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–

[5] 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, maize and rice cultivars. These are a factor of two more sensitive to ozone induced crop yield losses compared to their European and American counterparts.

[10] Relative yield losses based on the AOT40 metrics ranged from 27–41 % for wheat, 21–26 % for rice, 1–3 % 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

[15] 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.

[20] 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.

[25] Mitigation of high surface ozone would require relatively little investment in comparison to economic losses incurred presently. Therefore, ozone mitigation can yield massive benefits in terms of ensuring food security and boosting the economy. Co-benefits of ozone mitiga-

tion 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 devel-
opment have led to increasing emissions and have resulted in a statistically significant in-
crease 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 fur-
ther in the years to come (Giles, 2005).

Tropospheric ozone causes damage to crop at elevated levels and crop yields are ex-
tremely important to the Indian economy, as 17 % of India's GDP directly depends on agri-
culture 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 de-
mand for a large range of consumer products and cement depends directly on the year's
crop yield. Consequently every 1 % decrease in crop yields causes a 0.36 % decrease of In-
dia'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 In-
dia'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.
Therefore, it is extremely important to quantify crop losses due to ozone in the North West
Indo-Gangetic Plain (NW-IGP) accurately. (Agricultural Statistics, 2013).

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 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 (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; 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 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, 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 monsoon season. On the other hand, the yield of rice cultivars that show a healthy response to drought stress (i.e. close their stomata aperture rather than having a sluggish response) could substantially benefit from the system of rice intensification (SRI) cultivation practise (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 and could explain the higher yields frequently observed for SRI plots during field trials as well as the spatial variability of the yield difference between SRI plots and control treatments.

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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 (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 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; 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 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 induced defences 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 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).

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. 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
[5] (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
[10] over a threshold of 40 nmol mol^{-1} (AOT40) was adopted as 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
[15] 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 to address concerns that the
[20] 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 and have addressed the asynchronicity of maximum stomatal conductance (g_{sto}) and peak ozone in
[25] particular 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). Stomatal flux of ozone is modelled using a multiplicative algorithm adapted from Emberson et al. (2000) that 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}, 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 emphasised 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 South Asian wheat and rice has been reported in the peer reviewed literature. The wheat parameterization has been developed using European cultivars (Mills et al., 2011b) and for rice the parameterization has been developed using only one Japanese rice cultivar, Koshihikari (Yamaguchi et al., 2014), which is know for its ozone resistance (Sawada and Kohno, 2009). Depite the fact that the stomatal flux based model is recommended by the UNECE CLRTAP (United Nations Economic Commission for Europe Convention on Long-range Transboundary Air Pollution) for ozone risk assessment in Europe based on accumulated stomatal ozone fluxes over a threshold (UNECE, 2010), exposure yield relationships have so far been internatinally 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 relationship for Indian rice, wheat and maize cultivars derived through a review of the peer reviewed literature of open top chamber studies on South 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 coincidentally exposed

to different ozone levels by virtue of shifting their sowing date, but the relevant studies were
5   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 dataset 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
10 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
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

15 2.1   Site description and analytical details

All ozone measurements were performed at the IISER Mohali atmospheric chemistry mea-
surement facility (30.67° N–76.73° E, 310 m a.s.l., Fig. 1). The measurement site is region-
ally 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 ad-
20 joining 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
($< 1\,\mathrm{m\,s}^{-1}$), which occur only rarely (Sinha et al., 2014; Pawar et al., 2015). The predomi-
25 nant 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

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air masses from a fetch region covering irrigated cropland in the state of Haryana, southeast 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 ± 0.5 nmol mol^{-1} between two subsequent zero drift calibrations. The drift of the calibration factor during span calibrations was usually less than ± 3 % and always below ± 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 derive south Asia specific exposure yield relationships for wheat and rice. 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 the daylight hours 09:00–15:59 and 08:00–19:59 LT respectively in the crop growing season (Hollaway et al., 2012).

