



Crop yield losses due to ozone in Punjab and Haryana

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# Assessment of crop yield losses in Punjab and Haryana using two years of continuous in-situ ozone measurements

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## Abstract

In this study we use a high quality dataset of in-situ ozone measurements at a suburban site called Mohali in the state of Punjab to estimate ozone related crop yield losses for wheat, rice, cotton and maize for Punjab and the neighbouring state Haryana for the years 2011–2013. We inter-compare crop yield loss estimates according to different exposure metrics such as AOT40 and M7 for the two major crop growing seasons of Kharif (June–October) and Rabi (November–April) and establish a new crop yield exposure relationship for South Asian wheat and rice cultivars. These are a factor of two more sensitive to ozone induced crop yield losses compared to their European and American counterparts.

Relative yield losses based on the AOT40 metrics ranged from 27–41 % for wheat, 21–26 % for rice, 9–11 % for maize and 47–58 % for cotton. Crop production losses for wheat amounted to 20.8 million t in fiscal year 2012–2013 and 10.3 million t in fiscal year 2013–2014 for Punjab and Haryana jointly. Crop production losses for rice totalled 5.4 million t in fiscal year 2012–2013 and 3.2 million t year 2013–2014 for Punjab and Haryana jointly. The Indian National Food Security Ordinance entitles ~ 820 million of India's poor to purchase about 60 kg of rice/wheat per person annually at subsidized rates. The scheme requires 27.6 Mt of wheat and 33.6 Mt of rice per year. Mitigation of ozone related crop production losses in Punjab and Haryana alone could provide >50 % of the wheat and ~10 % of the rice required for the scheme.

The total economic cost losses in Punjab and Haryana amounted to USD 6.5 billion in the fiscal year 2012–2013 and USD 3.7 billion in the fiscal year 2013–2014. This economic loss estimate represents a very conservative lower limit based on the minimum support price of the crop, which is lower than the actual production costs. The upper limit for ozone related crop yield losses in entire India currently amounts to 3.5–20 % of India's GDP.

Mitigation of high surface ozone would require relatively little investment in comparison to economic losses incurred presently. Therefore, ozone mitigation can yield mas-

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sive benefits in terms of ensuring food security and boosting the economy. Co-benefits of ozone mitigation also include a decrease in the ozone related mortality, morbidity and a reduction of the ozone induced warming in the lower troposphere.

## 1 Introduction

India is a rapidly developing nation. Population growth, urbanization and industrial development have led to increasing emissions and have resulted in a statistically significant increase in the tropospheric ozone mixing ratios over the Indian subcontinent in the past decades (Lal et al., 2012). Tropospheric ozone mixing ratios are expected to increase further in the years to come (Giles, 2005).

Tropospheric ozone causes damage to crop at elevated levels. Extensive plant damage due to tropospheric ozone was first observed during the Los Angeles Smog episodes. In the early 1950's, Arie Haagen-Smit and co-workers reported that such plant damage could be reproduced in the laboratory by the reaction of organic trace gases or car exhaust with nitrogen oxides ( $\text{NO}_x$ ) in presence of sunlight (Haagen-Smit, 1952; Haagen-Smit and Fox, 1954).

The influence of ozone on vegetation is dependent on the ozone dose and plant phenotype (Pleijel et al., 1991). Ozone enters leaves through plant stomata during normal gas exchange in the daylight hours and impairs plant metabolism leading to yield reduction in agricultural crops (Wilkinson et al., 2012).

In certain phenotypes, ozone exposure interferes with the hormone levels in plants and has been shown to lead to accumulation of ethylene in the leaves. The presence of ethylene in the leaves interferes with the functioning of the hormone abscisic acid (ABA), a hormone which normally controls stomata closure and reduces water loss under drought conditions (Wilkinson et al., 2012). Consequently ozone related crop yield losses in such phenotypes may be enhanced in regions where plants are frequently exposed to temperature or water stress.

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In phenotypes that are unable to control their stomata opening under ozone stress,  $O_3$  enters the leaf and acts as a strong oxidant causing reactive oxygen stress (ROS) through hydrogen peroxide, superoxide, and hydroxyl radicals that alter the basic metabolic processes in plants. Ozone has been shown to destroy the structure and function of biological membranes leading to electrolyte leakage causing accelerated leaf senescence and reduced photosynthesis (Calatayud et al., 2004) and can cause pollen sterility or induce flower, ovule, or grain injury and abortion (Black et al., 2000). In such phenotypes ozone causes visible leaf injury, senescence, and abscission (Kangasjaärvi et al., 2005) and can eventually reduce crop yield, even if the damage occurs at early vegetative stages of crop growth by reducing the amount of healthy green leaf area available for photosynthesis. Symptoms of ozone associated leaf injury have been reported for 27 agricultural crops (Mills et al., 2011a).

Certain other phenotypes respond to ozone stress by reducing their stomata aperture (Torsethaugen et al., 1999). While this mechanism reduces the amount of ozone taken up by the plant and hence the oxidative stress inside the leaves, it also decreases  $CO_2$  uptake, leading to a reduction in photosynthesis. This affects the carbon transport to roots, reduces nutrient and water uptake and, as a result of this, limits the storage of carbohydrates in the grains. Plants of this phenotype may show little to no visible leaf damage, but crop yields might be very sensitive to  $O_3$  stress during the grain filling stage. Picchi et al. (2010) reported that for different wheat cultivars the phenotypes with least visible leaf damage were often the ones showing maximum reduction in crop yield due to ozone. The ozone induced physiological damage such as lower yields and inferior crop quality lead to large economic losses (Avnery et al., 2011a, b; van Dingenen et al., 2009; Wilkinson et al., 2012; Giles, 2005).

Crop yields are extremely important to the Indian economy, as 17 % of India's GDP directly depends on agriculture and allied activities (RBI, 2013). However, since 54 % of the total and 72 % of the rural working population of India still relies on agriculture as their main source of income (Census, 2011), crop yields have a much larger overall effect on the economy. Rural demand for a large range of consumer products and

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cement depends directly on the year's crop yield. Consequently every 1 % decrease in crop yields causes a 0.36 % decrease of India's GDP (Gadgil and Gadgil, 2006). Moreover, India has to meet the challenge of feeding 17 % of the world's human population with just 2.4 % of the world's geographical area and 4 % of its freshwater resources (FAO, 2013). Wheat and rice are the most important food crops. In 2010 India produced 20.5 % of the world's rice and 12.4 % of the world's wheat. India is also a major producer of fibre crops (26 % of the world's fibre crops, FAO, 2013), which provide raw material to the domestic textile industry. Punjab with an average cropping intensity of 190 %, contributes 17.4 % to India's wheat and 10.9 % to India's rice production and produces 60 % of the wheat and 30 % of the rice procured by the Department of Food and Public Distribution (Agricultural Statistics, 2013).

In this study we use a high quality dataset of in-situ ozone measurements at a regionally representative suburban site called Mohali to assess ozone related crop yield losses for wheat, rice, cotton and maize for Punjab and the neighbouring state Haryana for the years 2011–2013. Crop yield loss estimates calculated using two different exposure metrics, AOT40 and M7, are inter-compared for the two major crop growing seasons of Kharif (June–October) and Rabi (November–April). We also derive a new ozone exposure crop yield relationship for Indian rice and wheat cultivars by combining field data from relay seeding experiments and data from open top chamber studies reported in the peer reviewed literature.

## 2 Materials and methods

### 2.1 Site description and analytical details

All ozone measurements were performed at the IISER Mohali atmospheric chemistry measurement facility (30.67° N–76.73° E, 310 m a.s.l., Fig. 1). The measurement site is regionally representative (Sinha et al., 2014) and located in the north-west Indo-Gangetic Plain (NW IGP). Ozone measurements from several other sites located in the

IGP and the adjoining mountain regions (Fig. 1) will be discussed in detail in Sect. 3.1 to demonstrate that the measurements obtained at the facility are, indeed regionally representative.

The measurement site is located inside a residential campus of around 1.25 km<sup>2</sup> with 800–1000 residents. Local influence is expected to be significant only at low wind speeds (< 1 ms<sup>-1</sup>), which occur only rarely (Sinha et al., 2014; Pawar et al., 2015). The predominant daytime wind direction is west to northwest during winter, summer and post monsoon season and south to southeast during the monsoon season. The fetch region of air masses arriving at the site is dominated by irrigated cropland (marked in light blue in Fig. 1 in the state of Punjab, north-west of the site). During monsoon season south easterly winds bring air masses from a fetch region covering irrigated cropland in the state of Haryana, south-east of the site.

At the measurement site, inlets and meteorological measurements are co-located atop the Ambient Air Quality Station (AAQS) about 20 m above ground. A comprehensive description of the site and its representativeness for N.W. Indo Gangetic Plain can be found in Sinha et al. (2014) and a thorough description of the meteorology of the site for all seasons can be found in Pawar et al. (2015).

Ozone was measured using UV absorption photometry at a time resolution of 1 measurement every minute with an accuracy that is better than 3%, and overall uncertainty of less than 6%. Quality assurance of the large dataset was accomplished by regular calibrations using a NIST traceable ozone primary standard generator and frequent zero drift calibrations. Over the time span reported in this paper, zero drift always remained below  $\pm 0.5 \text{ nmol mol}^{-1}$  between two subsequent zero drift calibrations. The drift of the calibration factor during span calibrations was usually less than  $\pm 3\%$  and always below  $\pm 8\%$  even after preventive maintenance. A detailed description of the ozone measurements and the supporting meteorological measurements can be found in Sinha et al. (2014).

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has been adopted for crops, forest trees, and semi-natural vegetation (Fuhrer et al., 1997). The AOT40 is defined as the sum of differences between the hourly ozone concentrations and  $40 \text{ nmol mol}^{-1}$  during the crop growing season (Fuhrer et al., 1997) for  $[\text{O}_3] > 40 \text{ nmol mol}^{-1}$ .

$$5 \quad \text{AOT40} = \sum_{i=1}^n ([\text{O}_3]_i - 40) \quad \text{for } [\text{O}_3] > 40 \text{ nmol mol}^{-1} \quad (3)$$

AOT40 is the most widely used exposure plant response index and is used by the United Nations Economic Commission for Europe (UNECE), the United States Environmental Protection Agency (USEPA), the World Meteorological Organization (WMO) and the World Health Organization (WHO) (Hollaway et al., 2012).

