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# Assessment of crop yield losses in Punjab and Haryana using 2 years of continuous in situ ozone measurements

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**Abstract.** In this study we use a high-quality data set 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 intercompare crop yield loss estimates according to different exposure metrics, such as AOT40 (accumulated ozone exposure over a threshold of 40) and M7 (mean 7-hour ozone mixing ratio from 09:00 to 15:59), for the two major crop growing seasons of kharif (June–October) and rabi (November–April) and establish a new crop-yield–exposure relationship for southern Asian wheat, maize and rice cultivars. These are a factor of 2 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 to 41 % for wheat, 21 to 26 % for rice, 3 to 5 % for maize and 47 to 58 % for cotton. Crop production losses for wheat amounted to $20.8 \pm 10.4$ million t in the fiscal year of 2012–2013 and $10.3 \pm 4.7$ million t in the fiscal year of 2013–2014 for Punjab and Haryana taken together. Crop production losses for rice totalled $5.4 \pm 1.2$ million t in the fiscal year of 2012–2013 and $3.2 \pm 0.8$ million t in the year 2013–2014 for Punjab and Haryana taken together. The Indian National Food Security Ordinance entitles $\sim 820$ million of India's poor to purchase about 60 kg of rice or wheat per person annually at subsidized rates. The scheme requires 27.6 Mt of wheat and 33.6 Mt of rice per year. The mitigation of ozone-related crop production losses in Punjab and Haryana alone could provide $> 50$ % of the wheat and $\sim 10$ % of the rice required for the scheme.

The total economic cost losses in Punjab and Haryana amounted to USD $6.5 \pm 2.2$ billion in the fiscal year of 2012–2013 and USD $3.7 \pm 1.2$ billion in the fiscal year of 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 all of India currently amounts to 3.5–20 % of India's GDP.

The mitigation of high surface ozone would require relatively little investment in comparison to the economic losses incurred presently. Therefore, ozone mitigation can yield massive benefits in terms of ensuring food security and boosting the economy. The co-benefits of ozone mitigation also include a decrease in the ozone-related mortality and 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 crops at elevated levels, and crop yields are extremely important to the Indian economy: 17 % of India's GDP directly depends on agriculture and allied activities (RBI, 2013), and 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). As rural demand for a large range of consumer products and cement depends directly on the year's crop yield, crop yields have a much larger overall effect on the economy. 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 %, is considered to be the bread basket of India. It 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 and redistributed by the Department of Food and Public Distribution (Agricultural Statistics, 2013). Therefore, it is extremely important to quantify crop losses due to ozone in the northwest Indo-Gangetic Plain (NW-IGP) accurately.

### 1.1 Ozone effects on plants

Extensive plant damage due to tropospheric ozone was first observed during the Los Angeles smog episodes. In the early 1950s, Haagen-Smit (1952) reported that such plant damage could be reproduced in the laboratory by the reaction of organic trace gases or car exhaust with nitrogen oxides ($NO_x$) in the 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; Heath, 2008; Iriti and Faoro, 2009). 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; Ainsworth et al., 2012; Leisner and Ainsworth, 2012).

In certain phenotypes, ozone exposure interferes with the hormone levels in plants and has been shown to lead to the accumulation of ethylene in the leaves. The presence of ethylene in the leaves interferes with the functioning of the hormone abscisic acid (ABA). ABA is a hormone which normally controls stomata closure and reduces water loss under drought conditions (Wilkinson et al., 2012). Consequently, such plant phenotypes, when exposed to both drought and $O_3$ stress, will continue to lose water despite the potential for dehydration. Ozone-related crop yield losses in such phenotypes may be enhanced in rain-fed regions, where kharif cops are frequently exposed to mid-season drought during the monsoon season. On the other hand, the yield of rice cultivars that show a healthy response to drought stress (i.e. close their stomatal aperture under water stress) could substantially benefit from the system of rice intensification (SRI) cultivation practice (Turmel et al., 2011) in areas with high ozone mixing ratios. Paddy fields under SRI cultivation are irrigated only when rice plots dry too much and the crop starts withering. A healthy response of rice plants to soil drying would reduce the ozone uptake. This could explain the higher yields frequently observed for SRI plots during field trials as well as the spatial variability in the yield difference between SRI plots and control treatments.

In phenotypes that are unable to control their stomata opening under ozone stress, $O_3$ enters the leaf. It 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 (Heath, 2008; Iriti and Faoro, 2009; Kangasjaärvi and Kangasjaärvi, 2014). Ozone has been shown to destroy the structure and function of biological membranes leading to electrolyte leakage. This causes accelerated leaf senescence (Calatayud et al., 2004). Moreover, ozone 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). By reducing the amount of healthy green leaf area available for photosynthesis, the accumulated damage eventually reduces crop yield, even if the exposure occurred at early vegetative stages of crop growth. 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 stomatal aperture (Torsethaugen et al., 1999; Heath, 2008; Iriti and Faoro, 2009; Ainsworth et al., 2012). 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 the 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 and often allocate significant resources to defences induced following ROS, 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 the least visible leaf damage were often the ones showing a 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).

### 1.2 Metrics to assess the impact of ozone on crop yields

Several large-scale programs targeted at assessing the impact of ozone on crop yields have resulted in a variety of different exposure metrics (Tong et al., 2009; Mauzerall and Wang, 2001). The National Crop Loss Assessment Network (NCLAN) of the USA was the first systematic and large-scale study to assess the impact of $O_3$ on crops in the world. It relied mainly on open-top field fumigation chambers (OTC) (Heck et al., 1984b; Adams et al., 1989; Lesser et al., 1990) and used seasonal mean daytime exposure metrics (M7 and M12) to relate crop yield losses to ozone mixing ratios (Lefohn et al., 1988; Lee and Hogsett, 1999).

European researchers and policy makers focused on the critical-level concept as a tool to identify areas where the critical ozone levels are exceeded. The accumulated exposure over a threshold of 40 nmol mol$^{-1}$ (AOT40) was adopted as a metric during a workshop in Kuopio, Finland, in 1996, and a set of critical-level values based on this index has been adopted for crops, forest trees, and semi-natural vegetation (Fuhrer et al., 1997). AOT40 is the most widely used exposure plant response index. It 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) and is most frequently used in modelling studies targeted at assessing crop yield losses (Avnery et al., 2011a, b; Teixeira et al., 2011; Hollaway et al., 2012; Amin et al., 2013; Ghude et al., 2014; Feng et al., 2015; Chuwah et al., 2015).

Recently stomatal-flux-based critical levels were proposed. These address concerns that the AOT40-based critical levels 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. Models using stomatal uptake of $O_3$ (flux; $F$) or its cumulative value (dose; $D$) have significantly improved the prediction of plant injury. In particular, they have addressed the asynchronicity of maximum stomatal conductance ($g_{sto}$) and peak ozone in plants that close their stomata when temperatures or the water vapour pressure deficit around the leaves are too high (Ainsworth et al., 2012; Fares et al., 2013; Feng et al., 2012; Danielsson et al., 2013; Gonzalez-Fernandez et al., 2013; Yamaguchi et al., 2014). The stomatal flux of ozone is modelled using a multiplicative algorithm adapted from Emberson et al. (2000). This algorithm incorporates the effects of air temperature, vapour pressure deficit of the air surrounding the leaves, light, soil water potential, plant phenology and ozone concentration on the maximum stomatal conductance, i.e. the stomatal conductance under optimal conditions. The exposure–yield relationships based on this algorithm consider the accumulated stomatal flux over a specified time interval as $POD_Y$ (the phytotoxic ozone dose over a threshold flux of $Y$ nmol $O_3$ m$^{-2}$ projected leaf area (PLA) s$^{-1}$, with $Y$ ranging from 0 to 9 nmol $O_3$ m$^{-2}$ PLA s$^{-1}$; Mills et al. (2011b)). Studies evaluating the $POD_Y$-based exposure–yield relationship for a wide range of climate zones have emphasized the need for a local parametrization of the stomatal-flux model (Fares et al., 2013; Feng et al., 2012; Danielsson et al., 2013; Gonzalez-Fernandez et al., 2013; Yamaguchi et al., 2014). To the best of our knowledge, no parametrization for southern Asian wheat and rice has been reported in the peer-reviewed literature. The wheat parametrization has been developed using European cultivars (Mills et al., 2011b), and for rice the parametrization has been developed using only one Japanese rice cultivar, Koshihikari (Yamaguchi et al., 2014), which is known for its ozone resistance (Sawada and Kohno, 2009). Despite the fact that the stomatal-flux-based model is recommended by the UNECE CLRTAP (Convention on Long-range Transboundary Air Pollution) for ozone risk assessment in Europe (UNECE, 2010), exposure–yield relationships have so far been internationally agreed upon only for a limited number of crops (Mills et al., 2011b).

