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Key Points:

- Ozone-induced crop damage is sufficient to fed 94 million people in India
- Variability in NOx inventories introduces up to 36% uncertainty in crop loss
- NOx should be the primary target for reducing pollution impacts on food security

Supporting Information:

- Readme
- Text S1

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Reductions in India's crop yield due to ozone

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Abstract This bottom-up modeling study, supported by emission inventories and crop production, simulates ozone on local to regional scales. It quantifies, for the first time, potential impact of ozone on district-wise cotton, soybeans, rice, and wheat crops in India for the first decade of the 21st century. Wheat is the most impacted crop with losses of 3.5 ± 0.8 million tons (Mt), followed by rice at 2.1 ± 0.8 Mt, with the losses concentrated in central and north India. On the national scale, this loss is about 9.2% of the cereals required every year (61.2 Mt) under the provision of the recently implemented National Food Security Bill (in 2013) by the Government of India. The nationally aggregated yield loss is sufficient to feed about 94 million people living below poverty line in India.

1. Introduction

Long-term exposure to high concentration of surface O_3 damages vegetation with substantial reduction in crop yields and crop quality [*Krupa et al.*, 1998; *Morgan et al.*, 2006]. This is a major concern for developing countries like India where expanding economy has led to rapid increases in ozone-precursor gases such as NO_x, CO, and VOCs and to increased levels of ozone [*Horowitz*, 2006]. Climate change can further exacerbate the situation since it has been shown to increase O_3 in many regions of the world [*Horowitz*, 2006].

Agriculture in India is demographically the broadest economic sector, ranking worldwide second in farm output. It is the principal source of livelihood for more than 58% of population and hence plays an important role in the overall socioeconomic fabric of India. Recent studies have shown high surface O_3 concentration over major agriculture regions in India, particularly the Indo-Gangetic Plains (IGP), one of the world's most important fertile agricultural lands [*Engardt*, 2008; *Roy et al.*, 2009]. Ozone concentrations are projected to increase further in the future [*Avnery et al.*, 2011; *Levy et al.*, 2008], which could worsen the vulnerability of the agricultural sector. At present, in India there are currently no air quality standards to protect agriculture from ground level ozone. Intergovernmental efforts to raise awareness of the need for ozone standards, such as those pursued by the South Asian countries Male Declaration on Control and Prevention of Air Pollution (http://www.rrcap.unep.org/male/; Male Declaration, 2010), have yet to be successful in gaining political support for action to be taken to reduce the threat posed by ground level ozone on agriculture.

Several studies have quantified yield losses on global [*Van Dingenen*, 2009; *Avnery et al.*, 2011] or regional scale [*Wang and Mauzerall*, 2004; *Holland et al.*, 2006; *Aunan et al.*, 2000], typically using high-resolution global chemistry transport models. To our knowledge, the present study is the first high-resolution district-scale model study for India to study and quantify ozone-induced crop damages and to identify critical mitigation pathways to reduce ozone-induced crop losses. We estimate the potential reductions in crop yield due to O_3 exposure using a regional chemistry transport model, latest multiple NO_x emission inventories, and district-wise crop production data sets. We focus on the year 2005, which should be representative for the first decade of the 21st century.

The study adopts European matrix-accumulated exposure of vegetation to ozone above a threshold of 40 ppbv (AOT40) [*Mills et al.*, 2007] over the growing season for assessing ozone damage to crops. The focus of the study is on four major crops, viz., wheat and rice, which are the most important crops for ensuring food security for India's poor population, and cotton and soybean, which are known to be commercial crops. Productivity of different crops within India varies significantly among the Indian states, which is largely a function of microclimates, soil quality, and local resources (see supporting information for further details on how we account for these variabilities (Figure S1)). Surface ozone is produced by ozone precursor gases, notably NO_x,

