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Threats for global food supply of increasing surface ozone – spatial assessment of impacts and adaptation options

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Abstract

Surface ozone (O_3) is a potent phytotoxic air pollutant and significantly reduces the productivity of important agricultural crops. Growing use of fossil fuel and changes in climate are increasing the global background surface ozone concentrations to levels that threaten regional and global food supply. We performed an integrated modeling study, considering biophysical and crop management factors, to identify the spatial pattern of ozone damage in lands suitable for crop cultivation and to assess the potential for adaptation for four key crops (wheat, maize, rice and soybean) under current and future air quality legislation. Results indicate that China, India and the United States are by far the most affected countries, bearing more than half of all global losses and threatened areas. Short-term adaptive measures at farm level, such as shifting crop calendars (by changing sowing dates or using crop cultivars with different cycle lengths) can reduce ozone damage regionally but have only limited impact at the global level. Considering these limited benefits of adaptation, mitigation of O_3 precursors remains the main option to secure regional and global food production.

Key words: AEZ, adaptation, agriculture, air quality, ozone pollution, mitigation.

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1. Introduction

Global food production must double in the next four decades to ensure food security. The need to feed an increasing population (that may surpass 8.5 billion people by 2050), reduce the number of people at risk of hunger (today nearly 15% globally) and simultaneously protect the natural environment, imposes a colossal technological challenge to agricultural production (Shetty, 2006, Lutz et al., 2007).

Increasing ozone (O_3) pollution is an important environmental threat that could undermine the achievement of these critical development targets. When O_3 is formed in the troposphere, the so called 'surface-O_3', is toxic to a wide range of plant species (Mauzerall and Wang, 2001, Fuhrer and Booker, 2003). Like CO_2, O_3 is taken up by green leaves through the stomata (leaf pores) during photosynthesis. Among other negative effects, the oxidative action of O_3 destroys the key photosynthetic enzyme RuBisco (Ribulose-1,5-bisphosphate carboxylase/oxygenase). As a result plant biomass production and hence yields of grains and fruits are reduced (Fuhrer, 2009). Global background O_3 concentration has increased since the pre-industrial era due to anthropogenic emissions of its precursors - pollutants such as nitrogen oxides (NO_x) and volatile organic compounds (VOC) (Wang and Jacob, 1998). Fossil fuel combustion and biomass burning (causes of global increase in CO_2 concentration) are also among the main sources of O_3 precursors (Lelieveld and Dentener, 2000). Significant losses of agricultural production often occur at ozone exposures above 40 ppb, a level already reached in many Northern hemisphere countries (The Royal Society, 2008). Important food and feed crops, such as wheat and soybeans, are highly sensitive to O_3 (Mills et al., 2007, Morgan et al., 2006). This has raised increasing concern about the magnitude of O_3 impact on global food supply (Long et al., 2005, Schmidhuber and Tubiello, 2007). Previous regional and global assessments of yield losses have confirmed these concerns

(Aunan et al., 2000, Wang et al., 2007, Van Dingenen, 2009). A recent global impact assessment for major agriculture commodities has estimated production losses of US$ 14 to 26 billion under the present air quality legislation (Van Dingenen, 2009).

Assessments conducted so far have only considered damage by assuming the current global distribution of crops and used ‘average’ crop calendars (i.e. the period from crop sowing to harvest) extrapolated for large regions. For instance, the increasing global demand for food may require reallocation or expansion of cropping areas to other O_3 polluted regions. Farmers influence not only the allocation of crops but also crop calendars, through strategic management decisions (e.g. use of irrigation and selection of crop genotypes). This becomes critical to modulate O_3-damage because, unlike the long-lived CO_2 (which is relatively uniformly distributed in the atmosphere), surface-O_3 shows a strong seasonal and regional pattern. Hourly concentrations differ depending on precursors’ emissions and climatic factors that foster O_3 formation or degradation. For example, warm and sunny weather during spring/summer favors higher surface-O_3 formation which concurs with the growing period of most crops. Crop phenological stages and genetic differences (among and within crop species) also confer a wide range of plant sensitivities to O_3 (Soja et al., 2000). Crops are mostly sensitive to O_3 at periods of high growth rate, usually when climatic and atmospheric conditions are favorable for carbon assimilation and development (Pleijel et al., 2000).

This temporal matching between O_3 formation and plant sensitivity is therefore a critical feature influenced by crop calendars, which may change with crop genotype, environment and sowing date (Fischer et al., 2002). As a consequence, the strategic shift of crop calendars (by changing sowing dates or using crop cultivars with different cycle lengths) could be a possible adaptation option to minimize O_3 damage. In this sense, an important question to be addressed in this paper is: ‘How much O_3 damage can be avoided by the use of adaptive measures such as shifting crop calendars?’.

