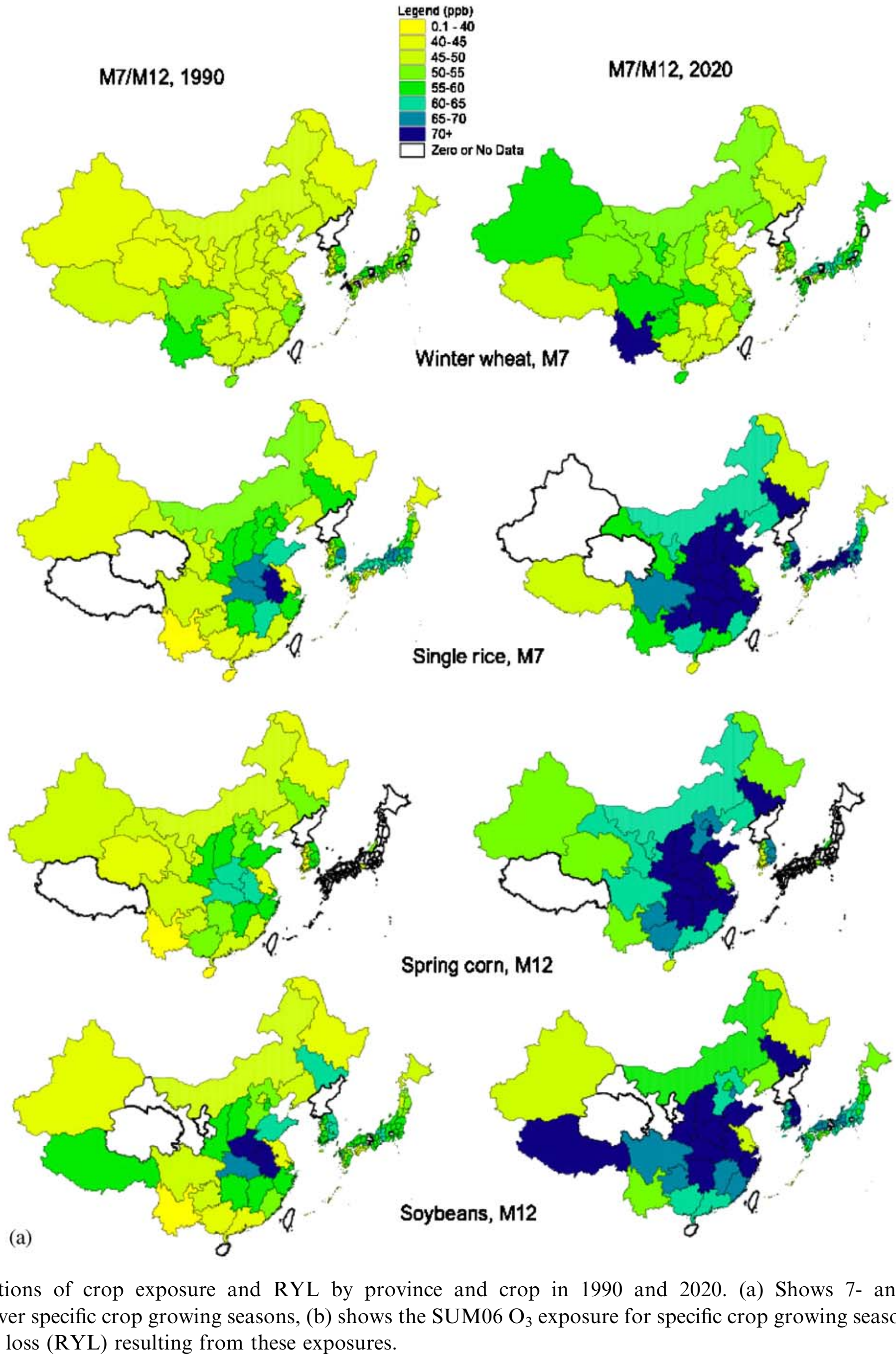


Fig. 6. Distributions of crop exposure and RYL by province and crop in 1990 and 2020. (a) Shows 7- and 12-h mean O_3 concentrations over specific crop growing seasons, (b) shows the SUM06 O_3 exposure for specific crop growing seasons, and (c) shows the relative yield loss (RYL) resulting from these exposures.