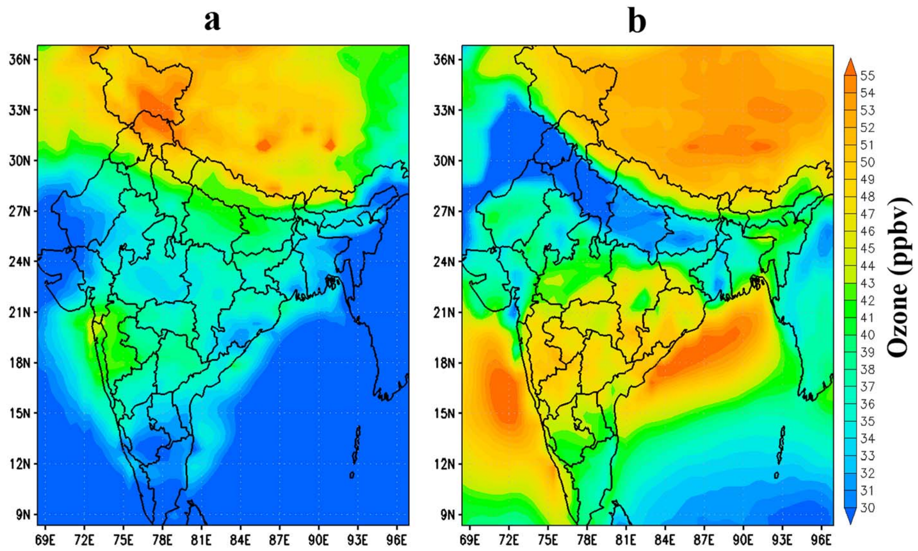

Figure 1. Averaged daytime surface ozone concentration (in ppbv) for the (a) kharif and (b) rabi crop growing season during 2005. Surface O_3 distribution shown is calculated from the O_3 simulation with six different NO_x emissions inventory, viz., INTEX-B, EDGAR, REAS, MACCity, SAFAR-India, Top-Down and gives the mean picture for India.

CO, VOCs, and methane. Emissions estimates for South Asian NO_x differ significantly between various emission inventories (developed by different groups). Therefore, the sensitivity of given crop yield loss depends on the choice of NO_x emission inventory. We make an integrated analysis of ozone impact on crop yield using ozone simulations with multiple NO_x emission inventories (see section 2). We find higher O_3 concentration over important agricultural lands and vary strongly between regions and crop-growing seasons (see Figure 1).

2. Method

2.1. Regional Chemistry Modeling

WRF-Chem (Version 3.2.2) regional chemistry transport model is used to simulate hourly surface ozone distribution at a 0.5° spatial resolution for 2005. The model was run with 27 vertical levels from the surface to 50 hPa and driven by National Centers for Environmental Prediction Final (FNL) meteorological reanalysis fields (Global Forecast System (GFS/FNL)) as provided by National Center for Atmospheric Research (NCAR; http://rda.ucar.edu/datasets/ds083.2/). The model uses Model for Ozone and Related chemical Tracers version 4 (MOZART-4) gas phase chemistry linked to the Goddard Chemistry Aerosol Radiation and Transport aerosol scheme, referred to as MOZCART. Spatially and temporally (6 hourly) varying chemical boundary conditions were provided by global model simulations from the Model for Ozone and related Chemical Tracers (MOZART-4) [*Emmons et al.*, 2010]. Anthropogenic emissions of CO, SO_2, nonmethane volatile organic compound, PM10, PM2.5, and black carbon/organic carbon are taken from the Intercontinental Chemical Transport Experiment-Phase B (INTEX-B) inventory [*Zhang et al.*, 2009]. Fire emissions were provided to the model using the Fire INventory from NCAR version 1 (FINNv1) [*Wiedinmyer et al.*, 2011], and biogenic emissions of trace species are calculated online using the Model of Emissions of Gases and Aerosols from Nature (MEGAN) [*Guenther et al.*, 2006]. Modeled O_3 (formation and titration) differs depending upon the magnitude and location of NO_x emission. Notable variability among the NO_x emission inventories (developed by different groups) is seen for South Asia. Here we first simulate six cases of surface O_3 concentration for six different anthropogenic NO_x emission inventory, viz., INTEX-B [*Zhang et al.*, 2009], EDGARv4.1 (http://edgar.jrc.ec.europa.eu/), Regional Emission Inventory in Asia (REAS) [*Ohara et al.*, 2007], MACCity [*Granier et al.*, 2011], SAFAR-India [*Sahu et al.*, 2012], and Top-Down NO_x [*Ghude et al.*, 2013] inventory. Second, we calculate O_3-induced crop yield loss for each case and finally estimate mean yield loss at a 0.5° resolution for wheat, soybeans, cotton, and rice. This aimed to capture the average yield loss due to ozone exposure under the present NO_x emission.