To explicitly address these issues, we performed a comprehensive modeling exercise taking into account biophysical and crop management factors to (i) spatially assess global O_3 damage for both ‘current’ and ‘potential’ crop cultivation areas, and (ii) to test the effectiveness of adaptive measures for four important food and feed crops (wheat, soybean, maize and rice).

2. Modeling methodology

Ozone damage was estimated globally at a 0.5º spatial resolution (~55 km at the equator) for maize (*Zea mays*), rice (*Oriza sativa*), soybeans (*Glycine max*) and wheat (*Triticum aestivum*) and further aggregated at country level. These four crops were selected because of their importance for global food supply; together they account for more than 40% of human calorie intake (FAOSTAT, 2009a). The structure of the modeling exercise is shown in Figure 1 and details on each step of the assessment are given in following sections.

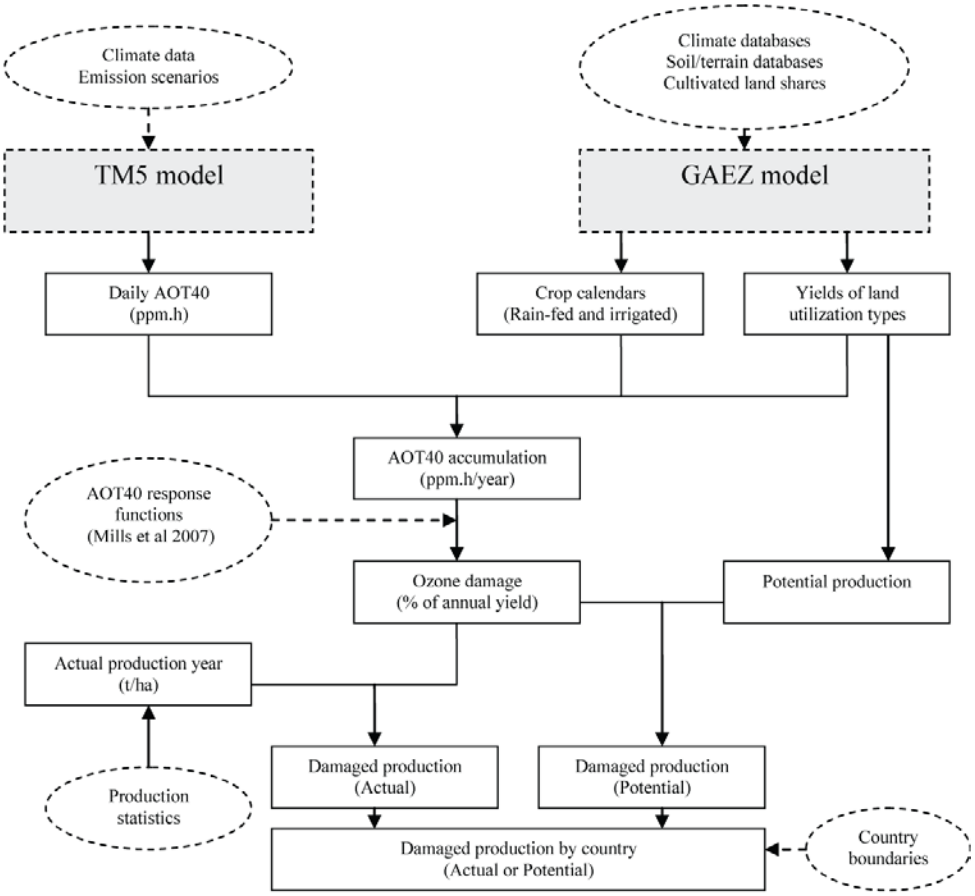

Figure 1. General structure of the modeling exercise.

2.1. Modeling ozone concentrations

The first step for the modeling exercise consisted of assessing spatially-explicit ozone concentrations throughout the reference year of study. For that, hourly surface O_3 concentrations were simulated by the Tracer Model version 5 (TM5) developed at the Joint Research Institute (JRC), Ispra, Italy (Krol et al., 2005). TM5 is an Eulerian chemistry-transport model (CTM) that runs globally at a horizontal resolution of 6^o x 4^o (longitude x latitude) and, for main ozone pollution regions (North America, Europe, North Africa and Asia), a nesting technique enables TM5 to run simultaneously at a resolution of 1^o x 1^o. The accuracy and consistency of TM5 simulations were previously evaluated in comparison with ozone concentrations from ground measurements and other CTM outputs (Ellingsen et al., 2008, Dentener et al., 2006).