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

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 $[O_3] >$

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40 nmol mol^{-1}.

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

Out 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 dataset 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 is 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 ≤ 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 the requirement to occasionally purge the system with dry zero air leads to longer data gaps and up to 21 % of the hourly averages had to be filled using the method described above.

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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 entire Punjab ($> 90\%$ of the area).

5   In Haryana kharif crops include rice, cotton, sugarcane and in most of the unirrigated areas of Haryana pearlmillet and sorghum (Panigrahy et al., 2010). Mayor Rabi crops in 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%

10   and cotton-wheat ∼20% rotation is popular in the north but in the dryer parts of Haryana pearlmillet-mustard and pearlmillet-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,

15   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. 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

20   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. Wheat cultivars take between 4 to 4.5 months from emergence to maturity. High temperatures and water stress during the grain filling stage result a shorter growth period. Therefore, accumulated and average ozone exposure (AOT40/M7) was calculated for a 4.5 month period for timely

25   sowings and for a 4 month period for late sowings.

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2.5 Ozone dose exposure yield relationships

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 coincidental change in
5 ozone exposure and one study that reported collocated yield and ozone measurements (Agrawal et al., 2003) to derive an empirical exposure-yield relationship for rice and wheat. The empirical field data supports the need to revise the exposure-yield relationship for Indian cultivars and demonstrates, that for rice optimizing the sowing date can be a suitable strategy to minimize ozone exposure and maximise crop yields.

10 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; Singh et al., 2009; Rai et al., 2010; Singh and Agrawal, 2010; Sarkar and Agrawal, 2010, 2012) For maize only one OTC study on two Indian cultivars
15 has been conducted and we use the fit of this 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., 1995b; Maggs et al., 1995; Maggs and Ashmore, 1998; Wahid, 2006; Akhtar et al., 2010a, b; Wahid et al., 2011) to investigate to which extent the results can be extrapolated to entire
20 South Asia. We refrain from including cultivars popular in South East Asia into 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 5 different sowing dates for rice and wheat, 3 for cotton and 2 for rabi and kharif maize both using exposure dose–response relationships established in several studies in

25 the West (Table 2) to provide a lower limit and our new the India specific functions to provide an upper limit to the possible loss.

We use both the old (Mills et al., 2007) the AOT40 based exposure yield function, as well as our revised AOT 40 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 summarises the ozone exposure dose–response relationships for relative yield loss
5 (RYL) for wheat, rice, maize and cotton based on the AOT40, and M7 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-
10 induced damages (Avnery et al., 2011a) calculated using the Eqs. (3) and (4)

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

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

wherein RY_i stands for relative yield in the year i, CPL_i stands for crop production loss in
15 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_3-induced damages for particular financial year. The minimum ECL is calculated for
20 different crops based on corresponding Minimum Support Prices (MSP) of the same fiscal year using the equation:

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

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The MSP are recommended by Commission for Agriculture Costs and Prices (Directorate
25 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 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
5 rains and the Indian GDP established by Gadgil and Gadgil (2006) using the equation.

$$\text{ECL}_i \, [\%\text{GDP}] = \text{RYL}_i \, [\%] \times 0.36 \tag{6}$$

3 Results and discussions

3.1 Ozone seasonal cycle and monthly ozone exposure indices

10 Figure 2 shows the seasonal box and whisker plot of the daytime (08:00–19:59 LT) 1 h av-
erage ozone mixing ratios for the period from October 2011 to January 2014. The high-
est ozone levels are observed in 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 favourable conditions such as high temperature, low
15 humidity and high solar radiation favour the photochemical production of O_3 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^{-1}. The post
monsoon season is characterized by lower levels of solar radiation (range of daytime max-
ima $\sim$ 480–720 W m^{-2}) compared to summer season (range of daytime maxima $\sim$ 600–
20 920 W m^{-2}), but the occurrence of large scale agricultural burning emissions of ozone pre-
cursors and a lower boundary layer still results in comparably high ozone levels.

