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Evaluation of the Effect of Surface Ozone on Main Crops in East Asia: 2000, 2005, and 2020

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Abstract In this paper, the possible effect of surface ozone on soybean, wheat, rice, and maize crops in East Asia in 2000, 2005, and 2020 is estimated. Spatial distribution and temporal variation of surface ozone concentrations are simulated using the Models-3 Community Multiscale Air Quality Modeling System coupled with the Regional Emission Inventory in Asia (CMAQ/REAS). The effect of surface ozone on main crops in East Asia is evaluated based on accumulated exposure over a threshold of 40 ppb (AOT40 index) during a period of 3 months of the growing season. We demonstrate some of the implications for policy-making in air quality management for East Asia by highlighting the effect of elevated surface ozone concentrations on harvest losses and the corresponding value of the main crops. These concentrations are calculated based on three scenarios of emission reduction policies in 2020: policy success case (PSC), reference case (REF), and policy failure case (PFC). Assuming no future changes in land use or cropping patterns from 2000 to 2020, we find that the highest relative yield (RY) losses are in wheat and soybean in East Asia. The RY losses for wheat are estimated to range between 17 and 35 % in 2000, 21 and 49 % in 2005, 18 and 36 % in 2020 (PSC), 20 and 46 % in 2020 (REF), and 22 and 62 % in 2020 (PFC); the corresponding values for rice are 6 and 12 %, 6 and 17 %, 6 and 15 %, 6 and 17 %, and 7 and 20 %; for soybean, they are 12 and 16 %, 19 and 25 %, 18 and 33 %, 21 and 40 %, and 25 and 49 %; and for maize, they are 3 and 4 %, 5.7 and 6 %, 6 and 9 %, 9 and 11 %, and 12 and 14 %. Quantitatively, the estimated losses in production of wheat in East Asia in 2000, 2005, and 2020 (PSC, REF, and PFC scenarios) are 32.4, 44.3, 42.2, 54.0, and 72.3 t, respectively; for rice, 34.9, 39.4, 42.4, 46.5, and 54.6 mmt; for soybean, 1.9, 3.3, 3.6, 4.9, and 7.0 mmt; and for maize, 3.6, 8.1, 11.4, 15.4, and 21.5 mmt. The estimated values of crop losses in East Asia in 2000, 2005, and 2020 (PSC, REF, and PFC scenarios) are as follows: 13.8, 17.4, 18.2, 21.3, and 26.7 billion Int. $. Therefore, adaptation

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measures in the PSC scenario in contrast to the PFC scenario could save around 8.5 billion Int. $ across East Asian countries in 2020.

Keywords AOT40 · CMAQ · Surface ozone · REAS · Relative yield · East Asia

1 Introduction

In recent years, environmental risks caused by exposure to surface ozone from both stationary and mobile sources in East Asia have been increasing annually (Nawahda and Yamashita 2013; Nawahda et al. 2012). Kobayashi et al. (1995); Wang and Mauzerall (2004); Feng et al. (2008); Frei et al. (2008); Kuribayashi et al. (2008); Emberson et al. (2009) Van Dingenen et al. (2009); and Avnery et al. Avnery et al. (2011a, b) showed that 1–29 % of yield losses of important crops in Asia including wheat, soybean, maize, and rice, which is the most important crop in Asia, were caused by exposure to elevated concentrations of surface ozone. Ellingsen et al. (2008) found that other than in Australia, ground-level ozone already exceeds the threshold for damaging sensitive vegetation in all regions of the world, including Asia. To estimate yield losses, a quantitative relationship must be established between losses of crop yields and elevated ozone concentrations. Emberson et al. (2009) compared North American yield–response functions to the effect of ozone on wheat, rice, and soybean with Asian functions. Mills et al. (2007) established ozone yield–response functions for a wide range of crops such as wheat, rice, maize, soybean, cotton, grapes, potatoes, and sugar beet based on the AOT40 index (accumulated exposure over a threshold of 40 ppb). Quantifying the effects of surface ozone on sensitive crops based on available emission inventories and emission reduction scenarios is viewed increasingly as an efficient tool for drawing the attention of policy-makers in East Asia to this issue. This study differs from other studies of the effects of surface ozone on main crops in Asia in the following ways (see Table 1). Aunan et al. (2000) estimated crop yield losses in 1990 and 2020 based on AOT40 and SUM06 by simulating surface ozone using a global three-dimensional photochemical tracer/transport model of the troposphere in which the resolution was 8° latitude by 10° longitude. Wang and Mauzerall (2004) evaluated crop production losses and damage costs based on Model of Ozone and Related Chemicals Tracers, Version 2 (MOZART-2) coupled with the Emission Database for Global Atmospheric Research Version 2 (EDGAR v2.0) inventory for the years 1990 and 2020 using an integrated assessment approach that involved satisfying ambient air quality standards for surface ozone to examine the implications for policy-making while also evaluating the corresponding economic benefits. The resolution of their simulations was 2.8° latitude by 2.8° longitude. Also, their analysis was mainly based on different exposure indexes (M7: annual mean of the weekly averages of the daily 7-h exposure, M12: annual mean of the weekly averages of the daily 12-h exposure, SUM06: sum of the hourly concentrations above a threshold of 60 ppb in a year, and W126: sum of the hourly concentrations from 8 A.M. to 8 P.M. from May to September, with each concentration being weighted by a sigmoidal function to account for higher concentrations (Paoletti et al. 2007)). These indexes were estimated based on dose–response functions from experiments in the US and could underestimate yield losses of crops in Asia (Emberson et al. 2009). Kuribayashi et al. (2008) estimated future effects of ozone on rice yields in China based only on the dose–response function from Kobayashi et al. (1995), which considers the accumulated exposure over a threshold of 20 ppb. Van Dingenen et al. (2009) used a global model (TM5) to estimate the effect of surface ozone on soybean, wheat, maize, and rice based on AOT40, M7, and M12. Avnery et al. (2011a, b) used almost the same modeling systems as Wang and Mauzerall (2004) to estimate the effects of surface ozone on soybean, wheat, and maize based on AOT40, M7, and M12 in 2000 and 2030.

In this study, we use the AOT40 index to estimate the effect of ozone on wheat, rice, soybean, and maize crops in East Asia in 2000, 2005, and 2020 based on the response functions published by Mills et al. (2007); these functions were calculated based on a large number of dose–response functions and exposure metrics. The ozone concentrations in this study are simulated using the Models-3 Community Multiscale Air Quality Modeling System coupled with the Regional Emission Inventory in Asia (CMAQ/REAS) for the period 1980–2020 (Ohara et al. (2007) and Yamaji et al. (2008)). The resolutions of the CMAQ/REAS simulations are higher than in previous studies and REAS was the only emission inventory when this calculation was done in East Asia for the period 1980–2020 that is based on a consistent methodology and three emission scenarios for sensitivity analysis (policy success case (PSC), reference case (REF), and policy failure case (PFC)). The

Table 1 Characteristics of the modeling systems used to estimate the effect of surface ozone on crops in Asia