2.2. Emission inventories and scenarios

TM5 simulations considered two possible global atmospheric environments: (i) pollutant emissions for the reference year 2000 assuming the air quality legislation ‘currently in place’ (CLE-2000) and, (ii) assuming ‘full implementation’ of current air quality legislation by year 2030 (CLE-2030). Both TM5 runs used climatic data for the year 2000. Global emission inventories were derived from the GAINS model (http://www.iiasa.ac.at/rains/gains-methodology.html?sb=12) developed by the Atmospheric Pollution and Economic Development Program (APD) at the International Institute for Applied Systems Analysis - IIASA (Dentener et al., 2005, Cofala et al., 2007).

2.3. Simulation of crop distribution, cropping calendars and yields

The simulation of crop distribution, cropping calendars and yields for the four selected crops (Table 1) was performed at a 0.5° spatial resolution using the FAO/IIASA Global Agro-Ecological Zones (GAEZ) model (Fischer et al., 2002). The presence of a crop in a given grid-cell (i.e. crop distribution) was evaluated by matching the physiological requirements of each ‘land utilization type’ (LUT) with the prevailing local climatic conditions. The LUT concept characterizes different crop sub-types within a crop species, including differences in crop cycle length (i.e. days from sowing to harvest), growth and development parameters. In the first stage of the assessment, O_3 damage was quantified in all areas suitable for crop cultivation under rain-fed conditions. With this, we created a global map of impact, not only in the regions where crops are ‘currently’ grown, but also where they can ‘potentially’ be grown given existing climatic conditions. GAEZ selected grid-cells ‘suitable’ for cropping by only considering land where yields were > 50% of constraint-free yield. In the model, yields are mainly determined by the availability of solar radiation and further regulated by temperature, water availability (for rain-fed conditions) and bio-physical limitations such as soil characteristics. For each crop species, different LUTs were tested within a grid-cell (Table 1). The model tested all possible “LUT/sowing date” combinations and selected the one with highest yield within the period of the year when conditions of moisture and temperature are conducive for crop growth (i.e. mean temperatures >5ºC and minimum limiting soil moisture conditions). The resulting sowing date and crop cycle length were used to define the period for which the O_3 exposure index (AOT40, see section 2.4) was calculated. The AOT40 yield-response slopes used to calculate O_3 damage are shown in Table 1.

Table 1. Details on land utilization types and correspondent O_3 damage functions.

Crop species	Number of Land Utilization Types (LUT) tested per crop species[1]	Range in crop cycles (days) for the tested LUTs[1]	Slope of AOT40 regression[2] Relative yield/ppm h
Maize (*Zea mays*)	24	90 to 300	-0.00293
Wetland rice (*Oriza sativa*)	8	105 to 150	-0.00578
Soybean (*Glycine max*)	6	105 to 135	-0.01083
Wheat (*Triticum aestivum*)	20	90 to 190	-0.01652

[1] Fischer et al 2002. [2] Adapted from regressions proposed by Mills et al. 2007. Intercepts of original linear regressions were not different from 1.0 at a 0.05 significance level, therefore slopes were re-calculated from original datasets by forcing intercepts to 1.0.

Datasets used in the GAEZ simulation are shown in Table 2.

Table 2. Datasets used for calculating spatial distribution of crop yields and ozone damage.

Fields	Source	Temporal resolution or reference period	Spatial resolution (arc-minutes)
Climate data	Climate Research Unit (CRU) http://www.cru.uea.ac.uk/cru/data/	Monthly Average for years 1961 to 1990	30
Precipitation (mm)	Global Precipitation Climatology Center (GPCC) http://www.ncdc.noaa.gov/oa/wmo/wdcamet-ncdc.html	Monthly Average for years 1961 to 1990	30
AOT40 index calculated from hourly O_3 concentration	Chemical Transport Model TM5 (Krol et al., 2005) http://ccu.jrc.ec.europa.eu/tm5_sci.php	Daily data for air legislation on emission for years 2000 and 2030 (climate for year 2000)	60
Land equipped for irrigation	Global Map of Irrigated Areas (GMIA) version 4.0 of (FAO/University of Frankfurt) (Siebert et al., 2005) http://www.fao.org/nr/water/aquastat/irrigationmap/index.stm	Year 2000	5