2.2. Crop Impacts and Economic Damage

The district-wise annual crop production data sets for cotton, soybeans, rice, and wheat used in this work is taken from the Special Data Dissemination Standard-Directorate of Economics and Statistics (SDDS-DES), Ministry of Agriculture (Government of India) for the year 2005. This district-wise crop data are converted to grid format using geographic information system-based statistical methodology to match the 0.5° resolution of WRF-Chem. We calculated yield reduction and crop production losses based on AOT40 exposure metrics [*Mills et al.*, 2007] (equation (1)) and its concentration response (CR) relationships [*Van Dingenen*, 2009; *Mills et al.*, 2007] that predict the yield reduction of a specific crop at different ozone exposure level.

$$\text{AOT40}(\text{ppmh}) = \sum_{i=1}^{n}\left([\text{O}_3]_i - 0.04\right), \quad \text{for } \text{O}_3 \geq 0.04 \text{ ppmv} \tag{1}$$

We select AOT40 exposure metrics because it is extensively tested [*Musselman and Lefohn*, 2007]; CR functions are available for all of the crops considered in this study and have been used to estimate the crop yield losses over different regions of the globe [*Van Dingenen*, 2009; *Avnery et al.*, 2011; *Hollaway et al.*, 2012].

$$\text{For wheat RY} = -0.0161 \times \text{AOT40} + 0.99$$

$$\text{For rice RY} = -0.0039 \times \text{AOT40} + 0.94$$

$$\text{For cotton RY} = -0.016 \times \text{AOT40} + 1.07$$

$$\text{For soybean RY} = -0.0116 \times \text{AOT40} + 1.02$$

We adopted the AOT40-based CR functions which were scaled such that relative yield is equal to 1 at zero exposure [*Van Dingenen*, 2009]. Using model-simulated hourly surface O_3 fields during daylight (i.e., $>50\,\text{W/m}^2$ global radiation), we calculated AOT40 over the crop-specific growing season on each grid and relative yield loss ($\text{RYL} = 1 - \text{RY}$) in every grid cell for each crop using crop-specific CR functions. AOT40 exposure requires accumulation of ozone concentration over 90 days of crop growing period in order to assess the crop loss. Due to lack of data on district-wise crop sowing and harvesting periods, we consider 90 days period over 15 June to 15 September as a kharif growing season for soybean, cotton, and rice and December–February as rabi growing season for wheat. However, to estimate the crop production loss for rice, we allow exposure both during kharif and rabi season depending upon seasonal rice production fields and fraction of total annual rice production within each season. Following the approach outlined in *Van Dingenen* [2009] and *Avnery et al*. [2011], we overlaid RYL fields with the actual 0.5° × 0.5° crop production grid (derived from the district level crop production) in the year 2005 for each relevant corp. For each grid cell, crop production loss (CPL) is calculated using the following equation:

$$\text{CPL} = \frac{\text{RYL}}{(1 - \text{RYL})} \times \text{CP} \tag{2}$$

where CP is the actual annual crop production for the year 2005. The national crop production loss for each relevant crop is estimated by summing all grid cells within the study area and finally estimated the total economic loss by multiplying national crop production loss by domestic market prices for each crop during 2005 (http://agmarknet.nic.in).

2.3. Surface Ozone Distribution

In Figures 1a and 1b, modeled mean surface ozone distribution over India at a 0.5° spatial resolution for the kharif and rabi crop growing season is shown. It should be noted that surface O_3 distribution shown in Figure 1 is calculated from the O_3 simulation with six NO_x emission, viz., INTEX-B, EDGAR, REAS, MACCity, SAFAR-India, and top-down NO_x inventory, and gives the mean picture for India under current NO_x emission Scenario. It can be seen that higher O_3 concentration varies strongly between regions and crop growing seasons. O_3 levels along the Indo-Gangetic Plains (IGP) and western Maharashtra are about 40–50 ppb during kharif season. In rabi season, modeled O_3 is higher (40–50 ppb) over most of the Indian region, except IGP (<33 ppb, Figure 1b). Low O_3 over IGP is likely due to the titration of O_3 by higher NO_x values during coolest winter months [*Ghude et al.*, 2013].