### 1.3 This study

In the present study, we present new ozone exposure crop yield relationships for Indian rice, wheat and maize cultivars derived through a review of the peer-reviewed literature of open-top chamber studies on southern Asian cultivars.

We verify these new relationships using ozone monitoring data from the atmospheric chemistry facility in Mohali and yield data from a number of relay seeding experiments conducted in Punjab and Haryana. In these experiments crops were unintentionally exposed to different ozone levels by virtue of their sowing date being shifted, but the relevant studies were not conducted to investigate the effect of ozone on yields and consequently they did not include on-site ozone monitoring or clean-air control treatments.

We subsequently use a high-quality data set of in situ ozone measurements at a regionally representative suburban site called Mohali and the newly derived exposure–yield functions 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 intercompared for a number of sowing dates and exposure–yield functions for the two major crop growing seasons of kharif (June–October) and rabi (November–April).

## 2 Materials and methods

### 2.1 Site description and analytical details

All ozone measurements were performed at the IISER (Indian Institute of Science Education and Research) 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 $km^2$ with 800–1000 residents. Local influence is expected to be significant only at low wind speeds ($< 1\,m\,s^{-1}$), which occur only rarely (Sinha et al., 2014; Pawar et al., 2015). The predominant daytime wind direction is west to north-west during winter, summer and in the post-monsoon season and south to south-east 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 the 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 the north-west 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 one measurement every minute, with an accuracy that is better than 3 % and an overall uncertainty of less than 6 %. Quality assurance of the large data set 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 $\pm 0.5\,nmol\,mol^{-1}$ 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).

### 2.2 Calculation of ozone exposure metrics

We use two metrics to investigate the ozone exposure for crops in Punjab and Haryana and derive southern-Asia-specific exposure–yield relationships for wheat, maize and rice. These are the mean daytime surface ozone (M7) and accumulated exposure over a threshold of $40\,nmol\,mol^{-1}$ (AOT40).

The Mx metric is defined as the mean daytime 7 (M7) and 12 h (M12) surface ozone concentrations during daylight hours, i.e. 09:00–15:59 and 08:00–19:59 LT respectively, in the crop growing season (Hollaway et al., 2012).

$$M7 = \frac{1}{n}\sum_{i=1}^{n}[O_3]_i \text{ for 09:00–15:59 LT} \quad (1)$$

AOT40 is defined as the sum of differences between the hourly ozone concentrations and $40\,nmol\,mol^{-1}$ during the crop growing season (Fuhrer et al., 1997) for $[O_3] > 40\,nmol\,mol^{-1}$.

$$AOT40 = \sum_{i=1}^{n}([O_3]_i - 40) \text{ for } [O_3] > 40\,nmol\,mol^{-1} \quad (2)$$

Of these parameters M7 gives equal importance to all measurements and accounts for the yield losses due to ozone concentrations of less than $40\,nmol\,mol^{-1}$, while AOT40 gives a higher weight to high ozone mixing ratios (Tuovinen, 2000). Hence, the former will perform better while evaluating plant damage and yield losses at low ozone concentration, while the latter will capture the effect of events with very high $O_3$ mixing ratios on plant physiology and yields better (Hollaway et al., 2012).

### 2.3 Missing data

For any long-term data set, gaps in the data are inevitable due to preventive maintenance, calibrations and technical problems that arise from time to time. The total number and percentage of missing hourly average ambient data for each month from October 2011 to November 2013 are listed in Table 1. For calculating AOT40 and M7, continuous and complete daytime data are required, since any missing value can potentially lead to an underestimation of the real ozone exposure. Hence, missing values need to be filled in. For short data gaps of $\leq 3$ h arising due to zero drift calibration or span calibrations we interpolated the measurements before and after the gap for filling in the missing values. Most gaps in the time series are due to calibrations. For longer data gaps we calculated the average diel ozone profile for the respective month and for each missing hour filled in the monthly average ozone value of the respective hour. In most months less than 5 % of the total hours were filled in. Only during the monsoon season does the requirement to occasionally purge the system with dry zero air lead to longer data gaps, and up to 21 % of the hourly averages had to be filled using the method described above.

### 2.4 Cropping seasons and major crops in Punjab and Haryana

Rabi (winter season) and kharif (summer monsoon) are the two main crop-growing seasons in northern India. In Punjab, kharif crops include rice, cotton, maize, sugarcane and vegetables (Sharma and Sood, 2003). During rabi season wheat is grown in almost all of Punjab (> 90 % of the area).

In Haryana, kharif crops include rice, cotton and sugarcane and, in most of the unirrigated areas of Haryana, pearl millet and sorghum (Panigrahy et al., 2010). Major rabi crops in

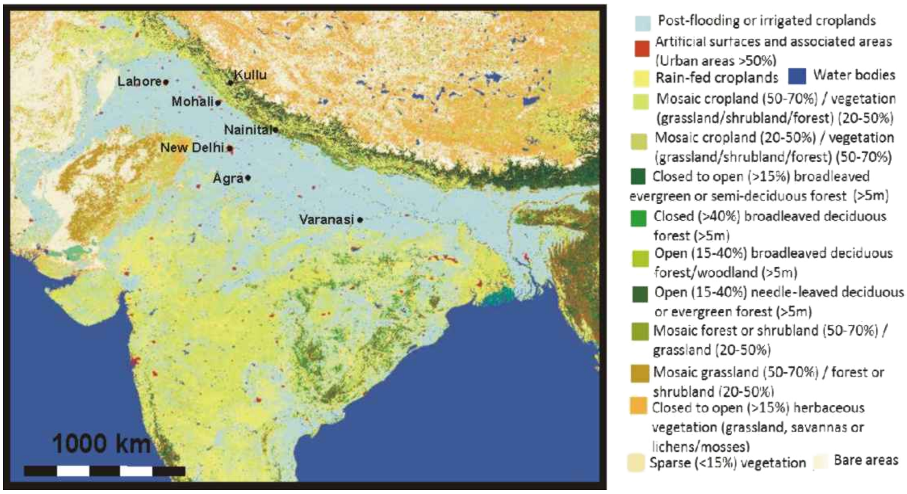


**Figure 1.** Location of our site and surrounding sites for which ozone measurements have been reported, superimposed on a land classification map (courtesy ESA GlobCover 2009 Project).

Haryana include wheat, gram, sugarcane and mustard (Panigrahy et al., 2010).

The most popular crop rotation systems in Punjab include rice–wheat (> 70 %) and cotton–wheat (∼ 20 %) as well as maize–wheat crop rotation systems. In Haryana rice–wheat (∼ 40 %) and cotton–wheat (∼ 20 %) 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). Maize is currently not very popular but heavily promoted as an alternative to rice when a deficient monsoon is anticipated.

The present study investigates crop yield losses for wheat and maize (rabi) and rice, maize and cotton (kharif). In 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. To summarize briefly, different rice cultivars take between 90 to 140 days to reach harvest maturity after the ∼ 20–30-day-old seedlings have been transplanted into the fields. In this study we calculate the accumulated and average ozone exposure (AOT40/M7) for a 4-month period (120 days), which is typical of cultivars popular in the NW-IGP. We investigate the following five periods:

- Period 1: 16 May (emergence) to 15 September (maturity);
- Period 2: 1 June (emergence) to 30 September (maturity);
- Period 3: 16 June (emergence) to 15 October (maturity);
- Period 4: 15 April (emergence) to 15 August (maturity);
- Period 5: 1 May (emergence) to 1 September (maturity).

Wheat cultivars take between 4 to 4.5 months from emergence to maturity. High temperatures and water stress during the grain filling stage result in a shorter growth period. Therefore, accumulated and average ozone exposure (AOT40/M7) was calculated for a 4.5-month period for timely sowings and for a 4-month period for late sowings. We investigate the following five periods:

- Period 1: 1 November (emergence) to 15 March (maturity);
- Period 2: 16 November (emergence) to 31 March (maturity);
- Period 3: 1 December (emergence) to 15 April (maturity);
- Period 4: 16 December (emergence) to 15 April (maturity);
- Period 5: 1 January (emergence) to 30 April (maturity).

For maize we investigate two periods for each of the growing seasons.