The lowest median daytime ozone mixing ratios of approximately 30 nmol mol^{-1} are ob-
served in August, during peak monsoon season, when cloudiness and wet scavenging of
ozone precursors limits the photochemical ozone production and during peak winter (De-

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25 cember and January). During winter 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 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 Febuary), however, the difference between the cumulative metrics (AOT40), that give higher weight to high values and low or no weight to low values and the average based metrics (M7) comes out

5 very clearly. For AOT40 the amplitude between peaks ($\sim 14\,000$ 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 num-

10 ber 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

15 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

20 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.

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25 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

$$AOT40 = 0.0201 \times M7^{3.0765} \qquad R^2 = 0.94 \qquad (7)$$

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.
5 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^{-1} h in May, 1500–2000 nmol mol^{-1} h in July and 6000–7000 nmol mol^{-1} 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 observa-
10 tions 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 $\sim$ 50 nmol mol^{-1} for Kharif season and $\sim$ 40 nmol mol^{-1} for Rabi
15 season for the Chandigarh UT. However, the authors considered only the time windows 15 June to 15 September and December to Febuary 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
20 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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Emberson et al. (2009) compared MATCH modelled M7 values with measured surface
ozone for Varanarsi and Lahore and found good agreement between model and obser-
vations for both cropping seasons. For our site, too, there is an excellent agreement be-
tween modelled and observed M7 values (model: 40–50 nmol mol^{-1} for Rabi season and
50–70 nmol mol^{-1} for Kharif season; observations: 40–52 nmol mol^{-1} for Rabi season and
47–64 nmol mol^{-1} for Kharif season).

van Dingenen et al. (2009) used a global model (TM5) 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 constraint for USA
and Europe (Avnery et al., 2011). The analyses of crop production losses so far made for
India are based on model derived O_3 mixing ratios (Deb Roy et al., 2009; Ghude et al.,
2014; van Dingenden et al., 2009, Avnery et al., 2011a) and apply O_3-dose–plant-response
metrics and formulae developed in the US (Adams et al., 1889; Lesser, 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 mod-
els, 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 season. Hence
model predictions need to be validated and improved using in-situ ozone measurements.

O_3-dose–plant-response metrics used in the modelling studies conducted so far also un-
derestimate crop production losses due to the fact that South Asian wheat and rice cultivars
are more sensitive to ozone. Emberson et al. (2009) reviewed a large number of Asian open
top chamber (OTC) and plant chamber studies, but refrained from deriving an 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 dif-
ferent 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 resis-

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tant 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 pho-
tosynthesis 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 cultivar, which did not suffer yield losses,
Koshihikari, 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 Ru-
BisCO and several energy metabolism related proteins were adversely affected by ozone
exposure in two indica cultivars Malviyadhan 36 and Shivani. These results seem to indi-
cate 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 iden-
tify high yielding cultivars, that are resistant to ozone stress, which can be promoted by the
relevant government agencies in affected areas.

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 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). For rice late sowing (1st of June) and late transplantation (1st
of July) leads to the lowest relative yield losses 18% while early sowing (1st April) and
transplantation (1st 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 open top chamber studies
(OTC) conducted 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
25 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.

5 It is clear from Fig. 4 and Table 5 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 and highest
relative yields, though this could be owed to the fact that the study was conducted in the
10 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) underestimates crop production losses in South Asia by approximately
20–30 % Table 5. For AOT 40 both the empirical relationship between crop yields and ozone
15 exposure and the OTC studies conducted in India lead to line fits with similar slopes, how-
ever, OTC studies show an intercept of 0.95 for AOT40 = 0 indicating that in South Asia
ozone levels below 40 nmol mol^{-1} damage local paddy cultivars. While deriving the empiri-
cal 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
20 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 5).
Table 5 summarises relative to yields for the five reference periods (which correspond to dif-

ferent sowing dates) and inter-compares 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
$\sim 10\%$. 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 cul-
tivars (Table 5). The difference between the two is $\sim 20\%$. After the revision relative yields
calculated using the M7 and AOT40 metrics agree within 4 % while previously the discrep-
ancy 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 de-
crease 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 $25\,\mathrm{nmol\,mol^{-1}}$ ozone. For AOT 40 the relative
yield is determined with respect to the yield that would have been obtained for $\mathrm{AOT40} = 0$).