2.4. Crop losses and yield-damage functions

Ozone yield-damage was estimated using the AOT40 exposure index (LRTAP, 2004). This ozone exposure index was developed for air quality standards to protect vegetation from ozone pollution. It is calculated by accumulating hourly O_3 concentrations above a threshold of 40 ppb during daylight hours for 90 days of growth for agricultural crops and is linearly correlated with yield (LRTAP, 2004). We used AOT40 linear damage functions adapted from Mills et al. (2007) by fitting linear regressions to original datasets and forcing intercepts to 1.0 (Figure 2) as original intercepts were not different from 1.0 at a 0.05 significance level. These datasets were derived from open top chamber (OTC) experiments in Europe and North America for non-limiting water and biotic conditions of crop growth (LRTAP, 2004). Despite of the existence of other exposure and flux-based indexes (Pleijel et al., 2007), we selected the AOT40 because model parameters are available for all selected crops of this study. The 90-day AOT40 accumulation period was centered on the mid-point of crop growth cycle, the rationale being to account for the period of most intense rates of growth and ozone uptake. The losses estimated by exposure or flux indices at global scale may be taken with caution as they extrapolate responses from controlled environment to field conditions and from few European and North American tested genotypes and climates to the global level (Fuhrer, 2009). Nevertheless, recent studies have shown that losses on open air experiments were similar to previous OTC assessments (Morgan et al., 2006) and crop types in Asia are as sensitive to ozone as the ones tested in Europe and the United States (Emberson et al., 2009).

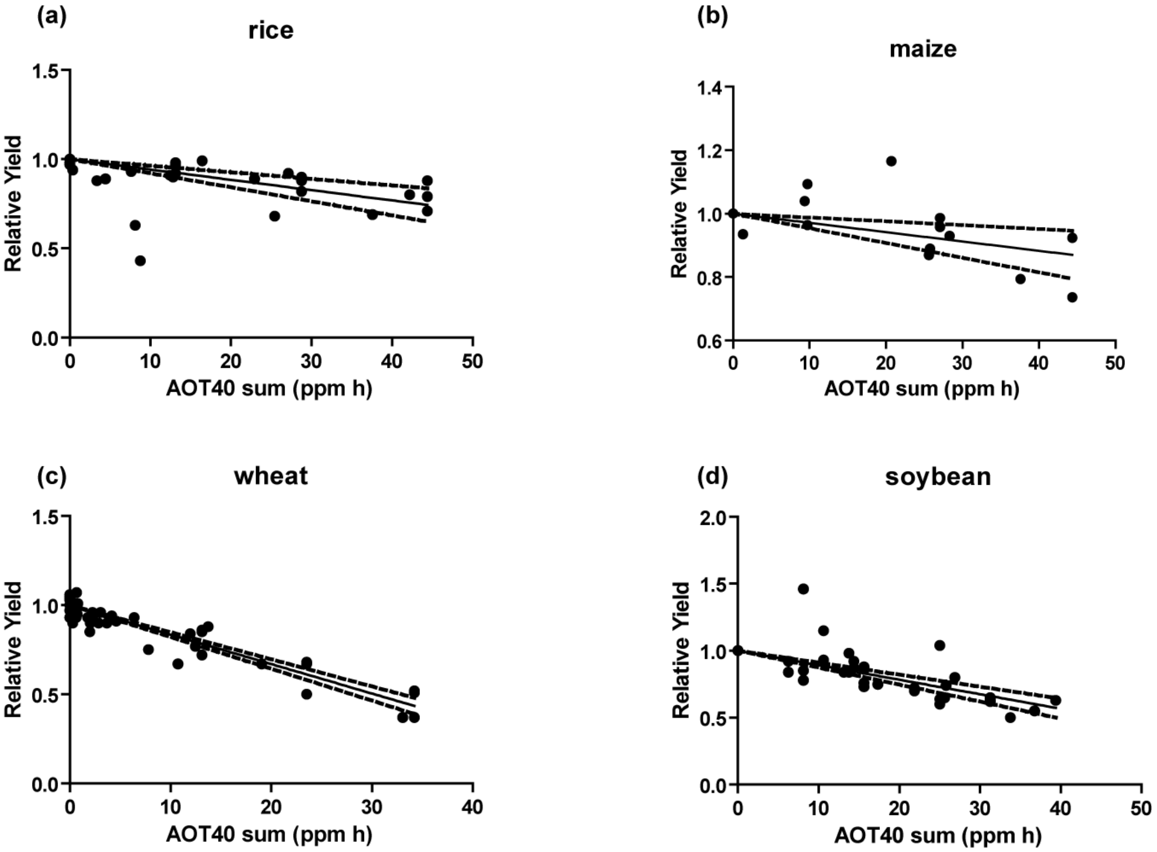

Figure 2. Relative yield as a function of AOT40 sums for (a) rice, (b) maize, (c) wheat and (d) soybeans adapted from Mills et al. (2007). Dotted lines represent the 95% confidence interval for regressions with intercept forced to 1.0.