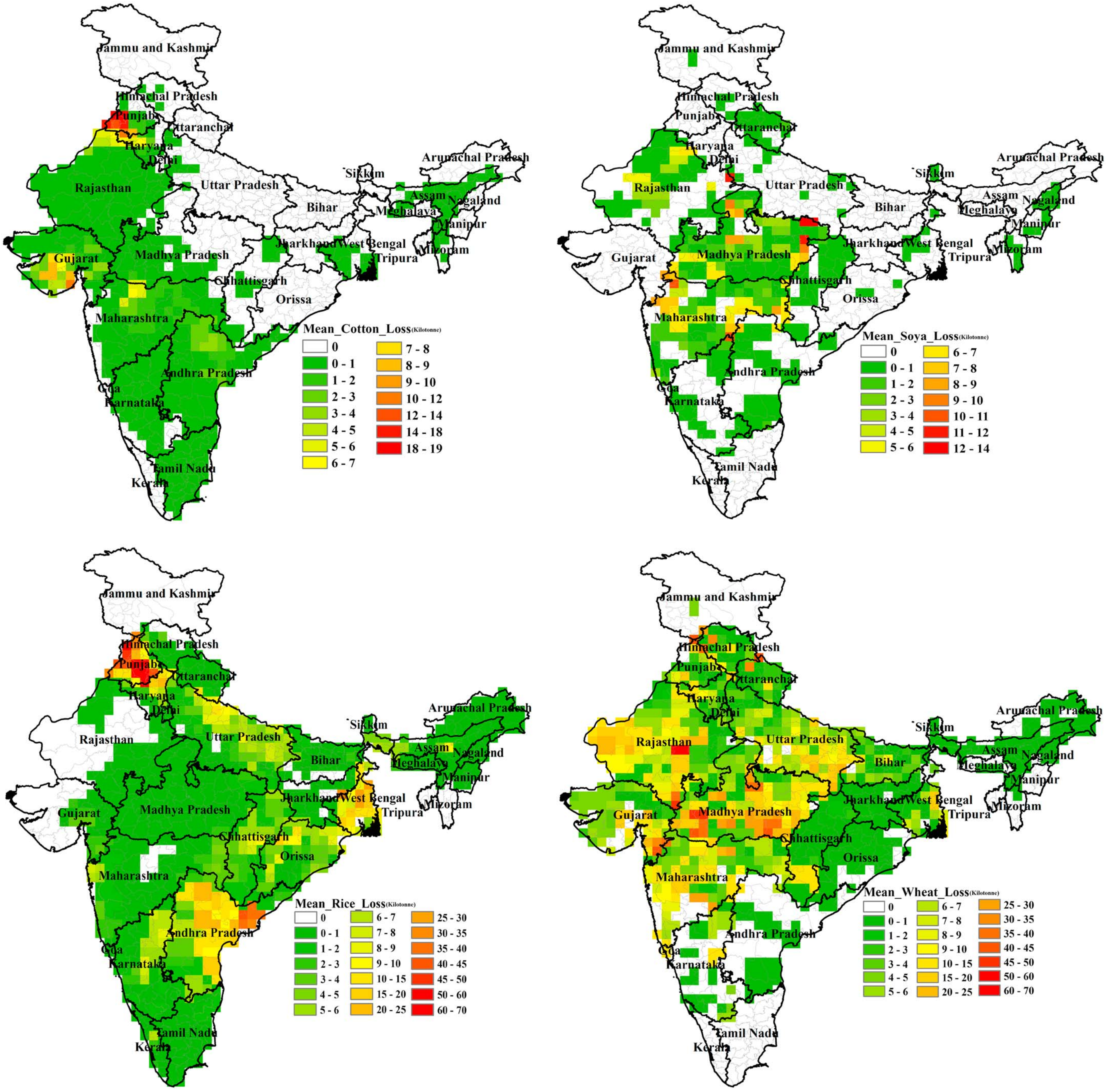

Figure 2. Average O_3-induced crop production loss from AOT40 metrics for cotton, soybean, rice, and wheat during 2005. The production loss numbers are given in kilotons/grid box.