Reference	Models	Grid size (resolution in °×height)	Emission inventory (resolution in °)	Crops, map (resolution in °)	Metric	Simulated years
Aunan et al. (2000)	Global 3D photochemical tracer/transport model (CTM) of the troposphere	8 latitude×10 longitude×250 m	Based on RAINS-ASIA methodology: (1×1)	—Wheat, rice, soybean, maize —China map (not mentioned)	AOT40, M7, SUM06	1990, 2020
Wang and Mauzerall (2004)	MOZART-2	2.8 latitude×2.8 longitude×120 m	EDGAR v2.0: (1×1)	—Wheat, rice, soybean, maize —China, Japan, and Korea maps: different sources (not mentioned)	M7, M12, SUM06, W126	1990, 2020
Kuribayashi et al. (2008)	CMAQ/REAS	0.7 latitude×0.7 longitude×150 m	REAS: (0.5×0.5)	—Rice —AARS Asia 30-s land cover data set with ground truth information (1/120×1/120)	AOT20	2000, 2020
Van Dingenen et al. (2009)	TM5	1 latitude×1 longitude×60 m	EDGAR v3.2	—Wheat, rice, soybean, maize —Global maps (1×1)	M7, M12, AOT40	2000, 2030
Avnery et al. (2011a, b)	MOZART-2	2.8 latitude×2.8 longitude×120 m	EDGAR v2.0: (1×1) Intergovernmental Panel on Climate Change (IPCC), special report on emissions scenarios (SRES) B1 and A2 storylines	—Wheat, soybean, maize —Global maps: satellite-derived maps(1/12×1/12 regridded to 2.8×2.8)	M7, M12, AOT40	2000, 2030
This study	CMAQ/REAS	0.7×0.7×150 m	REAS: (0.5×0.5)	—Wheat, rice, soybean, maize —East Asian countries: MIRCA2000 (1/12×1/12)	AOT40	2000, 2005, 2020

following emissions are included: SO_2, NO_x, CO, nonmethane volatile organic compounds (NMVOC), black carbon (BC), and organic carbon (OC) from fuel combustion and industrial sources. Compared to the emissions of China in 2000, which affect China and the neighboring countries as well, the emissions of NO_x in China under the PSC, REF, and PFC scenarios will change by −3, 142, and 232 %, respectively. Similarly, the emissions of VOCs under PSC, REF, and PFC will change by 201, 242, and 266 %, respectively (Ohara et al. 2007). The emissions in other countries of East Asia are assumed not to be affected by the three scenarios in 2020. Additionally, we use different crop distributions based on high resolution (1/12°) and comprehensive information about rainfed and irrigated crops (RFC and IRC) in East Asia from Portmann et al. (2010). These distributions of different crops are used to estimate the 3-month AOT40 index in each grid cell based on the crop calendar in each country. Previous studies (listed in Table 1) did not mention how the crop calendar in each grid cell was estimated or how AOT40 index in each grid cell was calculated. Additionally, we estimate the relative yield (RY) loss and its monetary value for wheat, rice, soybean, and maize crops in each country within the simulation domain in East Asia in 2000, 2005, and 2020 (PSC, REF, and PFC).

The objective of this study is to help provide a better understanding of the effect of surface ozone on main crops in each country of East Asia. We also report the distributed RYs of the four crops and the corresponding values of the yield losses during all possible growing seasons in each grid cell. This information could be valuable for selecting and screening mitigation measures against the current and future emissions of ozone precursors, and it could be used to examine the effect of many reduction polices and the corresponding spatiotemporal reallocation and shifting of ozone-sensitive crops in East Asia.

2 Methodology

2.1 CMAQ/REAS-simulated Surface Ozone

The CMAQ/REAS modeling system was used to simulate the hourly surface ozone concentration in East Asia for the years 2000, 2005, and for the future emission scenarios in 2020. The simulation domain was $6,240 \times 5,440$ km^2 on a rotated polar stereographic map projection centered at 25 N, 115 E (Fig. 1). The model was driven by the meteorological field simulated by the Regional Atmospheric Modeling System (RAMS) ver. 4.4 (for the years 2000–2005). The grid resolution was 80×80 km, with 14 layers for 23 km in the sigma-z coordinate system, and the height of the first layer was 150 m, the time step of the simulation was 3 h, and the Statewide Air Pollution Research Center (SAPRC)-99 scheme for gas chemistry (including more than 214 chemical reactions) was used. The initial and boundary conditions of the RAMS were obtained from the National Center of Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR). The initial and boundary conditions had a resolution of $2.5 \times 2.5°$ and a temporal resolution of 6 h. The initial conditions of the chemical transport modeling were obtained from the Chemical AGCM for study of atmospheric environment and radiative forcing (CHASER) for the simulation period from 2000 to 2005. Kurokawa et al. (2009) discussed the validation of surface ozone simulations during springtime, which is the key ozone season in Japan; they found that the simulated surface ozone reproduced well the observed springtime-averaged surface ozone over Japan. The simulated spatial distribution of the annual mean ozone concentration is shown in Fig. 1. Detailed descriptions of this modeling system and simulations, including parameterization, meteorological inputs, emission inventory, and evaluation of the simulations, were given by Uno et al. (2005); Yamaji et al. (2006), 2008); Ohara et al. (2007); Aikawa et al. (2010); and Nawahda et al. (2012). The simulated ozone concentrations are the concentrations of the first layer of CMAQ/REAS, which has a height of 150 m above the ground surface.

2.2 Crop Distribution in East Asia

We obtained spatial distributions of RFC and IRC in East Asia with a grid cell resolution of 1/12° from the global data set of the Monthly Irrigated and Rainfed Crop Areas around the year 2000 (MIRCA2000) (Portmann et al., 2010), as shown in Fig. 2. This classification of land uses and cropping patterns is based on three major methods: remote sensing, censusing, and modeling. Documentation and the complete data sets of MIRCA2000 are available on the MIRCA2000 website.

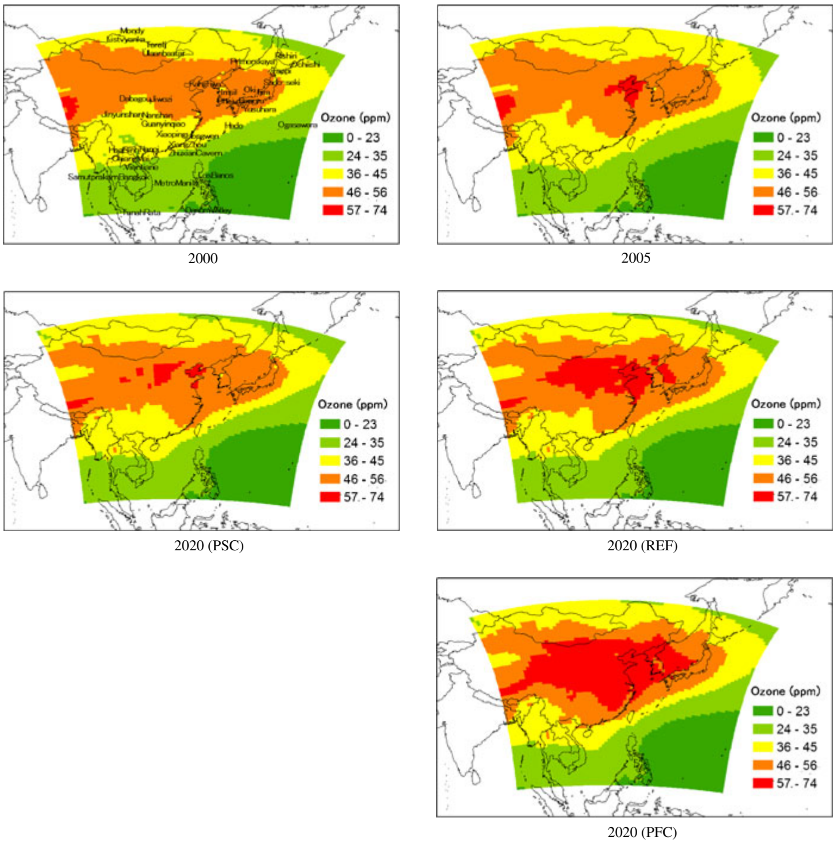


Fig. 1 Annual mean concentrations of surface ozone in East Asia in 2000, 2005, and 2020 (PSC, REF, PFC scenarios). The CMAQ simulation domain was 6,240×5,440 km^2 on a rotated polar stereographic map projection centered at 25 N, 115 E, with a grid size of approximately 80×80 km in the ground surface layer, which was 150-m thick. *Solid circles* in the ozone (2000) map are the locations of the monitoring sites of the Acid Deposition Monitoring Network in East Asia (EANET) (EANET 2010)

