

Reviewer comment:

The paper covers an important and interesting topic: Assessment of crop yield losses in Punjab and Haryana using two years of in-situ measurements. The study calculates the impact of present-day reductions of crop yield due to the background ozone from the measurements at Mohali and then extrapolates these fields to states of Punjab and Haryana. The most interesting part of the paper is new crop yield exposure relationship for South Asian wheat and rice cultivars which authors tried to develop based on scattered literature from south Asian specific studies. The manuscript is easy to read and the results are important. This paper is definitely a first step in achieving the objectives the authors have set up to achieve. My overall recommendation is acceptance after careful revision of the text and queries as under:

Authors response:

We thank the anonymous reviewer #1 for the support to publish this paper and for his review. Addressing the comments will greatly improve the clarity of the manuscript. Detailed below is our response to the queries raised by the reviewer and a list of the specific changes made in the text.

Reviewer comment:

Specific comments

I have some reservations about the authors finding that new crop yield exposure relationship are a factor of two more sensitive to ozone induced crop losses compared to European and American Indices, and authors have not specified likely explanation for the dissimilarity. Is it because only few OTC (inconsistent) experiments are available over this region and lack of consistent OTC experimental and robust data set could be the prime reason (compared to European and American counterpart)?

Authors response:

We agree that too few studies on South Asian cultivars are available - but this does not mean the studies available are of poor quality. Some of the studies have included metabolites and have elucidated the damage mechanism for individual cultivars. So far, different South Asian cultivars have been investigated by different author teams and hence at this stage there is no scope for revealing inconsistencies of the datasets. More detailed studies are clearly required.

Reviewer comment:

Or, Asian crops itself are highly sensitive to ozone than European and American crops?

Authors response:

We have not commented in detail on the difference between European, American and South Asian cultivars as no comparative study of these cultivars has been conducted under identical conditions. Therefore, only speculations are possible at this stage.

However, we pointed out on page 2371 line 7-10 " ... 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)."

Changes in the manuscript:

We replaced the text "*This suggests that the spread in the data is indeed caused by differences in the sensitivity of different cultivars.*" page 2371 line 10 with a longer statement that is more comprehensive to stress clearly that the differences are most likely related to the differential response of cultivars to ozone and that more data is required:

*"A follow up metabolomic analysis of selected cultivars by the same authors Sawada et al. 2012 showed that one japonica cultivar with high yield losses, Kirara 397, down-regulated proteins associated with photosynthetic electron transport as a response to ROS induced by ozone while an indica cultivar 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. A second japonica cultivar, which did not suffer yield losses, Koshihikari, showed ozone stress up-regulated the expression of certain proteins in the Calvin cycle of the energy metabolism. Sarkar & Agrawal 2012 reported the expression of the RuBisCO and several energy metabolism related proteins was adversely affected by ozone exposure in two indica cultivars Malviya dhan 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."*

Reviewer comment:

Or, crop exposure period for ozone to derive crop specific E-R function is different in SA, European and American (see below comments)?

AOT40 exposure requires accumulation of ozone concentrations over 90 days of crop growing period in order to assess the crop loss. Mills exposure functions are based on consistent 3 months (except for tomato which based on 3.5 months) growing period for wheat, rice, cotton and maize from various literatures.

Authors response:

All used in this work to derive the relationship expose the crop from emergence to maturity for wheat and from transplanted to maturity for rice. Mills exposure functions are based on crops expose for 3 months for wheat and from emergence to maturity for rice, cotton and maize. The paper explicitly states that for crops other than wheat and tomato Mills et al. 2007 filtered out only studies that complied with the condition that "*Experiments were conducted in the open field using a field release system or in open-top chambers. The crop should have been planted directly in the soil and should have been exposed to ozone from emergence to harvest. Only data from well-watered experiments were included in the analysis.*" Mills et al. 2007, p 2632 Therefore, the concern raised here and below regarding applying the Mills exposure -yield curve to the AOT40 accumulated over the full growth period is only valid for wheat not for rice, maize & cotton.