10 The W126 metric was proposed and adopted in United States by United States Environmental Protection Agency (USEPA) to assess potential vegetation damage from ozone exposure. The W126 metric is defined as the sum of hourly ozone concentrations (weighted by a sigmoidal function) during daylight hours (07:00–18:59 or 08:00–19:59 depending upon location of site) during the crop growing season (Eq. 1). The  
 15 W126 due to its sigmoidal weighting function gives more weight to higher ozone mixing ratios and is less sensitive to ozone mixing ratios between 40 and 50  $\text{nmol mol}^{-1}$  (Tong et al., 2009).

$$W126 = \sum_{i=1}^n \frac{[\text{O}_3]_i}{1 + 4403 + e^{-0.126 \times [\text{O}_3]_i}} \quad \text{for } [\text{O}_3] > 0 \text{ } \mu\text{mol mol}^{-1} \quad (4)$$

20 Recently stomatal flux-based critical levels were proposed to address concerns that the AOT40-based critical level are based on the concentration of ozone in the atmosphere whilst the ozone related damage depends on the amount of the pollutant reaching the sites of damage within the leaf. Stomatal flux of ozone is modelled using a multiplicative algorithm adapted from Emberson et al. (2000)

$$g_{\text{sto}} = g_{\text{max}} \times [\min(f_{\text{phen}}, f_{\text{O}_3})] \times f_{\text{light}} \times \max[f_{\text{min}}, (f_{\text{temp}} \times f_{\text{VDP}} \times f_{\text{SWP}})] \quad (5)$$

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rice-gram rotation is popular in the north but in the dryer parts of Haryana pearl millet-mustard and pearl millet-wheat rotations are preferred (Panigrahy et al., 2010).

The present study investigates crop yield losses for wheat and maize (Rabi) and rice, maize and cotton (Kharif). In the Supplement S1 we discuss the growth stages during which these crops are potentially sensitive to ozone related yield losses, as well as the time periods during which the plants reach those growth stages in the northern Indo Gangetic plain.

## 2.5 Ozone dose exposure yield relationships

Till date, only a limited number of field experiments to establish ozone related crop yield losses have been carried out in South Asia. Despite the fact that open top chamber studies in particular those conducted in Pakistani Punjab (Wahid et al., 1995a, b; Maggs et al., 1995; Maggs and Ashmore, 1998; Wahid, 2006; Wahid et al., 2011) and India (Rai et al., 2007, 2010; Rai and Agrawal, 2008; Singh et al., 2009; Singh and Agrawal, 2010; Sarkar and Agrawal, 2010, 2012) suggest that Asian cultivars are more sensitive to ozone related crop yield losses, no ozone exposure dose response relationship specific to the Indian subcontinent has been established in the literature so far.

In this study we use exposure dose–response relationships established in several studies in the West (Table 2) to provide a lower limit to the estimated crop yield losses, but also derive independent exposure dose–response relationships for South Asian cultivars. We obtain a yield exposure relationship by relating the crop yields obtained during several regional relay seeding trials to the ozone exposure of the crop and comparing the results with the relative yields (RY) for OTC studies reported in the peer reviewed literature. This provides an upper limit to the possible loss and helps to establish whether optimizing the sowing date can be a suitable strategy to minimize ozone exposure and maximise crop yields.

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## 2.6 Yield loss and economic loss calculations

Table 2 summarises the ozone exposure dose–response relationships for relative yield loss (RYL) for wheat, rice, maize and cotton based on the AOT40, W126, M7, and M12 collected from the peer reviewed literature.

All the ozone exposure dose–response relationships previously reported in the literature are based on field studies conducted in the USA or in Europe. Relative yield loss is defined as the crop yield reduction from the theoretical yield that would have resulted without O<sub>3</sub>-induced damages (Avnery et al., 2011a) calculated using the Eqs. (5) and (6)

$$RYL_i = 1 - RY_i \quad (6)$$

$$CPL_i = \frac{RYL_i}{1 - RYL_i} \times CP_i \quad (7)$$

wherein  $RY_i$  stands for relative yield in the year  $i$ ,  $CPL_i$  stands for crop production loss in the year  $i$  and  $CP_i$  stands for the crop production of the same year. The crop production per fiscal year was taken from the database of the Directorate of Economics and Statistics, Department of Agriculture and Cooperation 2013.

Economic cost loss (ECL) for any crop is defined as the amount of loss in terms of money due to O<sub>3</sub>-induced damages for particular financial year. The minimum ECL is calculated for different crops based on corresponding Minimum Support Prices (MSP) of the same fiscal year using the equation:

$$ECL_i = CPL_i \times MSP_i \quad (8)$$

The MSP are recommended by Commission for Agriculture Costs and Prices (Directorate of Economics and Statistics, 2013) and are announced by the Government of India at the beginning of each season for each year. These prices are defined as the fixed price at which government purchases crops from the farmers. All our crops of interest come under MSP valuation process. It should be noted, however, that the MSP

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is typically approximately 50 % less than the market value of the crop and often lower than the production costs. The upler limit for the ECL is calculated using the relationship between CPL due to deficient monsoon rains and the Indian GDP established by Gadgil and Gadgil (2006) using the equation.

$$ECL_i [\%GDP] = RYL_i [\%] \times 0.36 \quad (9)$$

### 3 Results and discussions

#### 3.1 Ozone seasonal cycle and monthly ozone exposure indices

Figure 2 shows the seasonal box and whisker plot of the daytime (08:00–19:59 LT) 1 h average ozone mixing ratios for the period from October 2011 to January 2014. The highest ozone levels are observed in summer season in April, May and June with median ozone mixing ratios of 60–80 nmol mol<sup>-1</sup> and peak ozone mixing ratios of approximately 130 nmol mol<sup>-1</sup>. This is expected, as favourable conditions such as high temperature, low humidity and high solar radiation favour the photochemical production of O<sub>3</sub> regionally.

After summer, the next highest ozone levels are observed during post monsoon season (October and November) with median ozone mixing ratios of 50–60 nmol mol<sup>-1</sup>. The post monsoon season is characterized by lower levels of solar radiation (range of daytime maxima ~ 480–720 W m<sup>-2</sup>) compared to summer season (range of daytime maxima ~ 600–920 W m<sup>-2</sup>), but the occurrence of large scale agricultural burning emissions of ozone precursors and a lower boundary layer still results in comparably high ozone levels.

The lowest median daytime ozone mixing ratios of approximately 30 nmol mol<sup>-1</sup> are observed in August, during peak monsoon season, when cloudiness and wet scavenging of ozone precursors limits the photochemical ozone production and during peak winter (December and January). During winter reduction in the solar radiation, low temperatures and fog result in less photochemical production of O<sub>3</sub>.

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Table 3 shows the monthly values of ozone exposure indices (AOT40, W126, M7 and M12) for the period October 2011 to January 2014. The yearly maximum and minimum monthly value for all indices correspond to the same months, May and August respectively in both years. All indices show maxima during summer (May and June) and post monsoon (October and November) and minima during monsoon (July to September) and winter (December to February), however, the difference between the cumulative metrics (AOT40 and W126), that give higher weight to high values and low or no weight to low values and the average based metrics (M7 and M12) comes out very clearly. For AOT40 and W126 the amplitude between peaks ( $\sim 14\,000\text{ nmol mol}^{-1}\text{h}$ ) and minima ( $\sim 500\text{ nmol mol}^{-1}\text{h}$ ) is very high. The annual peak values are 30 and 50 times higher for AOT40 and W126 respectively compared to the annual minima. For M7 and M12 peaks are only 2–3 times higher compared to the minima.

Few studies have so far reported ozone exposure indices over the IGP, however, a number of studies have reported average diel profiles for each month of the year (Jain et al., 2005; Kumar et al., 2010; Sharma et al., 2013) or a time series of average daytime ozone for their site (Maggs et al., 1995; Wahid, 2006; Wahid et al., 2011; Singla et al., 2011).

Table 4 shows the M7 or average daytime ozone calculated from the data in those studies. The seasonality and monthly average daytime ozone levels are similar for all urban and suburban sites in the IGP and the adjoining mountain valleys. However, sites located further to the East report lower M7 values during May and June, due to the higher frequency of summer rain, lower temperatures and earlier onset of the monsoon in the eastern part of the IGP. The only site further to the west for which ozone measurement have been reported is located close to the centre of the summertime “heat low” (Das, 1962) over the NW IGP and reports summertime and monsoon season M7 that are higher than those observed at our site and a strong anticorrelation of the observed ozone during monsoon season with the intensity of the monsoon rainfall.

Given the fact that the most reliable crop yield–exposure indices are based on AOT40 and not M7 values, there is urgent need to relate the available observations to AOT40

values. Debaje (2014) did so using a linear relationship. When applied to our data presented in Table 3 the relationship estimates reasonable AOT40 values (slope AOT40 predicted vs. AOT40 observed: 0.93,  $R^2 = 0.87$ ) but performs poorly, while reproducing peak AOT40 values. We find that at our site the actual data follows an exponential curve

$$\text{AOT40} = 0.0201 \times M7^{3.0765} \quad R^2 = 0.94 \quad (10)$$

and AOT40 values predicted using this curve match peak AOT40 observations better (slope AOT40 predicted vs. AOT40 observed: 1.03,  $R^2 = 0.97$ ).

Several studies attempted to model ozone levels and exposure metrics over the IGP. Deb Roy et al. (2009) modelled AOT40 over the Indian region for the year 2003 using the model REMO-CTM. For the north-western part of the IGP close to the foothills REMO-CTM models 5000–6000 nmol mol<sup>-1</sup> h in May, 1500–2000 nmol mol<sup>-1</sup> h in July and 6000–7000 nmol mol<sup>-1</sup> h in October. We find that the model underestimates the observed AOT40 in the north-west IGP by a factor 2 to 3 during May and July and reproduces the observations well during October. Consequently the model would be able to predict crop production losses during Rabi Season better and would underestimate crop production losses during Zayad and Kharif season.

In a more recent study conducted using WRF-Chem, Ghude et al. (2014) predicted ozone daytime concentrations of ~ 50 nmol mol<sup>-1</sup> for Kharif season and ~ 40 nmol mol<sup>-1</sup> for Rabi season for the Chandigarh UT. However, the authors considered only the time windows 15 June to 15 September and December to February for kharif and rabi season respectively. For those time windows, predicted ozone daytime concentrations agree well with the measured M12.