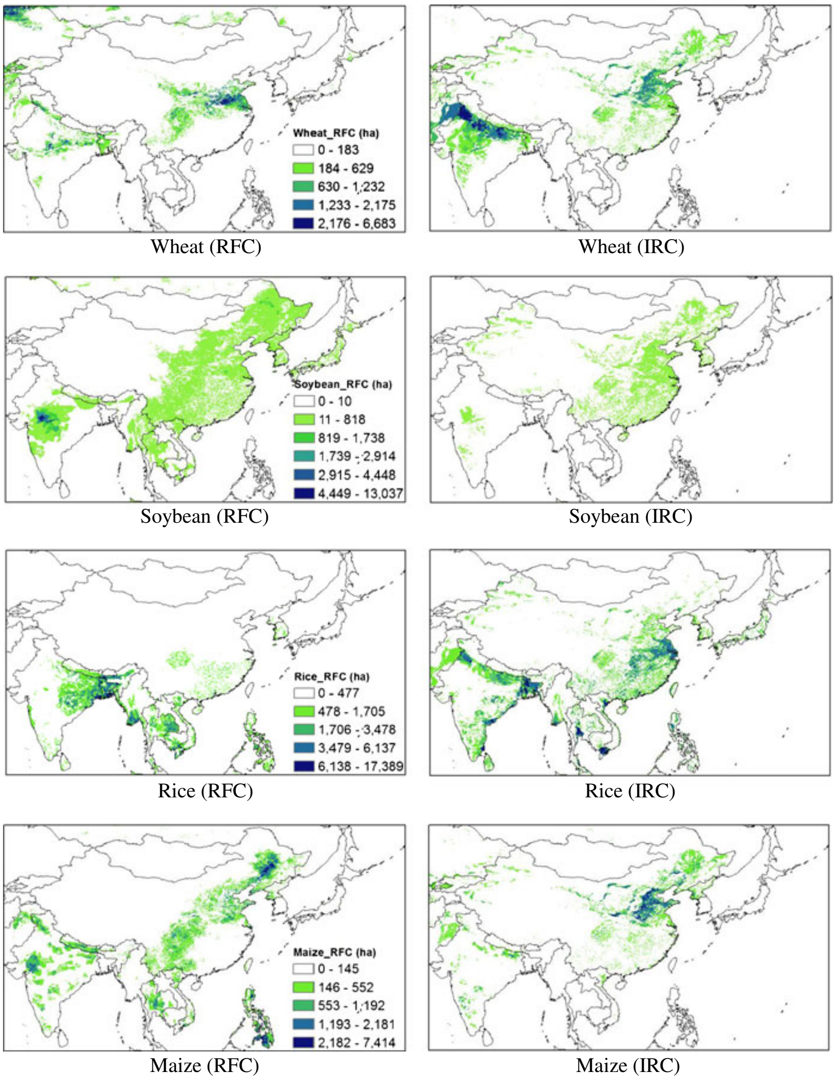
2.3 Effect of Surface Ozone on Crops: AOT40 Calculation

Seasonal distributions of the AOT40 index were calculated by summing the hourly concentrations of the surface ozone above 40 ppb from 6:00 A.M. to 8:00 P.M over a period of 3 months for all possible growing seasons of main crops in East Asia as follows:

$$\mathrm{AOT40_{CJ}} = \sum\nolimits_{i=1}^{n} [\mathrm{C(O_3)} - 40]_i \text{ for } \mathrm{C(O_3)} > 40\,\mathrm{ppb} \tag{1}$$

where CJ is the growing season number, n is the number of hours when $C(O_3)$ exceeds 40 ppb, and $C(O_3)$ is the hourly concentration of surface ozone. However, since the CMAQ/REAS simulations output data in 3-h time steps, we assumed a uniform distribution of the surface ozone concentration during each time step. Also, we assumed that the spatial distribution of main crops does not change from 2000 to 2020. The growing seasons, which cover the period from planting to ripening, differ by region in East Asia as discussed by Wang and Mauzerall (2004) and also as shown in the reports of the United States Department of Agriculture/Foreign Agricultural Service (USDA/FAS) (2010) and the country briefs published by the Food and Agriculture Organization (FAO) and the Global Information and Early Warning System on food and agriculture (GIEWS: http://www.fao.org/giews/countrybrief/). For example, in Japan, the growing season of rice crops extends over the period from April to October. The main rice season in northern Japan lasts from May–June to September–October. In central Japan, it is from April–May to August–October. In southern Japan, the rice season is from April–May to August–September (FAO 2004). The growing seasons for wheat, soybean, maize, and rice crops in East Asia extend over the

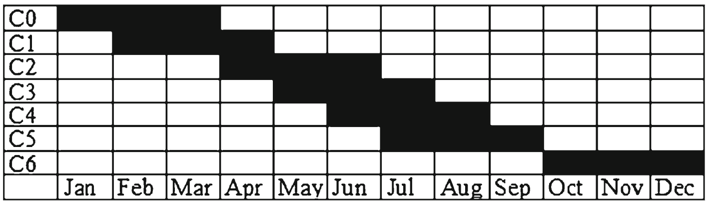
Fig. 2 Distribution of sown areas of wheat, soybean, rice, and maize in East Asia from MIRCA2000 (*IRC* irrigated crops, *RFC* rainfed crops)



period from January to December. Therefore, we performed the following analysis based on the USDA handbook no. 664 (1994) "Major world crop areas and climate profiles" and country briefs by GIEWS: we assumed the following possible cases in order to consider different growing seasons (CJ); C0 (Jan, Feb, Mar), C1 (Feb, Mar, Apr), C2 (Apr, May, Jun), C3 (May, Jun, Jul), C4 (Jun, Jul, Aug), C5 (Jul, Aug, Sep), and C6 (Oct, Nov, Dec). Figure 3 shows the countries in East Asia and all possible CJs of main crops selected based on data availability (land use, yield, and prices from FAO) and ozone sensitivity. Owing to limited information about the spatial distribution and temporal variation of the growing seasons of main crops in each country in East Asia, the same seven CJs were assigned for grid cells with RFC and IRC crops, based on the country briefs by GIEWS within the boundaries of each country. Accordingly, the seven distributions of the AOT40 index were calculated for the whole simulation domain and then overlaid on both the RFC and IRC crop distributions in Fig. 2 to estimate the effect of surface ozone on each crop. This only estimates the effects in applicable grid cells. Subsequently, based on the information about the CJs of main crops in each country, the calculated distributions of RYs of

Fig. 3 Crop calendar of main crops in East Asia and the possible 3-month periods for calculating the AOT40 index

Country	Wheat	Rice	Maize	Soybean
South Korea	C1	C5	C4	
Philippines		C6,C0	C4,	
Myanmar	C0	C5,C0	C0	
Lao		C5,C0	C4,C2	
Japan	C1	C4		C4
North Korea	C1	C5	C4	C4
China	C1,C3	C2,C4,C5	C2,C4	C4
Cambodia		C0,C6	C4	C4
Mongolia	C3			
Vietnam		C0,C2,C4,C6	C4,C2	
Bangladesh	C0	C0, C2,C5		
Bhutan	C0	C0, C2,C5	C4	
Thailand		C5,C0	C4	



each crop were selected for further analysis in the next section.