The 3 month period considered for wheat has historical reasons. Most of the early studies for wheat looked only at a shorter time spans of ~3 months prior to harvest. This has been caused by the fact that "*... in most experiments, fumigations with ozone began several weeks after emergence.*" Adams et al. 1989 p 962. For wheat, Mills et al. 2007 relies on the compilation of older experiments by Fuhrer et al. 1997 and the 3 month limitation is again imposed by the fact that "*...duration of exposure varied between experiments, with an upper limit of about 90 days.*" Fuhrer et al. 1997 p95.

The fact that many early studies on wheat did not fumigate throughout, should not be used to imply that no damage occurs in the initial growth stages, though some select studies have shown, that wheat is more sensitive to ozone levels during anthesis & grain filling (Amundsen *et al.*, 1987, Pleijel *et al.*, 1996, Picchi *et al.* 2010).

Reviewer comment:

This study derives empirical exposure-yield relationship based on various OTC studies conducted in India and Pakistan for wheat and rice (section 2.5 (last para), 3.2, 3.2.1 and 3.2.2). Here, author failed to mention what time-frame (exposure days, number of days from emergence to maturity) studies in India and Pakistan considered for the yield loss due to ozone (for wheat and rice)? Is it 3 months period? If not, whether the growing period is consistent in all these regional studies? This is important because if the exposure period differs within the various studies for the same crops (eg. wheat) then obviously crop exposed for longer duration (eg 120 days) will show higher yield loss compared to the same crop exposed for shorter duration (eg 90 days), and therefore derived empirical exposure yield relationship based on different exposure periods will be unrealistic. Author should cite (probably in table) the growing period/exposure period considered in OTC studies in India and Pakistan for different crops

Authors response:

All studies presented in this paper exposed crops from the date of transplanted till harvest for rice. For wheat exposure was from emergence till harvest in all cases. We have added a sentence clarifying this in the relevant figure captions and the text.

The number of days the crop takes from emergence to maturity varies from cultivar to cultivar. It also varies from year to year for multi-year field studies of the same cultivar; as the speed at which the cultivars reach maturity in the fields depends on meteorological conditions which vary from year to year. Listing this information for such a large number of different multi-year studies several of which included multiple different cultivars will make the paper lengthy. It would also imply that each cultivar should be labelled differently in figure 4 & 6 which would obscure the clarity of the figure. Since there is no evidence supporting systematic differences between e.g. rice cultivars that reach

maturity rapidly (90 day) and those that take longer (120 or 140) we believe that it is better if the interested reader refers to the original papers for these details. All the references have been provided in the figures and in the text. The fact that the ozone sensitivity is not systematically correlated with the time the respective cultivars take to reach harvest maturity can be most clearly seen from two studies that included a large number of rice cultivars Akhtar et al. (2010) and Sawada et al (2009).

Akhtar et al. 2010 studied four different Bangladeshi cultivars two of which had a longer (120 day) growth period and two of which had a shorter 90 day growth period. Both sets of cultivars, the one with the shorter 90 and the one with a longer 120 day growth period, included one ozone sensitive and one ozone resistant cultivar. Similarly Sawada et al. 2009 studied cultivars that took between 99 and 143 days from emergence to harvest. Two cultivars with almost identical growing periods IR 64 and IR36 (~120 days) stand at opposing ends when it comes to the ozone sensitivity of the studied indica cultivars, while suphanburi a cultivar with a ~140 day growth period shares its lower sensitivity to elevated ozone mixing ratios with IR64.

We would also like to point out that the anonymous reviewer is wrong in implying that exposure for the full growth period will lead to unrealistic high yield losses! Exposure for the full growth period will lead to more robust estimates, while exposure-response curves based on experiments that limited fumigation to certain growth stages, can suffer from a systematic bias. It should be noted, that in the real world, the crop has no shield that protects it from ozone from emergence till 3 months prior to harvest.