Mittal et al. (2007) inter-compared model predicted ozone with surface observation for the HANK model. The model could not resolve the daytime ozone peak in Delhi and, hence, will perform poorly in predicting AOT40. Comparing the reported values for Chandigarh with our measurements we find that the model has equal difficulty in resolving the seasonality, in particular the high ozone levels in summer.

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sowed on different sowing dates has been calculated using our data (Table S2). Yield data for rice has been taken from the peer reviewed literature (Chahal et al., 2007; Jalota et al., 2009; Mahajan et al., 2009; Brar et al., 2012). There is a significant trend of the reported crop yields as a function of ozone exposure indices (Fig. 3,  $R^2 = 0.58$  for M7 and  $R^2 = 0.57$  for AOT40).

Figure 4 compares the empirical ozone exposure response curve derived from the field data presented in Fig. 3 (solid line) with RY values determined in open top chamber studies (OTC) conducted in India (squares, dash and dot line fit) and Pakistani Punjab (diamonds). Large diamonds indicate studies on Basmati, all other studies were conducted on paddy. Circles show plant chamber studies on Bangladeshi rice cultivars conducted in Japan and the dashed line delineates the European (AOT40, Mills et al., 2007) and American (M7, Adams et al., 1989) dose response relationship. For studies that did not report AOT40 but did report monthly or seasonal M7, M8 or M12, AOT40 was calculated using the relationship between the respective index and AOT40 at our site. For M7 all data points of OTC studies lie close to the line derived from the empirical relationship between crop yields and ozone exposure in Punjab. The fit for the OTC studies gives a similar slope as the linear fit of the yield data. Since OTC studies compare yield losses of plants exposed to ozone with those of plants grown under identical conditions but in clean filtered air, the ozone exposure response curve derived from OTC studies of Indian cultivars provides the most accurate estimate of the RYL. A new RYL equation for Indian rice cultivars (Table 2) is derived by fitting all relative yields for Indian cultivars from OTC studies (Fig. 4). We calculate relative yields for all 5 reference periods defined in Supplement S1 both using the old (Mills et al., 2007; Adams et al., 1989) and the revised RYL relationships.

It is clear from Fig. 4 and Table S2 that the RY curve derived by Adams et al. (1989) overestimates the RY of *Oryza sativa* L. *Indica* cultivars planted in the IGP significantly and interesting to note that there seems to be a East–West gradient in the sensitivity of local cultivars to ozone exposure. Bangladeshi cultivars showed the lowest sensitivity

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and highest relative yields and Pakistani cultivars showed the highest sensitivity to ozone exposure and the lowest relative yields.

Crop production losses calculated using the equation derived based on American studies (Adams et al., 1989) underestimates crop production losses in South Asia by approximately 20–30 % (Table S2). For AOT 40 both the empirical relationship between crop yields and ozone exposure and the OTC studies conducted in India lead to line fits with similar slopes, however, OTC studies show an intercept of 0.95 for AOT40 = 0 indicating that in South Asia ozone levels below 40 nmol mol<sup>-1</sup> damage local paddy cultivars. While deriving the empirical relationship from field data the RY for AOT40 = 0 was defined as 1 due to the absence of clean air controls. The slope obtained in the current steeper than the slope reported by Mills et al. (2007) and the intercept of the Indian OTC studies is also lower, hence RY and crop production losses calculated using the equation derived based on European studies underestimates crop production losses in South Asia by approximately 5–15 % (Table S2). Table S2 summarises relative yields for the five reference periods (which correspond to different sowing dates) and inter-compares RY obtained by our calculation with RY calculated using the old relationships. It can be noted that AOT40 shows a better degree of agreement between the exposure yield relationship of Mills et al. (2007) and the exposure yield relationship for Indian cultivars (Table S2) the difference between the two is generally ~ 10 %. On the other hand, M7 shows a lower degree of agreement between the exposure yield relationship of Adams et al. (1989) and the exposure yield relationship for Indian cultivars (Table S2). The difference between the two is ~ 20 %. After the revision relative yields calculated using the M7 and AOT40 metrics agree within 5–6 % while previously the discrepancy between the crop yield losses calculated using M7 and AOT40 metrics exceeded 10 %. Our revised ozone exposure crop yield relationships show significantly lower relative yields than those using the previous exposure response relationships. This can be attributed to the variety of cultivars. The Indian cultivars are more sensitive to O<sub>3</sub> concentration.

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### 3.2.2 Wheat

Figure 5 shows the empirical correlation of rice yields and ozone exposure indices for field studies with variations in sowing in Punjab and Haryana. Ozone exposure for wheat sowed on different sowing dates has been calculated using our data (Table S3).

Yield data for wheat have been taken from the peer reviewed literature (Agrawal et al., 2003; Chahal et al., 2007; Jalota et al., 2008; Coventry et al., 2011; Buttar et al., 2013; Ram et al., 2013). Agrawal et al. (2003) reported co-located measurements of ozone exposure and yields for a number of urban locations that included residential areas and kerb site locations, where NO titration leads to low wintertime ozone levels. Other studies reported yields corresponding to different sowing date. The yield data has been positioned in conformation to the emergence dates (Period 1 to 5) defined in Supplement S1. There is a significant decrease in yield as a function of increasing ozone exposure (Fig. 5) for both ozone exposure indices ( $R^2 = 0.55$  of M7 and  $R^2 = 0.7$  for AOT40). Based on the values of slopes and y-intercept, we determined our own values of the relative yield relationship (solid line, Fig. 6) by calculating the relative yield at the observed M7 compared to the yield that would be obtained for background concentrations of  $25 \text{ nmol mol}^{-1}$  ozone. For AOT 40 the relative yield is determined with respect to the yield that would have been obtained for AOT40 = 0).

Figure 6 compares the empirical ozone exposure response curve derived from field data (solid line) with RYL relationships reported in the literature (Mills et al., 2007; Heck et al., 1984b; Lesser et al., 1990; Adams et al., 1989) with open top chamber studies (OTC) conducted in India (squares, dash and dot line) and Pakistani Punjab (diamonds). Circles show plant chamber studies on Bangladeshi wheat cultivars conducted in Japan. For studies that did not report AOT40 but did report monthly or seasonal averaged M7 or M12, AOT40 was estimated. For M7 most data points of OTC studies with Indian cultivars lie close to the line derived from the empirical relationship between crop yields and ozone exposure in Punjab. However, the exposure response relationship for wheat can only be appropriately described by fitting a Weibull func-

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tion. Since OTC studies compare yield losses of plants exposed to ozone with those of plants grown under identical conditions but in clean filtered air, the ozone exposure response curve derived from OTC studies of Indian cultivars provides the most accurate estimate of the RYL. A new RYL equation for Indian wheat cultivars (Table 2) is derived by fitting all relative yields for Indian cultivars from OTC studies (Fig. 6). We calculate relative yields for all 5 reference periods defined in Supplement S1 both using the old (Mills et al., 2007; Adams et al., 1989) and the revised RYL relationships. It is clear from Fig. 6 that the RY curves for winter wheat derived by Lesser et al. (1990) and Heck et al. (1984b) overestimates the RY of most *Triticum aestivum* L. cultivars planted in the IGP. For *Triticum aestivum* L. there is no significant trend between cultivars planted in different countries. Crop production losses calculated using the M7 index and the equation derived based on American studies (Lesser et al., 1990; Heck et al., 1984b) underestimates crop production losses in South Asia by approximately 10 and 20 % for the equation of Heck et al. (1984b) and Lesser et al. (1990) respectively (Table S3).

For AOT 40 both the empirical relationship between crop yields and ozone exposure and the OTC studies conducted in India lead to line fits with similar slopes and intercepts. The slope obtained in the current study is steeper than the slope reported by Mills et al. (2007), although a limited number of cultivars planted in the IGP show an exposure RY relationship similar to that reported by Mills et al. (2007). Cultivars with lower sensitivity to ozone include Bijoy (Akhtar et al., 2010a), Inqilab-91, Punjab-96 and Pasban-90 (Wahid, 2006), HUW234, PBW343 and Sonalika (Singh et al., 2009; Sarkar and Agrawal, 2010). For HUW468 the sensitivity obtained by Singh et al. (2009) and Singh and Agrawal (2010) differ. However, for most cultivars crop production losses calculated using the equation derived based on European studies underestimates crop production losses in South Asia. Table S3 summarises relative yield that are obtained by our calculation. For AOT40 the exposure yield relationship of Mills et al. (2007) and the exposure yield relationship for Indian cultivars (Table S3) differ by ~ 15 %. For M7 the exposure yield relationship of Lesser et al. (1990) overestimates the yields by ~ 20 % and the exposure yield relationship of Heck et al. (1984b) by ~ 10 % (Table S3).



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yield dependence on rain should not be related to drought stress. Ozone levels in Punjab during monsoon season are strongly influence by wet scavenging of precursors and cloudiness, hence rain spells can be taken as a proxy for times of low photochemical ozone production. The lowest yields were observed for Period 1 sowings in 2004 that were affected by a prolonged dry spell from 60 days after sowing to 100 days after sowing. This corresponds to the period of maximum square production and peak bloom in a cotton plant. In 2005 the same Period 1 sowings received regular rain (every 5–7 days) in the same time period (total 400 mm between 60 to 100 days after sowing) and showed the highest yields (2.4 times the yield of the previous year on average). The Period 2 sowings in 2005 received rain from 40 to 80 days after sowing but were subjected to a dry spell during the second half of the square production and peak bloom period. Observed yields were 1.9 times higher compared to the plants that were subjected to a dry spell during the entire period. Period 2 sowings in 2004 received a short ( $\sim 7$  day) rain spell around 80 days after sowings during the peak square production period and showed yields that were 1.4 times the dry spell yields. Considering the average difference between dry spell and rain spell M7 of approximately  $10\text{--}20\text{ nmol mol}^{-1}$  the observations described above seem to suggest a strong sensitivity of the plant to ozone levels during square production and peak bloom (60–100 days after sowing) but it is difficult to separate the effect of yield losses due to adverse meteorological conditions from that due to ozone exposure. In the absence of dedicated OTC fumigation studies conducted in India that separate the two effects we use the relationship of Mills et al. (2007) and Heck et al. (1984b) to calculate relative yields (Table S4).

For cotton there are extreme differences of 30–60 % between the relative yields calculated using AOT40 (Mills et al., 2007) and M7 (Heck et al., 1984b). Ozone fumigation studies on Indian cultivars are urgently required to constrain relative yields and crop production losses due to ozone more accurately.