2.4 Exposure and RY Analysis

We estimated the distributions of the RYs of main crops, based on the relationships of the AOT40 index by Mills et al. (2007) shown in Table 2. The critical levels in this table are the lowest levels of the AOT40 index at which a tangible impact (5 % yield reduction) could be observed. We developed a computer program by using Intel Fortran to read the distributed hourly concentrations of surface ozone, which were simulated by the CMAQ/REAS modeling system and then calculated the AOT40 index in each grid cell based on the growing seasons shown in Fig. 3. The Arc-GIS system was used to implement the relationships in Table 2 and, thus, to estimate the distributed RYs in the sown lands of main crops based on the AOT40 index value in each grid cell within the simulation domain of CMAQ/REAS.

2.5 Economic Evaluation of Yield Losses

The yield losses of main crops in East Asia in 2000, 2005, and 2020 were estimated based on the FAO database (FAO, 2005) for the period from 2000 to 2010. It includes annual productions and the corresponding monetary values of main crops in each country; for 2020, the data from 2010 or the most recently available value was used. Of course, these prices do not consider changes that would take place in production and market; however, these prices serve as a convenient metric for comparing crop loss with other costs of pollution. The damage cost was estimated by multiplying the monetary value by (1−RY). To deal with multicropping, the calculated RYs of IRC and RFC crops were taken as the mean value of RYs of the crops that are grown during different seasons at the same place. However, since we did not have enough information about the spatial distribution of the yields of main crops and their prices, we calculated the RY

Table 2 AOT40-based yield–response functions and the corresponding critical levels (Mills et al. 2007). RY is the relative yield, x is the AOT40 in ppm h, and r^2 is the regression coefficient

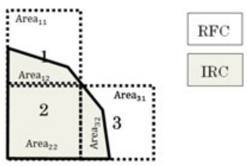
Crop	Yield–response function	Critical level (ppm h)
Wheat	$RY = -0.0161x + 0.99(r^2 = 0.89)$	3.3
Soybean	$RY = -0.0116x + 1.02(r^2 = 0.61)$	4.3
Rice	$RY = -0.0039x + 0.94(r^2 = 0.2)$	12.8
Maize	$RY = -0.0036x + 1.02(r^2 = 0.35)$	13.9

for each country as illustrated by the following example of a crop in one of the CJ seasons in country x. RY_x is estimated using the distributed RYs in each grid cell (RY_{grid}), the sown area with both IRC and/or RFC crops in each grid cell ($Area\_IRC_{grid}$ and/or $Area\_RFC_{grid}$), and the total sown area with IRC and RFC crops in x (Area_IRC+Area_RFC) as follows:

$$RY_{x,CJ} = \left\{ \sum \left(RY_{grid\_IRC} \times Area\_IRC_{grid} \right) + \sum \left(RY_{grid\_RFC} \times Area\_RFC_{grid} \right) \right\} / (Area\_IRC + Area\_RFC). \qquad (3)$$

Equation 3 gives an area-representative RY as illustrated in Fig. 4, and it is based on the idea that in a country (x), there could be areas (grid cells) for RFC and IRC, where the ozone concentration is not the same, and using the functions from Table 2, could give different RY values. Also, the same area could be designated for both IRC and RFC crops; in this case, the calculated RY will be the same during the same season. In the case of countries where there are several cropping seasons, such as rice crops in China and Vietnam, the averages of the RYs are considered for estimating the country-representative RY values for each IRC and RFC crop.

According to the FAO-Statistics Division (FAOSTAT 2012), the International Dollar Prices (Int. $) are the world average prices converted to a common currency, i.e., the US dollar, using purchasing power parities (PPPs) instead of exchange rates. International prices and PPPs are obtained by solving a system of Geary–Khamis simultaneous equations (Chatterji and Gangopadhyay 2005). Thus, international prices are not representative of price levels in a single country but are useful for international comparisons and aggregations. Furthermore, international prices are compiled for the index reference period only, currently the 2004–2006 3-year average, which precedes the 2008 increases. We use the Arc-GIS system to evaluate Eq. 3 based on the crop distributions in Fig. 2. and to draw the



$$RY = \frac{RY_{11}Area_{11} + RY_{12}Area_{12} + RY_{22}Area_{22} + RY_{31}Area_{31} + RY_{32}Area_{32}}{Area_{11} + Area_{12} + Area_{22} + Area_{31} + Area_{32}}$$

Fig. 4 Calculation method of the country representative RY using Eq. 3, *shaded areas* are IRC areas (subscript 2), and *clear areas* are RFC areas (subscript 2)

distributions of the estimated RYs in all possible growing seasons of the four crops in East Asia.

3 Results

3.1 AOT40 Index

Figure 5 shows the AOT40 index variations in 2000 and 2020 (PFC) based on the seven cases of the 3-month AOT40 index values. The AOT40 index distributions in 2020 (PFC) in Fig. 5 indicate that the highest AOT40 values are expected at midlatitudes. Additionally, it shows possible changes from the year 2000 to 2020 based on different CJs in Asian countries. In the southern countries of East Asia, the ozone-sensitive crops such as wheat and soybean are not strongly affected by surface ozone, owing to its low concentration there.

3.2 RY Losses

RY distributions of both IRC and RFC crops were calculated based on the possible seven cases of the 3-month AOT40 index values. Figure 6 shows a sample of the RY distributions of the most sensitive crops (wheat and soybean) in 2020 in East Asia.

The yield losses in metric tons (t) and corresponding monetary values for wheat, rice, soybean, and maize crops in East Asia, which are likely to be affected by elevated concentrations of surface ozone, are summarized in Tables 3, 4, 5, and 6, respectively. Detailed descriptions of these tables are provided in the Supplementary Materials. The country-representative RY values for both RFC and IRC crops in these tables are calculated using Eq. 3.

From the data in Tables 3, 4, 5, and 6, and in Fig. 7, China, North and South Korea, and Japan are expected to have the lowest RYs of main crops in East Asia. The RY of the RFC-soybean crop in the C4 growing