1. kharif:
   - Period 1: 15 June (emergence) to 15 September (maturity);
   - Period 2: 1 July (emergence) to 1 October (maturity).
2. Rabi:
   - Period 3: 1 January (emergence) to 31 March (maturity);
   - Period 4: 1 February (emergence) to 30 April (maturity).

**Table 1.** Total number ($N$) of missing hourly average ambient data (mh), total number of hours per month (th), percentage (%) of missing hourly average ambient data for each month and number of short ($\leq 3$ h) and long ($> 3$ h) data gaps.

| Month | mh/th ($N/N$) | Missing values (%) | Short gaps ($N$) | Long gaps ($N$) |
|---|---|---|---|---|
| October 2011 | 2/672 | 0.3 | 2 | 0 |
| November 2011 | 2/720 | 0.3 | 1 | 0 |
| December 2011 | 4/744 | 0.5 | 2 | 0 |
| January 2012 | 3/744 | 0.4 | 1 | 0 |
| February 2012 | 1/696 | 0.1 | 1 | 0 |
| March 2012 | 4/744 | 0.5 | 0 | 1 |
| April 2012 | 45/720 | 6.3 | 2 | 1 |
| May 2012 | 13/744 | 1.7 | 5 | 1 |
| June 2012 | 3/720 | 0.4 | 2 | 0 |
| July 2012 | 153/744 | 20.6 | 1 | 1 |
| August 2012 | 57/744 | 7.7 | 2 | 1 |
| September 2012 | 92/720 | 12.8 | 2 | 1 |
| October 2012 | 8/744 | 1.1 | 2 | 1 |
| November 2012 | 4/720 | 0.6 | 4 | 0 |
| December 2012 | 33/744 | 4.3 | 2 | 2 |
| January 2013 | 1/744 | 0.1 | 1 | 0 |
| February 2013 | 1/672 | 0.1 | 1 | 0 |
| March 2013 | 25/744 | 3.4 | 1 | 1 |
| April 2013 | 5/720 | 0.7 | 2 | 0 |
| May 2013 | 3/744 | 0.4 | 1 | 0 |
| June 2013 | 108/720 | 15.0 | 1 | 3 |
| July 2013 | 63/744 | 8.5 | 1 | 2 |
| August 2013 | 73/744 | 9.8 | 1 | 1 |
| September 2013 | 33/720 | 4.6 | 1 | 3 |
| October 2013 | 42/744 | 5.6 | 1 | 1 |
| November 2013 | 49/720 | 6.8 | 2 | 2 |
| December 2013 | 2/672 | 0.3 | 2 | 0 |
| January 2014 | 2/720 | 0.3 | 1 | 0 |
| February 2014 | 4/744 | 0.5 | 2 | 0 |

3. For cotton, to cover the entire range of potential ozone damage, three time windows are investigated:
   - Period 1: 1 May–15 December; three pickings;
   - Period 2: 31 May–15 December; three pickings;
   - Period 3: 1 May–31 December; four pickings.

It should be noted, however, that these time windows do not correspond to the same number of pickings and more pickings will result both in higher yields and a longer time window in which plants can accumulate damage.

### 2.5 Relationships between ozone dose exposure and yield

We derive specific exposure–yield relationships for Indian wheat and rice cultivars using a two-pronged approach.

Firstly, we use our ozone measurements conducted at a suburban site in Punjab and a number of field studies conducted in the region that reported variations in the sowing date of crops (Chahal et al., 2007; Jalota et al., 2008, 2009; Mahajan et al., 2009; Brar et al., 2012; Buttar et al., 2013; Ram et al., 2013), which lead to an unintentional change in ozone exposure, and one study that reported co-located yield and ozone measurements (Agrawal et al., 2003) to derive an empirical exposure–yield relationship for rice and wheat. The empirical field data support the need to revise the exposure–yield relationship for Indian cultivars and demonstrate that for rice optimizing, the sowing date can be a suitable strategy to minimize ozone exposure and maximize crop yields.

Secondly, we derive India-specific exposure–yield relationships by plotting relative yields (RY) and ozone exposure for all OTC studies on Indian cultivars reported in the peer-reviewed literature and fitting the data to obtain an exposure–yield relationship (Rai et al., 2007; Rai and Agrawal, 2008; Rai et al., 2010; Singh et al., 2009; Singh and Agrawal, 2010; Sarkar and Agrawal, 2010, 2012). For maize, only one OTC study on two Indian cultivars has been conducted, and we use the fit of these data to obtain an exposure–yield relationship (Singh et al., 2014). We compare these exposure–yield relationships for rice and wheat with RY observed for cultivars commonly grown in Pakistan and Bangladesh (Wahid et al., 1995a, b; Maggs et al., 1995; Maggs and Ashmore, 1998; Wahid, 2006; Akhtar et al., 2010a, b; Wahid et al., 2011) to investigate to what extent the results can be extrapolated to all of southern Asia. We refrain from including cultivars popular in south-east Asia in our study, as they have been reported to show a very different sensitivity to ozone exposure (Sawada and Kohno, 2009). We provide an upper and lower limit for RY and crop yield losses for a set of five different sowing dates for rice and wheat, of three for cotton and of two for rabi and kharif maize, using both exposure-dose–response relationships established in several studies in the west (Table 2) to provide a lower limit and our new India-specific functions to provide an upper limit to the possible loss.

We use both the old (Mills et al., 2007) AOT40-based exposure–yield function and our revised AOT40-based relationship to calculate crop production losses and economic cost losses and contrast the two.

### 2.6 Yield loss and economic loss calculations

Table 2 summarizes the ozone exposure-dose–response relationships for relative yield loss (RYL) for wheat, rice, maize

**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) |
| | $POD_{10}$ | $RY = 0.996 - 0.487 \times POD_{10}$ | Yamaguchi et al. (2014); ozone-resistant rice |
| | 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) |
| | $POD_6$ | $RY = 1 - 0.038 \times POD_6$ | 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 | M7 | $RY = e^{-(M7/158)^{3.69}}/e^{-(25/158)^{3.69}}$ | Heck et al. (1984b) |
| | AOT40 | $RY = -0.0000036 \times AOT40 + 1.02$ | Mills et al. (2007) |
| | AOT40 | $RY = -0.0000067 \times AOT40 + 1.03$ | Indian maize; Singh et al. (2014) |
| 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) |

and cotton based on AOT40 and M7 values 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 $O_3$-induced damages (Avnery et al., 2011a), calculated using Eqs. (3) and (4):

$$RYL_i = 1 - RY_i, \tag{3}$$

$$CPL_i = \frac{RYL_i}{1 - RYL_i} \times CP_i, \tag{4}$$

where $RY_i$ 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 (2013).

Economic cost loss (ECL) for any crop is defined as the financial loss due to $O_3$-induced damage in a given financial year. The minimum ECL is calculated for different crops based on corresponding minimum support prices (MSPs) of the same fiscal year using the following equation:

$$ECL_i = CPL_i \times MSP_i. \tag{5}$$

The MSPs 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 the MSP valuation process. It should be noted, however, that the MSP is typically approximately 50 % less than the market value of the crop and often lower than the production costs. The upper 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 following equation:

$$ECL_i\,[\%GDP] = RYL_i\,[\%] \times 0.36. \tag{6}$$

## 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 the summer season in April, May and June, with median ozone mixing ratios of 60–80 nmol mol$^{-1}$ and peak ozone mixing ratios of approximately 130 nmol mol$^{-1}$. This is expected, as conditions such as high temperature, low humidity and high solar radiation favour the photochemical production of $O_3$ regionally.

After summer, the next highest ozone levels are observed during the post-monsoon season (October and November), with median ozone mixing ratios of 50–60 nmol mol$^{-1}$. The post-monsoon season is characterized by lower levels of solar radiation (range of daytime maxima ∼480–720 W m$^{-2}$)

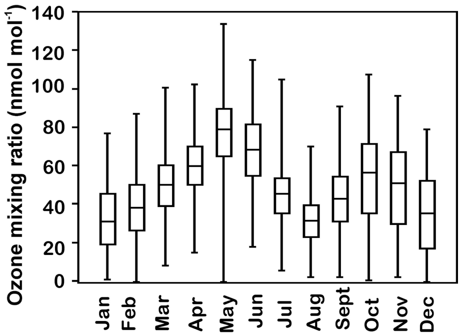


**Figure 2.** Seasonal box-and-whisker plot of the 1 h average daytime (08:00–19:59 LT) ozone mixing ratios. Whiskers denote the monthly minimum and maximum value, the box represents the upper and lower quarter value and the horizontal line within the box represents the median.

compared to the summer season (range of daytime maxima ~ 600–920 W m$^{-2}$), but the occurrence of large-scale agricultural burning emissions of ozone precursors and a lower boundary layer still result in comparably high ozone levels.