### 3.2.4 Maize

Maize is planted both as Rabi and Kharif crop, however, cultivation occurs only on a limited area. We could not find any study reporting crop yields for maize planted in Punjab or Haryana in the peer reviewed literature. Neither could we identify any study investigating ozone related crop yield losses for Indian maize cultivars, In the absence of suitable data we were unable to derive a ozone exposure RY relationship for Indian maize cultivars and use the relationship of Mills et al. (2007) and Heck et al. (1984b) to calculate relative yields (Table S5).

### 3.3 Yield loss and economic loss in Punjab and Haryana

Table 5 summarises the relative yield loss calculated according to different exposure indices. In general crop production losses calculated using the M7 index exposure response relationships based on American studies conducted in the 1970's and 1980's (Heck et al., 1984b; Adams et al., 1989; Lesser et al., 1990) tend to underestimate the actual yield losses of Indian cultivars, as the M7 index fails to capture the effect of extreme events on plant physiology and yields (Tuovinen, 2000; Hollaway et al., 2012). The old AOT40 exposure-response-relationship by Mills et al. (2007) does not capture the sensitivity of most South Asian cultivars. Only Bangladeshi rice cultivars and a few select wheat cultivars follow this relationship while most Indian wheat and rice cultivars are far more sensitive to elevated ozone levels. We propose a revised relationship (Table 2, Figs. 4 and 6) based on a literature review of OTC studies conducted on Indian cultivars and demonstrate that this relationship adequately describes the empirical relationship between crop yield and AOT40 in field trials that were not aimed at studying the effect of ozone on crops. The revised equation (Table 2) predicts that RYL for Indian cultivars are 1.5–2 times the RYL predicted based on the equation by Mills et al. (2007).

A recent modeling studies for the year 2005 predicted RYL of 1 and 1.2 % for Punjab and Haryana respectively for wheat and 8.1 % for Punjab for rice (Ghude et al., 2014).

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These relative yield losses are a factor of 15–30 lower compared to the RYL calculated using the same equation (Mills et al., 2007) but employing in-situ measurements for calculating AOT40 for wheat and a factor of 1.5 to 1.8 lower for rice (Table 5 Column  $RYL_{AOT40}$ , Mills et al., 2007).

5 Debaje (2014) estimated the crop production loss of winter wheat based on a review of measured ozone mixing ratios published in the peer reviewed literature for the years 2000–2007. The calculated relative yield losses both based on the M7 exposure response relationship for winter wheat proposed by Lesser et al. (1990) of 10.8 % and for the AOT40 based exposure response relationship by Mills et al. (2007) of 29.8 %  
10 RYL for Punjab and Haryana agree well with crop yield losses calculated by applying the same equations, to our in-situ observations (Table S3) for the years 2011–2014 (Table 5 Column  $RYL_{AOT40}$ , Mills et al., 2007). This indicates that the underestimation of RYL by Ghude et al. (2014) is due to an underestimation of the AOT40 values during the wheat growing season in the north west IGP caused by the fact that the  
15 Ghude and co-workers only considered December to February as the ozone sensitive growth periods and excluded the months of March and April, which show the highest AOT40 values in the growing season of wheat. However, in the NW-IGP the grain filling stage of the crop is only reached in March and wheat has been shown to be extremely sensitive to high ozone during the grain filling stage (Picchi et al., 2010). Avnery et al.  
20 (2011a) used the Mozart-2 model to predict national average RYL of 25–30 % for wheat using the AOT40 based equation, which agrees well with our observations. van Dingenen et al. (2009) using TM5 model predicted RYL ranging from 20–30 % for wheat, 10–15 % for rice and 5–10 % for maize for the year 2000, which agrees well with the observations.

25 Table 6 shows the crop production, crop production loss and MSP for the fiscal year 2012–2013 and 2013–2014. Data on crop production was obtained from the following sources: Directorate of Economics and Statistics (2013); Agricultural Statistics (2013), Procurement data was obtained from the Food Corporation of India (2013). For the fiscal year 2013–2014 data for Punjab are based on estimates while final data for

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Haryana was obtained from Department of Agriculture Haryana (2014). The table also presents economic cost losses calculated for wheat, rice, maize and cotton using the old (Mills et al., 2007) and revised exposure-yield relationship. The losses are present for both Haryana and Punjab separately and cumulatively.

The highest crop production loss is seen for wheat: 20.8 million t in fiscal year 2012–2013 and 10.3 million t in fiscal year 2013–2014 for Punjab and Haryana jointly. Ghude et al. (2014) predicted crop production losses of 0.25 million t only for the year 2005 for both states. The discrepancy is mostly due to the fact that this study assumed the ozone sensitive growth period of wheat lasts only from December to February and, hence, did not capture the effect of the high AOT40 during the grain filling stage of the crop in March (factor ~ 15–30) and partially due to the revision of the exposure response relationship (Table 2; factor ~ 2). Debaje (2014) estimated crop production losses of 10.9 million t year<sup>-1</sup> on average for both states combined. The estimate falls within the same order of magnitude as our estimate. Avnery et al. (2011a) estimated CPL of 26 million t for entire India but did not resolve losses for individual states. Economic cost losses amount to INR 243.67 billion and INR 132.65 billion in the fiscal year 2012–2013 and 2013–2014 respectively. At an exchange rate of 60 INR/\$ this amounts to USD 4.06 and 2.21 billion respectively.

Rice shows crop production losses of 5.4 million t in fiscal year 2012–2013 and 3.2 million t in fiscal year 2013–2014 for Punjab and Haryana jointly. Ghude et al. (2014) predicted crop production losses of 0.85 million t only for the year 2005 for both states. The discrepancy is caused both by an underestimation of the AOT40 due to the fact that the author considered a shorer ozone sensitive growth period (factor 1.5–1.8) and the revision of the exposure yield relationship (Table 2) to account for the sensitivity of Indian rice cultivars (factor 1.9). Economic losses amount to INR 67.42 billions and INR 42.34 billions for the fiscal year 2012–2013 and 2013–2014 respectively. At an exchange rate of 60 INR/\$ this amounts to USD 1.1 and 0.7 billion respectively.

The Indian National Food Security Ordinance entitles ~ 820 million of India's poor to purchase about 60 kg of rice/wheat per person annually at subsidized rates. The

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scheme requires 27.6 Mt of wheat and 33.6 Mt of rice per year. Cutting down ozone related crop production losses in Punjab and Haryana alone could provide > 50 % of the wheat and 10 % of the rice required for the scheme. For cotton and maize economic losses amount to INR 79.15 billion and 47.50 billion (USD 1.3 and 0.8 billion) for cotton and INR 0.65 billion and INR 0.85 billion (USD 11 and 14 million) for maize in the fiscal year 2012–2013 and 2013–2014 respectively.

The total economic losses for the agricultural sector in Punjab and Haryana amount to INR 390.89 billion (USD 6.5 billion) in the fiscal year 2012–2013 and INR 223.34 billion (USD 3.7 billion) in the fiscal year 2013–2014. The loss estimates presented above underestimate the real economic losses due to ozone on several accounts.

Firstly, the crop is valued only at the MSP for common grade crops. The MSP is often even lower than the actual production cost and the economic value of the crop is typically much higher. This is particularly true for high quality rice varieties like Basmati.

Secondly, we do not account for the losses in the food processing sector and other allied industries. The value gain from MSP to final end consumer product ranges from a factor of 2 to 20 for food crops to a factor of > 100 for cotton.

Thirdly, this calculation does not consider the relationship between the rural demand for consumer products and rural income. 78 % of the rural population depends on agriculture as primary source of income. Hence, rural income is affected strongly by crop yields.

Previous studies investigating the relationship between monsoon rainfall, food grain production and the Nations GDP for the years 1951–2003 (Gadgil and Gadgil, 2006) found that one percent decrease in food grain production due to deficient monsoon lead to a 0.36 % decrease in Indias GDP. Ozone related crop production losses are likely subject to the same multiplication factor. With relative yields losses currently ranging from 10 to 58 % for the different crops (Avnery et al., 2011a; van Dingenen et al., 2009), the real economic burden of current ozone levels in terms of the Indias GDP is likely to fall into the range from 3.6 to 20 % (Eq. 8).

## 4 Conclusions

Using a high quality dataset of in-situ ozone measurements in the NW-IGP and yield data from the two neighbouring states of Punjab and Haryana we derived a new crop yield ozone exposure relationship for Indian rice and wheat cultivars. Indian cultivars are a factor of 2–3 more sensitive to ozone compared to their European and South East Asian counterparts. Relative yield losses based on the AOT40 metrics ranged from 30–42 % for wheat, 22–26 % for rice, 9–11 % for maize and 47–58 % for cotton.

Crop production losses for wheat amounted to 20.8 million t in fiscal year 2012–2013 and 10.3 million t in fiscal year 2013–2014 for Punjab and Haryana jointly. Crop production losses for rice totaled 5.4 million t in fiscal year 2012–2013 and 3.2 million t year 2013–2014 for Punjab and Haryana jointly. Cutting these ozone related crop production losses alone could provide 50 % of the wheat and 10 % of the rice required to provide 60 kg of subsidized wheat/rice to ~ 820 million of India's economically weaker sections of society.

The lower limit for economic cost losses in Punjab and Haryana amounted to USD 6.5 billion in the fiscal year 2012–2013 and USD 3.7 billion in the fiscal year 2013–2014. The upper limit for the ozone related economic losses incurred at current ozone levels for entire India amount to 3.5–20 % of India's GDP. The wealth gained by mitigating tropospheric ozone and decreasing ozone related economic losses would be distributed among a large group of beneficiaries, as 54 % of the India's population and 79 % of India's rural population still rely on agriculture as their principle source of income. Co-benefits of ozone mitigation include a decrease in the ozone related mortality and morbidity, a reduction of healthcare related costs and the number of workdays lost and a reduction of the ozone induced warming in the lower troposphere.

At current tropospheric ozone levels optimizing the sowing date of rice towards sowing at the start of June and transplantation in the first week of July can increase crop yields substantially by reducing ozone exposure of the crop. Reaching out to farmers for promoting this change in cropping practise will yield co-benefits in terms of increas-

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ing the water productivity of the crop and preserving precious ground water. It will also increase the profit margin, as farmers often run tubewells on diesel, whenever grid power supply is not available.