3. Results

3.1. Crop Production Losses

Figure 2 shows O_3-induced annual crop yield lost (kilotons/grid box) for each of four crops type during 2005 and primarily highlights the crop-specific region with highest risk. Substantial areas of crop production experience sufficient damage to vegetation and crop yield loss (see section 2 for details of these calculations). For top 10 wheat- and rice-producing states in India (Figures 3a and 3b), O_3-induced fractional loss of wheat is greatest in Maharashtra (~17%) followed by Madhya Pradesh (~8%), Gujarat (~8%), West Bengal (~6%),

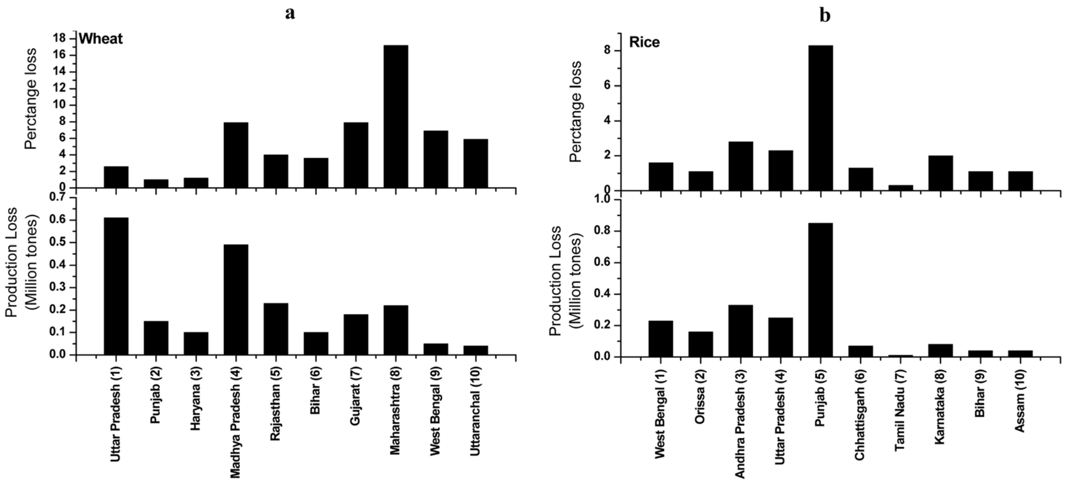

Figure 3. Estimated crop production losses for (a) wheat and (b) rice for the 10 highest ranked states in India during the year 2005. Numbers along the states in bar chart represent the order by their production value. Number 1 state is the highest producing state for wheat and rice while number 10 is the lowest producing state. Figures 3a (top) and 3b (top) show percentage loss and Figures 3a (bottom) and 3b (bottom) show loss by weight.

and Uttaranchal (~5%). In terms of weight, greatest loss of wheat is noticed in Uttar Pradesh (~0.6 million tons (Mt)) and Madhya Pradesh (~0.5 Mt), which accounts for about 32% of total wheat lost in India during 2005. Although Punjab and Haryana are the second and third largest wheat-producing states in India, wheat loss is significantly less (<1%) due to exposure to low ozone values (<30 ppb) during wheat-growing winter seasons (see Figure 1b). Though precursors' emission are substantially high in this region [*Ghude et al.*, 2012], low O_3 levels during winter are attributed to less solar radiation, low boundary layer height, stagnant wind pattern, which enhances NO_x concentration and enable titration of O_3. For rice, overall pattern for O_3-induced yield loss for top 10 rice-producing states shows similar pattern in terms of loss by weight and fraction (Figure 3b). For major rice-producing sates like West Bengal, Orissa, Andhra Pradesh, and Uttar Pradesh, O_3-induced fractional loss of rice is between 1 and 3% (0.1–0.3 Mt), whereas it is greatest in the state of Punjab (0.8 Mt, more than 8%). It can be seen that, compared to wheat loss, rice loss is greatest in Punjab. During rice-growing season, O_3 levels are relatively high in this region (see Figure 1a). This increase is associated with an increase in solar radiation and ozone precursors concentrations associated with a change in wind patterns.