The lowest median daytime ozone mixing ratios of approximately 30 nmol mol$^{-1}$ are observed in August, during the 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, a reduction in the solar radiation, low temperatures and fog result in less photochemical production of $O_3$.

Table 3 shows the monthly increment in AOT40 and the monthly M7 for the period October 2011 to January 2014. The yearly maximum and minimum monthly values for all indices correspond to the same months, May and August, in both years. All indices show maxima during summer (May and June) and post-monsoon (October and November) and minima during the monsoon (July to September) and winter (December to February); however, the difference between the cumulative metric (AOT40), which gives higher weight to high values and low or no weight to low values, and the average-based metric (M7) comes out very clearly. For AOT40 the amplitude between peaks (~ 14 000 nmol mol$^{-1}$ h) and minima (~ 500 nmol mol$^{-1}$ h) is very high. The annual peak values are 30 times higher for AOT40 compared to the annual minima. For M7 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 the earlier onset of the monsoon in the eastern part of the IGP. The only site further to the west for which ozone measurements have been reported is located close to the centre of the summertime "heat low" (Das, 1962) over the NW IGP; it reports summertime and monsoon season M7 that are higher than those observed at our site and also a strong anticorrelation of the observed ozone during monsoon season with the intensity of the monsoon rainfall.

**Table 3.** Monthly values of M7 and increments in AOT40 for the period October 2011 to January 2014.

| Month | AOT40 | M7 |
|---|---|---|
| October 2011 | 7770 | 71 |
| November 2011 | 6150 | 63 |
| December 2011 | 2879 | 46 |
| January 2012 | 1705 | 39 |
| February 2012 | 2729 | 47 |
| March 2012 | 5391 | 57 |
| April 2012 | 7286 | 64 |
| May 2012 | 14 783 | 83 |
| June 2012 | 12 544 | 77 |
| July 2012 | 4005 | 49 |
| August 2012 | 478 | 32 |
| September 2012 | 2760 | 46 |
| October 2012 | 6951 | 63 |
| November 2012 | 5041 | 57 |
| December 2012 | 1820 | 42 |
| January 2013 | 1372 | 32 |
| February 2013 | 1133 | 37 |
| March 2013 | 3714 | 51 |
| April 2013 | 7608 | 64 |
| May 2013 | 13 381 | 80 |
| June 2013 | 8123 | 63 |
| July 2013 | 3014 | 46 |
| August 2013 | 883 | 37 |
| September 2013 | 3310 | 49 |
| October 2013 | 4968 | 55 |
| November 2013 | 4730 | 56 |
| December 2013 | 2617 | 43 |
| January 2014 | 1370 | 36 |

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 follow an exponential curve,

$$\text{AOT40} = 0.0201 \times \text{M7}^{3.0765} \quad R^2 = 0.94, \tag{7}$$

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 (REgional MOdel chemistry transport model). For the north-western part of the IGP, close to the foothills, REMO-CTM models 5000–6000 $\text{nmol mol}^{-1}$ h in May, 1500–2000 $\text{nmol mol}^{-1}$ h in July and 6000–7000 $\text{nmol mol}^{-1}$ h in October. We find that the model underestimates the observed AOT40 in the north-west IGP by a factor of 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 seasons.

In a more recent study conducted using WRF-Chem (weather research and forecasting chemistry model), Ghude et al. (2014) predicted ozone daytime concentrations of $\sim 50\,\text{nmol mol}^{-1}$ for kharif season and $\sim 40\,\text{nmol mol}^{-1}$ for rabi season for the Chandigarh UT. However, the authors considered only the time windows of 15 June to 15 September and of December to February for kharif and rabi seasons respectively. For these time windows, predicted ozone daytime concentrations agree well with the measured M12.

Mittal et al. (2007) intercompared 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.

Emberson et al. (2009) compared MATCH (Model of Atmospheric Transport and Chemistry)-modelled M7 values with measured surface ozone for Varanarsi and Lahore and found good agreement between model and observations for both cropping seasons. For our site, too, there is excellent agreement between modelled and observed M7 values (model: 40–50 $\text{nmol mol}^{-1}$ for rabi season and 50–70 $\text{nmol mol}^{-1}$ for kharif season; observations: 40–52 $\text{nmol mol}^{-1}$ for rabi season and 47–64 $\text{nmol mol}^{-1}$ for kharif season).

van Dingenen et al. (2009) used a global model (TM5 – TM stands for transport model) to predict surface ozone over India, and the model reproduces surface observations for our site equally well.

### 3.2 Ozone-exposure–yield relationships

Crop yield losses and associated economic losses due to ozone are well constrained for the USA and Europe (Avnery et al., 2011a). The analyses of crop production losses made so far for India are based on model-derived $O_3$ mixing ratios (Deb Roy et al., 2009; Ghude et al., 2014; van Dingenen et al., 2009; Avnery et al., 2011a) and apply $O_3$-dose–plant-response metrics and formulae developed in the US (Adams et al., 1989; Lesser et al., 1990; Heck et al., 1984b; Wang and Mauzerall, 2004) or in Europe (Mills et al., 2007). Such predictions may underestimate crop yield losses. It has already been pointed out above that for some models, the model predicted daytime $O_3$ mixing ratios or AOT40 values tend to be lower than the observed $O_3$ mixing ratios or AOT40 in particular for zayad and kharif seasons. Hence, model predictions need to be validated and improved using in situ ozone measurements.

The $O_3$-dose–plant-response metrics used in the modelling studies conducted so far also underestimate crop production losses due to the fact that southern Asian wheat and rice cultivars are more sensitive to ozone (Oksanen et al., 2013). Emberson et al. (2009) reviewed a large number of Asian OTC and plant chamber studies but refrained from deriving Asia-specific dose response curves for wheat and rice due to the large spread in the observational data. Emberson et al. (2009) suggested that the spread could be due to the large variety of different cultivars studied or due to the diversity of experimental conditions. In the same year Sawada and Kohno (2009) compared 20 different rice cultivars under identical conditions in a plant chamber and showed that most *Oryza sativa* L. *Japonica* cultivars were resistant to ozone damage (11 out of 12), while most *Oryza sativa* L. *Indica* cultivars showed significant yield losses (5 out of 8). A follow-up metabolomic analysis of selected cultivars by the same authors, Sawada et al. (2012), showed that the only japonica cultivar with high yield losses, Kirara 397, down-regulated proteins associated with photosynthetic electron transport as a response to ROS induced by ozone. One of the indica cultivars with high yield losses, Takanari, showed no noteworthy changes in the metabolic pathway of photosynthesis resulting from ozone exposure, but its yields were equally sensitive to ozone, and most down-regulated proteins were associated with protein destination and storage and unknown functions. In one of the japonica cultivars (Koshihikari), which did not suffer yield losses, ozone stress up-regulated the expression of certain proteins in the Calvin cycle of the energy metabolism. Sarkar and Agrawal (2012) reported the expression of the RuBisCO, and several energy-metabolism-related proteins were adversely affected by ozone exposure in the two indica cultivars Malviyadhan 36 and Shivani. These results seem to indicate that the responses to ozone are indeed cultivar-specific. More studies are required to understand the damage mechanisms in different cultivars at a fundamental level and identify high-yielding cultivars that are resistant to ozone stress, which can be promoted by the relevant government agencies in affected areas.