For wheat, too, timely sowing is crucial to minimize ozone exposure during the grain filling stage of the crop. New tillage practises that facilitate timely sowing such as relay seeding into cotton and zero or low tillage regimes that incorporates rice straw or machinery to rapidly clear rice residues from the fields are urgently required to facilitate timely sowings. However, screening a large number of cultivars to identify and promote those cultivars that are less susceptible to ozone damage also offers a way forward.

Mitigating the increasing tropospheric ozone levels in India remains a challenging task for policy makers and the regulatory authorities. Enforcing existing legislation aimed at reducing the emission of ozone precursors remains a challenge even in metropolitan cities. Most area sources of ozone precursors, which include domestic cooking and heating, emissions from cottage industries, waste burning and crop residue burning are either not within the purview or not within the reach of the regulatory authorities. Low cost indigenous solutions which are attractive alternatives to the existing technologies are urgently required to curb precursor emissions and should be a major research focus. Developing suitable solutions requires interdisciplinary efforts, as technical feasibility, costs and social acceptability of the proposed solutions needs to be assessed in order to ensure widespread implementation.

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2009 Project (ESA 2010 and UCLouvain) for providing a high resolution land classification map of the region.

## References

5 Adams, R. M., Glycer, J. D., Johnson, S. L., and McCarl, B. A.: Assessment of the economic effects of ozone on United States agriculture, JAPCA J. Air Waste Ma., 39, 960–968, 1989. 2361, 2372, 2373, 2374, 2375, 2378, 2394

agripb.gov.in, available at: [http://agripb.gov.in/pub/pdf/cotton\\_brief.pdf](http://agripb.gov.in/pub/pdf/cotton_brief.pdf) (last access: 6 June 2014) and [http://agripb.gov.in/pub/pdf/agronomic\\_practices\\_of\\_rice.pdf](http://agripb.gov.in/pub/pdf/agronomic_practices_of_rice.pdf) (last access: 6 June 2014), 2014.

10 Agricultural Statistics: Government of India, Ministry of Agriculture, Department of Agriculture and Cooperation, Directorate of Economics and Statistics. Pocket Book on Agricultural Statistics 2013, New Delhi, 2013. 2359, 2379

Agrawal, M., Singh, B., Rajput, M., Marshall, F., and Bell, J. N. B.: Effect of air pollution on peri-urban agriculture: a case study, Environ. Pollut., 126, 323–329, 2003. 2371, 2374

15 Akhtar, N., Yamaguchi, M., Inada, H., Hoshino, D., and Kondo, T.: Effects of ozone on growth, yield and leaf gas exchange rates of four Bangladeshi cultivars of rice (*Oryza sativa* L.), Environ. Pollut., 158, 2970–2973, 2010a. 2371, 2375

Akhtar, N., Yamaguchi, M., Inada, H., Hoshino, D., Kondo, T., and Izuta, T.: Effects of ozone on growth, yield and leaf gas exchange rates of two Bangladeshi cultivars of wheat (*Triticum aestivum* L.), Environ. Pollut., 158, 1763–1767, 2010b. 2371

20 Avnery, S., Mauzerall, D. L., Liu, J., and Horowitz, L. W.: Global crop yield reductions due to surface ozone exposure 1: Year 2000 crop production losses and economic damage, Atmos. Environ., 45, 2284–2296, 2011a. 2358, 2366, 2379, 2380

Avnery, S., Mauzerall, D. L., Liu, J., and Horowitz, L. W.: Global crop yield reductions due to surface ozone exposure 2: year 2030 potential crop production losses and economic damage under two scenarios of O<sub>3</sub> pollution, Atmos. Environ., 45, 2297–2309, 2011b. 2358

25 Black, V. J., Black, C. R., Roberts, J. A., and Stewart, C. A.: Impact of ozone on the reproductive development of plants, New Phytol., 147, 421–447, 2000. 2358

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- Brar, S. K., Mahal, S. S., Brar, A. S., Vashist, K. K., Sharma, N., Buttar, G. S.: Transplanting time and seedling age affect water productivity, rice yield and quality in north-west India, *Agr. Water Manage.*, 115, 217–222, 2012. 2371, 2372
- Buttar, G. S., Sidhu, H. S., Singh, V., Jats, M.L, Gupta, R., Singh, Y., and Singh, B.: Relay planting of wheat in cotton: an innovative technology for enhancing productivity and profitability of wheat in cotton-wheat production systems of South Asia, *Exp. Agr.*, 49, 19–30, 2013. 2371, 2374, 2376
- Cakir, R.: Effect of water stress at different development stages on vegetative and reproductive growth of corn, *Field Crop. Res.*, 89, 1–16, 2004.
- Calatayud, A., Iglesias, D., Talon, M., and Barreno, E.: Response of spinach leaves (*spinacia oleracea* L.) to ozone measured by gas exchange, chlorophyll *a* fluorescence, antioxidant systems, and lipid peroxidation, *Photosynthetica*, 42, 23–29, 2004. 2358
- Census 2011: Government of India, Ministry of Home Affairs, Office of the Registrar General and Census Commissioner, India, available at: <http://www.censusindia.gov.in/pca/default.aspx> (last access: 6 June 2014), 2011. 2358
- Chahal, G. B. S., Sood, A., Jalota, S. K., Choudhury, B. U., and Sharma, P. K.: Yield, evapotranspiration and water productivity of rice (*Oryza sativa* L.) and wheat (*Triticum aestivum* L.) system in Punjab (India) as influenced by transplanting date of rice and weather parameters, *Agr. Water Manage.*, 88, 14–22, 2007. 2371, 2372, 2374
- Coventry, D. R., Gupta, R. K., Yadav, A., Poswal, R. S., Chhokar, R. S., Sharma, R. K., Yadav, V. K., Gill, S. C., Kumar, A., Metha, A., Kleeman, S. G. L., Bonamanof, A., and Cummin, J. A.: Wheat quality and productivity as affected by varieties and sowing time in Haryana, India, *Field Crop. Res.*, 123, 214–225, 2011. 2374
- Das, P. K.: Mean vertical motion and non-adiabatic heat sources over India during the monsoon, *Tellus*, 14, 212–220, 1962. 2368
- Das, P. K.: Estimated crop yield losses due to surface ozone exposure and economic damages in India, *Environ. Sci. Pollut. Res.*, 21, 7329–7338, 2014. 2369, 2379, 2380
- Deb Roy, S., Beig, G., and Ghude, Sachin D.: Exposure-plant response of ambient ozone over the tropical Indian region, *Atmos. Chem. Phys.*, 9, 5253–5260, doi:10.5194/acp-9-5253-2009, 2009. 2369
- Department of Agriculture Haryana: Rabi crop production , available at: [http://www.agriharyana.nic.in/Stat\\_Info/Final%20Estimates%20Rabi%202013-14.pdf](http://www.agriharyana.nic.in/Stat_Info/Final%20Estimates%20Rabi%202013-14.pdf) (last access: 21 September 2014) and Kharif crop production, available at:

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[http://www.agriharyana.nic.in/Stat\\_Info/Final%20estimates%202013-2014.doc](http://www.agriharyana.nic.in/Stat_Info/Final%20estimates%202013-2014.doc) (last access: 21 September 2014), 2014. 2380

Directorate of Economics and Statistics, Department of Agriculture and Cooperation, Agricultural Statistics At a Glance 2013, available at: [http://eands.dacnet.nic.in/latest\\_2013.htm](http://eands.dacnet.nic.in/latest_2013.htm) (last access: 18 September 2014), 2013. 2366, 2379

Emberson, L. D., Ashmore, M. R., Cambridge, H. M., Simpson, D., and Tuovinen, J.-P.: Modelling stomatal ozone flux across Europe, *Environ. Pollut.*, 109, 403–413, 2000. 2362

Emberson, L. D., Buker, P., Ashmore, M., Mills, G., Jackson, L., Agrawal, M., Atikuzzaman, M., Cinderby, S., Engardt, M., Jamir, C., Kobayashi, K., Oanh, N., Quadir, Q., and Wahid, A.: A comparison of North-American and Asian exposure-response data for ozone effects on crop yields, *Atmos. Environ.*, 43, 1945–1953, 2009. 2370, 2371

FAO (Food and Agriculture Organization) of the United Nations: Statistical Yearbook 2013, ISBN 978-92-5-107396-4, Rome, 2013. 2359

Food Corporation of India 2013, available at: <http://fciweb.nic.in/procurements/view/43> (last access: 21 September 2014), 2013. 2379

Fuhrer, J., Skärby, L., and Ashmore, M.: Critical levels for ozone effects on vegetation in Europe, *Environ. Pollut.*, 97, 91–106, 1997. 2361, 2362

Gadgil, S. and Gadgil, S.: The Indian monsoon, GDP and agriculture, *Econ. Polit. Weekly*, 41, 4889–4895, 2006. 2359, 2381

Ghuman, B. S. and Sur, H. S.: Tillage and residue management effects on soil properties and yields of rainfed maize and wheat in a subhumid subtropical climate, *Soil Till. Res.*, 58, 1–10, 2001.

Giles, J.: Hikes in surface ozone could suffocate crops, *Nature*, 435, p. 7, doi:10.1038/435007a, 2005. 2357, 2358

Ghude, S. D., Jain, S. L., Arya, B. C., Beig, G., Ahammed, Y. N., Kumar, A., and Tyagi, B.: Ozone in ambient air at a tropical megacity, Delhi: characteristics, trends and cumulative ozone exposure indices, *J. Atmos. Chem.*, 60, 237–252, 2008. 2396

Ghude, S. D., Jena, C., Chate, D. M., Beig, G., Pfister, G. G., Kumar, R., and Ramanathan, V.: Reduction in Indias crop yield due to ozone, *Geophys. Res. Lett.*, 41, 51971, doi:10.1002/2014GL060930, 2014. 2369, 2378, 2379, 2380

Haagen-Smit, A. J.: Chemistry and Physiology of Los Angeles smog, *Ind. Eng. Chem.*, 44, 1342–1346, 1952. 2357