If indeed the damage for wheat occurs mostly during anthesis & grain filling as suggested by Picchi et al. 2010 and Mills et al 2007, (i.e. damage is limited to the last 3 months prior to harvest), the slope of the curve in Figure 6 would become steeper for the South Asian wheat cultivars (i.e. the implication would be that the cultivars are even more sensitive). According to that hypothesis, early fumigation does not affect the crop yield and hence the observed loss would not change for a delayed onset of fumigation (anthesis & grain filling are part of the 3 month prior to harvest time window) while AOT40 would decrease (due to the fact that AOT is a cumulative index and a shorter time window necessarily leads to a lower number). It is, therefore, unlikely that the manner in which we presented the results are biased towards higher sensitivity, by considering a longer rather than shorter exposure period while deriving the exposure-yield relationship. As the data presented in figure 4&6 was acquired on crops exposed throughout, the above ground growth stages we consider ambient ozone for the same period while calculating RY and economic losses.

We would also like to emphasize that this criticism cannot be applied to crops other than wheat, as Mills et al. 2007 derived the exposure-yield relationship for those crops only based on studies that exposed the crops to ozone from emergence to harvest. Mills et al. 2007, p 2632

#### Changes in the manuscript:

We added the following text to clarify this

Figure caption of figure 4. *"In all studies presented in this figure rice plants were exposed to elevated ozone from the date of transplantation till harvest."*

page 2372 line 12 *" In all studies rice plants were exposed to elevated ozone levels from the date of transplantation till harvest."*

Figure caption of figure 5. *"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."*

Page 2374 line 23 *"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 were exposed to elevated ozone only during the last 3 months prior to harvest."*

#### Reviewer comment:

(Table 6 and sections 3.2, 3.2.1, 3.2.2, 3.3) Mills exposure functions are based on 3 months growing season, therefore while estimating crop yield losses based on Mills functions one generally consider 3 months growing period of exposure regardless of days from emergence to maturity. Here, authors have considered around 4-5 months period for rice and 5-5.5 months for wheat, and 6 months for cotton. Using Mills exposure functions and accumulated ozone above 40 ppb for more than 3 months will therefore provide unreal estimates.



We modified Page 2383 line 7ff "*For wheat, too, timely sowing is crucial to minimize ozone exposure during the grain filling stage of the crop. New tillage practises that facilitate timely sowing such as relay seeding into cotton and zero or low tillage regimes that incorporates rice straw or machinery to rapidly clear rice residues from the fields are urgently required to facilitate timely sowings.*"

to "*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). Kumar et al. 2015 showed that ozone precursor emissions from crop residue burning lead to significant enhancements of the observed ozone mixing ratios. Therefore, mitigating ozone precursor emissions from paddy residue burning will reduce the ozone exposure of the young wheat plants just after emergence. Providing a baler, which will allow speedy clearance of the crop residue from the fields, to every village in Punjab would cost ~0.1 billion USD. The baled crop residue could be co-combusted in coal fired power plants. A rate of 750-1000 INR/tonne would provide sufficient revenue to the farmers to make bailing viable while not increasing the cost/tonne of feedstock for the power plants. Alternately, proving an equal number of "Happy Seeder" machines would cost ~0.04 billion 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, 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. Moreover, sowing operations can be completed within a week after paddy harvest and this timely sowing reduces ozone exposure during the grain filling stage of the crop. Co-benefits of this technology include a higher carbon sequestration in the soil and a higher water productivity of the crop.*"

Reviewer comment:

Page 1, Line 13-14: Why wheat loss is a factor of two higher in 2012-13 compared to 13-14?

Authors response:

Ozone levels were a factor 2 higher in 2011-12 compared to 2012-13. The winter 2012-13 had a higher than usual number western disturbances including some very late in the season. The associated wet scavenging of ozone precursors resulted in much lower ozone levels during the grain filling stage of the crop.