**Table 4.** Comparison of the average monthly ozone exposure indices observed at a suburban site in Mohali with measurements at other urban (superscript letters a–h) and suburban (superscript i and j) sites in the IGP and nearby remote mountain (superscript l) and suburban valley (superscript k) sites indicated in Fig. 1.

| Site | Mohali[a] | Mohali[a] | Lahore[b] | Lahore[c, d] | New Delhi[e] | New Delhi[f] | Agra[g] | Agra[h] | Varanarsi[i, j] | Kullu[k] | Nainital[l] |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 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 |
| January | 36 | 32 | 40 | 66 | 35 | 32 | 56 | 28 | 35 | 46 | 38 |
| February | 42 | 37 | 48 | 80 | 57 | 46 | 11 | 45 | 41 | 53 | 42 |
| March | 54 | 48 | 47 | 92 | 60 | 50 | 45 | 52 | 48 | 70 | 43 |
| April | 64 | 58 | 52 | 96 | 62 | 55 | 19 | 60 | 53 | 65 | 61 |
| May | 82 | 74 | – | – | 50 | 55 | 19 | 61 | 56 | 77 | 63 |
| June | 70 | 66 | 61 | 95 | 41 | 41 | 27 | 46 | 51 | 62 | 41 |
| July | 48 | 45 | 43 | 93 | 51 | 30 | 16 | 22 | 34 | 48 | 27 |
| August | 35 | 31 | 48 | 84 | 30 | 24 | 11 | 12 | 25 | – | 23 |
| September | 48 | 42 | 55 | 69 | 45 | 30 | 25 | 29 | 29 | – | 27 |
| October | 63 | 51 | 58 | 60 | 56 | 40 | 36 | 42 | 42 | 58 | 40 |
| November | 59 | 46 | 33 | 53 | 53 | 41 | 53 | 51 | 41 | 53 | 43 |
| December | 44 | 38 | 36 | 57 | 56 | 34 | 30 | 34 | 37 | 53 | 39 |

[a] this study; [b] Maggs et al. (1995); [c] Wahid (2006); [d] Wahid et al. (2011); [e] Jain et al. (2005); [f] Ghude et al. (2008); [g] Satsangi et al. (2004); [h] Singla et al. (2011); [i] Tiwari et al. (2008); [j] Rai and Agrawal (2008); [k] Sharma et al. (2013); [l] Kumar et al. (2010). Except in the case of values from this study, from Ghude et al. (2008) and from Tiwari et al. (2008), values in the table were calculated from the available diel profiles or time series plots.

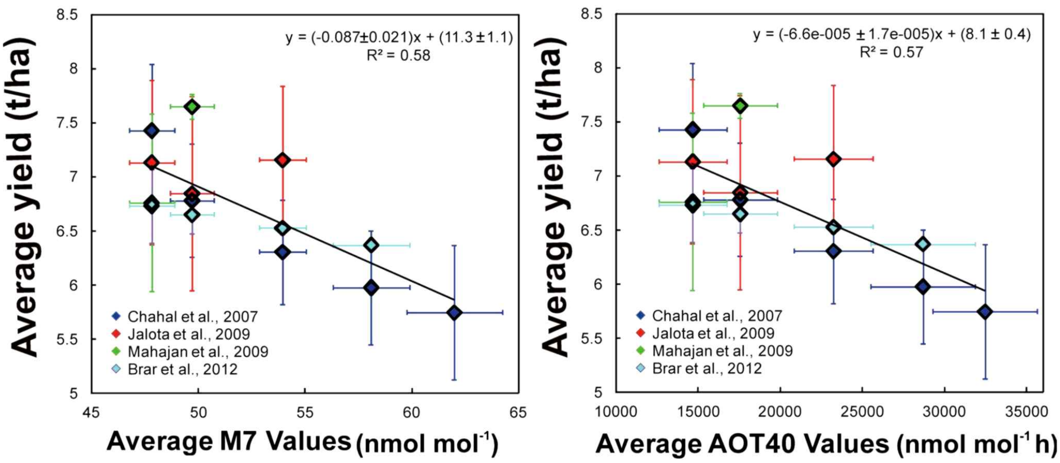


**Figure 3.** Empirical correlation of rice yields and ozone exposure indices for field studies with variations in sowing date. Ozone exposure for rice sown on different dates has been calculated using our data (Table 5). Yield data for rice have been taken from the peer-reviewed literature (Chahal et al., 2007; Jalota et al., 2009; Mahajan et al., 2009; Brar et al., 2012). 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) and in several years or by transplanting seedlings with a different age at the time of transplanting.

### 3.2.1 Rice

Figure 3 shows the empirical correlation of rice yields and ozone exposure indices for field studies with variations in sowing in Punjab and Haryana. There is a significant trend in 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). For rice, late sowing (1 June) and late transplantation (1 July) leads to the lowest relative yield losses (18 %), while early sowing (1 April) and transplantation (1 May) doubles ozone-related yield losses (35 %; Table 5).

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 OTC studies con-

**Table 5.** Ozone exposure according to different exposure indices and relative yields for rice. Data for the five periods used to plot Fig. 3 are provided in the table. Periods (P) 1–3 correspond to the periods in which rice is usually grown in Punjab and Haryana, and the average yield loss of these three periods is used to calculate crop production loss and economic loss for each fiscal year.

| Time | AOT40 | M7 | $RY_{AOT40}$ Mills et al. (2007) | $RY_{M7}$ Adams et al. (1989) | $RY_{AOT40}$ Indian OTC studies | $RY_{M7}$ Indian OTC studies |
|---|---|---|---|---|---|---|
| 2012 P1 | 25 641 | 55 | 0.84 | 0.97 | $0.69 \pm 0.05$ | $0.75 \pm 0.06$ |
| 2012 P2 | 19 788 | 51 | 0.86 | 0.97 | $0.75 \pm 0.04$ | $0.80 \pm 0.06$ |
| 2012 P3 | 16 715 | 49 | 0.87 | 0.98 | $0.78 \pm 0.04$ | $0.82 \pm 0.06$ |
| 2012 P4 | 35 640 | 64 | 0.80 | 0.95 | $0.59 \pm 0.06$ | $0.65 \pm 0.07$ |
| 2012 P5 | 31 853 | 60 | 0.82 | 0.96 | $0.63 \pm 0.05$ | $0.70 \pm 0.07$ |
| Average P1–3 | 20 715 | 52 | 0.86 | 0.97 | $0.74 \pm 0.04$ | $0.79 \pm 0.06$ |
| 2013 P1 | 20 839 | 53 | 0.86 | 0.97 | $0.74 \pm 0.04$ | $0.78 \pm 0.06$ |
| 2013 P2 | 15 330 | 49 | 0.88 | 0.98 | $0.80 \pm 0.04$ | $0.82 \pm 0.05$ |
| 2013 P3 | 12 623 | 47 | 0.89 | 0.98 | $0.82 \pm 0.03$ | $0.84 \pm 0.05$ |
| 2013 P4 | 29 259 | 60 | 0.83 | 0.96 | $0.66 \pm 0.05$ | $0.70 \pm 0.07$ |
| 2013 P5 | 25 498 | 56 | 0.84 | 0.96 | $0.70 \pm 0.05$ | $0.74 \pm 0.06$ |
| Average P1–3 | 16 264 | 49 | 0.88 | 0.98 | $0.79 \pm 0.04$ | $0.81 \pm 0.06$ |

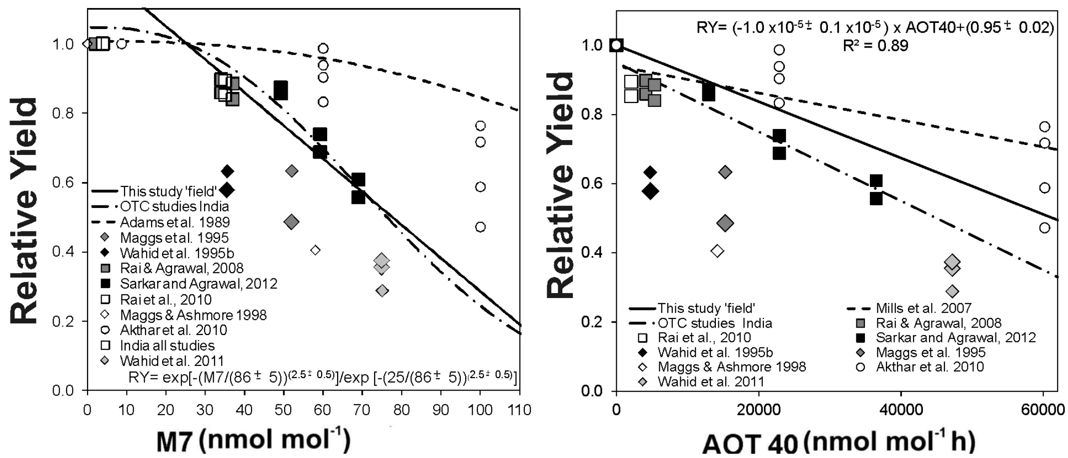


**Figure 4.** Comparison of the empirical exposure–response relationship based on field data (solid line) with OTC studies conducted in India (squares with dash and dot fit) and Pakistan (diamonds, not included in line fit). Large diamonds indicate studies conducted on basmati; all other studies were conducted on paddy. Circles show 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. In all studies presented in this figure, rice plants were exposed to elevated ozone from the date of transplantation until harvest.

ducted in India (squares, dash and dot line fit) and Pakistani Punjab (diamonds). 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 to 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 five reference periods defined in Supplement S1, using both the old (Mills et al., 2007; Adams et al., 1989) and the revised RYL relationships.