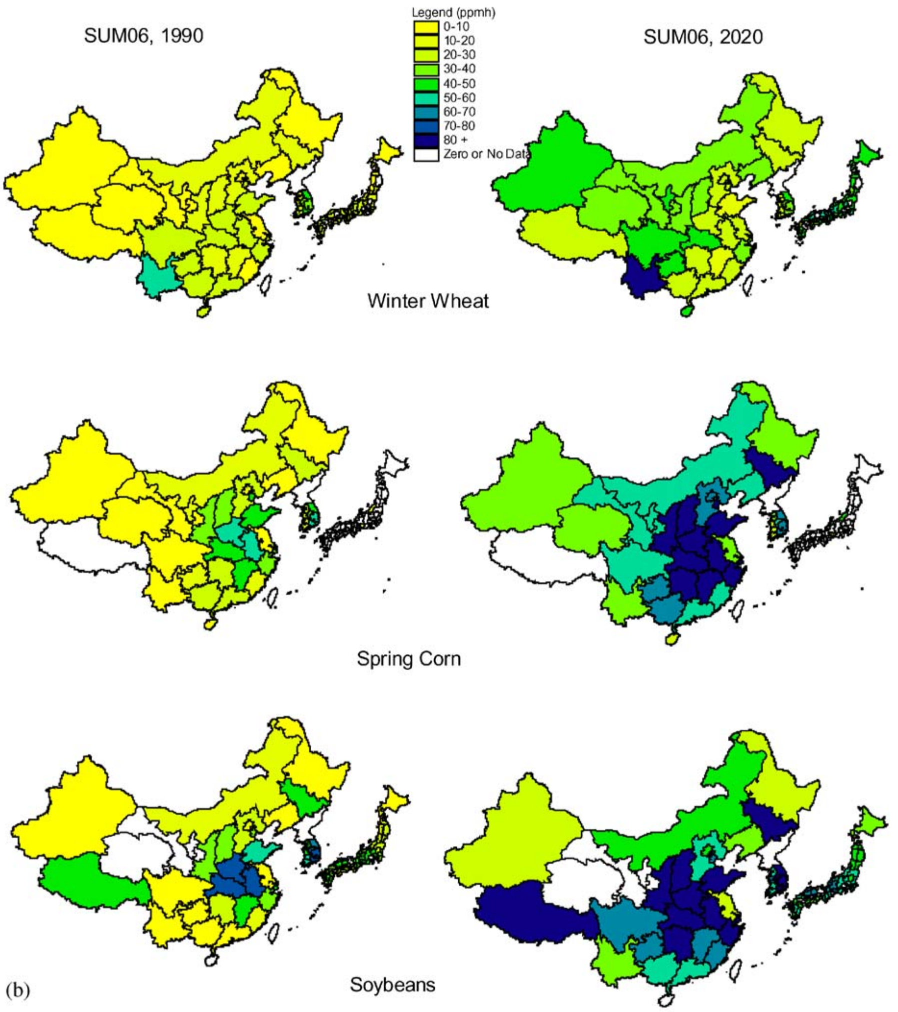


Fig. 6 (*continued*).

dose–response functions and O_3 concentrations during different growing seasons are the two factors that determine the differences in RYL between crops. Both factors contribute to soybeans having a very high RYL. As shown in Fig. 2, the last 3 months of the growing season for soybeans are usually from mid-August to mid-November when seasonal O_3 concentrations are highest.

While the three countries have similar RYL in 1990 for rice, the RYLs for wheat and soybeans in South Korea are much higher than in China and Japan. As we use the same dose–response functions for all three countries, exposure, determined by growing season periods and O_3 concentrations, is the only factor determining the inter- and intra-country variations in RYL for the same crop. Higher O_3 concentrations during the growing season in major agricultural production areas (particularly for soybeans) in the south of South Korea contribute to higher RYL nationwide.

We project that the RYL in 2020 will increase tremendously in all three countries for all crops with the increase more than doubling in China, being moderate in South Korea and modest in Japan. Using the SUM06 metric, we project enormous reductions in yields of winter wheat (63%), summer corn (64%) and soybeans (45%) in China and similar reductions of 50–60% of these crops in South Korea. Using the mean indices, RYLs are smaller and range between 7 and 35%. The cumulative index-based RYLs project larger yield reductions in 2020 than the seasonal mean RYLs because as O_3 concentrations increase, the cumulative indices, which give greater weight to higher concentrations and lower or zero weight to lower concentrations,

