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

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In our study we use a high quality dataset of in-situ ozone measurements at a regionally representative suburban site called Mohali to assess ozone related crop yield losses for wheat, rice, cotton and maize for Punjab and the neighbouring state Haryana for the years 2011-2013.

Crop yield loss estimates are calculated using two different exposure metrics, AOT40 and M7 and are inter-compared for the two major crop growing seasons of Kharif (June-October) and Rabi (November-April).

For Rabi season crop yield losses are calculated for wheat and maize and for Kharif season crop yield losses are calculated rice, maize and cotton.

In supplementary text 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.

Supplementary tables S2 to S5 show the ozone exposure for rice, wheat, maize and cotton sowed on different sowing dates in the cropping season according to different exposure metrics and relative yields calculated according to different exposure-yield relationships.

1 Supplementary text S1

1.1 Rice

The life cycle of the rice plant is generally 100 to 210 days. The developmental phases are broadly classified into vegetative phase (from seed germination to panicle initiation), reproductive phase (from panicle initiation to anthesis) and the ripening phase (from anthesis to full maturity) (Vergara, 1991). However, for quantifying ozone damage the early vegetative phase from seed germination to emergence can be neglected, as plants are not affected by air pollution prior to emergence. In Asia, emergence typically takes two weeks after sowing. After sowing, anthesis is reached 70-100 days and maturity in 100- 140 days respectively (Timsina and Humphreys, 2006). Typically crops are not harvested directly after reaching maturity (the stage at which the flag leaves and spikes start turning yellow). In the absence of drying facilities, farmers wait till grains reach the optimum moisture content for threshing. During the corresponding drying period (typically up to 2 weeks) no further ozone damage can be incurred. While direct seeding of rice both into wet and dry soil is possible (Vergara, 1991), sowing seeds into nurseries and transplanting them into the puddled fields is still the most popular rice planting method in Punjab and Haryana. In Punjab, May 15th to May 30th is recommended as the optimum time of sowing for all the recommended rice varieties (agripb.gov.in, 2014). Seedlings are transplanted 25-45 days after sowing. The greening of most rice growing areas in Punjab takes place between June 1st and July 1st (Upadhyay et al., 2008) and would correspond to the date at which rice is transplanted into the fields. However, the ozone sensitive growth stage would already be reached two weeks prior to transplantation. Paddy crop typically reaches maturity in September or early in October. According to remote sensing estimates harvesting starts in the first half of September in a limited area and is completed by October 11th in most of the state (Upadhyay et al., 2008). Only in a few regions harvest takes place after October 11th (Upadhyay et al., 2008). For calculating the economic losses in Punjab and Haryana due to ozone three time periods have been considered:

Period 1: May 16th (emergence) to September 15th (maturity)

Period 2: June 1st (emergence) to September 30th (maturity)

Period 3: June 16th (emergence) to October 15th (maturity)

Several studies report crop yields for a wider range of transplantation dates (Chahal et al., 2007; Jalota et al., 2009; Mahajan et al., 2009; Brar et al., 2012). Since the variance of the average AOT40 and M7 indices of the same months in different years is much smaller that the difference of the average AOT40 and M7 for different reference periods outlined above, those datasets in combination with our measurements can be used to investigate potential yield reductions due to ozone. Since some studies reported yields for a larger variety of transplantation dates, we also consider the following additional time windows while deriving the empirical relationship between crop yields and ozone exposure:

Period 4: April 15th (emergence) to August 15th (maturity)

Period 5: May 1st (emergence) to September 1st (maturity)