It is clear from Fig. 4 and Table 5 that the RY curve derived by Adams et al. (1989) significantly overestimate the RY of *Oryza sativa* L. *Indica* cultivars planted in the IGP, and it is

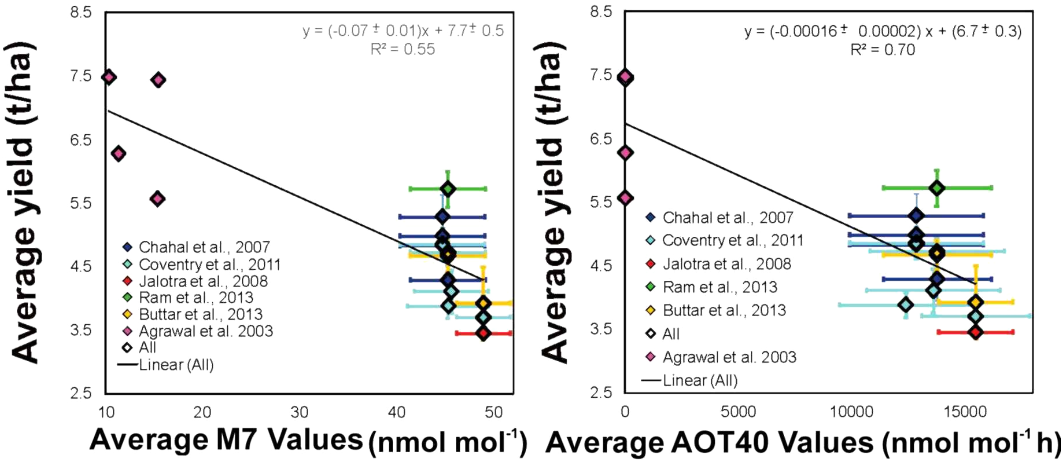


**Figure 5.** Empirical correlation of wheat yields and ozone exposure indices for field studies with variations in sowing date. Ozone exposure for wheat sown on different dates has been calculated using our data (Table 6). Yield data for wheat have been taken from the peer-reviewed literature (Agrawal 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 dates. The yield data have been positioned to conform with the emergence dates (Periods 1 to 5) defined in Supplement S1. 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 multiple years or varying growing conditions and by the number of irrigations and or the tillage practices.

interesting to note that there seems to be an east–west gradient in the sensitivity of local cultivars to ozone exposure. Bangladeshi cultivars showed the lowest sensitivity and highest relative yields, though this could be due to the fact that the study was conducted in the sheltered environment of a plant chamber. 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) underestimate crop production losses in southern Asia by approximately 20–30 % (Table 5). For AOT40 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 southern Asia ozone levels below 40 nmol mol$^{-1}$ 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 of the revised equation is 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 underestimate crop production losses in southern Asia by approximately 5–15 % (Table 5). Table 5 summarizes relative yields for the five reference periods (which correspond to different sowing dates) and intercompares RY calculated using the new equation 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 5). 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 5). The difference between the two is ∼ 20 %. Using the revised relationship, relative yields calculated using the M7 and AOT40 metrics agree within the uncertainty, 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 $O_3$ exposure.

### 3.2.2 Wheat

Figure 5 shows the empirical correlation of wheat yields and ozone exposure indices for field studies with variations in sowing in Punjab and Haryana. 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). For AOT40 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

**Table 6.** Ozone exposure according to different exposure indices and relative yields for wheat. Data for the five periods used to plot Fig. 5 are provided in the table. Period 2 (P2) and Period 3 (P3) correspond to the periods in which wheat is usually grown in Punjab and Haryana in the rice–wheat cropping cycle, while Period 4 (P4) and 5 (P5) correspond to the cotton–wheat cropping cycle. The average yield loss of the rice–wheat cycle is used to calculate crop production loss and economic loss for each fiscal year as most of the area is cultivated in the rice–wheat cropping system.

| Time | AOT40 | M7 | $RY_{AOT40}$ Mills et al. (2007) | $RY_{M7}$ Lesser et al. (1990) | $RY_{M7}$ Heck et al. (1984b) | $RY_{AOT40}$ Indian OTC studies | $RY_{M7}$ Indian OTC studies |
|---|---|---|---|---|---|---|---|
| 2012 P1 | 15 843 | 49 | 0.73 | 0.93 | 0.85 | $0.60 \pm 0.10$ | $0.74 \pm 0.07$ |
| 2012 P2 | 15 807 | 49 | 0.74 | 0.93 | 0.86 | $0.60 \pm 0.10$ | $0.75 \pm 0.07$ |
| 2012 P3 | 16 168 | 49 | 0.73 | 0.93 | 0.86 | $0.59 \pm 0.10$ | $0.75 \pm 0.07$ |
| 2012 P4 | 14 754 | 49 | 0.75 | 0.93 | 0.85 | $0.63 \pm 0.10$ | $0.74 \pm 0.07$ |
| 2012 P5 | 17 110 | 52 | 0.71 | 0.92 | 0.84 | $0.57 \pm 0.11$ | $0.69 \pm 0.07$ |
| Average P2–3 | 15 987 | 49 | 0.73 | 0.93 | 0.86 | $0.59 \pm 0.10$ | $0.75 \pm 0.07$ |
| 2013 Period-1 | 11 384 | 42 | 0.81 | 0.96 | 0.91 | $0.71 \pm 0.09$ | $0.88 \pm 0.05$ |
| 2013 Period-2 | 9887 | 40 | 0.83 | 0.96 | 0.92 | $0.75 \pm 0.08$ | $0.90 \pm 0.05$ |
| 2013 Period-3 | 11 375 | 41 | 0.81 | 0.96 | 0.91 | $0.71 \pm 0.09$ | $0.88 \pm 0.05$ |
| 2013 Period-4 | 10 012 | 41 | 0.83 | 0.96 | 0.91 | $0.75 \pm 0.08$ | $0.89 \pm 0.05$ |
| 2013 Period-5 | 13 817 | 46 | 0.77 | 0.94 | 0.88 | $0.65 \pm 0.10$ | $0.81 \pm 0.06$ |
| Average P2–3 | 10 631 | 41 | 0.82 | 0.96 | 0.91 | $0.73 \pm 0.08$ | $0.89 \pm 0.05$ |

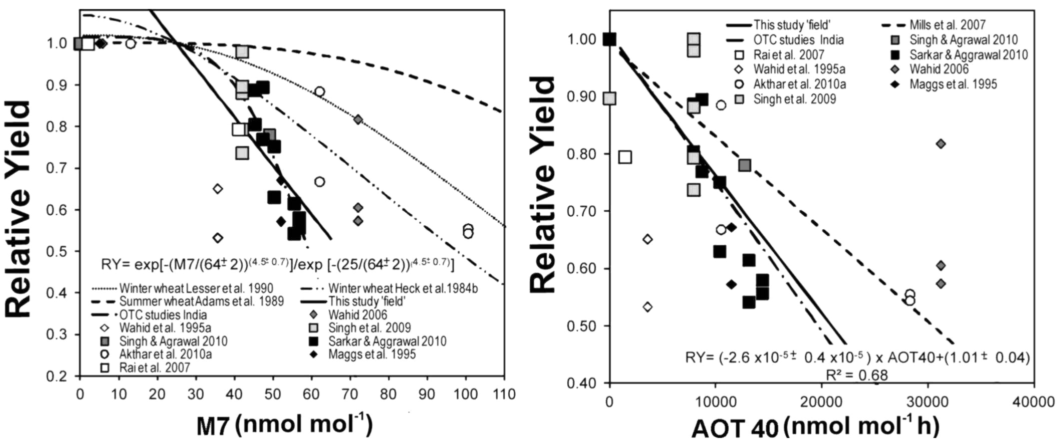


**Figure 6.** Comparison of the empirical exposure–response relationship based on field data (solid line) with OTC studies conducted in India (squares with line fit) and Pakistan (diamonds, not included in line fit). Circles show plant chamber studies on Bangladeshi wheat cultivars conducted in Japan. The exposure–response relationship based on American and European studies is plotted in the same graph for comparison. In all studies on southern Asian cultivars, wheat was exposed to elevated ozone levels from emergence to harvest, while the European and American exposure–response curves include data sets acquired on wheat crops that were exposed to elevated ozone during the last 3 months prior to harvest.

relationships reported in the literature (Mills et al., 2007; Heck et al., 1984b; Lesser et al., 1990; Adams et al., 1989) and with OTC studies conducted in India (squares, dash and dot line) and Pakistani Punjab (diamonds). 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 function. 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 five 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 southern Asia by approximately 10 and 20 % for the equation of Heck et al. (1984b) and Lesser et al. (1990) respectively (Table 6).