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- Haagen-Smit, A. J. and Fox, M. M.: Photochemical ozone formation with hydrocarbons and automobile exhaust, *JAPCA J. Air Waste Ma.*, 4, 105–109, 1954. 2357
- Heck, W. W., Cure, W. W., Rawlings, J. O., Zaragoza, L. J., Heagle, A. S., Heggestad, H. E., Kohut, R. J., Kress, L. W., and Temple, P. J.: Assessing impacts of ozone on agricultural crops: I: Overview, *JAPCA J. Air Waste Ma.*, 34, 729–735, 1984a. 2361
- Heck, W. W., Cure, W. W., Rawlings, J. O., Zaragoza, L. J., Heagle, A. S., Heggestad, H. E., Kohut, R. J., Kress, L. W., and Temple, P. J.: Assessing impacts of ozone on agricultural crops: II: Crop yield functions and alternative exposure statistics, *JAPCA J. Air Waste Ma.*, 34, 729–735, 1984b. 2361, 2374, 2375, 2377, 2378, 2394
- Hollaway, M. J., Arnold, S. R., Challinor, A. J., and Emberson, L. D.: Intercontinental transboundary contributions to ozone-induced crop yield losses in the Northern Hemisphere, *Biogeosciences*, 9, 271–292, doi:10.5194/bg-9-271-2012, 2012. 2361, 2362, 2363, 2378
- Jain, S. L., Arya, B. C., and Kumar, A.: Observational study of surface ozone at New Delhi, India, *Int. J. Remote Sens.*, 26, 3515–3526, 2005. 2368, 2396
- Jalota, S. K., Buttar, G. S., Sood, A., Chahal, G. B. S., Ray, S. S., and Panigrahy, S.: Effects of sowing date, tillage and residue management on productivity of cotton (*Gossypium hirsutum* L.), *Soil Till. Res.*, 99, 76–83, 2008. 2371, 2374, 2376
- Jalota, S. K., Singh, K. B., Chahal, G. B. S., Gupta, R. K., Chakraborty, S., Sood, A., Ray, S. S., and Panigrahy, S.: Integrated effect of transplanting date, cultivar and irrigation on yield, water saving and water productivity of rice (*Oryza sativa* L.) in Indian Punjab: field and simulation study, *Agr. Water Manage.*, 96, 1096–1104, 2009. 2371, 2372
- Kangasjaarvi J., Jaspers, P., and Kollist, H.: Signalling and cell death in ozone-exposed plants, *Plant Cell Environ.*, 28, 1021–1036, 2005. 2358
- Kumar, R., Naja, M., Venkataramani, S., and Wild, O.: Variations in surface ozone at Nainital: a high-altitude site in the central Himalayas, *J. Geophys. Res.*, 115, D16302, doi:10.1029/2009JD013715, 2010. 2368, 2396
- Lal, D. M., Ghude, S. D., Patil, S. D., Kulkarni, S. H., Jena, C., Tiwari, S., and Srivastava, M. K.: Tropospheric ozone and aerosol long-term trends over the Indo-Gangetic Plain (IGP), India, *Atmos. Res.*, 116, 82–92, 2012. 2357
- Lee, E. H. and Hogsett, W. E.: Role of concentration and time of day in developing ozone exposure indices for a secondary standard, *J. Air Waste Manage.*, 49, 669–681, 1999. 2361

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- Lefohn, A. S., Laurence, J. A., and Kohut, R. J.: A comparison of indices that describe the relationship between exposure to ozone and reduction in the yield of agricultural crops, *Atmos. Res.*, 22, 1229–1240, 1988. 2361
- Lesser, V. M., Rawlings, J. O., Spruill, S. E., and Somerville, M. C.: Ozone effects on agricultural crops: statistical methodologies and estimated dose–response relationships, *Crop Sci.*, 30, 148–155, 1990. 2361, 2374, 2375, 2378, 2379, 2394
- Lobell, D. B., Ortiz-Monasterio, I., Sibley, A. M., and Sohu, V. S.: Satellite detection of earlier wheat sowing in India and implications for yield trends, *Agr. Syst.*, 115, 137–143, 2013.
- Maggs, R. and Ashmore, M. R.: Rowth and yield responses of Pakistan rice (*Oryza sativa* L.) cultivars to O<sub>3</sub> and NO<sub>2</sub>, *Environ. Pollut.*, 103, 159–170, 1998. 2365, 2371
- Maggs, R., Wahid, A., Shamsi, S. R. A., and Ashmore, M. R.: Effects of ambient air pollution on wheat and rice yield in Pakistan, *Air Soil Pollut.*, 85, 1311–1316, 1995. 2365, 2368, 2371, 2396
- Mahajan, G., Bharaj, T. S., and Timsina, J.: Yield and water productivity of rice as affected by time of transplanting in Punjab, India, *Agr. Water Manage.*, 96, 525–532, 2009. 2371, 2372
- Mauzerall, D. L. and Wang, X.: Protecting agricultural crops from the effects of tropospheric ozone exposure: reconciling science and standard setting in the United States, Europe, and Asia, *Annu. Rev. Energ. Env.*, 26, 237–268, 2001.
- Mills, G., Buse, A., Gimeno, B., Bermejo, V., Holland, M., Emberson, L., and Pleijel, H.: A synthesis of AOT40-based response functions and critical levels for ozone for agricultural and horticultural crops, *Atmos. Environ.*, 41, 2630–2643, 2007. 2372, 2373, 2374, 2375, 2377, 2378, 2379, 2380, 2394, 2398
- Mills, G., Hayes, F., Simpson, D., Emberson, L., Norris, D., Harmens, H., and Buüker P.: Evidence of widespread effects of ozone on crops and semi–natural vegetation in Europe (1990–2006) in relation to AOT40 – and flux–based risk maps, *Glob. Change Biol.*, 17, 592–613, 2011a. 2358
- Mills, G., Pleijel, H., Braun, S., Büker P., Bermejo, V., Calvo, E., Danielsson, H., Emberson, L., Gonzalez Fernandez, I., Grünhage L., Harmens, H., Hayes, F., Karlsson, P.-E., and Simpson, D.: New stomatal flux-based critical levels for ozone effects on vegetation., *Atmos. Environ.*, 45, 5064–5068, 2011b. 2363, 2394
- Mittal, M. L., Hess, P. G., Jain, S. L., Arya, B. C., and Sharma, C.: Surface ozone in the Indian region, *Atmos. Environ.*, 41, 6572–6584, 2007. 2369

## Crop yield losses due to ozone in Punjab and Haryana

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- Oksanen, E., Pandey, V., Pandey, A., Keski-Saari, S., Kontunen-Soppela, S., and Sharma, C.: Impacts of increasing ozone on Indian plants, *Environ. Pollut.*, 177, 189–200, 2013.
- Oosterhuis, D. M.: Growth and development of a cotton plant, in: *Nitrogen Nutrition of Cotton: Practical Issues*, American Society of Agronomy, Madison, WI, 1–24, 1990.
- 5 Panigrahy, S., Upadhyay, G., Ray, S. S., and Parihar, J. S.: Mapping of cropping system for the Indo-Gangetic plain using multi-date SPOT NDVI-VGT data, *J. Indian Soc. Remote Sens.*, 38, 627–632, 2010. 2364, 2365
- Pawar, H., Sachan, H., Garg, S., Arya, R., Kumar, V., Sakar, C., Chandra, P., Sinha, B.: Quantifying the contribution of long-range transport to Particulate Matter (PM) loading at a suburban site in the north-western Indo Gangetic Basin, *Atmos. Chem. Phys. Discuss.*, submitted, 10 2015. 2360
- Picchi, V., Iritia, M., Quaroni, S., Saracchic, M., Viola, P., and Faoro, F.: Climate variations and phenological stages modulate ozone damages in field-grown wheat. A three-year study with eight modern cultivars in Po Valley (Northern Italy), *Agr. Ecosyst. Environ.*, 135, 310–317, 15 2010. 2358, 2376, 2379
- Pleijel, H., Skärby L., Wallin, G., and Sellden, G.: Yield and grain quality of spring wheat (*triticum aestivum* L., cv. drabant) exposed to different concentrations of ozone in open-top chambers, *Agriculture, Environ. Pollut.*, 69, 151–168, 1991. 2357
- Porter, J. R. and Gawith, M.: Temperatures and the growth and development of wheat: a review, *Agriculture, Eur. J. Agron.*, 10, 23–36, 1999.
- 20 Rai, R., Agrawal, M., and Agrawal, S. B.: Assessment of yield losses in tropical wheat using open top chambers, *Agriculture, Environ. Pollut.*, 41, 9543–9554, 2007. 2365, 2371
- Rai, R. and Agrawal, M.: Evaluation of physiological and biochemical responses of two rice (*Oryza sativa* L.) cultivars to ambient air pollution using open top chambers at a rural site in India, *Sci. Total Environ.*, 407, 679–691, 2008. 2365, 2371, 2396
- 25 Rai, R., Agrawal, M., and Agrawal, S. B.: Threat to food security under current levels of ground level ozone: a case study for Indian cultivars of rice, *Atmos. Environ.*, 44, 4272–4282, 2010. 2365, 2371
- Ram, H., Dadhwal, V., Vashist, K. K., and Kaur, H.: Grain yield and water use efficiency of wheat (*Triticum aestivum* L.) in relation to irrigation levels and rice straw mulching in North West India, *Agr. Water. Manage.*, 128, 92–101, 2013. 2371, 2374
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RBI (Reserve Bank of India): Handbook of Indian Statistics 2012–2013, available at: <http://rbidocs.rbi.org.in/rdocs/Publications/PDFs/FHB160913FLS.pdf> (last access: 6 June 2014), 2013. 2358

Ryerson, T. B., Trainer, M., Holloway, J. S., Parrish, D. D., Huey, L. G., Sueper, D. T., Frost, G. J., Donnelly, S. G., Schauffler, S., Atlas, E. L., Kuster, W. C., Goldan, P. D., Häubler G., Meagher, J. F., and Fehsenfeld, F. C.: Observations of ozone formation in power plant plumes and implications for ozone control strategies, *Science*, 292, 719–723, 2001.