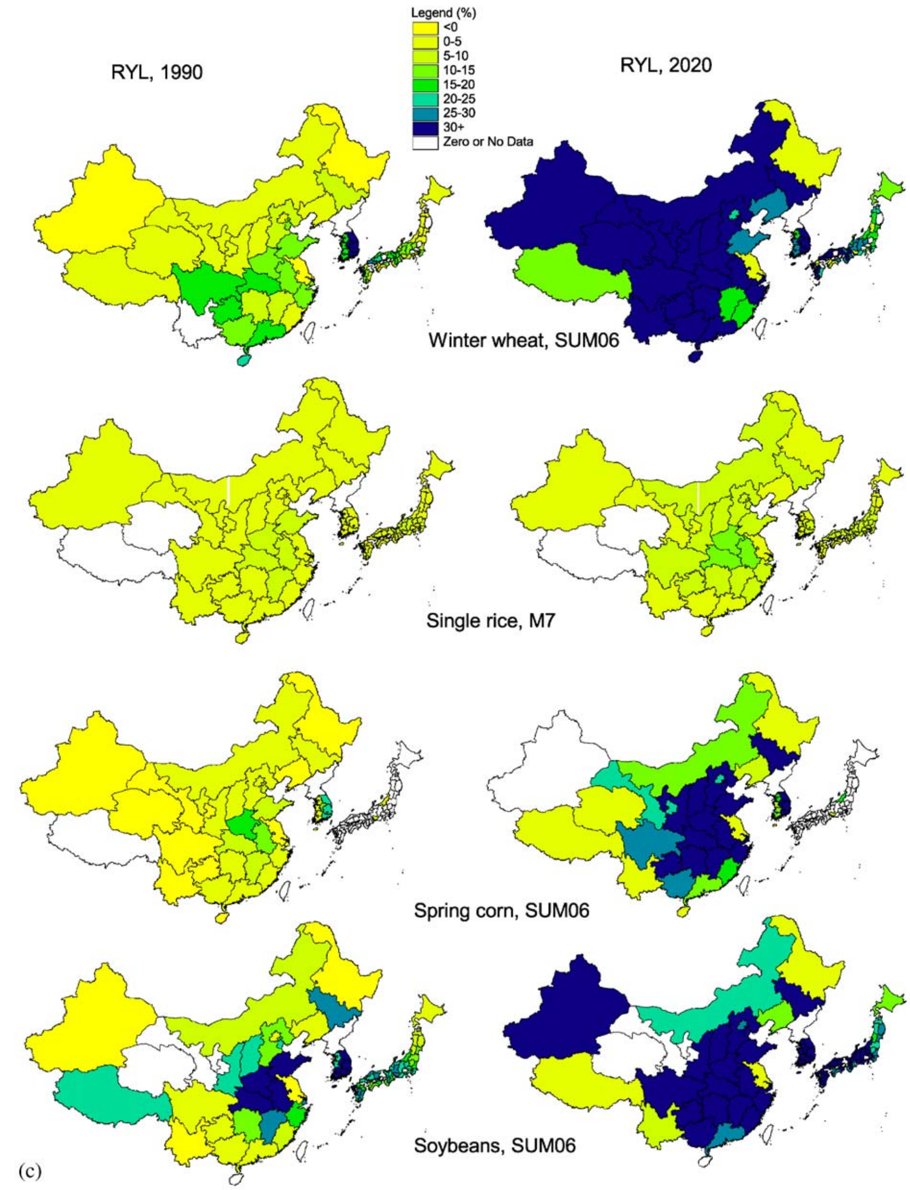


Fig. 6 (*continued*).

increase much faster than M7 or M12 which give equal weight to all concentrations.

3.4. Crop production loss and economic damage

Table 6 shows calculated crop production losses due to O_3 exposure and the associated economic costs in 1990 for each crop and country under consideration. Based on M7/M12 indices, the crop production losses of the four grain crops in China, Japan and South Korea in 1990 were 25, 0.6 and 0.2 million metric tons, respectively. The associated economic costs (EC) were approximately 3.5, 1.2 and 0.24 billon US dollars respectively given the producer prices of grain in each country in 1990 (Food and Agricultural Organization, 2003). Cross-comparison of the total economic costs based on M7/M12, SUM06 and W126 cannot be made due to lack of SUM06 or W126 data for rice.

As it is difficult to predict the actual yields and grain prices in 2020, we calculate the CPL and EC for 2020 by making a simple and conservative assumption that the

Table 5
O_3-induced relative yield loss (%) for East Asia

		1990			2020		
		M7/M12	SUM06	W126	M7/M12	SUM06	W126
China	Winter wheat	6	13	12	7	63	41
	Spring wheat	0.8	0.5	3	2	30	22
	Single rice	4			8		
	Double E rice	3			7		
	Double L rice	5			10		
	Spring corn	8	3.5	1	16	39	24
	Summer corn	8	9.2	4	16	64	45
	Soybeans	23	19	15	33	45	37
Japan	Winter wheat	7	5	6	8.7	16	14
	Single rice	4			5.3		
	Soybeans	24	18	15	28	32	25
South Korea	Winter wheat	8.8	43	39	8	59	47
	Single rice	2			4		
	Corn	3	18	4	4	50	27
	Soybeans	27	36	26	35	59	47

Table 6
O_3-induced crop production loss (CPL) and associated economic cost (EC) in 1990

Actual grain output		M7/M12		SUM06		W126	
		CPL	EC	CPL	EC	CPL	EC
China							
Wheat	99,356	5,523	735	12,738	1694	12,584	1674
Rice	191,748	8,018	1187				
Corn	96,819	8,237	824	6,636	664	2,745	275
Soybeans	11,000	3,225	722	2,603	583	1,960	439
Subtotal		25,002	3467				
Japan							
Wheat	913	63	70	50	56	58	65
Rice	10,356	419	967				
Soybeans	254	78	130	54	90	44	73
Subtotal		560	1168				
Korea							
Wheat	1	0	0	1	0.5	1	0.5
Rice	5,606	112	129				
Corn	120	4	1	26	10	5	2
Soybeans	233	85	110	130	169	83	108
Subtotal		200	241				

Notes: 1. The unit for actual yields and CPL is kton yr^{-1}, and for EC is million 1990 US dollars.
2. Actual yields are obtained from the country statistical yearbooks (China State Statistics Administration, 1992; Japan Statistical Bureau, 1992; The Korean Statistical Association, 1991).

actual yields and grain prices in 2020 are the same as in 1990. The grain yields in China have in fact constantly increased over the last two decades thanks to the introduction of increasingly productive varieties, implementation of a rural household responsibility system and the increasing use of fertilizer. However, growth rates have slowed in recent years due to diminishing returns from increased fertilizer use and agricultural

Table 7
O_3-Induced crop production loss (CPL) and associated economic cost (EC) in 2020

Assumed grain output		M7/M12		SUM06		W126	
		CPL	EC	CPL	EC	CPL	EC
China							
Wheat	99,356	6,835	909	152,248	20,257	63,481	8,447
Rice	191,748	16,801	2,489				
Corn	96,819	18,410	1,845	114,416	11,466	55,619	5,574
Soybeans	11,000	5,354	1,202	9,023	2,026	6,334	1,422
Subtotal		47,400	6,445				
Japan							
Wheat	913	84	94	171	191	150	167
Rice	10,356	580	1,339				
Soybeans	254	99	166	119	199	85	142
Subtotal		764	1,599				
Korea							
Wheat	1	0		1	1	1	0
Rice	5,606	202	233				
Corn	120	5	2	119	44	44	16
Soybeans	233	123	160	334	433	206	268
Subtotal		330	395				