On national scale, cotton suffered the highest fractional loss of 5.3 ± 3.1% followed by wheat (5.0 ± 1.2%), soybean (2.7 ± 1.9%), and rice (2.1 ± 0.9%) (See Table 1 and section 2 for calculation of national aggregated numbers). The fraction loss of wheat (5.0 ± 1.2%) due to ozone exposure estimated in this study is double in magnitude to that of $-2.3 \pm 13.2\%$ loss of winter wheat crops globally caused by 2°C temperature rise [*Liu et al.*, 2010]. In terms of weight, wheat is most affected crop amounting losses of the order of 3.5 ± 0.8 Mt, double than that of the averaged wheat exported (1.8 ± 2.0 Mt) during this decade. For rice, we estimated annual loss of 2.1 ± 0.8 Mt, comparable to the half of the amount of averaged rice (4.7 ± 2.5 Mt) exported from India during this decade. Production loss estimate for wheat and rice in this work differ significantly with *Van Dingenen* [2009], estimate of 11–29 Mt for wheat and 7.7–11.4 Mt for rice for the year 2000. The Indian National Food Security Ordinance came into force in September 2013. The intent of this bill is to ensure availability of sufficient food grains to meet the domestic demand and access to adequate quantity of

Table 1. Production Losses and Economic Damage (Year 2005) for Four Crop Types Considered

Commodities	Production (million tons)	Crop Production Loss (million tons)	Fractional Loss (%)	Economic Damage (billion USD)
Cotton	3.3	0.17 (±0.10)	5.3 (±3.1)	0.07 (±0.12)
Soybean	8.6	0.23 (±0.16)	2.7 (±1.9)	0.06 (±0.04)
Rice	95.1	2.1 (±0.8)	2.1 (±0.9)	0.54 (±0.23)
Wheat	71	3.5 (±0.8)	5.0 (±1.2)	0.62 (±0.15)
Total				1.29 (±0.47)

subsidies food to about two third of India's 1.2 billion population. Under the provision of the bill, about 61.2 Mt of the cereals (27.6 Mt of wheat and 33.6 Mt of rice) are expected to distribute annually in which ~820 million poor populations are able to purchase about 60 kg of rice/wheat per person annually at subsidized rates prescribed by the Government of India. National aggregated yield loss of wheat and rice of 5.6 Mt in 2005 is roughly about 9.2% of the cereals required every year (61.2 Mt) under the provision of the food security bill, or sufficient to feed approximately 94 million poor people (~35%) living below poverty line in India.

On national scale, we estimate economic damage of 1.29 ± 0.47 billion USD_{2005} annually under the present-day NO_x emission Scenario. Among the four crop types, most of the economic losses in terms of absolute damage occur for wheat of about 620 ± 150 million USD_{2005}. For rice, estimated economic damage is about 540 ± 230 million USD_{2005}, which is comparable to the economic value (1.25 billion USD_{2005}) of the ~4.7 Mt rice exported during 2005. This is a point of concern because India ranks second worldwide in the farm outputs and significant share of the world's rice (~22%) and wheat (12%) production comes from the India. Flooding due to climate variability is a significant problem for rice farming, especially in the lowlands of South and Southeast Asia. Flooding already affected about 10 to 15 million hectares of rice fields in South and South East Asia, causing an estimated 1 billion USD in yield losses per year [*Bates et al*., 2008]. The economic loss (0.54 ± 0.23 Mt) due to O_3-induced rice damage in India is half of the estimated annual loss of 1 billion USD due to flooding in South and Southeast Asia. Warming since 1981 declined global wheat production by 5.5% resulting ~ 19 Mt/yr (about 2.6 billion USD) wheat loss, and roughly 40 Mt (equivalent to 5 billion USD) loss combined for wheat, maize, and barley globally due to global warming [*Lobell and Field*, 2007; *Lobell et al*., 2011]. Economic loss due to O_3-induced wheat damage alone in India is one third of the estimated 5 billon USD per year, the present-day losses due to crop globally, and half of the estimated 2.6 billion USD loss due to wheat caused by global warming.

4. Conclusion

Overall, our study suggests that widespread ozone pollution under present emission scenario has considerable impact on productivity of crops important for food security in India. The present-day ozone-induced damage to wheat (3.5 ± 0.8 Mt) and rice (2.1 ± 0.8 Mt) is sufficient enough to feed roughly 35% (94 million poor people) of 270 million below poverty line population in India.