1.2 Wheat

The plant development of wheat is generally classified into the following stages: germination to emergence (beneath the ground, not sensitive to O_3); growth stages 1-3, wherein growth stage 3, which includes the grain filling period (from anthesis to maturity) is most susceptible to O_3 damage (Picchi et al., 2010). Physiological maturity is usually defined as the time when the flag leaf and spikes turn yellow. Harvesting can occur any time after physiological maturity but typically does not occur till two weeks after, because of high kernel moisture (Porter and Gawith, 1999). In Punjab and Haryana wheat is sown in October (middle) to December (beginning). Emergence takes two weeks. In Asian winter wheat varieties anthesis is typically reached 80-100 days after sowing and maturity 110- 140 days after sowing (Timsina and Humphreys, 2006). Sowings in October are considered early, sowings in the first two weeks of November timely and sowing after that are considered to be late (Coventry et al., 2011). Generally late sowings reach maturity faster – after 4 rather than 5 months – as they are exposed to higher temperatures and ozone in the later part of their development during the grain filling state (Porter and Gawith, 1999; Timsina and Humphreys, 2006). The sowing time depends heavily on the harvesting time of the previously planted Kharif crop (Chahal et al., 2007; Buttar et al., 2013) and on the tillage method adopted. Conventional field preparation takes at least two weeks for clearing the crop residue ploughing and disking. Planting an additional potato crop in between Kharif and Rabi also delays the wheat sowing. A large number of studies report crop yields for different tillage methods and sowing dates (Chahal et al., 2007; Jalota et al., 2008; Coventry et al., 2011; Buttar et al., 2013; Ram et al., 2013). In this study we consider the following time windows for the ozone sensitive period from emergence (two weeks after sowing) till maturity (4-5 months after sowing).

Period 1: November 1st (emergence) to 15th March (maturity)

Period 2: November 16th (emergence) to 31st March (maturity)

Period 3: December 1st (emergence) to 15th April (maturity)

Period 4: December 16th (emergence) to 15th April (maturity)

Period 5: January 1st (emergence) to 30th April (maturity)

Period 2 and Period 3 are most relevant for calculating ozone related losses in the rice-wheat cropping system and correspond to the most popular sowing dates in the rice-wheat cropping system as reported by satellite retrievals (Lobell et al., 2013). However, since crop yields corresponding to the other sowing dates are reported in the literature we use the available data to estimate dose-response relationships for Asian winter wheat cultivars.

1.3 Maize

The plant development of maize is generally classified into the vegetative stage, tasseling stage, cob formation stage and milk stage. The vegetative stage is completed 30-40 days post emergence and tasselling, cob formation and milk stage 60-70, 70-80 and 80-90 days post emergence, respectively (Cakir, 2004). Emergence can take as little as 5-7 days in warm soil and up to 30 days under cold conditions. In Punjab and Haryana kharif maize is sown in June or July and harvested in September or October (Upadhyay et al., 2008; Ghuman and Sur , 2001). Spring maize is grown from December or January - April. Maize has extremely high crop yields in spring, but cultivation of spring maize is actively discouraged due to high water consumption. Nevertheless, cultivation of spring maize does occur in Jalandhar, Hoshiarpur, Gurdaspur and parts of Malwa. We investigate two periods to evaluate potential yield losses of maize due to ozone for each of the growing seasons.

Kharif:

Period 1: 15th June (emergence) to 15th September (maturity)

Period 2: 1st July (emergence) to 1st October (maturity)
Rabi:
Period 3: 1st January (emergence) to 31st March (maturity)
Period 4: 1st February (emergence) to 30th April (maturity)

1.4 Cotton

The growth stages of cotton are commonly divided into emergence, presquare, preflower, mid-season, and late season growth (Oosterhuis , 1990). Cotton is a 240 day crop in Punjab. The recommended sowing date is April (beginning) to 15 May (agripb.gov.in, 2014; Jalota et al., 2008). Early sowing helps to escape the attack of American bollworm to great extent but also exposes the crop to high ozone concentrations during summer. Whenever sowing has to be delayed due to delayed harvesting of the rabi crops or unavailability of canal water, the cultivated area decreases as some farmers opt to plant other kharif crops instead, however, on a limited area sowing can occur as late as May end. Emergence of cotton takes 5-10 days. The period in which cotton is sensitive to ozone damage hence begins approximately one to two weeks after sowing. Cotton sown in April is typically ready for the first picking in the third week of September to beginning of October (Oosterhuis , 1990; Buttar et al., 2013); the second picking takes place in November and the third picking in December. A fourth picking is also possible, if the rabi crop is sown into the standing cotton (Buttar et al., 2013) or if the field is left barren during rabi season. In Punjab and Haryana picking is performed manually. The practise of defoliation, prior to one single machine picking, which is widely followed in the West is not followed in India as a consequence the plant continues to be sensitive to O_3 damage throughout the picking period. Picking continues into December or even January and the termination of the picking often conflicts with the ideal sowing dates of the following rabi crop. In the cotton-wheat rotation wheat is often sown far later than the ideal recommended date. To cover the entire range of potential ozone damage, three time windows are investigated:
Period 1: 1st May - 15th December; three pickings
Period 2: 31st May - 15th December; three pickings
Period 3: 1st May - 31st December; four pickings

It should be noted, however, that these time windows do not correspond to the same number of pickings.