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) and with open top chamber studies (OTC)
conducted in India (squares, dash and dot line) and Pakistani Punjab (diamonds). For stud-
ies 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
25 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 pro-
vides 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 form 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.

5 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 6).

10 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

15 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 Eu-
ropean studies underestimates crop production losses in South Asia. Table 6 summarises

20 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 6) differ
by $\sim 10-15$ %. 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 %

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(Table 6). After the revision relative yields calculated using the M7 and AOT40 metrics still
25 show ~ 15 % discrepancy. 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 nmol mol^{-1} 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 ~ 70–100 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 high
5 sensitivity of wheat cultivars to ozone exposure during the grain filling stage and our obser-
vations agree well with their finding. Therefore, for South 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 rela-
tive yields than those obtained by previously used exposure response relationships (-15 %
10 for AOT40). This can be attributed to the variety of cultivars. Most Indian cultivars are more
sensitive to high O_3 concentration, though few individual cultivars show higher resistance.

3.2.3 Cotton

Cotton yield data for this region has 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
15 till date. Buttar et al. (2013) reported yields for different number of pickings (period 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 shows very high variability
and no significant influence of ozone on yields, when the results are averaged over 2 years
20 (Jalota et al., 2008). However, there is a significant intra and inter–annual variability of 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 monsoon season are strongly

influence by wet scavenging of precursors and cloudiness, hence rain spells can be taken
25 as a proxy for times of low photochemical ozone production. The lowest yields were ob-
served 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 previ-
ous 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
5 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 10–20 nmol mol^{-1} the ob-
10 servations 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.
15 (1984b) to calculate relative yields (Table 7).

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

20 **3.2.4 Maize**

Maize is planted both as Rabi and Kharif crop, however, cultivation occurs only on 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
25 losses for Indian maize cultivars (Singh et al., 2014), found Indian maize cultivars are twice
as sensitive to ozone compared to their American and European counterparts. However,
maize is one 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) add[] 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

5 Table 9 summarises the relative yield loss calculated according to different exposure in-
dices. 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
10 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
15 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 equa-
tion (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).

20 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). 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 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 % 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 the 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. (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 1–3 % for maize for the year 2000, which agrees well with the observations.

Table 10 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 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 $\sim$ 15–30) and 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 year^{-1} 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 $\sim$ 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. 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 0.18 billion and INR 0.24 billion (USD 3 and 4 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 reduc-
tion 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 promot-
ing this change in cropping practise will yield co-benefits in terms of increasing 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 avail-
able.

For wheat, too, timely sowing is crucial to minimize ozone exposure during the grain filling
stage of the crop by advancing the harvest from April end to (March/ early April). New tillage

₂₅ practises that facilitate timely sowing such as relay seeding into cotton and zero or low tillage regimes that incorporates rice straw are urgently required to facilitate timely sowings. Proving a "Happy Seeder" machine to every village in Punjab would cost ∼0.04 billon USD. 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 post monsoon season (Sarkar et al., 2013), it would also protect the young seedlings against ozone as the mulch acts as protective cover and reduces the dry deposition of ozone onto

₅ 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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Table 1. Total number (N) of missing hourly average ambient data (mh) and total number of hours per month (th) and percentage (%) of missing hourly average ambient data for each month and number of short (≤ 3 h) and long (> 3 h) data gaps.