In reality, estimated crop yield damage is subject to several sources of uncertainty including uncertainty in the crop growing season and present uncertainties about the emission inventories and concentration response (CR) relationships that predict the yield reduction at different ozone exposure [*Mills et al*., 2007]. Taking into account the variability in NO_x emissions within the emission inventories considered, the uncertainty on combined economic losses can be as much as 36%. Additional source of uncertainty in our estimate lies in the application of AOT40 exposure-response function derived for European and North American (because of the lacking of experimental ER data for India) crops without taking into account O_3 exposure sensitivity to Indian crops field conditions. Due to lack of India-specific ER data, the uncertainty due to AOT40 exposure response is difficult to quantify. However, some of the recent individual studies have shown that some of the Asian crop cultivars are equally or more sensitive to ozone than the Europe and U.S. cultivars [*Aunan et al*., 2000; *Feng and Kobayashi*, 2009; *Sarkar and Agrawal*, 2010; *Agrawal et al*., 2003]. While there are still remaining uncertainties in our O_3-induced crop and economic damage estimate, these results provide firsthand important information to policy makers to propose or implement emission control of O_3 precursors to benefit more security on national food production. These results may have important policy implications for India where surface O_3 is expected to increase in future considering the recent upward trend in precursor emissions and implementation of National Food Security Bill. Global and regional climate change may also directly affect the crop production through changes in monsoonal rainfall pattern in India, temperature, atmospheric conditions, soil moisture, land use change, and local conditions. However, little is known about the combined effects of ozone pollution and climate change on agriculture and this requires further research.

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References

Agrawal, M., B. Singh, M. Rajput, F. Marshall, and J. N. B. Bell (2003), Effect of air pollution on periurban agriculture: A case study, *Environ. Pollut.*, *126*, 323–339.

Aunan, K., T. K. Berntsen, and H. M. Seip (2000), Surface ozone in China and its possible impact on agricultural crop yields, *AMBIO: A J. Human Environ.*, *29*, 294–301.

Avnery, S., D. L. Mauzerall, J. Liu, and L. W. Horowitz (2011), Global crop yield reductions due to surface ozone exposure: 1. Year 2000 crop production losses and economic damage, *Atmos. Environ.*, *45*, 2284–2296.

Bates, B. C., Z. W. Kundzewicz, S. Wu, and J. P. Palutikof (Eds.) (2008), Climate change and water, *Tech. Paper*, 210 pp., IPCC Secretariat, Geneva, Switzerland.

Emmons, L. K., et al. (2010), Description and evaluation of the Model for Ozone and Related Chemical Tracers, version 4 (MOZART-4), *Geosci. Model Dev.*, *3*, 43–67.

Engardt, M. (2008), Modelling of near-surface ozone over South Asia, *J. Atmos. Chem.*, *59*, 61–80.

Feng, Z., and K. Kobayashi (2009), Assessing the impacts of current and future concentrations of surface ozone on crop yield with meta-analysis, *Atmos. Environ.*, *43*, 1510–1519.

Ghude, S. D., G. G. Pfister, C. Jena, R. J. van der A, L. K. Emmons, and R. Kumar (2012), Satellite constraints of nitrogen oxide (NO_x) emissions from India based on OMI observations and WRF-Chem simulations, *Geophys. Res. Lett.*, *40*, D10303, doi:10.1029/2012GL053926.

Ghude, S. D., S. H. Kulkarni, C. Jena, G. G. Pfister, G. Beig, S. Fadnavis, and R. J. van der A (2013), Application of satellite observations for identifying regions of dominant sources of nitrogen oxides over the Indian Subcontinent, *J. Geophys. Res. Atmos.*, *118*, 1075–1089, doi:10.1029/2012JD017811.

Granier, C., et al. (2011), Evolution of anthropogenic and biomass burning emissions of air pollutants at global and regional scales during the 1980–2010 period, *Clim. Change*, *109*(1–2), 163–190, doi:10.1007/s10584-011-0154-1.

Guenther, A., T. Karl, P. Harley, C. Wiedinmyer, P. I. Palmer, and C. Geron (2006), Estimates of global terrestrial isoprene emissions using MEGAN (Model of Emissions of Gases and Aerosols from a Nature), *Atmos. Chem. Phys.*, *6*, 3181–3210.