Table 1. 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	W126	M7	M12	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	37.27	55	51	0.84	0.97	0.75	0.69
2012 P2	19788	27.13	51	47	0.86	0.97	0.80	0.75
2012 P3	16715	21.82	49	44	0.87	0.98	0.82	0.78
2012 P4	35640	52.29	64	60	0.80	0.95	0.65	0.59
2012 P5	31853	47.47	60	56	0.82	0.96	0.70	0.63
Average P1-3	20715	28.74	52	47	0.86	0.97	0.79	0.74
2013 P1	20839	27.37	53	49	0.86	0.97	0.78	0.74
2013 P2	15330	18.25	49	45	0.88	0.98	0.82	0.80
2013 P3	12623	13.98	47	42	0.89	0.98	0.84	0.82
2013 P4	29259	41.27	60	55	0.83	0.96	0.70	0.66
2013 P5	25498	35.63	56	52	0.84	0.96	0.74	0.70
Average P1-3	16264	19.87	49	45	0.88	0.98	0.81	0.79

2 Supplementary table S2

Table 2. 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	W126	M7	M12	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	17.99	49	41	0.73	0.93	0.85	0.74	0.60
2012 P2	15807	17.33	49	41	0.74	0.93	0.86	0.75	0.60
2012 P3	16168	17.40	49	42	0.73	0.93	0.86	0.75	0.59
2012 P4	14754	15.95	49	43	0.75	0.93	0.85	0.74	0.63
2012 P5	17110	19.33	52	46	0.71	0.92	0.84	0.69	0.57
Average P2-3	15987	17.36	49	42	0.73	0.93	0.86	0.75	0.59
2013 Period-1	11384	12.69	42	36	0.81	0.96	0.91	0.88	0.71
2013 Period-2	9887	9.71	40	35	0.83	0.96	0.92	0.90	0.75
2013 Period-3	11375	11.34	41	37	0.81	0.96	0.91	0.88	0.71
2013 Period-4	10012	9.73	41	37	0.83	0.96	0.91	0.89	0.75
2013 Period-5	13817	15.25	46	41	0.77	0.94	0.88	0.81	0.65
Average P2-3	10631	10.53	41	36	0.82	0.96	0.91	0.89	0.73

3 Supplementary table S3

Table 3. 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	W126	M7	M12	RY_{AOT40} Mills et al. (2007)	RY_{M7} Heck et al. (1984b)
2012 P1	47926	68.33	57	51	0.30	0.91
2012 P2	33728	45.91	53	47	0.53	0.91
2012 P3	48342	68.70	56	50	0.30	0.92
Average P1-2	40825	57.12	55	49	0.42	0.91
2013 P1	40029	52.65	55	48	0.43	0.92
2013 P2	27312	33.12	51	45	0.63	0.92
2013 P3	41046	55.56	53	51	0.41	0.93
Average P1-2	33670	42.89	53	47	0.53	0.92

4 Supplementary table S4

Table 4. Ozone exposure according to different exposure indices and relative yields for rabi and kharif maize.

Time	AOT40	W126	M7	M12	RY_{AOT40} Mills et al. (2007)	RY_{M7} Heck et al. (1984b)
2012 P1	11346	14.79	46	43	0.90	0.99
2012 P2	7522	8.39	43	39	0.91	0.99
Average	9434	11.59	45	41	0.91	0.99
2011/2012 P3	9824	10.00	48	42	0.90	0.99
2011/2012 P4	15406	17.91	56	50	0.88	0.98
Average	12615	13.96	52	46	0.89	0.99
2013 P1	9496	10.80	46	42	0.90	0.99
2013 P2	7209	7.15	44	40	0.91	0.99
Average	8353	8.98	45	41	0.91	0.99
2012/2013 P3	6219	5.54	40	36	0.92	0.99
2012/2013 P4	12455	14.13	51	46	0.89	0.99
Average	9337	9.84	46	41	0.91	0.99

5 Supplementary table S5

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