Notes: 1. The unit for actual grain production and CPL is kton yr^{-1}, and for EC is million 1990 US dollars.
2. A simple, conservative assumption that actual grain output in 2020 is the same as in 1990 is made (see text for explanation).

reforms (Heilig, 2000; Oi, 1999). Thus, our calculations are intended to be illustrative estimates of the magnitude of grain yield loss and associated economic costs in 2020. As is shown in Table 7, based on M7/M12 indices, the 2020 crop production losses of the four grain crops in China, Japan and South Korea are estimated to be 47.4, 0.8 and 0.3 million metric tons, and the associated economic costs are estimated to be 6.4, 1.6 and 0.4 billon 1990 US dollars, respectively.

3.5. *The effect compliance with current O_3 regulatory standards would have on grain yields*

The Class II O_3 standard in China, which is 75 ppb O_3 not be exceeded at any hour in designated areas (which include agricultural regions in China), is stricter than the corresponding secondary standard for O_3 in the US which requires that the daily maximum 8-h average concentration not exceed 0.08 ppm. However, the Chinese standard appears to have been widely exceeded in 1990. Based on our modeling results, shown in Fig. 7, exceedence of the Class II O_3 standard in 1990 occurred in 25 Chinese provinces and the number of exceedences at the provincial level was as high as 706 in Anhui Province alone.

If all provinces in China had met the Class II standard for ambient O_3 in 1990, hourly mean O_3 concentration would not have exceeded 75 ppb at any time. By setting all O_3 concentration values above 75 to 75 ppb we estimate the minimum benefit of meeting the standard. This truncation technique in fact underestimates the benefit of meeting the standard since it is not accounting for the downward shift in all O_3 concentrations that would be necessary to assure that no O_3 concentration exceeded 75 ppb. Meeting the standard in 1990 would not have significantly increased grain production relative to the no-control case except in Anhui, Henan, Hubei and Jilin since exceedence of the Class II standard in China mainly occurred in these four provinces and was not by a large margin (see Fig. 5). As shown in Table 8, in 1990 the RYL would have been reduced by $<1\%$ for wheat and rice, and $<2\%$ for corn and soybeans, regardless of the exposure indices used; the total economic damage would have been reduced by approximately 0.2 billion dollars. However, the O_3 levels in 2020 are predicted to be much higher than in 1990 due to the increase of anthropogenic emissions of O_3 precursors. Assuming the same O_3 standard is in place in 2020, compliance would result in an increase of 1% (winter wheat, M7)–34% (summer corn, W126) yield with an increase in grain revenues compared to the business-as-usual scenario of 2.6 (M7/M12)–27 (SUM06) billion 1990 US dollars. Potential gains from compliance are substantial; we estimate that compliance would reduce the yield loss projected to occur in 2020 by more than one-third.

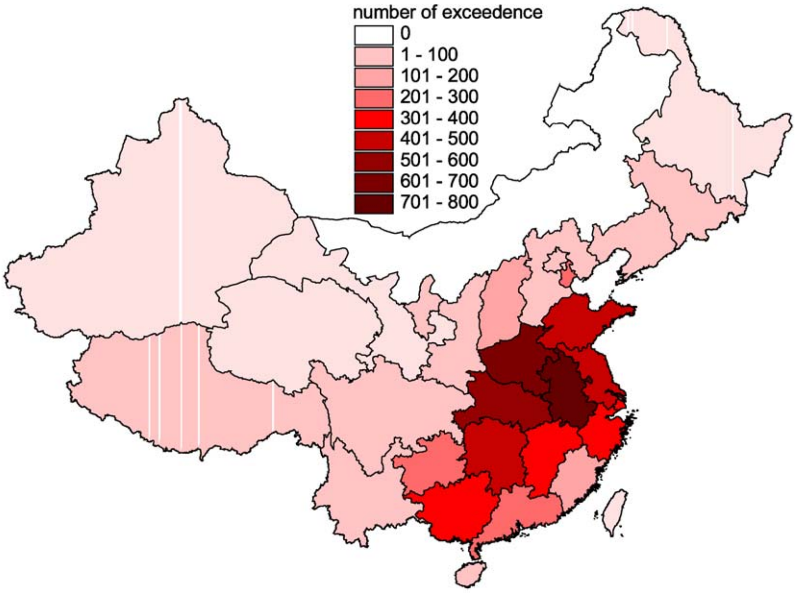


Fig. 7. Number of times in 1990 that the 75 ppb hourly Class II O_3 standard was exceeded in each Chinese province.

Table 8
Difference in RYL (%) between calculated O_3 levels and national O_3 attainment scenarios for 1990 and 2020 in China

	1990			2020		
	M7/M12	SUM06	W126	M7/M12	SUM06	W126
Winter wheat	0	0.2	0.4	0.9	8.8	10.2
Single rice	0.2			2.5		
Summer corn	0.6	1.7	1.6	6.0	29.8	33.6
Soybeans	0.9	1.3	2	6.4	9	11.8

4. Discussion

4.1. Uncertainty analysis

One source of uncertainty that affects our analysis is the distribution of MOZART-2 surface O_3 concentrations. In 1990, O_3 concentrations in China were at a level that when cumulative exposure indices (SUM06 and W126) are used, a small change in peak O_3 concentrations could make a large difference in calculated yield loss. MOZART-2 appears to over-predict O_3 concentrations in the fall of 1990, possibly resulting in an overestimate of yield loss of rice, corn and soybeans. In addition, literature has shown a wide range of possibilities for anthropogenic emissions in 2020 in Asia (IPCC, 2000; Klimont et al., 2001; Streets and Waldhoff, 2000). We have chosen the IPCC B2-Message 2020 emission scenario for reactive pollutants (IPCC, 2000) which is supported by the literature for the study region (Streets and Waldhoff, 2000).