Reviewer comment:

Section 3.2, 3.2.1 and 3.2.2: Figure 3 and Figure 4: Variation in sowing dates and exposure shows the significant trend of the crop yields as a function of ozone exposure indices. Here, how can one ignore the influence of micro climate suitable for more yields based on sowing dates and year to year variation of crop yield (because crop yield of rice/wheat reported in figure 3 and 4 are for different years) Is this relationship mere a coincidence? Can authors verify whether the yield of rice and wheat is similar during 2007 -2013 for same sowing dates?

Authors response:

The data presented in Figure 3 and 5 covers different years ranging from 2003-2011. The year to year variations of crop yield have already been taken care of by the fact that individual studies shown were replicated in at least 2 years. The concerns regarding micro-climate too were addressed in the original experimental design as most studies were performed on different plots in some cases even in different districts. Moreover, studies included different cultivars and tillage practises. The variability introduced by all these factors combined is indicated by the vertical bars of each data point. Similarly the variability in ozone mixing ratios for the same period in different years is indicated as horizontal bar. Different studies were started in different years, therefore the overall period covered is 2004-2008 for rice and 2003-2011 for wheat. It is, true that it is difficult to completely disentangle the effect of ozone from that of heat and water stress without a clean air control grown under identical conditions. Heat waves and ozone episodes unfortunately coincide and are likely to reinforce each other when it comes to yield losses. However, the fact that the empirical exposure response curve agrees so well with exposure response curve from OTC studies that do have a clean air control grown under identical conditions in the same field, seems to suggest that most of the yield loss is due to the ozone and not due to meteorological factors.

Reviewer comment:

Section 3.2.1: East-west gradient in sensitivity of local cultivars to ozone exposure is due to difference in exposure period considered in these various studies?

Authors response:

No. All cultivars were exposed from transplantation to maturity but the data seems to indicate that length of growth period is not the factor controlling sensitivity. Akhtar et al. 2010 had four different Bangladeshi cultivars two of which had a 1 month longer (120 day) growth period. Both the cultivars with the shorter 90 day period from emergence to maturity and the cultivars with a longer 120 day growth period included one more sensitive and one resistant cultivar. Similarly Sawada et al. 2009 studied cultivars that took between 99 and 143 days from emergence to maturity. Two cultivars with almost identical growing periods IR 64 and IR36 (~120 days) stand at opposing ends when it comes to the ozone sensitivity of the studied indica cultivars, while suphanburi a cultivar with a ~140 day growth period shares its lower sensitivity to elevated ozone with IR64. However, it is possible that relative yields obtained during plant chamber studies, in a completely controlled and sheltered system in which temperatures remain within the optimum range throughout and water stress never occurs, are systematically higher (i.e. losses are lower) compared to RY obtained in open top chamber studies under field conditions. We have added a note of caution regarding this.

Changes in the manuscript:

*"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 sheltered environment of a plant chamber. Pakistani..."*

Reviewer comment:

Pl. check. Table 2: I suggest to normalize these RY calculations by the RY obtained for AOT40 = 0, such that the intercept of the relative yield equals 1. Because the value of "a" in the Mills regressions and also the regression obtained in the present study is not always equal to 1 as would be expected for Table AOT40 = 0 (particularly for rice and cotton) (for rice it would mean an additional 5

Authors response:

We have checked table 2 carefully. Equations taken from other publications are reported as reported by the relevant authors. Our equation is based on the regression of the data presented in this study.

We do not agree with the anonymous reviewer that regression lines should be forced through 0 as AOT40=0 does not mean [O<sub>3</sub>]=0. Forcing the regression through 0 has never been the practise of the scientific community. The "a" value of the regression line carries scientific meaning. If the intercept is less than one then ozone levels below 40 ppbv have a negative impact on the cultivar in question. An intercept > 1 suggest that the plant is only sensitive to higher levels of ozone and does not suffer much damage if ozone levels only slightly exceed the threshold of 40 ppbv.

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