month	mh/th [N/N]	missing values [%]	short gaps [N]	long gaps [N]
Oct 2011	2/672	0.3	2	0
Nov 2011	2/720	0.3	1	0
Dec 2011	4/744	0.5	2	0
Jan 2012	3/744	0.4	1	0
Feb 2012	1/696	0.1	1	0
Mar 2012	4/744	0.5	0	1
Apr 2012	45/720	6.3	2	1
May 2012	13/744	1.7	5	1
Jun 2012	3/720	0.4	2	0
Jul 2012	153/744	20.6	1	1
Aug 2012	57/744	7.7	2	1
Sep 2012	92/720	12.8	2	1
Oct 2012	8/744	1.1	2	1
Nov 2012	4/720	0.6	4	0
Dec 2012	33/744	4.3	2	2
Jan 2013	1/744	0.1	1	0
Feb 2013	1/672	0.1	1	0
Mar 2013	25/744	3.4	1	1
Apr 2013	5/720	0.7	2	0
May 2013	3/744	0.4	1	0
Jun 2013	108/720	15.0	1	3
Jul 2013	63/744	8.5	1	2
Aug 2013	73/744	9.8	1	1
Sep 2013	33/720	4.6	1	3
Oct 2013	42/744	5.6	1	1
Nov 2013	49/720	6.8	2	2
Dec 2013	2/672	0.3	2	0
Jan 2014	2/720	0.3	1	0
Feb 2014	4/744	0.5	2	0

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)

Table 3. Monthly values of =M7 and increment in AOT40 in the respective month for the period October 2011 to January 2014.

Month	AOT40	M7
Oct 2011	7770	71
Nov 2011	6150	63
Dec 2011	2879	46
Jan 2012	1705	39
Feb 2012	2729	47
Mar 2012	5391	57
Apr 2012	7286	64
May 2012	14 783	83
Jun 2012	12 544	77
Jul 2012	4005	49
Aug 2012	478	32
Sep 2012	2760	46
Oct 2012	6951	63
Nov 2012	5041	57
Dec 2012	1820	42
Jan 2013	1372	32
Feb 2013	1133	37
Mar 2013	3714	51
Apr 2013	7608	64
May 2013	13 381	80
Jun 2013	8123	63
Jul 2013	3014	46
Aug 2013	883	37
Sep 2013	3310	49
Oct 2013	4968	55
Nov 2013	4730	56
Dec 2013	2617	43
Jan 2014	1370	36

Table 4. Comparison of the average montly ozone exposure indices observed at at suburban site in Mohali with measurements at other urban[b, c, d, e, f, g, h] and suburban [i, j] sites in the IGP and nearby remote mountain[l] and suburban valley[k] sites indicated in Fig. 1. Letters denote the following sources: [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 for a, f and i values in this table were calculated from the available diel profiles or time series plots.

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
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. Ozone exposure according to different exposure indices and relative yields for rice. Data for the five periods used to plot Figure 3 is provided in the table. Period (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	25641	55	0.84	0.97	0.69	0.72
2012 P2	19788	51	0.86	0.97	0.75	0.77
2012 P3	16715	49	0.87	0.98	0.78	0.79
2012 P4	35640	64	0.80	0.95	0.59	0.62
2012 P5	31853	60	0.82	0.96	0.63	0.67
Average P1-3	20715	52	0.86	0.97	0.74	0.76
2013 P1	20839	53	0.86	0.97	0.74	0.75
2013 P2	15330	49	0.88	0.98	0.80	0.79
2013 P3	12623	47	0.89	0.98	0.82	0.81
2013 P4	29259	60	0.83	0.96	0.66	0.67
2013 P5	25498	56	0.84	0.96	0.70	0.71
Average P1-3	16264	49	0.88	0.98	0.79	0.78