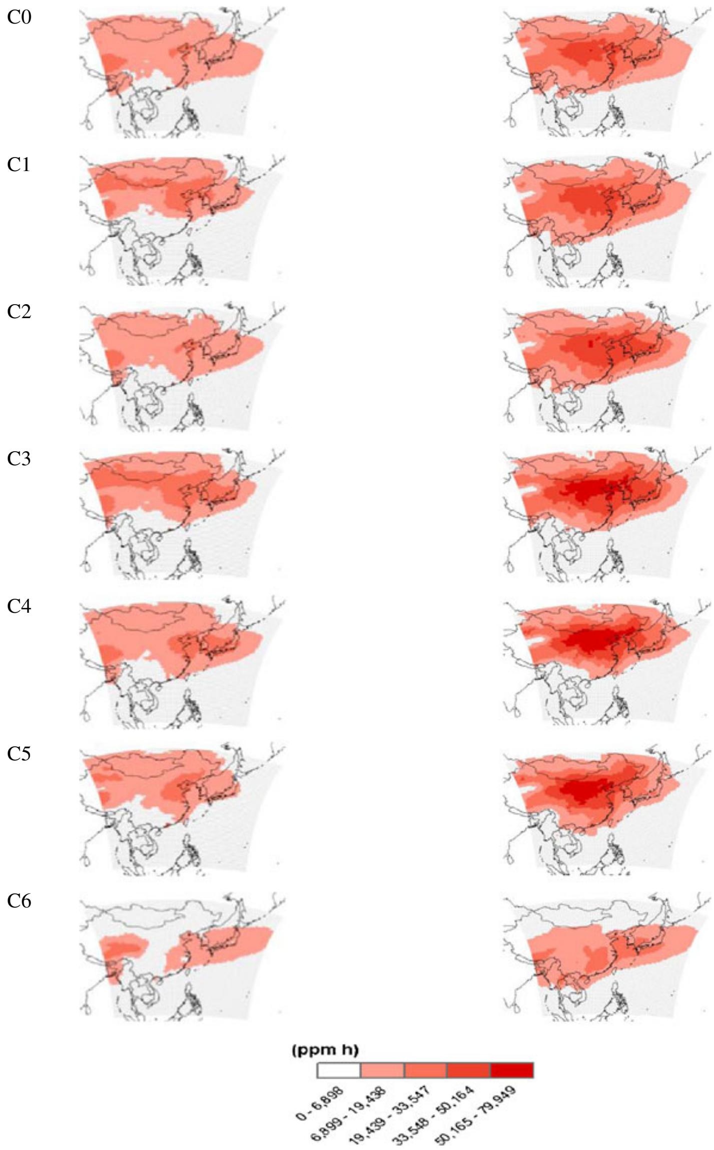


Fig. 5 Distributed AOT40 (ppm h) in 2000 (*left*) and 2020 (PFC scenario) (*right*) based on the following seven periods: C0 (Jan–Mar), C1 (Feb–Apr), C2 (Apr–Jun), C3 (May–Jul), C4 (Jun–Aug), C5 (Jul–Sep), and C6 (Aug–Oct)

season decreases from 90 % in 2000 to 60 % in 2020-PFC, which is the worst-case scenario, and it decreases from 85 to 56 % for the IRC-soybean crop during the same period. The IRC-wheat crop in the C3 growing season was found to be the most affected crop and showed the most damage; the RY decreased from 65 % in 2000 to 28 % in 2020-PFC. Quantitatively, the highest losses of harvest are expected to be in wheat and rice crops in China. The mitigation measures based on PSC as compared to PFC in 2020 could save 30, 11.4, 10, and 3.3 t of wheat, rice, maize, and soybean crops, respectively. The associated monetary values of these losses are about 4.3, 2.8, 0.6, and 0.7 billion Int. $, respectively.

In Japan, the IRC-wheat crop in the C1 growing season and the RFC-soybean crop in the C4 growing season are expected to be most affected, as the RYs of these crops decreased from 77 and 86 % in 2000 to 66 and 75 % in 2020-PFC, respectively. The mitigation measures based on PSC as compared with PFC in 2020 could save 61,400, 215,000, and 14,300 mt of wheat, rice, and soybean crops, respectively, which

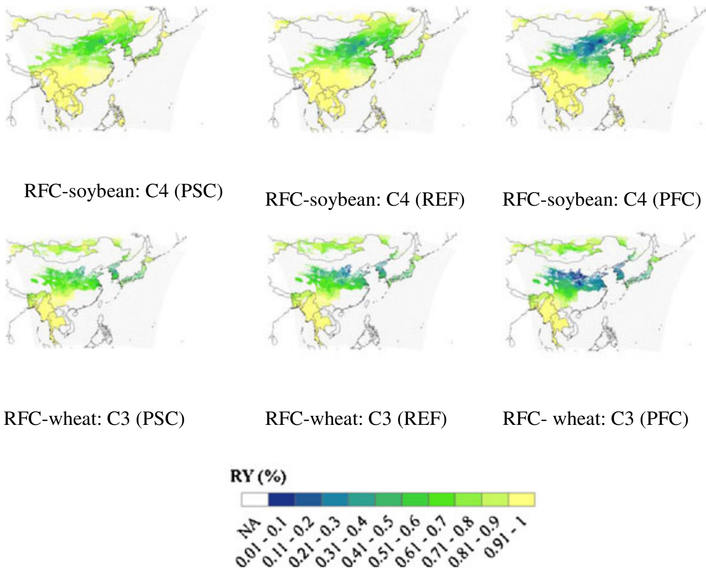


Fig. 6 Distribution of relative yields of RFC-soybean and RFC-wheat crops in East Asia for the 2020 PSC, REF, and PFC scenarios

would cost about 4.4, 60, and 5.7 million Int. $ (in US $ and not Int. $ for soybean only), respectively.

In North Korea, the RYs of both RFC- and IRC-wheat and soybean crops decreased from 65 and 84 % in 2000 to 49 and 51 % in 2020-PFC in the C1 and C4 growing seasons, respectively. The highest losses of harvest are expected to be in rice and maize crops. Mitigation measures based on PSC relative to PFC in 2020 could save 25,315, 111,421, 85,871, and 57,417 t of wheat, rice, maize, and soybean crops, respectively. The associated monetary values of these losses are about 3.5, 27.4, 8.5, and 14.7 million Int. $, respectively.

In South Korea, the RYs of the RFC wheat crop decreased from 70 % in 2000 to 53 % in 2020-PFC in the C1 growing season. However, the highest harvest losses are expected to be for the rice crop because areas sown with wheat are minuscule. Adaptation measures based on PSC in comparison to PFC in 2020 could save 778 and 170,438 t of wheat and rice crops, respectively. The associated monetary values of these losses are about 0.107 and 47.133 million Int. $, respectively.

The RYs of wheat crops in other countries are expected to decrease from 76 % in 2000 to 75 % in 2020-PFC in Bangladesh and from 80 to 75 % in Bhutan for the same years. However, in Mongolia, the RY of the wheat crop increased from 74 % in 2000 to 78 % in 2020-PFC in the C3 growing season (Fig. 7). This was to be expected because the wheat crop is mainly sown in northern parts of Mongolia (Fig. 3) and the simulated surface ozone concentrations there decrease from 2000 to 2020 (PFC), as shown in Fig. 1. The mitigation measures following PSC in comparison to PFC in Mongolia could save 13,856 t of wheat, which would cost about 1.8 million Int. $. However, in Bangladesh and Bhutan, similar mitigation measures do not improve the RY of the wheat crop.

The RYs calculated based on Eq. 3 for rice crops in other Asian countries (South Korea, the Philippines, Myanmar, Laos, Cambodia, Vietnam, Bangladesh, Bhutan, and Thailand) were almost the same or decreased by 0–6 % from 2000 to 2020-PFC, as shown in Fig. 6. Accordingly, the mitigation measures based on PSC relative to PFC in 2020 in South Korea, the Philippines, Myanmar, Laos, Cambodia, Vietnam, Bangladesh, Bhutan, and Thailand could save 170,438, 37,024, 39,511, 15,945, 15,487, 186,926, 5,676, 12, and 67,267 t of rice, respectively. The harvest losses and corresponding values of main crops in all of the countries in East Asia within the CMAQ/REAS domain are summarized in Tables 7 and 8.