2.5. Quantifying the benefits of adaptation

We evaluated the possible benefits of avoiding periods with high O_3 concentrations through the shift of crop calendars. Farmers may change crop calendars by sowing the crop in a different date and by selecting crop varieties with different cycle lengths. The effectiveness of adaptation to reduce O_3-damage was quantified by comparing net country production between two simulations (Figure 3): (i) ‘no adaptation’ simulation was done by selecting crop calendars for highest yield based on climatic factors only (i.e. O_3 damage is not taken into account), and (ii) a ‘with adaptation’ simulation in which crop calendars for the highest yield were chosen after accounting for O_3 damage. This rationale assumes an optimum scenario in which farmers would be aware of periods of high O_3 and take it into consideration in the selection of sowing dates and crop types.

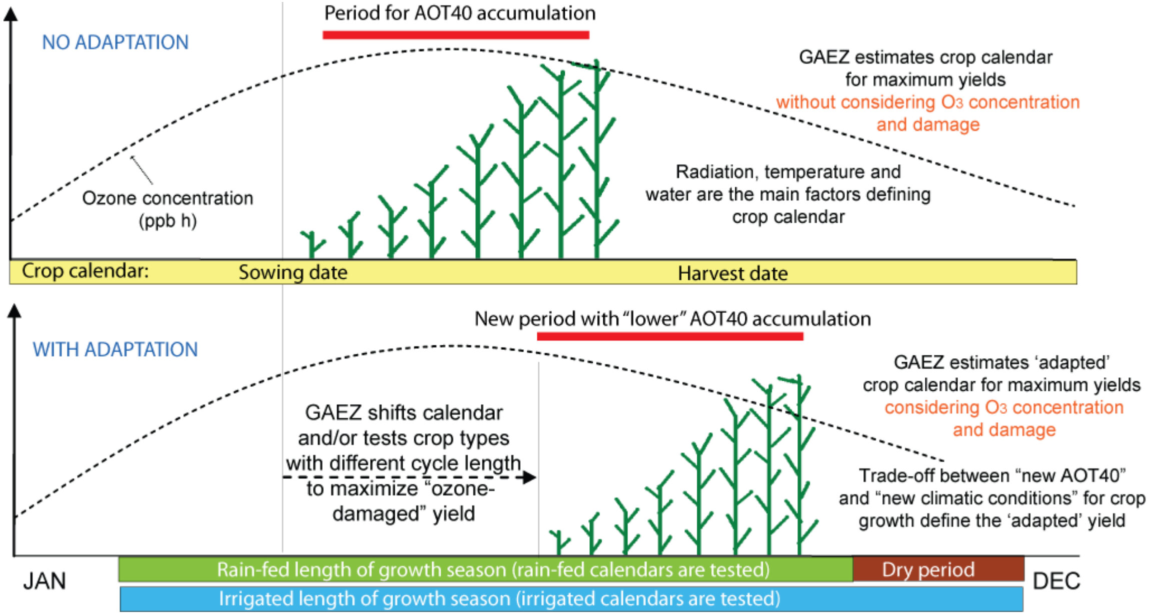

Figure 3. Schematic representation of the methodology used in the GAEZ model to test the effectiveness of adaptation. Independent runs where done for a rain-fed and an irrigated cropping calendar.

2.6. Downscaling of production statistics

After the evaluation of potential O_3 losses (using modeled GAEZ crop distributions and yield results), we also estimated O_3 impact on currently cultivated areas considering published yield statistics. For that, the most recent statistics of crop production for each of the selected countries (see section 3.1 for criteria) was downscaled to 0.5º grid-cells. Statistics at 'county' level were used for the downscaling of actual yields for year 2000 for the United States from the US Census of Agriculture (http://www.agcensus.usda.gov) and for China from the Chinagro Project (Keyzer and van Veen, 2005). For India, data at 'state' level from the Agricultural Statistics year 2000 (http://agricoop.nic.in/) was downscaled proportionally to GAEZ yield projections in each grid-cell (i.e. assuming more production is allocated to areas with higher potential productivity).

3. Results and discussion

3.1. Potential yield losses

As expected, simulated yield losses were particularly high in the Northern hemisphere, with ‘hot spots’ being East Asia, North India and Eastern United States (Figure 4, maps). For the selected crops, the share of suitable land at risk of O_3 damage - assumed as grid-cells where losses were > 5% (LRTAP, 2004) - ranged from 12% for maize to 44% for wheat. An average increase of 8 percentage points in affected global areas was estimated for future emission scenario (CLE-2030) when pooling results for all crops. Therefore, O_3 damage is likely to expand in the future, even when the full implementation of year 2000 air quality legislation is considered because the level of implementation of control measures assumed for 2030 is insufficient to compensate the increases in absolute emissions (driven by population and economic growth).