Sarkar, A. and Agrawal, S. B.: 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, 2010. 2365, 2371, 2375

Sarkar, A. and Agrawal, S. B.: Evaluating the response of two high yielding Indian rice cultivars against ambient and elevated levels of ozone by using open top chambers, *J. Environ. Manage.*, 95, 19–24, 2012. 2365, 2371

Saroj, Sharma, M. P., and Prawasi, R.: Geospatial approach to cropping system analysis a case study of Hisar district in Haryana, *Int. J. Comput Appl. T.*, 5, 457–461, 2014. 2364

Satsangi, G. S., Lakhani, A., Kulshrestha, P. R., and Taneja, A.: Seasonal and diurnal variation of surface ozone and a preliminary analysis of exceedance of its critical levels at a semi-arid site in India, *J. Atmos. Chem.*, 47, 271–286, 2004. 2396

Sawada, H. and Kohno, Y.: Differential ozone sensitivity of rice cultivars as indicated by visible injury and grain yield, *Plant Biol.*, 11, 70–75, 2009. 2371

Sharma, P., Kuniyal, J. C., Chand, K., Guleria, R. P., Dhyani, P. P., and Chauhan, C.: Surface ozone concentration and its behaviour with aerosols in the northwestern Himalaya, India, *Atmos. Environ.*, 71, 44–53, 2004. 2368, 2396

Sharma, P. K. and Sood, A.: Remote sensing and GIS techniques in agricultural development? A case study of Punjab, *J. Agr. Phys.*, 3, 174–181, 2003. 2364

Singh, S., Agrawal, S. B., and Agrawal, M.: Use of ethylene diurea (EDU) in assessing the impact of ozone on growth and productivity of five cultivars of Indian wheat (*Triticum aestivum* L.), *Environ. Monit. Assess.*, 159, 125–141, 2009. 2365, 2371, 2375

Singh, S. and Agrawal, M.: Impact of tropospheric ozone on wheat (*Triticum aestivum* L.) in the eastern Gangetic plains of India as assessed by ethylenediurea (EDU) application during different developmental stages, *Ecosyst. Environ.*, 138, 214–221, 2010. 2365, 2371, 2375

## Crop yield losses due to ozone in Punjab and Haryana

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- Singla, V., Satsangi, A., Pachauri, T., Lakhani, A., and Kumari, K. M.: Ozone formation and destruction at a sub-urban site in North Central region of India, *Atmos. Res.*, 101, 373–385, 2011. 2368, 2396
- Sinha, V., Kumar, V., and Sarkar, C.: Chemical composition of pre-monsoon air in the Indo-Gangetic Plain measured using a new air quality facility and PTR-MS: high surface ozone and strong influence of biomass burning, *Atmos. Chem. Phys.*, 14, 5921–5941, doi:10.5194/acp-14-5921-2014, 2014. 2359, 2360
- Timsina, J. and Humphreys, E.: Performance of CERES-Rice and CERES-Wheat models in rice? Wheat systems: a review, *Agr. Syst.*, 90, 5–531, 2006.
- Tiwari, S., Rai, R., and Agrawal, M.: Annual and seasonal variations in tropospheric ozone concentrations around Varanasi, *Int. J. Remote Sens.*, 29, 4499–4514, 2008. 2396
- Tong, D. Q., Mathur, R., Kang, D. W., Yu, S. C. Schere, K. L., and Pouliot, G.: Vegetation exposure to ozone over the continental United States: Assessment of exposure indices by the Eta-CMAQ air quality forecast model, *Atmos. Environ.*, 43, 724–733, 2009.
- Torsethaugen, G., Pell, E. J., and Assmann, S. M.: Ozone inhibits guard cell K<sup>+</sup> channels implicated in stomatal opening, *P. Natl. Acad. Sci. USA*, 96, 13577–13582, 1999. 2358
- Tuovinen, J. P.: Assessing vegetation exposure to ozone: properties of the AOT40 index and modifications by deposition modelling, *Environ. Pollut.*, 109, 361–372, 2000. 2363, 2378
- Upadhyay, G., Ray, S. S., and Panigrahy, S.: Derivation of Crop Phenological Parameters using Multi-Date SPOT-VGT-NDVI Data: A Case Study for Punjab, *J. Indian Soc. Remote Sens.*, 36, 37–50, 2008.
- Van Dingenen, R., Dentener, F. J., Raes, F., Krol, M. C., Emberson, L., and Cofala, J.: The global impact of ozone on agricultural crop yields under current and future air quality legislation, *Atmos. Environ.*, 43, 604–618, 2009. 2358, 2370, 2379
- Vergara, B. S.: Rice plant growth and development, in: *Rice 13*, edited by: Luh, B. S., Springer, New York, 13–22, 1991.
- Wahid, A., Maggs, R., Shamsi, S. R. A., Bell, J. N. B., and Ashmore, M. R.: Air pollution and its impact on wheat yield in the Pakistan Punjab, *Environ. Pollut.*, 88, 147–154, 1995a. 2365
- Wahid, A., Maggs, R., Shamsi, S. R. A., Bell, J. N. B., and Ashmore, M. R.: Effects of air pollution on rice yield in the Pakistan Punjab, *Environ. Pollut.*, 90, 323–329, 1995b. 2365, 2371

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- Wahid, A.: Influence of atmospheric pollutants on agriculture in developing countries: a case study with three new wheat varieties in Pakistan, *Sci. Total Environ.*, 371, 304–313, 2006. 2365, 2368, 2371, 2375, 2396
- 5 Wahid, A., Ahmad, S. S., Butt, Z. A., and Ahmad, A. M.: Exploring the hidden tread of gaseous pollutants using rice (*Oryza sativa* L.) plants in Pakistan, *Pak. J. Bot.*, 43, 365–382, 2011. 2365, 2368, 2371, 2396
- Wang, X. and Mauzerall, D. L.: 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, 2004. 2394
- 10 Wilkinson, S., Mills, G., Illidge, R., and Davies, W. J.: How is ozone pollution reducing our food supply?, *J. Exp. Bot.*, 63, 527–536, doi:10.1093/jxb/err317, 2012. 2357, 2358



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**Table 2.** Exposure–relative yield (RY) relationships established in the literature and comparison with our own exposure–relative yield relationships. RY stands for Relative Yield.

Crop	Index	Exposure–RY relationship	References
Rice	M7	$RY = e^{-(M7/202)^{2.47}} / e^{-(25/202)^{2.47}}$	Adams et al. (1989)
	AOT40	$RY = -0.0000039 \times AOT40 + 0.94$	Mills et al. (2007)
	M7	$RY = e^{-(M7/86)^{2.5}} / e^{-(25/86)^{2.5}}$	this study, Indian rice cultivars
	AOT40	$RY = -0.00001 \times AOT40 + 0.95$	this study, Indian rice cultivars
Wheat	M7	$RY = e^{-(M7/137)^{2.34}} / e^{-(25/137)^{2.34}}$	Lesser et al. (1990); winter wheat
	M7	$RY = e^{-(M7/114)^{1.8}} / e^{-(25/114)^{1.8}}$	Heck et al. (1984b); winter wheat
	M7	$RY = e^{-(M7/186)^{3.2}} / e^{-(25/186)^{3.2}}$	Adams et al. (1989); spring wheat
	AOT40	$RY = -0.0000161 \times AOT40 + 0.99$	Mills et al. (2007)
	W126	$RY = e^{-(W126/51.2)^{1.747}}$	Wang and Mauzerall (2004)
	POD <sub>6</sub>	$RY = 1 - 0.038 \times POD_6$	Mills et al. (2011b)
	M7	$RY = e^{-(M7/62)^{4.5}} / e^{-(25/62)^{4.5}}$	this study, Indian wheat cultivars
AOT40	$RY = -0.000026 \times AOT40 + 1.01$	this study, Indian wheat cultivars	
Maize	M12	$RY = e^{-(M12/124)^{2.83}} / e^{-(20/124)^{2.83}}$	Lesser et al. (1990)
	M7	$RY = e^{-(M7/158)^{3.69}} / e^{-(25/158)^{3.69}}$	Heck et al. (1984b)
	W126	$RY = e^{-(W126/93.7)^{3.392}}$	Wang and Mauzerall (2004)
	AOT40	$RY = -0.0000036 \times AOT40 + 1.02$	Mills et al. (2007)
Cotton	AOT40	$RY = -0.000016 \times AOT40 + 1.07$	Mills et al. (2007)
	M7	$RY = e^{-(M7/152)^{2.2}} / e^{-(25/152)^{2.2}}$	Heck et al. (1984b)



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**Table 4.** Comparison of the average monthly ozone exposure indices observed at at suburban site in Mohali with measurements at other urban<sup>b, c, d, e, f, g, h</sup> and suburban<sup>i, j</sup> sites in the IGP and nearby remote mountain<sup>l</sup> and suburban valley<sup>k</sup> sites indicated in Fig. 1. Letters denote the following sources: <sup>a</sup>this study, <sup>b</sup>Maggs et al. (1995), <sup>c</sup>Wahid (2006), <sup>d</sup>Wahid et al. (2011), <sup>e</sup>Jain et al. (2005), <sup>f</sup>Ghude et al. (2008), <sup>g</sup>Satsangi et al. (2004), <sup>h</sup>Singla et al. (2011), <sup>i</sup>Tiwari et al. (2008), <sup>j</sup>Rai and Agrawal (2008), <sup>k</sup>Sharma et al. (2013), <sup>l</sup>Kumar et al. (2010). Except for a, f and i values in this table were calculated from the available diel profiles or time series plots.

Site	Mohali <sup>a</sup>	Mohali <sup>a</sup>	Lahore <sup>b</sup>	Lahore <sup>c, d</sup>	New Delhi <sup>e</sup>	New Delhi <sup>f</sup>	Agra <sup>g</sup>	Agra <sup>h</sup>	Varanarsi <sup>i, j</sup>	Kullu <sup>k</sup>	Nainital <sup>l</sup>
Years	2011–2014	2011–2014	1992–1993	2003–2004; 2007	2001	1997–2004	2000–2002	2008–2009	2003–2005	2010	2006–2008
Index	M7	M12	10:00–16:00	08:00–16:00	M7	11:00–18:00	09:00–18:00	09:00–17:00	M12	M7	M7
Jan	36	32	40	66	35	32	56	28	35	46	38
Feb	42	37	48	80	57	46	11	45	41	53	42
Mar	54	48	47	92	60	50	45	52	48	70	43
Apr	64	58	52	96	62	55	19	60	53	65	61
May	82	74	–	–	50	55	19	61	56	77	63
Jun	70	66	61	95	41	41	27	46	51	62	41
Jul	48	45	43	93	51	30	16	22	34	48	27
Aug	35	31	48	84	30	24	11	12	25	–	23
Sept	48	42	55	69	45	30	25	29	29	–	27
Oct	63	51	58	60	56	40	36	42	42	58	40
Nov	59	46	33	53	53	41	53	51	41	53	43
Dec	44	38	36	57	56	34	30	34	37	53	39

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**Table 5.** Relative yield losses calculated according to different ozone exposure response relationships for rice, wheat cotton and maize.