For AOT40 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 sensitivities 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 underestimate crop production losses in southern Asia. Table 6 summarizes relative yields 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 6) differ by $\sim$ 10–15 %. For M7 the exposure–yield relationship of Lesser et al. (1990) overestimates the yields by $\sim$ 20 % and the exposure–yield relationship of Heck et al. (1984b) by $\sim$ 10 % (Table 6). After the revision, relative yields calculated using the M7 and AOT40 metrics still show a $\sim$ 15 % discrepancy although the estimates do overlap within the combined uncertainty. The quality of the fit for M7 is better than the fit for AOT40; however, given the very steep slope of the M7 curve at $> 35\,\mathrm{nmol\,mol^{-1}}$ and the large number of points below the fit line for higher M7 values, it is credible that cultivars with such a sensitivity to ozone would respond very strongly to even a few days with extremely high ozone, and such behaviour will only be captured by the AOT40 index. Daytime peaks with $\sim$ 70–100 $\mathrm{nmol\,mol^{-1}}$ are observed in March and April (Fig. 2) during the grain filling stage of the plants, and the M7 for the full growth period does not capture such extreme events. AOT40 is the better indicator to accurately reflect exposure when the variance of the amplitude of daytime peak ozone is high. Picchi et al. (2010) reported a high sensitivity of wheat cultivars to ozone exposure during the grain filling stage, and our observations agree well with their finding. Therefore, for southern Asian wheat cultivars, the revised exposure–response curve using AOT40 will provide the best estimate of the crop production losses. Our revised ozone-exposure–crop-yield relationships show significantly lower relative yields than those obtained by exposure–response relationships used previously (−15 % for AOT40). This can be attributed to the variety of cultivars. Most Indian cultivars are more sensitive to a high $O_3$ concentration, although a few individual cultivars show higher resistance.

**Table 7.** Ozone exposure according to different exposure indices and relative yields for cotton. Period 1 (P1) and Period 2 (P2) correspond to the periods in which cotton is usually grown.

| Time | AOT40 | M7 | $RY_{AOT40}$ Mills et al. (2007) | $RY_{M7}$ Heck et al. (1984b) |
|---|---|---|---|---|
| 2012 P1 | 47926 | 57 | 0.30 | 0.91 |
| 2012 P2 | 33 728 | 53 | 0.53 | 0.91 |
| 2012 P3 | 48 342 | 56 | 0.30 | 0.92 |
| Average P1–2 | 40 825 | 55 | 0.42 | 0.91 |
| 2013 P1 | 40 029 | 55 | 0.43 | 0.92 |
| 2013 P2 | 27 312 | 51 | 0.63 | 0.92 |
| 2013 P3 | 41 046 | 53 | 0.41 | 0.93 |
| Average P1–2 | 33 670 | 53 | 0.53 | 0.92 |

#### 3.2.3 Cotton

Cotton yield data for this region have only been reported in two studies (Jalota et al., 2008; Buttar et al., 2013), and OTC studies on cotton in India have not been conducted to date. Buttar et al. (2013) reported yields for different numbers of pickings (Periods 2 and 3), and hence his observations cannot be used to investigate the crop response to ozone. Exposure–yield relationships acquired abroad indicate that cotton is potentially extremely sensitive to ozone-induced damage. The yield data from India show very high variability and no significant influence of ozone on yields when the results are averaged over 2 years (Jalota et al., 2008). However, there is a significant intra- and interannual variability in yields as a function of rainfall reported from the site on which the crop was grown (Jalota et al., 2008). Since the crop was irrigated sufficiently, this yield dependence on rain should not be related to drought stress. Ozone levels in Punjab during the monsoon season are strongly influenced by the 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 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 of 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 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 (∼ 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 10–20 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 7).

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 in a limited area, but maize is heavily promoted as an alternative to rice when a deficient monsoon is anticipated. We could not find any study reporting crop yields for maize planted in Punjab or Haryana in the peer-reviewed literature. A recent study investigating ozone-related crop yield losses for Indian maize cultivars (Singh et al., 2014) found that Indian maize cultivars are twice as sensitive to ozone as their American and European counterparts. However, maize is 1 order of magnitude less sensitive to ozone compared to rice and wheat and is, therefore, a suitable alternative for drought years. We use all three ozone exposure RY relationships (Heck et al., 1984b; Mills et al., 2007; Singh et al., 2014) to calculate relative yields (Table 8) and find that in the real world both the differences between the revised and old relationship and the overall losses are minor.

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

Table 9 summarizes 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 1970s and 1980s (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 southern 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 modelling study for the year 2005 predicted RYLs of 1 and 1.2 % for Punjab and Haryana respectively for wheat and 8.1 % for Punjab for rice (Ghude et al., 2014). 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 9 Column $RYL_{AOT40}$, Mills et al., 2007).

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, based both on the M7 exposure–response relationship for winter wheat proposed by Lesser et al. (1990) of 10.8 % and on the AOT40-

**Table 8.** Ozone exposure according to different exposure indices and relative yields for rabi and kharif maize.

| Time | AOT40 | M7 | $RY_{AOT40}$ Mills et al. (2007) | $RY_{M7}$ Heck et al. (1984b) | $RY_{AOT40}$ Indian OTC |
|---|---|---|---|---|---|
| 2012 P1 | 11 346 | 46 | 0.98 | 0.97 | 0.95 |
| 2012 P2 | 7522 | 43 | 0.99 | 0.99 | 0.98 |
| Average | 9434 | 45 | 0.99 | 0.99 | 0.97 |
| 2011/2012 P3 | 9824 | 48 | 0.98 | 0.99 | 0.96 |
| 2011/2012 P4 | 15 406 | 56 | 0.96 | 0.98 | 0.93 |
| Average | 12 615 | 52 | 0.97 | 0.99 | 0.95 |
| 2013 P1 | 9496 | 46 | 1.00 | 0.99 | 0.97 |
| 2013 P2 | 7209 | 44 | 0.98 | 0.99 | 0.98 |
| Average | 8353 | 45 | 0.99 | 0.99 | 0.97 |
| 2012/2013 P3 | 6219 | 40 | 0.99 | 0.99 | 0.99 |
| 2012/2013 P4 | 12 455 | 51 | 0.99 | 0.99 | 0.95 |
| Average | 9337 | 46 | 0.99 | 0.99 | 0.97 |

**Table 9.** Relative yield losses calculated according to different ozone exposure–response relationships for rice, wheat cotton and maize.

| Time | $RYL_{AOT40}$ Mills et al. (2007) | $RYL_{M7}$ Adams et al. (1989) | $RYL_{M7}$ Heck et al. (1984b) | $RYL_{M7}$ Lesser et al. (1989) | $RYL_{M7}$ this study | $RYL_{AOT40}$ this study |
|---|---|---|---|---|---|---|
| Rabi 2011–2012 | | | | | | |
| Wheat | 0.27 | | 0.14 | 0.07 | $0.25 \pm 0.07$ | $0.41 \pm 0.10$ |
| Maize | 0.03 | | 0.01 | | | 0.05 |
| Kharif 2012 | | | | | | |
| Rice | 0.14 | 0.03 | | | $0.21 \pm 0.06$ | $0.26 \pm 0.04$ |
| Cotton | 0.58 | | 0.09 | | | |
| Maize | 0.01 | | 0.01 | | | 0.03 |
| Rabi 2012–2013 | | | | | | |
| Wheat | 0.18 | | 0.09 | 0.04 | $0.11 \pm 0.05$ | $0.27 \pm 0.08$ |
| Maize | 0.01 | | 0.01 | | | 0.03 |
| Kharif 2013 | | | | | | |
| Rice | 0.12 | 0.02 | | | $0.19 \pm 0.06$ | $0.21 \pm 0.04$ |
| Cotton | 0.47 | | 0.08 | | | |
| Maize | 0.01 | | 0.01 | | | 0.03 |

based exposure–response relationship by Mills et al. (2007) of 29.8 % RYL for Punjab and Haryana, agree well with crop yield losses calculated by applying the same equations to our in situ observations (Table 7) for the years 2011–2014 (Table 9 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 Ghude and colleagues 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. (2011a) used the MOZART-2 (Model for OZone and Related chemical Tracers, version 2) to predict a 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 the TM5 model, predicted RYL ranging from 20–30 % for wheat, 10–15 % for rice and 1–3 % for maize for the year 2000, which agrees well with the observations.