Impacts were most severe in China, India and the United States. These countries accounted for more than half of all global cropping areas at O_3 risk (Figure 4, *a* insets) and for the largest share of global production losses; of about 50% for wheat to 77% for rice (Figure 4, *b* insets).

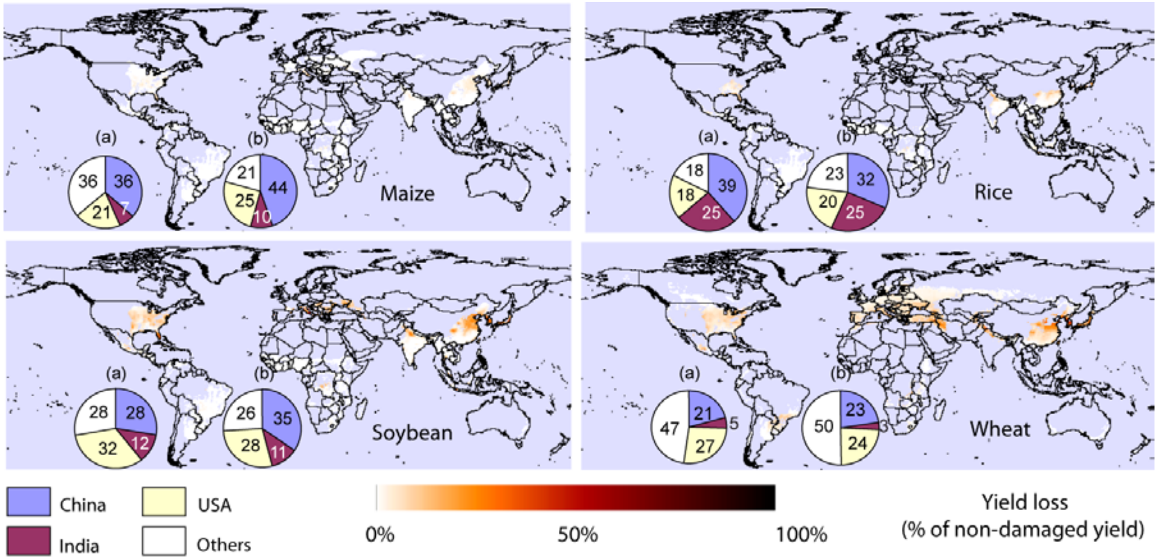

Figure 4. Maps show estimated yield loss caused by surface O_3 (% of potential yield) using AOT40 index. Inset graphs show the percentage by country of (a) global areas at risk and (b) global loss of production for China, India, United States and other countries. Simulations were performed considering air quality legislation in place in the year 2000 and for land suitable for rain-fed cultivation.

3.2. Actual yield losses

For the three most affected countries we also estimated production losses in ‘current’ producing areas (Figure 5). To estimate exposure of major crops to spatial-temporal patterns of O_3 formation, recent production statistics available at county (China and USA) or state (India) level were allocated by means of downscaling techniques to agricultural areas on a spatial grid of 0.5^o longitude/latitude (Section 2.5). Analysis was performed for rain-fed and irrigated cropping calendars separately.