Table 6. Ozone exposure according to different exposure indices and relative yields for wheat. Data for the five periods used to plot Figure 5 is 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	15843	49	0.73	0.93	0.85	0.60	0.74
2012 P2	15807	49	0.74	0.93	0.86	0.60	0.75
2012 P3	16168	49	0.73	0.93	0.86	0.59	0.75
2012 P4	14754	49	0.75	0.93	0.85	0.63	0.74
2012 P5	17110	52	0.71	0.92	0.84	0.57	0.69
Average P2-3	15987	49	0.73	0.93	0.86	0.59	0.75
2013 Period-1	11384	42	0.81	0.96	0.91	0.71	0.88
2013 Period-2	9887	40	0.83	0.96	0.92	0.75	0.90
2013 Period-3	11375	41	0.81	0.96	0.91	0.71	0.88
2013 Period-4	10012	41	0.83	0.96	0.91	0.75	0.89
2013 Period-5	13817	46	0.77	0.94	0.88	0.65	0.81
Average P2-3	10631	41	0.82	0.96	0.91	0.73	0.89

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	33728	53	0.53	0.91
2012 P3	48342	56	0.30	0.92
Average P1-2	40825	55	0.42	0.91
2013 P1	40029	55	0.43	0.92
2013 P2	27312	51	0.63	0.92
2013 P3	41046	53	0.41	0.93
Average P1-2	33670	53	0.53	0.92

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	11346	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	15406	56	0.96	0.98	0.93
Average	12615	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	12455	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	0.41
Maize	0.03		0.01			0.05
Kharif 2012						
Rize	0.14	0.03			0.21	0.26
Cotton	0.58		0.09			
Maize	0.01		0.01			0.03
Rabi 2012–2013						
Wheat	0.18		0.09	0.04	0.11	0.27
Maize	0.01		0.01			0.03
Kharif 2013						
Rize	0.12	0.02			0.19	0.21
Cotton	0.47		0.08			
Maize	0.01		0.01			0.03

Table 10. 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)[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 in bales (b.)