Holland, M., S. Kinghorn, L. Emberson, S. Cinderby, M. Ashmoe, G. Mills, and H. Harmens (2006), Development of a framework for probabilistic assessment of the economic losses caused by ozone damage to crops in Europe, *CEH Rep.* C02309NEW, NERC/Centre for Ecology and Hydrology, Bangor, U. K.

Hollaway, M. J., S. R. Arnold, A. J. Challinor, and L. D. Emberson (2012), Intercontinental trans-boundary contributions to ozone-induced crop yield losses in the Northern Hemisphere, *Biogeosciences*, *9*, 271–292.

Horowitz, L. W. (2006), Past, present and future concentrations of tropospheric ozone and aerosols: Methodology, ozone evaluation, and sensitivity to aerosol wet removal, *J. Geophys. Res.*, *111*, D22211, doi:10.1029/2005JD006937.

Krupa, S. V., M. Nosal, and A. H. Legge (1998), A numerical analysis of the combined open-top chamber data from the USA and Europe on ambient ozone and negative crop responses, *Environ. Pollut.*, *101*, 157–160.

Levy, H., II, M. D. Schwarzkopf, L. Horowitz, V. Ramaswamy, and K. L. Findell (2008), Strong sensitivity of late 21st century climate to projected changes in short-lived air pollutants, *J. Geophys. Res.*, *113*, D06102, doi:10.1029/2007JD009176.

Liu, S., X. Mo, Z. Lin, X. Yueqing, J. Jinjun, G. Wen, and J. Richey (2010), Crop yield responses to climate change in the Huang-Huai-Hai Plain of China, *Agric. Water Manage.*, *97*, 1195–1209.

Lobell, D. B., and C. B. Field (2007), Global scale climate-crop yield relationships and the impact of recent warming, *Environ. Res. Lett.*, *2*, doi:10.1088/1748-9326/2/1/014002.

Lobell, D. B., W. Schlenker, and J. Costa-Roberts (2011), Climate trends and global crop production since 1980, *Science*, *333*, 616–620.

Mills, G., A. Buse, B. Gimeno, V. Bermejo, M. Holland, L. Emberson, and H. Pleijel (2007), A synthesis of AOT40-based response functions and critical levels of ozone for agricultural and horticultural crops, *Atmos. Environ.*, *41*, 2630–2643.

Morgan, P. B., T. A. Mies, G. A. Bollero, R. L. Nelson, and S. P. Long (2006), Season-long elevation of ozone concentration to projected 2050 levels under fully open-air conditions substantially decreases the growth and production of soybean, *New Phytol.*, *170*, 333–343.

Musselman, R. C., and A. S. Lefohn (2007), The use of critical levels for determining plant response to ozone in Europe and in North America, *Sci. World J.*, *7*, 15–21.

Ohara, T., H. Akimoto, J. Kurokawa, N. Horii, K. Yamaji, X. Yan, and T. Hayasaka (2007), An Asian emission inventory of anthropogenic emission sources for the period 1980–2020, *Atmos. Chem. Phys.*, *7*, 4419–4444.

Roy, S. D., G. Beig, and S. D. Ghude (2009), Exposure-plant response of ambient ozone over the tropical Indian region, *Atmos. Chem. Phys.*, *9*, 5253–5260.

Sahu, S. K., G. Beig, and N. S. Parkhi (2012), Emerging pattern of anthropogenic NO_x emission over Indian subcontinent during 1990s and 2000s, *Atmos. Pollut. Res.*, *3*(3), 262–269.

Sarkar, A., and S. B. Agrawal (2010), Elevated ozone and two modern wheat cultivars: An assessment of dose dependent sensitivity with respect to growth, reproductive and yield parameters, *Environ. Exp. Bot.*, *69*, 328–337.

Van Dingenen, R. (2009), The global impact of O_3 on agricultural crop yields under current and future air quality legislation, *Atmos. Environ.*, *43*, 604–618.

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

Wiedinmyer, C., S. K. Akagi, R. J. Yokelson, L. K. Emmons, J. A. Al-Saadi, J. J. Orlando, and A. J. Soja (2011), The Fire Inventory from NCAR(FINN): A high resolution global model to estimate the emissions from open burning, *Geosci. Model Dev.*, *4*, 625–641.

Zhang, Q., et al. (2009), Asian emissions in 2006 for the NASA INTEX-B mission, *Atmos. Chem. Phys.*, *9*, 5131–5153.