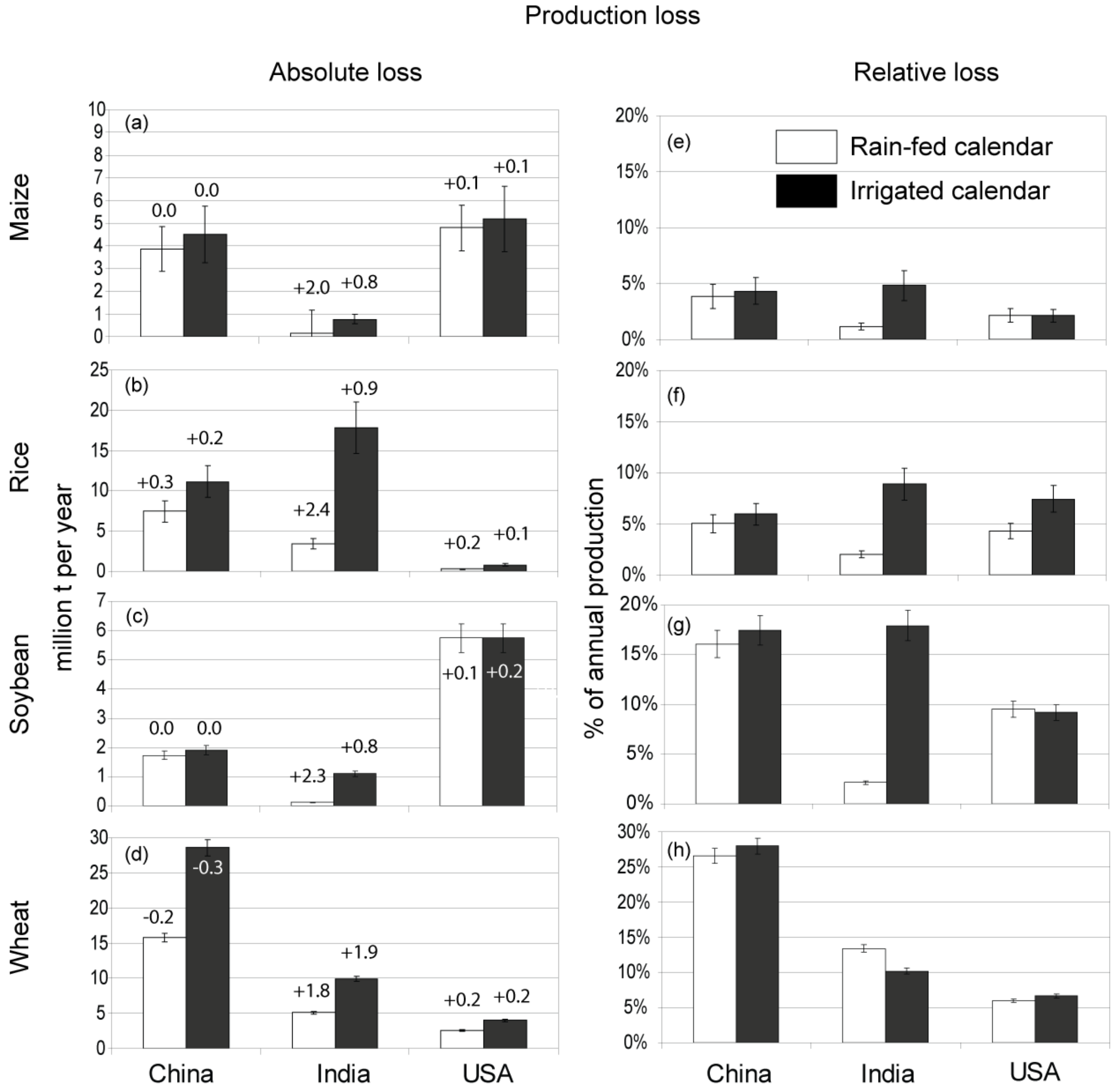

Figure 5. Bars show estimated losses of produce due to O_3 damage in absolute amounts (*a – d*) and as percentages of national production (*e – h*) for selected crops, crop calendars and most affected countries for 2000 emissions. Numbers accompanying bar graphs (*a – d*) represent the fractional change in losses projected for the 2030-CLE scenario. Error bars represent the 95% confidence interval of yield response functions slopes.

The estimated impact of O_3 largely differed among regions, cropping systems (rain-fed or irrigated) and crop species (Figure 5). Irrigated crops suffered the highest production losses amounting to 18±3 million t/year for rice in India and 11±2 million t/year for rice in China. Nearly 50% of the world's rice production, of ~650 million t/year, comes from these two countries and is mostly grown under irrigated crop calendars (FAOSTAT, 2009b). For soybean, absolute losses were up to 3 times higher in United States as compared to India and China (Figure 5 c-d). China lost the largest share of its national production, nearly one quarter of wheat and 15% of soybean (Figure 5 g-h). India suffers the greatest increase in losses for the future, nearly 2 fold for most of the crops (Figure 5 a-d). China was the only country to show partial benefits of full implementation of current legislation by 2030 with losses falling by 20 to 30% for wheat (Figure 5 d). Although these estimations are prone to errors, partially due to the uncertainties in the estimations of damage for a given ozone concentration (Fuhrer, 2009) and emission inventories (Van Dingenen, 2009), they provide a valuable comparison of O_3 impacts among regions, crops, emission scenarios and cropping systems. Our analysis indicated that yield losses for irrigated crop calendars were usually equal to or greater than for rain-fed crops, notably in India (Figure 5 a-d). The use of irrigation allows growers to shift cropping calendars to periods when radiation and temperature are optimum for crop growth. However, abundance of radiation and high temperatures are also ideal for the formation of surface O_3, which explains high estimated losses under irrigated conditions.