To evaluate the effect of possible variations of simulated O_3 concentrations on our results, we conduct a sensitivity analysis by artificially increasing or decreasing the calculated provincial hourly mean O_3 concentrations in 1990 and 2020 by 25%. The resulting RYL change is shown in Fig. 8. The change in RYLs is smallest for M7/M12 indices, intermediate for W126 and largest for SUM06 in all three countries. In 1990 the effect of lowering O_3 concentrations is a lot smaller than that of increasing the concentrations due to the fact that for SUM06, the concentrations that were below the cutoff point of 60 ppb, and thus uncounted in the SUM06 values, are elevated above 60 ppb with a 25% increase, thus substantially increasing the SUM06 values. The same reasoning applies to the W126 values, though the increase of the W126 values is not as large as

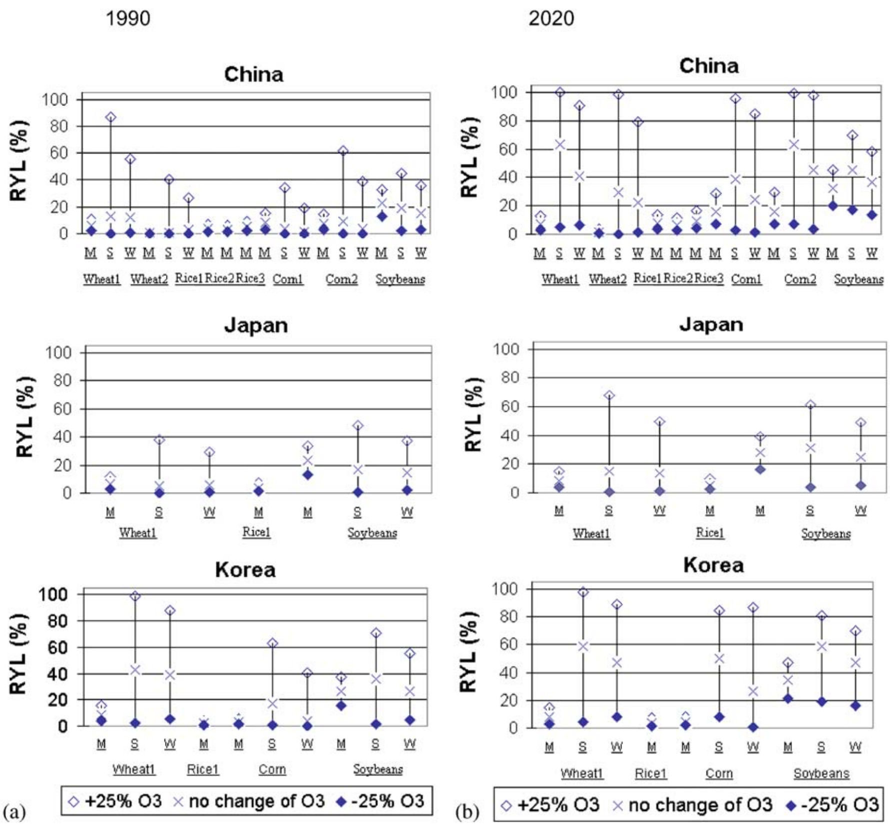


Fig. 8. Sensitivity of the RYL to O_3 concentrations in China, Japan and South Korea. The upper bounds, mid-points and lower bounds of the vertical lines define the RYL that corresponds to increases of all O_3 concentrations by 25%, no change in O_3 concentrations, and decreases of all O_3 concentrations by 25%, respectively. Abbreviations: M = M7 or M12, S = SUM06, W = W126, Wheat1 = Winter Wheat, Wheat2 = Spring Wheat, Rice1 = Single Rice, Rice2 = Double Early Rice, Rice3 = Double Late Rice, Corn1 = Spring Corn, Corn2 = Summer Corn.

that of SUM06 because the weights on the W126 index are gradually increased around 60 ppb. In contrast, in 2020 after the threshold O_3 level of 60 ppb is exceeded for most crops, the RYLs are more evenly responsive to an increase or decrease in O_3. A few species such as wheat and corn in China, as well as wheat in South Korea will experience 100% RYL if the O_3 concentrations are 25% above the simulated levels in 2020 based on the existing exposure–yield response functions. A caveat is that such high O_3 concentrations were not observed in the experimental studies, thus we are extrapolating the existing O_3 exposure–yield response functions beyond the range in which they are supported by observations. Nonetheless, our results indicate that potential future increases in O_3 concentrations could cause devastating decreases in crop yields.