|	CP	CP	CP	MSP	CPL[a]	CPL[a]	CPL[a]	ECL[a]	ECL[a]	ECL[a]	CPL[b]	CPL[b]	CPL[b]	ECL[b]	ECL[b]	ECL[b]
	PB	HR	Total		PB	HR	Total	PB	HR	Total	PB	HR	Total	PB	HR	Total
2012–2013	10^6 t	10^6 t	10^6 t	INR/kg	10^6 t	10^6 t	10^6 t	10^6INR	10^6INR	10^6INR	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
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	0.48	0.02	0.50	11.75	0.005	0.0002	0.005	56	2	59	0.015	0.001	0.015	173	7	180
Cotton	10^6 b	10^6 b	10^6 b	INR/b	10^6 b	10^6 b	10^6 b	10^6INR	10^6INR	10^6INR						
	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	10^6INR	10^6INR	10^6INR	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
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	0.006	0.0003	0.006	74	4	78	0.017	0.001	0.018	228	11	239
Cotton	10^6 b	10^6 b	10^6 b	INR/b	10^6 b	10^6 b	10^6 b	10^6INR	10^6INR	10^6INR						
	2.1	2.0	4.1	13 064	1.9	1.8	3.6	24 329	23 170	47 499						
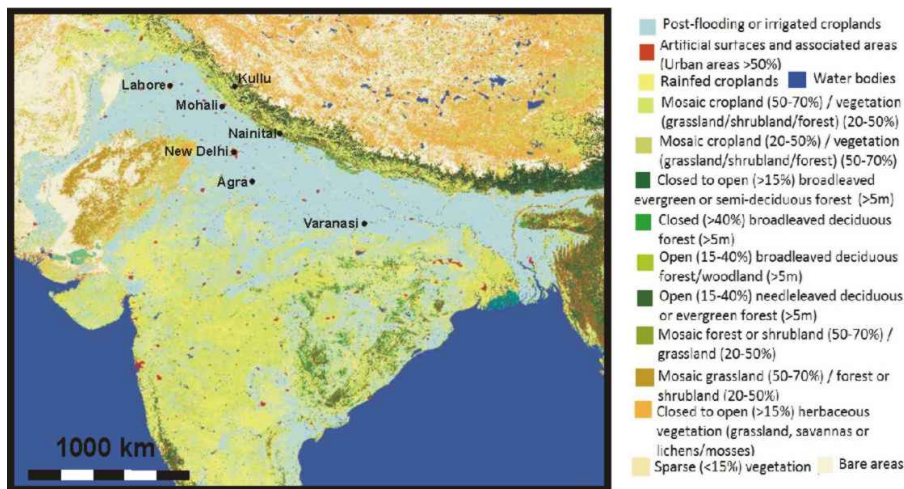
Figure 1. Location of our site and surrounding sites for which ozone measurements have been reported superimposed on a land classification map (courtesy ESA GlobCover 2009 Project).
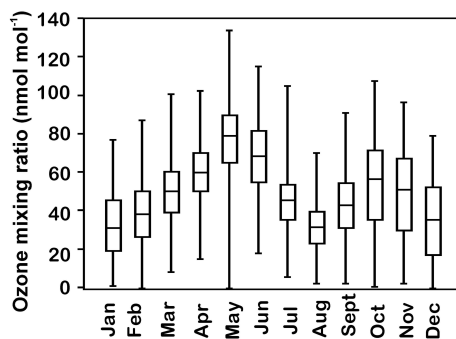
Figure 2. Seasonal box and whisker plot of the 1 h average daytime (08:00–19:59 LT) ozone mixing ratios. Whiskers denote the monthly minimum and maximum value, the box the upper and lower quarter value and the horizontal line within the box the median.
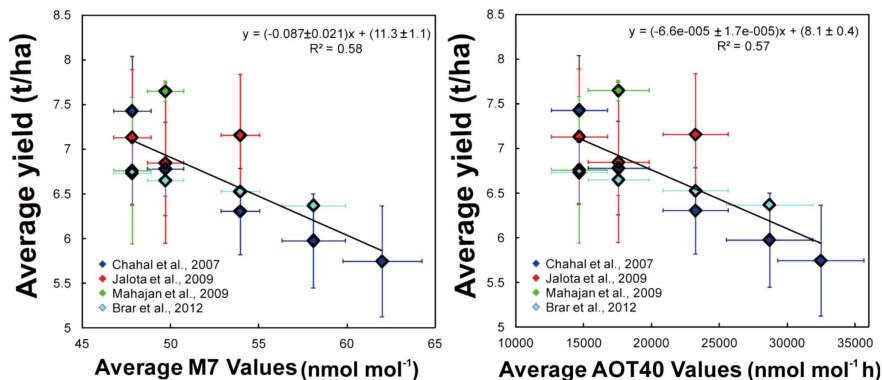
Figure 3. Empirical correlation of rice yields and ozone exposure indices for field studies with variations in sowing date. Ozone exposure for rice sowed on different sowing dates has been calculated using our data (Table 5). Yield data for rice has been taken from the peer reviewed literature (Chahal et al., 2007; Jalota et al., 2009; Mahajan et al., 2009; Brar et al., 2012). 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.