4 Discussion

Our estimations of the effect of surface ozone on the RYs of main crops in East Asia are conservative, since

Table 3 Estimated relative yields of wheat crops and the corresponding yield losses and monetary valuations in East Asia (RFC: rainfed crops, IRC: irrigated crops, RY: relative yield)

Crop	Year (+2000)	RY_RFC (%)	RY_IRC (%)	Damages	
				Monetary value (Int. $1,000)	Harvest (MT)
	2000	73	66	4,564,346	31,800,692
	2005	60	53	6,307,007	43,743,733
China	2020_S	67	62	5,912,735	41,690,944
	2020_R	57	52	7,573,585	53,401,663
	2020_F	39	37	10,168,526	71,698,703
	2000	85	77	6,031	117,853
	2005	80	70	13,813	202,743
Japan	2020_S	82	73	12,859	180,806
	2020_R	80	70	14,627	205,666
	2020_F	76	66	17,225	242,198
	2000	65	65	2,671	33,780
	2005	50	51	13,007	94,842
North Korea	2020_S	64	65	7,798	56,689
	2020_R	58	58	9,307	67,659
	2020_F	49	49	11,281	82,004
	2000	70		137	1,733
	2005	60		318	2,320
South Korea[1]	2020_S	66		273	1,981
	2020_R	61		318	2,305
	2020_F	53		381	2,759
	2000	74	77	4,511	36,139
	2005	75	77	1,722	18,035
Mongolia	2020_S	82	86	8,107	62,179
	2020_R	75	85	8,836	67,773
	2020_F	78	84	9,913	76,035
	2000	77	76	64,672	427,855
	2005	76	75	36,196	241,243
Bangladesh	2020_S	76	75	33,688	222,809
	2020_R	76	75	33,694	222,850
	2020_F	76	75	33,711	222,964
	2000	80	81	124	858
	2005	79	79	361	2,401
Bhutan	2020_S	75	76	167	1,125
	2020_R	75	76	168	1,126
	2020_F	75	76	168	1,127

our analysis are based on dose/exposure–response functions from Europe and the United States and do not consider future development of agricultural practices and land use changes between 2000 and 2020 in which ozone-sensitive crops could be planted based on elevated surface ozone concentrations. On the other hand, quantifying the distributed crop yield is not easy because it depends on agricultural practices and field management as well as fertilizers and pesticides employed. However, our results show that the RYs of ozone-sensitive crops are decreasing annually in areas with high AOT40 indexes. Our estimates of the

Table 4 Estimated relative yields of rice crops and the corresponding yield losses and monetary valuations in East Asia (RFC: rainfed crops, IRC: irrigated crops, RY: relative yield)

Crop	Year (+2000)	RY_RF C (%)	RY_IRC (%)	Damage	
				(Int. $1,000)	(MT)
	2000	91	88	5,305,675	22,186,069
	2005	89	86	6,153,356	24,657,015
China	2020_S	90	87	6,316,423	25,544,319
	2020_R	88	85	7,308,153	29,554,985
	2020_F	85	81	9,126,168	36,907,242
	2000		87	437,222	1,578,328
	2005		86	436,655	1,574,057
Japan	2020_S		87	391,125	1,409,845
	2020_R		86	414,083	1,492,597
	2020_F		85	450,638	1,624,364
	2000	88	88	49,776	203,841
	2005	83	83	106,840	433,625
North Korea	2020_S	85	85	89,530	363,633
	2020_R	83	83	101,234	411,168
	2020_F	80	80	116,964	475,054
	2000	89	89	224,319	810,937
	2005	87	87	238,496	862,205
South Korea	2020_S	86	86	218,787	791,165
	2020_R	85	85	237,546	859,002
	2020_F	84	83	265,920	961,603
	2000	94	92	221,006	855,838
	2005	94	92	263,856	1,019,252
Philippine	2020_S	94	91	307,698	1,166,715
	2020_R	94	91	299,775	1,136,674
	2020_F	94	91	317,462	1,203,738
	2000	93	93	346,366	1,431,317
	2005	93	93	450,998	1,855,146
Myanmar	2020_S	93	93	559,204	2,280,288
	2020_R	93	93	560,142	2,284,117
	2020_F	93	93	568,893	2,319,799
	2000	93	93	35,085	146,402
	2005	93	93	41,300	172,338
Laos	2020_S	93	93	53,001	221,162
	2020_R	93	93	53,304	222,425
	2020_F	92	92	56,822	237,108
	2000	94	94	65,040	246,601
	2005	94	94	101,046	378,204
Cambodia	2020_S	94	94	142,043	530,855
	2020_R	94	94	139,562	521,584
	2020_F	93	93	146,187	546,342
	2000	93	94	566,017	2,115,845
	2005	93	93	672,515	2,513,948

Table 4 (continued)

Crop	Year (+2000)	RY_RF C (%)	RY_IRC (%)	Damage	
				(Int. $1,000)	(MT)
Vietnam	2020_S	93	93	737,532	2,756,989
	2020_R	93	93	727,082	2,717,926
	2020_F	93	93	787,537	2,943,915
	2000	90	90	1,010,870	3,679,740
	2005	90	90	1,098,989	3,996,961
Bangladesh	2020_S	90	90	1,411,595	5,126,943
	2020_R	90	90	1,411,956	5,128,252
	2020_F	90	90	1,413,158	5,132,619
	2000	91	91	1,044	4,036
	2005	91	91	1,654	6,321
Bhutan	2020_S	90	89	1,732	6,605
	2020_R	90	89	1,732	6,607
	2020_F	90	89	1,735	6,618
	2000	94	94	422,745	1,658,968
	2005	93	94	491,432	1,962,683
Thailand	2020_S	93	93	544,571	2,174,452
	2020_R	93	93	546,225	2,181,058
	2020_F	93	93	561,417	2,241,719

Table 5 Estimated relative yields of soybean crops and the corresponding yield losses and monetary valuations in East Asia (RFC: rainfed crops, IRC: irrigated crops, RY: relative yield)

Crop	Year (+2000)	RY_RFC (%)	RY_IRC (%)	Damage	
				(Int. $1,000)	(MT)
	2000	90	85	392,831	1,836,510
	2005	83	77	632,569	3,122,821
China	2020_S	79	77	705,484	3,482,783
	2020_R	72	69	957,025	4,724,575
	2020_F	60	56	1,365,829	6,742,729
	2000	84	84	14,272	55,861
	2005	75	74	21,588	84,683
North Korea	2020_S	67	68	29,360	114,917
	2020_R	60	61	35,397	138,547
	2020_F	51	51	44,029	172,334
	2000	86		5,961	32,399
	2005	79		11,303	47,293
Japan	2020_S	82		16,707	41,768
	2020_R	79		18,919	47,298
	2020_F	75		22,425	56,061

Table 6 Estimated relative yields of maize crops and the corresponding yield losses and monetary valuations in East Asia (RFC: rainfed crops, IRC: irrigated crops, RY: relative yield)

Crop	Year (+2000)	RY_RFC (%)	RY_IRC (%)	Damage	
				(Int. $1,000)	(MT)
	2000	98	95	50,498	3,602,561
	2005	96	93	316,538	8,017,439
China	2020_S	95	92	646,898	11,271,827
	2020_R	93	90	875,671	15,258,056
	2020_F	90	86	1,218,603	21,233,452
	2000	96	96	4,605	37,129
	2005	94	94	11,708	103,358
North Korea	2020_S	91	91	14,667	148,394
	2020_R	89	89	18,160	183,731
	2020_F	86	86	23,155	234,265