Concerns may arise about applying the exposure–response relationships obtained in North America to East Asia. The cultivars studied in the NCLAN program were chosen for their economic importance in the US and cultivar selection is region-specific. Hence, cultivars selected for the NCLAN study are likely to differ from those grown in East Asia. In addition, ambient air quality is much different in the US and East Asia, with O_3 concentrations tending to be lower in East Asia in 1990. Therefore, the exposure indices developed under the NCLAN study that best fit US data might not apply as well to East Asia. However, the climate is the primary consideration in introducing a crop species from one region to another, and the crop climates in the major production zones on the two continents are similar (Cui, 1994). Given the limited experimental data from East Asia, no alternative approach is possible. Our results are indicative of the yield reductions that were actually experienced in 1990. They suggest that future yield reductions will be large.

To simplify our analysis, we have assumed that the baseline crop yield (i.e. Y_{base} in Eq. (5)) does not change between 1990 and 2020. However, as discussed in Section 3.4, the grain yields in China have in fact consistently increased over the last two decades, and improvements in agricultural techniques are likely to continue this trend into the future. Thus, our analysis provides a lower-bound estimate of the potential yield reductions.

Finally, how grain prices in China will change after its WTO accession is also uncertain. Having become a WTO member, China is expected to import more agricultural products at prices lower than the domestic ones, which could result in a drop in domestic prices. However, an opposing view is that in the past when China needed to import large quantities of grain, world prices were driven up (Brown, 1995; Yang and Tian, 2000). Although potential future price fluctuations will not affect our economic cost calculations for 1990 when the agricultural market in China was largely isolated from the world market, it will affect the estimates of economic loss in the future and hence the economic basis for making government policy. Lower prices might reduce the incentive to control air pollution in rural areas. While addressing these issues are beyond the scope of this paper, we suggest that more field research be launched in East Asia on the impact of air pollution on the growth of local crop cultivars, taking into account local climate and soil conditions. For any large-scale pollution control programs, it would be valuable to conduct comprehensive integrated assessments that scrutinize not only the impact of pollution on agricultural production but also the potential co-benefits and other socio-economic consequences of pollution control.

Aunan et al. (2000) examined crop loss in China due to O_3 exposure. Our estimates of relative yield loss for all grain crops except spring wheat are higher than those of Aunan et al. (2000) for both 2000 and 2020. The difference can be attributed to several factors. First, different atmospheric chemistry models are used to calculate ambient O_3 concentrations. MOZART-2, the model used in this analysis, has higher spatial resolution, includes more complete chemistry, and uses different emission inventories for both 1990 and 2020 than does the model used in Aunan et al. (2000). Second, although the O_3 exposure–yield response functions based on SUM06 used in both studies are derived from the US NCLAN studies, we developed a function where the Weibull parameters are medians of all cultivars of a crop. Aunan et al. (2000) used the function for a specific cultivar which is closest to an average of all cultivars of a crop. Third, the growing season data used in the analyses was collected from different sources, and thus could be slightly different.

4.2. Policy implications

Although grain yield loss in China due to O_3 exposure was not large in 1990, China is likely to suffer much higher yield losses from elevated O_3 in the future. Controls on the emissions of air pollutants could become an increasingly effective way to improve agricultural yields and alleviate China's struggle to attain grain self-sufficiency. Such control could also benefit grain production in South Korea and Japan which are receiving air pollution outflow from China (Mauzerall et al., 2000). Nonetheless, given that the economic damages suffered by the agricultural sector from O_3 pollution in Japan and South Korea are much less severe than in China, the largest benefits of controlling China's air pollution will be local. This should provide a great incentive for China to implement pollution controls.

While the potential for increasing agricultural yields through additional application of fertilizer and agricultural reforms in China is limited (Ash and Edmonds, 2000; Oi, 1999; Wang et al., 1996), selection and further development of crop cultivars that are resistant to O_3 may provide a mechanism for increasing crop yields. Agricultural research in China has mainly focused on increasing yields and quality. Environmental pollution caused by or affecting agricultural production should be added to the agenda of agricultural research. China is among the leading countries in genetically modified (GM) crop production (Schrope, 2001), and could benefit from development of crop varieties with enhanced resistance to pollution. In addition, based on the field studies conducted in the US, rice yields seem less sensitive to O_3 concentrations than other crops; meanwhile, the cultivars of rice in China were found to be more O_3 sensitive than cultivars grown in Pakistan, Japan and the US (Kats et al., 1985; Mauzerall and Wang, 2001). This warrants further field research in China to examine the impact of O_3 on local rice yields.

5. Conclusions and future work

We find that given projected increases in air pollution levels in the region, East Asian countries are presently on the cusp of substantial losses of agricultural yields due to projected increases in O_3 concentrations. Between 1990 and 2020 grain yield loss due to O_3 exposure is projected to increase by 35%, 65% and 85% in Japan, Korea and China, respectively, with resulting economic costs increasing by approximately the same amount. China's compliance with its current ambient O_3 standard would have had a small effect in decreasing yield reductions of grain crops in 1990. However, non-compliance is estimated to account for one third of the yield loss projected to occur in 2020. A future field experimental study on the impact of O_3 on agriculture in East Asia is needed. In addition, a careful examination of the combined effects on agricultural yields of O_3, particulate pollution, and possible changes in temperature and the hydrological cycle occurring as a result of climate change could be beneficial. We conclude that East Asian countries can avert substantial decreases in agricultural yields by reducing O_3 air pollution and potentially through the development and use of pollution-resistant crop cultivars.