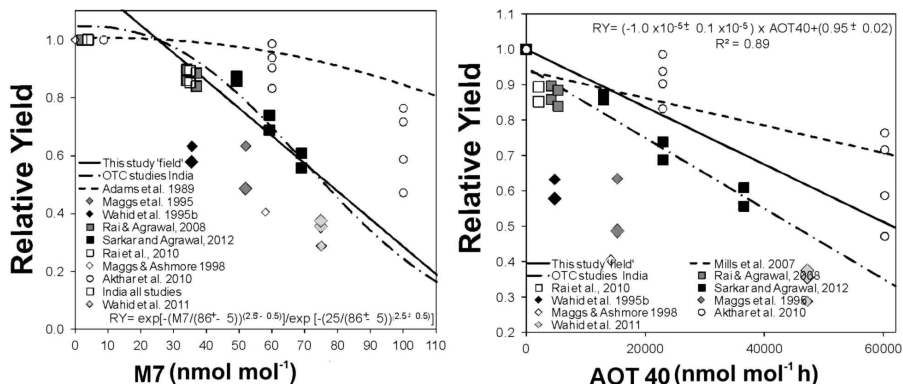
Figure 4. Comparison of the empirical exposure response relationship based on field data (solid line) with OTC studies conducted in India (squares with dash and dot fit) and Pakistan (Diamonds, not included in line fit). Large diamonds indicate studies conducted on Basmati, all other studies were conducted 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 till harvest.
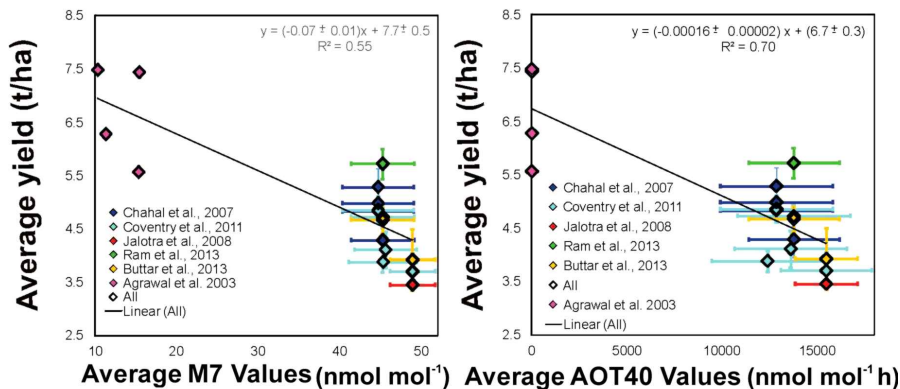
Figure 5. Empirical correlation of wheat yields and ozone exposure indices for field studies with variations in sowing date. Ozone exposure for wheat sowed on different sowing dates has been calculated using our data (Table 6). Yield data for wheat have been taken from the peer reviewed literature (Agrawal 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 date. The yield data has been positioned in conformation to the emergence dates (Period 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, number of irrigations and tillage practises.
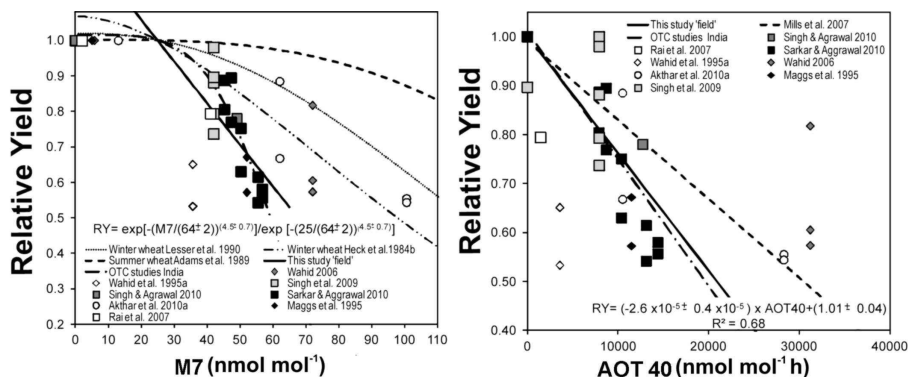
Figure 6. Comparison of the empirical exposure response relationship based on field data (solid line) with OTC studies conducted in India (squares with line fit) and Pakistan (Diamonds, not included in line fit). Circles show plant chamber studies on Bangladeshi wheat cultivars conducted in Japan. The exposure response relationship based on American and European studies is plotted in the same graph for comparison.In all studies on South Asian cultivars wheat was exposed to elevated ozone levels from emergence to harvest, while the European and American exposure-response curves include datasets acquired on wheat crops that exposed to elevated ozone during the last 3 months prior to harvest.