RY of each crop could be improved by providing a spatial and temporal crop calendar for East Asia as well as by considering the effects of climate change and other air pollutants such as particulate matter. Additional necessary information such as the spatial and temporal distributions of the yield factor (tons per hectare) could improve our results. Wang and Mauzerall (2004) estimated that yield losses in China in 2020 for wheat (2–63 %), rice (8–10 %), maize (16–64 %), and soybean (33–45 %) based on three different metrics, which then produced completely different estimates, as shown in Fig. 8. Our estimates of the RY losses of main crops in China are close to those of Wang and Mauzerall (2004), except for maize. Wang and Mauzerall (2004) estimated crop production losses of main crops in China to be 47.4 Mt. These estimates are less than ours for 2020-REF (103 Mt). The reason for the difference between the two values is mainly because Wang and Mauzerall (2004) used crop production in 1990 to evaluate the losses in 2020, whereas we used recent information, e.g., 2009 and later. Additionally, we compared the yield losses of

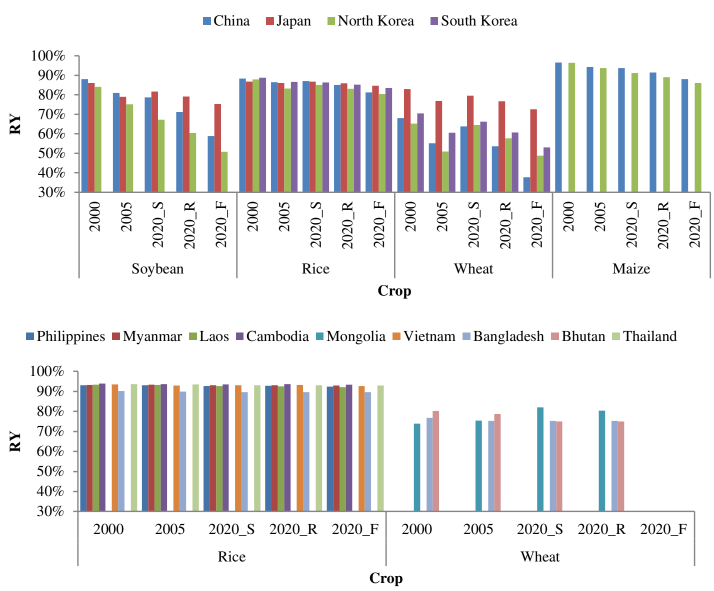


Fig. 7 Relative yields of main crops in East Asia for the years 2000, 2005, 2020_PFC (F), 2020_REF (R), and 2020_PSC (S)

Table 7 Summary of total harvest losses and corresponding values of main crops in East Asia within the CMAQ/REAS simulation domain

	Crop					
Year		Rice	Wheat	Soybean	Maize	Total
2000	(Int. $×1,000)	8,685,165	4,642,492	413,065	55,102	13,795,687
	(MT)	34,917,920	32,418,911	1,924,770	3,639,689	72,899,557
2005	(Int. $×1,000)	10,057,136	6,372,423	665,460	328,246	17,422,947
	(MT)	39,431,753	44,305,317	3,254,796	8,120,796	95,110,343
2020 (PSC)	(Int. $×1,000)	10,773,244	5,975,628	751,551	661,565	18,161,720
	(MT)	42,372,982	42,216,534	3,639,468	11,420,221	99,647,265
2020 (REF)	(Int. $×1,000)	11,800,716	7,640,535	1,011,341	893,830	21,346,098
	(MT)	46,516,107	53,969,043	4,910,420	15,441,787	120,835,010
2020 (PFC)	(Int. $×1,000)	13,812,900	10,241,205	1,432,283	1,241,757	26,727,765
	(MT)	54,600,119	72,325,791	6,971,125	21,467,717	155,361,993

rice crops in China with the findings of Kuribayashi et al. (2008), who based their analysis on different yield–response functions using the same CMAQ/REAS simulations of surface ozone and their estimates of the yield losses of the rice crop in China were 6.4, 6.7, 7.6, and 9.3 % in 2000 and 2020 (PSC, REF, and PFC), respectively. The values in this study were almost twice their estimates (12, 13, 15, and 19 %), which was mainly due to the different yield–response function used. However, the RY loss based on the AOT40 index calculated by Avnery et al. (2011a) for wheat (15–20 %), soybean (20–25 %), and maize (2–4 %) in China differs from our findings, especially for the RY loss of soybean, which is almost twice the value we estimated. The main reasons of this discrepancy are considered to be the model resolution and the used crop calendar. The calculation of yield loss with coarse resolution tends to be overestimated, and deferent crop calendars for spring wheat and winter wheat lead to other results even though the information on the crop calendar in China is limited (Sacks et al. 2010).

Table 8 Summary of total harvest losses of main crops (rice, wheat, soybean, and maize) in East Asian countries within the CMAQ/REAS simulation domain

Country	Year				
	2000 (Int. $×1,000)	2005 (Int. $×1,000)	2020 (PSC) (Int. $×1,000)	2020 (REF) (Int. $×1,000)	2020 (PFC) (Int. $×1,000)
China	10,313,350	13,409,470	13,581,540	16,714,433	21,879,126
Japan	449,214	461,770	420,691	447,629	490,288
North Korea	71,324	153,144	141,355	164,098	195,428
South Korea	224,456	238,814	219,061	237,865	266,300
Philippines	221,006	263,856	307,698	299,775	317,462
Myanmar	346,366	450,998	559,204	560,142	568,893
Laos	35,085	41,300	53,001	53,304	56,822
Cambodia	65,040	101,046	142,043	139,562	146,187
Mongolia	4,511	1,722	8,107	8,836	9,913
Vietnam	566,017	672,515	737,532	727,082	787,537
Bangladesh	1,075,542	1,135,185	1,445,283	1,445,650	1,446,869
Bhutan	124	361	167	168	168
Thailand	422,745	491,432	544,571	546,225	561,417

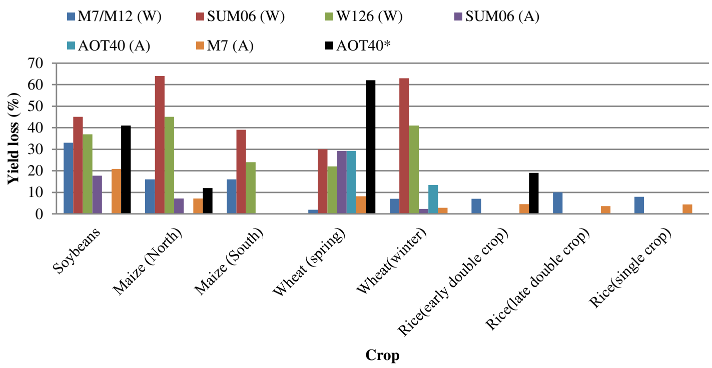


Fig. 8 The estimated yield losses of main crops in China in 2020 for the 2020 PFC scenario, without classification of crops based on growing season or location. Estimates are based on different indexes from Wang and Mauzerall (2004) (W), Aunan et al. (2000) (A), and this study (AOT40*)

For Japan, Wang and Mauzerall (2004) estimated the RY losses of wheat (8.7–16 %) and rice (5.3 %) in 2020. These estimates are almost one-third of ours. However, their value of the yield loss in the soybean crop (25–32 %) is similar to our results. The crop production losses of the main crops in Japan estimated by Wang and Mauzerall (2004) were 0.8 Mt, which is less than our estimate (1.8 Mt). Also, for South Korea, they estimated a RY loss for rice crop (4 %) that was almost one-third of our value. Aunan et al. (2000) estimated the RY loss (13.4–29.3 %) of the wheat crop in China in 2020 based on the AOT40 index (Fig. 8). Their estimates are almost half the size of ours. The differences between the previously published RYs of main crops in East Asia and our results are for the following reasons: different modeling systems coupled with different emission inventories, different land use data, and different yield–response functions with higher thresholds (in the case of Wang and Mauzerall (2004)). There might be underestimations in their results because the horizontal resolution in their modeling system (Wang and Mauzerall (2004): 2.8×2.8°; Aunan et al. (2000): 8×10°) was greater than the grid size of the CMAQ/REAS modeling system (0.7×0.7°). Thus, elevated concentrations of surface ozone hardly appeared in those coarser resolutions. On the other hand, our results are close to the estimated RY losses of the wheat crop from 1980 to 2007 (29 %; CI: 24–34 %) determined by Feng et al. (2008) based on a meta-analysis.