Acknowledgements

We thank Larry Horowitz for helpful conversations, and Michael Oppenheimer and Robert Mendelsohn for comments on an earlier version of the manuscript. We are grateful to the Geophysical Fluid Dynamics Laboratory in Princeton, New Jersey for computational resources used to conduct the MOZART-2 simulations and to the Woodrow Wilson School of Public and International Affairs at Princeton University for the financial support.

References

Adams, R.M., Glyer, J.D., Johnson, S.L., McCarl, B.A., 1989. A reassessment of the economic effects of ozone on united states agriculture. Journal of the Air Pollution Control Association 39 (7), 960–968.

Ash, R.F., Edmonds, R.L., 2000. China's land resources, environment and agricultural production. In: Edmonds, R.L. (Ed.), Managing the Chinese environment. Oxford University Press, Oxford, pp. 112–155.

Ashmore, M.R., Marshall, F.M., 1999. Ozone impacts on agriculture: an issue of global concern. Advances in Botanical Research Incorporating Advances in Plant Pathology 29, 31–52.

Aunan, K., Berntsen, T.K., Seip, H.M., 2000. Surface ozone in China and its possible impact on agricultural crop yields. Ambio 29 (6), 294–301.

Brown, L.R., 1995. Who Will Feed China?: Wake-up Call for a Small Planet, Earthscan, London, 160pp.

Chadha, K.K., 2000. China abandons policy on grain, to import more. Asia Today.

Chameides, W.L., Li, X., Tang, X., Zhou, X., Luo, C., Kiang, C., St. John, J., Saylor, R.D., Liu, S.C., Lam, K.S., Wang, T., Giorgi, F., 1999. Is ozone pollution affecting crop yields in China. Geophysical Research Letters 26 (7), 867–870.

China State Statistics Administration, 1992. China Statistical Yearbook, China Statistical Press, Beijing, China, pp. 266.

Cui, D., 1994. World agroclimate and crop climate. Zhejiang Science and Technology Press, China.

EEA, 1999. Environmental assessment Report No. 2. Environment in the European Union at the turn of the century. European Environmental Agency, Copenhagen, 446pp.

EPA, 1996. Air quality criteria for ozone and related photochemical oxidants. United States Environmental Protection Agency (EPA), pp. 1–1 to 1–33.

Food and Agricultural Organization, 2003. FAO Statistical Databases, FAO.

Ghim, Y.S., Chang, Y.-S., 2000. Characteristics of ground-level ozone distributions in Korea for the period of 1990–1995. Journal of Geophysical Research 105 (D7), 8877–8890.

Gui, D., Liu, H., 1984. Main Crop Climatic Atlas of China. China Meteorology Press, Beijing, China.

Heilig, G.K., 2000. Can China feed itself? An analysis of China's food prospects with special reference to water resources. International Journal of Development World Ecology 7, 153–172.

Hogsett, W.E., Tingey, D.T., Lee, E.H., 1988. Ozone exposure indices: concepts for development and evaluation of their use. In: Heck, W. (Ed.), Assessment of Crop Loss From Air Pollutants. Elsevier Science Publishers Ltd., London, pp. 107–138.

Horowitz, L.W., Walters, S., Mauzerall, D.L., Emmons, L.K., Rasch, P.J., Granier, C., Tie, X., Lamarque, J.-F., Schultz, M., Tyndall, G.S., Orlando, J.J., Brasseur, G.P., 2003. A global simulation of tropospheric ozone and related tracers: description and evaluation of MOZART, version 2. Journal of Geophysical Research 108 (D24), 4784, doi:10.1029/2002JD002853.

International Energy Agency, 1999. Key World Energy Statistics from the IEA, International Energy Agency, pp. 74.

IPCC, 2000. Emission Scenarios, In: Intergovernmental Panel on Climate Change (IPCC) (Ed.). Special Report on Emission Scenarios.

Jacob, D.J., Crawford, J.H., Kleb, M.M., Connors, V.S., Bendura, R.J., Raper, J.L., Sachse, G.W., Gille, J.C., Emmons, L., Heald, C.L., 2003. The transport and chemical evolution over the pacific (TRACE-P) aircraft mission: design, execution, and first results. Journal of Geophysical Research 108 (D20), 1–19.

Jaffe, D., McKendry, I., Andersonc, T., Price, H., 2003. Six 'new' episodes of trans-Pacific transport of air pollutants. Atmospheric Environment 37, 391–404.

Japan Statistical Bureau, 1992. Japan Statistical Yearbook 1992, Statistical Bureau, Management and Coordination Agency, Government of Japan, Tokyo, Japan, pp. 224–238.

Kats, G., Dawson, P.J., Bytnerowicz, A., Wolf, J.W., Thompson, C.R., Olszyk, D.M., 1985. Effects of ozone or sulfur dioxide on growth and yield of rice. Agriculture, Ecosystems and Environment 14, 103–117.

Kim, J., 2003. Personal communication.

Klimont, Z., Cofala, J., Schopp, W., Amann, M., Streets, D.G., Ichikawa, Y., Fujita, S., 2001. Projections of SO_2, NO_x, NH_3 and VOC emissions in East Asia up to 2030. Water, Air, and Soil Pollution 130, 193–198.

Kobayashi, K., 2001. Personal communication.

Kobayashi, K., Okada, M., Nouchi, I., 1995. Effects of ozone on dry matter partitioning and yield of Japanese cultivars of rice (*Oryza sativa* L.). Agriculture, Ecosystems and Environment 53, 109–122.