Time	$RY_{AOT40}$ Mills et al. (2007)	$RY_{M7}$ Adams et al. (1989)	$RY_{M7}$ Heck et al. (1984b)	$RY_{M7}$ Lesser et al. (1989)	$RY_{M7}$ this study	$RY_{AOT40}$ this study
Rabi 2011–2012						
Wheat	0.27		0.14	0.07	0.25	0.41
Maize	0.11		0.01			
Kharif 2012						
Rize	0.14	0.03			0.21	0.26
Cotton	0.58		0.09			
Maize	0.10		0.01			
Rabi 2012–2013						
Wheat	0.18		0.09	0.04	0.11	0.27
Maize	0.10		0.01			
Kharif 2013						
Rize	0.12	0.02			0.19	0.21
Cotton	0.47		0.08			
maize	0.09		0.01			

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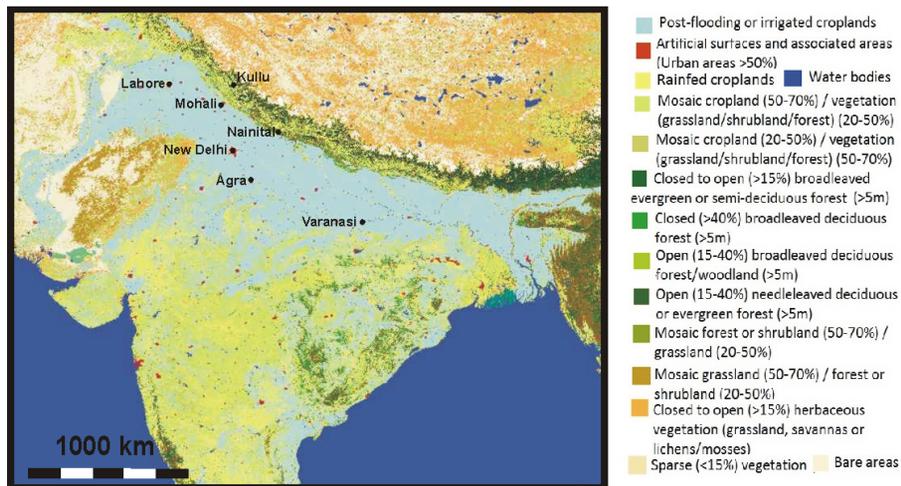
**Table 6.** Crop production (CP) for Punjab (PB) and Haryana (HR) and MSP for the fiscal year 2012–2013 and 2013–2014. Crop production loss (CPL) and economic cost losses (ECL) are calculated for wheat, rice, maize and cotton using the old AOT40 based exposure-yield relationship (Mills et al., 2007)<sup>a</sup> and for wheat and rice also using the revised AOT40 based exposure-response relationship<sup>b</sup>. CP and CPL for rice, wheat and maize are given in tonnes (t); CP and CPL in bales (b.)

	CP			MSP	CPL <sup>a</sup>			ECL <sup>a</sup>			CPL <sup>b</sup>			ECL <sup>b</sup>		
	PB	HR	Total		PB	HR	Total	PB	HR	Total	PB	HR	Total	PB	HR	Total
2012–2013	10 <sup>6</sup> t	10 <sup>6</sup> t	10 <sup>6</sup> t	INR/kg	10 <sup>6</sup> t	10 <sup>6</sup> t	10 <sup>6</sup> t	10 <sup>6</sup> INR	10 <sup>6</sup> INR	10 <sup>6</sup> INR	10 <sup>6</sup> t	10 <sup>6</sup> t	10 <sup>6</sup> t	10 <sup>6</sup> INR	10 <sup>6</sup> INR	10 <sup>6</sup> INR
Wheat	17.28	12.69	29.97	11.7	6.39	4.69	11.09	74 777	54 915	129 692	12.01	8.80	20.81	140 495	103 176	243 671
Rize	11.37	3.98	15.35	12.5	1.85	0.65	2.50	23 137	8099	31 235	4.00	1.40	5.39	49 936	17 480	67 416
Maize	0.23	0.02	0.49	11.75	0.05	0.002	0.06	620	25	645						
Cotton	10 <sup>6</sup> b 2	10 <sup>6</sup> b 2.5	10 <sup>6</sup> b 4.5	INR/b 12 737	10 <sup>6</sup> b 2.8	10 <sup>6</sup> b 3.5	10 <sup>6</sup> b 6.2	10 <sup>6</sup> INR 35 179	10 <sup>6</sup> INR 43 974	10 <sup>6</sup> INR 79 154						
2013–2014	10 <sup>6</sup> t	10 <sup>6</sup> t	10 <sup>6</sup> t	INR/kg	10 <sup>6</sup> t	10 <sup>6</sup> t	10 <sup>6</sup> t	10 <sup>6</sup> INR	10 <sup>6</sup> INR	10 <sup>6</sup> INR	10 <sup>6</sup> t	10 <sup>6</sup> t	10 <sup>6</sup> t	10 <sup>6</sup> INR	10 <sup>6</sup> INR	10 <sup>6</sup> INR
Wheat	16.11	11.80	27.91	12.85	3.54	2.44	6.13	45 442	33 285	78 727	5.93	4.36	10.32	76 567	56 082	132 649
Rize	8.16	4.00	12.16	13.1	1.11	0.55	1.66	14 577	7142	21 719	2.17	1.06	3.23	28 415	13 922	42 338
Maize	0.56	0.03	0.60	13.1	0.06	0.003	0.07	818	39	857						
Cotton	10 <sup>6</sup> b 2.1	10 <sup>6</sup> b 2.0	10 <sup>6</sup> b 4.1	INR/b 13 064	10 <sup>6</sup> b 1.9	10 <sup>6</sup> b 1.8	10 <sup>6</sup> b 3.6	10 <sup>6</sup> INR 24 329	10 <sup>6</sup> INR 23 170	10 <sup>6</sup> INR 47 499						



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**Figure 1.** Location of our site and surrounding sites for which ozone measurements have been reported superimposed on a land classification map (courtesy ESA GlobCover 2009 Project).

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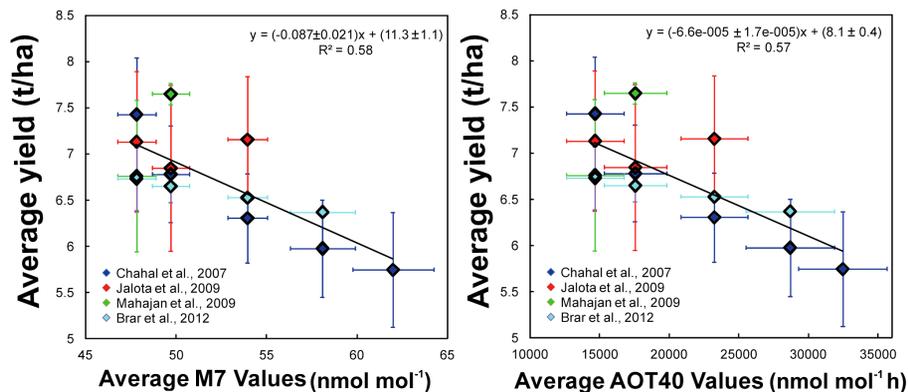
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**Figure 3.** Empirical correlation of rice yields and ozone exposure indices for field studies with variations in sowing date. Error bars on the x axis show the variance in the ozone exposure metrics for the same growth period (see Supplement S1 for definition) for different years. Error bars on the y axis show the variance in the yield obtained. Variance is introduced by replicating the study on several test plots, in different districts, plots with different soil properties using different cultivars, replicating the study in several years or transplanting seedlings with a different age at the time of transplanting.

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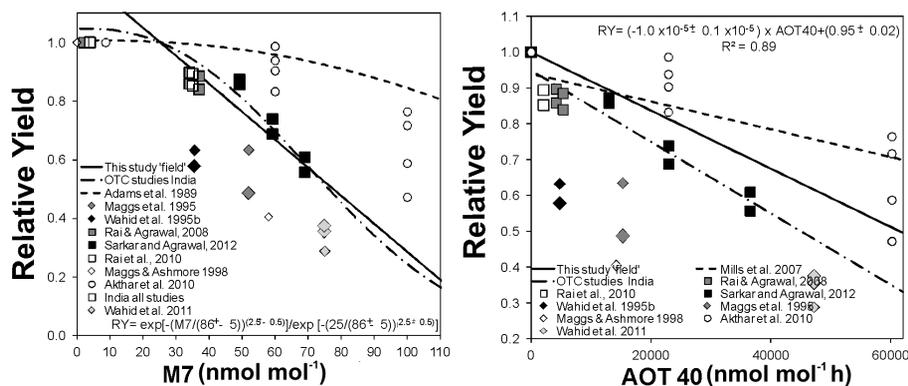
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**Figure 4.** Comparison of the empirical exposure response relationship based on field data (solid line) with OTC studies conducted in India (squares with dash and dot fit) and Pakistan (Diamonds, not included in line fit). Large diamonds indicate studies conducted on Basmati, all other studies were conducted on paddy. Circles show data from a plant chamber study on Bangladeshi rice cultivars conducted in Japan. The exposure response relationship based on American and European studies is marked with a dashed line.

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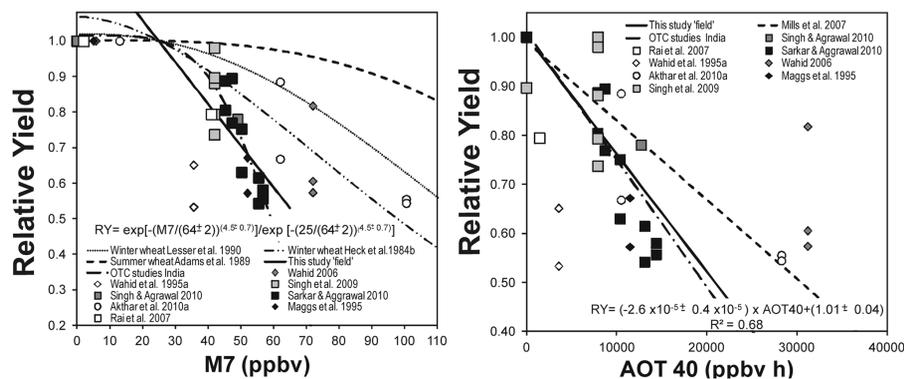
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**Figure 6.** Comparison of the empirical exposure response relationship based on field data (solid line) with OTC studies conducted in India (squares with line fit) and Pakistan (Diamonds, not included in line fit). Circles show data from a plant chamber study on Bangladeshi rice cultivars conducted in Japan. The exposure response relationship based on American and European studies is plotted in the same graph for comparison.

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