3.3. Effectiveness of adaptation

In most cases, adaptation by shifting crop calendars was hardly effective to reduce O_3 damage at national level (Table 3). For more than 80% of the 48 'country/crop/water-management/emission' combinations tested, the selected adaptive measures increased national production by less than 1%. India was an exception with a considerable benefit from shifting cropping calendars, with for example increased soybean production of 12.1% for CLE-2000 and 27.9% for CLE-2030 (Table 3, marked in grey). This peculiar pattern of response in India seems to be the result of a strong seasonality of O_3 formation (with peaks in pre- and post-monsoon months) in combination with a long length of growing period for irrigated crops (as temperature is not the main limiting factor in large cropping areas in India). This potentially creates a large window to shift crops to avoid months with high ozone concentration.

Table 3. The effectiveness of adaptation: percentage of national production gained by the use of selected adaptive measures. Combinations where estimates exceed 1% are highlighted in grey for comparison.

	Maize		Rice		Soybean		Wheat	
	Rain-fed	Irrigated	Rain-fed	Irrigated	Rain-fed	Irrigated	Rain-fed	Irrigated
	(% of national production)							
Current air quality legislation for year 2000								
China	0.2	0.0	0.2	1.0	0.8	0.2	0.3	0.2
India	0.9	0.0	3.6	0.5	12.1	0.8	0.8	0.9
USA	0.1	0.0	0.5	0.2	0.0	0.0	0.1	0.1
Scenario of air quality legislation for year 2030								
China	0.2	0.1	0.2	0.7	0.2	0.2	0.3	0.2
India	1.6	0.3	7.9	2.0	27.9	9.9	5.4	1.6
USA	0.1	0.0	0.5	0.3	0.1	0.0	0.1	0.1

However, the results for India must be interpreted with some caution due to issues previously raised by Van Dingenen (2009): (i) the uncertainties in projected O_3 formation, (ii) the limited ground-based measurements available for model testing and (iii) unknown future pace of implementation of air-quality control measures. Nevertheless, a recent assessment using a regional chemistry-transport model and local emission inventory for India also shows that AOT40 accumulation is likely to surpass critical levels for crop protection even within single months, particularly for the important cropping areas in the Indo-Gangetic plain (Roy et al., 2009).

3.4. Implications for ozone mitigation and adaptation policies

The presence of O_3 and its effects on crops are often not visible, in contrast with other yield-reducing factors such as insects or diseases. Therefore, without proper monitoring of O_3 concentrations in rural areas, as is the case in most developing countries, the problem remains unnoticed and lower yields unexplained. This makes it difficult for policy makers to decide on specific air-quality legislations and for researchers and farmers to develop and apply adaptive strategies.

Our results suggest that the potential to minimize O_3 damage by adapting agronomic practices, although not valid for all affected countries, may exist for specific regions and crop systems as shown for some irrigated crops in India. The flexibility to ‘escape’ from O_3 peaks by shifting cropping calendars under irrigation may however not fully materialize under field conditions for different reasons. Firstly, because crops under irrigation are in reality more sensitive to O_3 damage as stomatal pores are fully open under these conditions, enhancing O_3 uptake (Fuhrer, 2009). This response is not captured by exposure-based indices. Secondly, irrigated agriculture has higher production costs and can already become unprofitable at small yield losses. Finally, multi-cropping already occurs in regions with long sowing windows (like India) and the calendar shift of one of the crops would imply the temporal reallocation or exclusion of others.

Alternative long-term adaptive strategies could be considered to minimize O_3 damage, such as for example, the breeding or engineering of novel O_3-resistant plant varieties (Fuhrer, 2009). So far conventional genetic improvement of wheat, by screening for high-yielding varieties, has moved in the opposite direction by indirectly selecting genotypes with even higher sensitivity to O_3 (Biswas et al., 2008). The exclusion of O_3-sensitive crop species from the portfolio of land use options in ‘hot-spot’ areas hardly seems to be an acceptable option. This would reduce the flexibility of growers to respond to other seasonal threats (e.g. pest outbreaks) or market opportunities through the use of different crop species. Anticipating these other threats would leave farmers with only few options to adapt to the damage caused by O_3. In addition, even for regions where crops would benefit from adaptation strategies, O_3 would still remain a threat to human health and natural ecosystems (Ellingsen et al., 2008).

On the other hand, the reduction in the emission of ozone precursors, through the implementation of already existing technologies for industrial and transport sectors, is a straightforward means to reduce O_3 concentrations and therefore minimize the negative impacts on crop productivity (Amann et al., 2008).

4. Conclusions

Our assessment provides further evidence that ozone is increasingly affecting global food production due to its prevalence in current and potential agricultural areas during critical stages of crop growth. Adaptation by shifting crop calendars renders little effect on global and national food production but can be of local importance. Results further suggest that, given the limited effectiveness of selected adaptive measures, security of global food supply may be better improved by fostering policies that drastically mitigate emissions of O_3-precursors.

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