Table 10 shows the crop production loss and MSP for the fiscal years of 2012–2013 and 2013–2014. Data on crop production were obtained from the following sources: the Directorate of Economics and Statistics (2013) and Agricultural Statistics (2013). Procurement data were obtained from the Food Corporation of India (2013). For the fiscal year of 2013–2014, data for Punjab are based on estimates, while final data for Haryana were obtained from the 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 Haryana and Punjab, both separately and cumulatively.

The highest crop production loss is seen for wheat: $20.8 \pm 10.4$ million t in the fiscal year of 2012–2013 and $10.3 \pm 4.7$ million t in the fiscal year of 2013–2014 for Punjab and Haryana taken together. Ghude et al. (2014) predicted crop production losses of only 0.25 million t for the year 2005 for both states. The discrepancy is mostly due to the fact that this study assumed that the ozone-sensitive growth period of wheat lasts only from December to February, and, hence, this study did not capture the effect of the high AOT40 during the grain filling stage of the crop in March (factor $\sim$15–30). Thus, the discrepancy is also partially due to the revision of the exposure–response relationship (Table 2; factor $\sim$2). Debaje (2014) estimated crop production losses of 10.9 million t $yr^{-1}$ on average for both states combined. The estimate falls within the same order of magnitude as our estimate. Avnery et al. (2011a) estimated a CPL of 26 million t for all of India but did not resolve losses for individual states. Economic cost losses amount to INR $244 \pm 121$ billion and INR $133 \pm 60$ billion in the fiscal years of 2012–2013 and 2013–2014 respectively. At an exchange rate of 60 INR/USD, this amounts to USD $4.1 \pm 2.0$ and $2.2 \pm 1.0$ billion respectively.

Rice shows crop production losses of $5.4 \pm 1.2$ million t in the fiscal year of 2012–2013 and $3.2 \pm 0.8$ million t in the fiscal year of 2013–2014 for Punjab and Haryana taken together. Ghude et al. (2014) predicted crop production losses of only 0.85 million t for the year 2005 for both states. The discrepancy is caused both by an under-

**Table 10.** Crop production (CP) for Punjab (PB) and Haryana (HR) and MSP for the fiscal years of 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)[a] and for wheat and rice, also using the revised AOT40-based exposure–response relationship[b]. CP and CPL for rice, wheat and maize are given in tonnes (t); CP and CPL are given in bales (b).

| | CP PB | CP HR | CP Total | MSP | CPL[a] PB | CPL[a] HR | CPL[a] Total | ECL[a] PB | ECL[a] HR | ECL[a] Total | CPL[b] PB | CPL[b] HR | CPL[b] Total | ECL[b] PB | ECL[b] HR | ECL[b] Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2012–2013 | $10^6$ t | $10^6$ t | $10^6$ t | INR/kg | $10^6$ t | $10^6$ t | $10^6$ t | $10^6$INR | $10^6$INR | $10^6$INR | $10^6$ t | $10^6$ t | $10^6$ t | $10^6$ INR | $10^6$ INR | $10^6$ 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 |
| Rice | 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 | 0.48 | 0.02 | 0.50 | 11.75 | 0.005 | 0.0002 | 0.005 | 56 | 2 | 59 | 0.015 | 0.001 | 0.015 | 173 | 7 | 180 |
| | $10^6$ b | $10^6$ b | $10^6$ b | INR/b | $10^6$ b | $10^6$ b | $10^6$ b | $10^6$INR | $10^6$INR | $10^6$INR | | | | | | |
| Cotton | 2 | 2.5 | 4.5 | 12 737 | 2.8 | 3.5 | 6.2 | 35 179 | 43 974 | 79 154 | | | | | | |
| 2013–2014 | $10^6$ t | $10^6$ t | $10^6$ t | INR/kg | $10^6$ t | $10^6$ t | $10^6$ t | $10^6$INR | $10^6$INR | $10^6$INR | $10^6$ t | $10^6$ t | $10^6$ t | $10^6$ INR | $10^6$ INR | $10^6$ 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 |
| Rice | 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 | 0.006 | 0.0003 | 0.006 | 74 | 4 | 78 | 0.017 | 0.001 | 0.018 | 228 | 11 | 239 |
| | $10^6$ b | $10^6$ b | $10^6$ b | INR/b | $10^6$ b | $10^6$ b | $10^6$ b | $10^6$INR | $10^6$INR | $10^6$INR | | | | | | |
| Cotton | 2.1 | 2.0 | 4.1 | 13 064 | 1.9 | 1.8 | 3.6 | 24 329 | 23 170 | 47 499 | | | | | | |

estimation of the AOT40 due to the fact that the author considered a shorter ozone-sensitive growth period (factor 1.5–1.8) and by 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 $67 \pm 15$ billion and INR $42 \pm 11$ billion for the fiscal years of 2012–2013 and 2013–2014 respectively. At an exchange rate of 60 INR/USD, this amounts to USD $1.1 \pm 0.2$ and $0.7 \pm 0.2$ billion respectively.

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

Economic losses amount to INR 79.15 billion and 47.50 billion (USD 1.3 and 0.8 billion) for cotton and INR 0.18 billion and INR 0.24 billion (USD 3 and 4 million) for maize in the fiscal years of 2012–2013 and 2013–2014 respectively.

The total economic losses for the agricultural sector in Punjab and Haryana amount to INR $391 \pm 136$ billion (USD $6.5 \pm 2.2$ billion) in the fiscal year of 2012–2013 and INR $223 \pm 71$ billion (USD $3.7 \pm 1.2$ billion) in the fiscal year of 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 such as basmati.

Secondly, we do not account for the losses in the food processing sector and other allied industries. The value gain from MSP to the 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. Rural income is affected strongly by crop yields, 78 % of the rural population depends on agriculture as primary source of income.

Previous studies investigating the relationship between monsoon rainfall, food grain production and the nation's GDP for the years 1951–2003 (Gadgil and Gadgil, 2006) found that a 1 % decrease in food grain production due to a deficient monsoon led to a 0.36 % decrease in India's 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 India's GDP is likely to fall into the range from 3.6 to 20 % (Eq. 8).

## 4 Conclusions

Using a high-quality data set 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 than 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, 3–5 % for maize to 47–58 % for cotton.

Crop production losses for wheat amounted to $20.8 \pm 10.4$ million t in the fiscal year of 2012–2013 and $10.3 \pm 4.7$ million t in the fiscal year of 2013–2014 for Punjab and Haryana taken together. Crop production losses for rice totaled $5.4 \pm 1.2$ million t in the fiscal year of 2012–2013 and $3.2 \pm 0.8$ million t in the year 2013–2014 for Punjab and Haryana taken together. 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 or rice to $\sim$ 820 million of India's economically weaker members of society.

The lower limit for economic cost losses in Punjab and Haryana amounted to USD $6.5 \pm 2.2$ billion in the fiscal year of 2012–2013 and USD $3.7 \pm 1.2$ billion in the fiscal year of 2013–2014. The upper limit for the ozone-related economic losses incurred at current ozone levels for all of India amounts 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 in healthcare-related costs and the number of workdays lost and a reduction in 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 the ozone exposure of the crop. Reaching out to farmers in order to promote this change in cropping practice will yield co-benefits in terms of increasing the water productivity of the crop and preserving precious groundwater. It will also increase the profit margin, as farmers often run tube wells 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 by advancing the harvest from the normal time (end of April to beginning of May) to an earlier time window (end of March to early April). New tillage practices that facilitate timely sowing, such as relay seeding into cotton and zero or low tillage regimes that incorporate rice straw, are urgently required to facilitate timely sowings. Providing a

"Happy Seeder" machine to every village in Punjab would cost ~ USD 0.04 billion. The Happy Seeder sows through the crop residue and leaves it as mulch on the fields. Promoting this technology would not only reduce ambient ozone mixing ratios by curbing crop residue burning, which contributes significantly to ozone precursor emission in the post-monsoon season (Sarkar et al., 2013), but it would also protect the young seedlings against ozone as the mulch acts as protective cover and reduces the dry deposition of ozone onto the leaf surface. Co-benefits of this technology include a higher carbon sequestration in the soil and a higher water productivity of the crop.

For all crops, screening a large number of domestic cultivars using the new stomatal-flux-based exposure metrics to identify and promote those cultivars that are less susceptible to ozone damage also offers a way forward.

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