4.1 Uncertainty

We think that uncertainty in our estimates of the RY losses of main crops, which are caused by exposure to elevated concentrations of surface ozone in East Asia, and their monetary valuation is moderate. In addition to the usual large uncertainties in global environmental risk assessments, which were discussed by Wang and Mauzerall (2004) and Aunan et al. (2000), we will discuss other uncertainties in our treatment in the following.

4.2 Yield–Response Function

Assessing the effect of surface ozone on crops in East Asia based on the AOT40 yield–response functions in Table 2 (Mills et al. 2007) involves considerable uncertainties, especially with respect to the rice and maize crops, which have the lowest regression coefficients, for the following two reasons: (1) these functions were derived for different types of crops under optimum growing conditions and (2) these functions were developed mainly based on the conditions and the environment of European agricultural lands. Thus, more experimental work must be conducted to assess the actual RY losses in East Asia because: (1) crops in East Asia are likely to be affected by surface ozone as well as other air pollutants such as SO_2 Emberson et al. (2009) and (2) different meteorological conditions strongly affect the stomatal activity of the crops (Aunan et al. 2000).

4.3 Land Use Change and Crop Calendar

The assumption of no change in land use and field management practices from the year 2000 to the year 2020 in our analysis could affect the total yields because of the rapid development in these practices in East Asia. On the other hand, there is no available information about the spatial distribution of crop calendars of main crops in East Asia. Therefore,

Table 9 Production of rice and wheat crops in China from 2006 to 2010

Year	Rice		Wheat	
	Production (Int. $1,000)	Production (MT)	Production (Int. $1,000)	Production (MT)
2010	48,759,651	197,212,010	16,169,704	115,181,303
2009	48,611,727	196,681,170	16,324,971	115,115,364
2008	47,798,879	193,284,180	15,988,727	112,464,292
2007	46,462,225	187,397,460	15,525,479	109,298,296
2006	45,035,093	183,276,050	15,578,806	108,466,271
Average	47,333,515	191,570,174	15,917,537	112,105,105
% of 2010 price/average−1	3	3	2	3

considering only seven possible growing seasons in East Asia could have slightly affected our results. Attempts to estimate the distributed crop calendar based on flowering dates of certain crops such as wheat (Carver 2009) are not practical for estimating the 3-month period for calculating the AOT40 index, which takes the value of 60 according to the Zadoks scale (Zadoks et al. 1974). Additionally, the flowering date of a crop depends on meteorological conditions and crop phenology.

4.4 Monetary Valuation of Crop Losses

Estimated monetary valuation of the harvest losses of main crops in East Asia in our analysis contains uncertainties, as we assumed fixed annual prices based on information from the FAOSTAT database. Prices of main crops change monthly, as can be seen in the annual reports of the Ministry of Agriculture Forest and Fishers in Japan (MAFF 2008). Furthermore, assuming the future prices of main crops in 2020 based on recent prices is also highly uncertain, as prices fluctuate annually. Assuming higher prices for crops owing to the increased demand of growing populations and economies in the future, we expect greater monetary losses associated with the main crops in East Asia than those estimated in this study.

Despite these uncertainties, this study gives an estimate of the large magnitude of the growing threat caused by exposure to surface ozone in the midlatitude countries in East Asia and of the efficacy of adopting a mitigation policy in China to reduce crop losses in China as well as the surrounding countries. There is still uncertainty in the monetary valuation of yield losses of main crops in 2020 because of year-to-year price fluctuations in recent years. Using an average across several years could be more robust, as shown in Table 9, for the case of rice and wheat crops in China, but there will always be levels of unavoidable uncertainty as prices are increasing, in general.

5 Conclusions

Assessing the effects of surface ozone on the RYs of main crops in East Asia from 2000 to 2020 involves unique challenges in a region that is experiencing rapid urbanization with inadequate information about emissions, crop yields, and crop calendars, and with large uncertainties in the model. Our results are based on simulations of surface ozone from 2000 to 2020 using the CMAQ/REAS modeling system and show that surface ozone emissions in East Asia could affect main crops such as wheat, rice, maize, and soybean. Assuming no change in field management practices from 2000 to 2020, we found that China, North Korea, and Japan could face the highest RY losses of main crops in 2000, 2005, and 2020 (PFC, REF, and PSC scenarios) compared to other Asian countries within the CMAQ/REAS simulation domain. The RY losses for wheat were estimated to range between 17 and 35 % in 2000, 21 and 49 % in 2005, 18 and 36 % in 2020 (PSC), 20 and 46 % in 2020 (REF), and 22 and 62 % in 2020 (PFC); for rice, between 6 and 12 %, 6 and 17 %, 6 and 15 %, 6 and 17 %, and 7 and 20 %; for soybean, between 12 and 16 %, 19 and 25 %, 18 and 33 %, 21 and 40 %, and 25 and 49 %; and for maize, between 3 and 4 %, 5.7 and 6 %, 6 and 9 %, 9 and 11 %, and 12 and 14 %. Quantitatively, the estimated losses in the yields of wheat in East Asia in

2000, 2005, and 2020 (PSC, REF, and PFC scenarios) were found to be 32.4, 44.3, 42.2, 54.0, and 72.3 Mt, respectively; for rice, 34.9, 39.4, 42.4, 46.5, and 54.6 t; for soybean, 1.9, 3.3, 3.6, 4.9, and 7.0 t; and for maize, 3.6, 8.1, 11.4, 15.4, and 21.5 t. Additionally, the estimated values of the losses in the yield of main crops in East Asia in 2000, 2005, and 2020 (PSC, REF, and PFC scenarios) were found to be 13.8, 17.4, 18.2, 21.3, and 26.7 billion Int. $, respectively. Therefore, adaptation measures against PFC based on PSC in 2020 in East Asia could save around 8.5 billion Int. $. Further work includes adaptation measures based on the spatiotemporal variability of cropping to avoid seasons of high ozone concentrations. However, it should be noted that there is a need to update the available emission inventories taking into account the recent rapid development in East Asia, as uncertainties in the available data are high, and further research will be needed to estimate the combined effects of air pollution and climate change on crop production. The adverse effects of ozone are not a problem that can be solved by a single country; rather, it is a problem that all countries in the region need to address collaboratively. Based on this study, regional characteristics should be considered with respect to the emission of ozone precursors and mitigation policies. Addressing the regional effects of surface ozone on main crops in East Asia requires multidisciplinary environmental atmospheric management as it poses a potential threat to food security in the whole region.

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