Lee, E.H., Hogsett, W.E., 1999. Role of concentration and time of day in developing ozone exposure indices for a secondary standard. Journal of the Air and Waste Management Association 49, 669–681.

Lefohn, A.S., Foley, J.K., 1992. Nclan results and their application to the standard-setting process: protecting vegetation from surface ozone exposures. Journal of the Air and Waste Management Associtiont 62 (8), 1046–1052.

Lefohn, A.S., Krupa, S.V., Runeckles, V.C., Shadwick, D.S., 1989. Important considerations for establishing a secondary ozone standard to protect vegetation. Journal of the Air Pollution Control Association 39 (8), 1039–1045.

Lesser, V.M., Rawlings, J.O., Spruill, S.E., Somerville, M.C., 1990. Ozone effects on agricultural crops: statistical methodologies and estimated dose-response relationships. Crop Science 30, 148–155.

Li, X., He, Z., Fang, X., Zhou, X., 1999. Distribution of surface ozone concentration in the clean areas of China and its possible impact on crop yields. Advances in Atmospheric Sciences 16 (1), 154–158.

Mauzerall, D.L., Wang, X., 2001. Protecting agricultural crops from the effects of tropospheric ozone exposure-reconciling science and standard setting. Annual Review of Energy and Environment 26, 237–268.

Mauzerall, D.L., Narita, D., Akimoto, H., Horowitz, L., Waters, S., Hauglustaine, D., Brasseur, G., 2000. Seasonal characteristics of tropospheric ozone production and mixing ratios of East Asia: a global three-dimensional chemical transport model analysis. Journal of Geophysical Research 105, 17895–17910.

Oi, J.C., 1999. Two decades of rural reform in China: an overview and assessment. China Quarterly 159, 616–628.

Olivier, J.G.J., Bouwman, A.F., van der Maas, C.W.M., Berdowski, J.J.M., Veldt, C., Bloos, J.P.J., Visschedijk, A.J.H., Zandveld, P.Y.J., Haverlag, J.L., 1996. Description of EDGAR version 2.0: a set of global emission inventories of greenhouse gases and ozone-depleting substances for all anthropogenic and most natural sources on a per country basis and on a 1*1 degree grid. National Institute of Public Health and the Environment, Bilthoven.

Pochanart, P., Akimoto, H., Kinjo, Y., Tanimoto, H., 2002. Surface ozone at four remote island sites and the preliminary assessment of the exceedances of its critical level in Japan. Atmospheric Environment 36, 4235–4250.

Pochanart, P., Kato,, S., Katsuno, T., Akimoto, H., 2004. Eurasian continental background and regionally polluted levels of ozone and CO observed in northeast Asia. Atmospheric Environment 38, 1325–1336.

Ryou, M.-S., 2001. Personal communication, March 2001.

Schrope, M., 2001. UN backs transgenic crops for poorer nations. Nature 412, 109.

State Environmental Protection Agency of China, 1999. Working Handbook of Air Ambient Standards. Internal materials, Beijing, 485pp.

Streets, D.G., Waldhoff, S.T., 2000. Present and future emissions of air pollutants in China: SO_2 NO_x and CO. Atmospheric Environment 34, 363–374.

The Korean Statistical Association, 1991. Korea Statistical Yearbook 1991. The Korean Statistical Association, Seoul, Korea, 611pp.

Tingey, D.T., Hogsett, W.E., Lee, E.H., Herstrom, A.A., Azevedo, S.H., 1991. An evaluation of various alternative ambient ozone standards based on crop yield loss data. In: Bergland, R.L., Lawson, D.R., McKee, D.J. (Eds.), Tropospheric Ozone and the Environment, Journal of the Air and Waste Management Association, Pittsburgh, pp. 272–288.

Tuan, F., Hsu, H.-H., 2001. US China Bilateral WTO Agreement and Beyond. US Department of Agriculture, pp. 4. http://www.ers.usda.gov/publications/wrs012/wrs012c.pdf.

Wahid, A., Maggs, R., Shamsi, S.R.A., Bell, J.N.B., Ashmore, M.R., 1995a. Air pollution and its impacts on wheat yield in the Pakistan Punjab. Environmental Pollution 88, 147–154.

Wahid, A., Maggs, R., Shamsi, S.R.A., Bell, J.N.B., Ashmore, M.R., 1995b. Effects of air pollution on rice yield in the Pakistan Punjab. Environmental Pollution 90, 323–329.

Wang, Q., Halbrendt, C., Johnson, S.R., 1996. Grain production and environmental management in China's fertilizer economy. Journal of Environmental Management 47, 283–296.

Wang, T., Cheung, V.T.F., Anson, M., Li, Y.S., 2001. Ozone and related gaseous pollutants in the boundary layer of eastern China: overview of the recent measurements at a rural site. Geophysical Research Letters 28 (12), 2373–2376.

Westenbarger, D.A., 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.

Wild, O., Akimoto, H., 2001. Intercontinental transport of ozone and its precursors in a three-dimensional global CTM. Journal of Geophysical Research 106 (D21), 27729–27744.

Yang, Y., Tian, W., 2001. China's Agriculture at the Crossroads. St. Martin's Press, New York. pp. 297.

Zheng, Y., Stevenson, K.J., Barrowcliffe, R., Chen, S., Wang, H., Barnes, J.D., 1998. Ozone levels in Chongqing: a potential threat to crop plants commonly grown in the region. Environmental Pollution 99, 299–308.