Chapter 15
Impact of Increasing Ozone on Agricultural Crop Yields

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15.1   Introduction

Urbanization, industrialization, and increasing levels of anthropogenic emissions in the last two decades have resulted in an increase in tropospheric ozone (O_3) levels and substantial deterioration of air quality (Lal et al. 2008). The two main sources in the troposphere which determine the levels of surface O_3 are stratospheric input and photochemical O_3 formation (Sicard et al. 2009) (Fig. 15.1). O_3 is a secondary air pollutant formed by photochemical reactions of biogenic and anthropogenic volatile organic compounds (VOCs) and carbon monoxide (CO) in the presence of nitrogen oxides (NO_x) (Lin et al. 1988). Among biogenic VOCs, terpenes and isoprene are the most abundantly emitted species from deciduous trees (Atkinson and Arey 2003). Crops also contribute to biogenic VOCs emission but their emission rate is relatively lower as compared to deciduous trees (König et al. 1995; Redeker et al. 2003). Therefore, the contribution of biogenic VOCs emitted from crops is relatively less towards O_3 formation in the troposphere.

The rise in the concentration of O_3 negatively affects the growth of crops and is most likely to threaten food production in the future (Dingenen et al. 2009; Avnery et al. 2011). The influence of O_3 on crops is a function dependent on the plant phenotype and O_3 exposure dosage. In some phenotypes, O_3 enters in plants during normal gas exchange through stomata and results in impairment of plant metabolism while in certain other phenotypes exposure to O_3 results in interference with the plant hormone levels (Iriti and Faoro 2009). In some plants, O_3 exposure causes reactive oxygen stress (ROS), visible leaf injury, abscission, and senescence (Mills et al. 2011). Field experiment studies: National Crop Loss Assessment Network (NCLAN)

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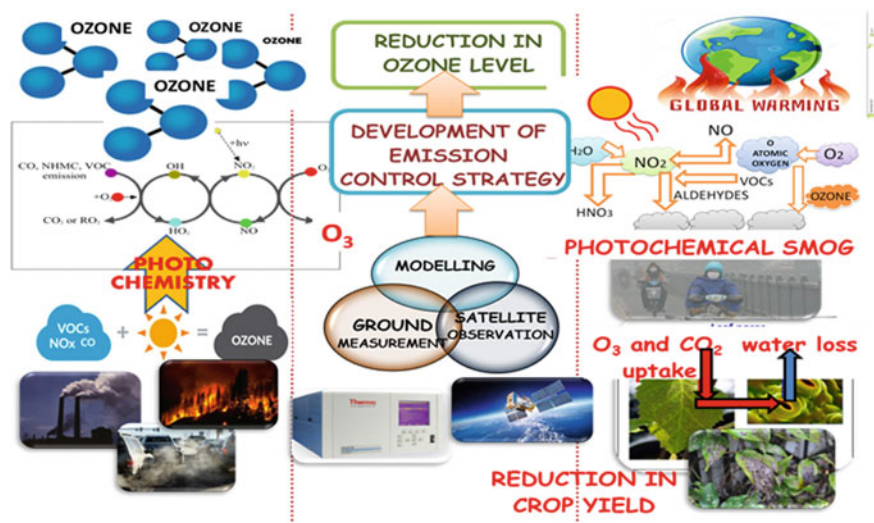e-mail: maharajkumari.k@rediffmail.com

Fig. 15.1 Ozone production, its effects, and development of control strategies

in the USA and European Open Top Chamber Programme (EOTCP) in Europe have found 5–10% reduction in crop yield by O_3 exposure and reported that crop yield losses can increase in the future (Mauzerall and Wang 2001; Emberson et al. 2003). Global studies using M7 (mean 7-h ozone mixing ratio) and AOT40 (accumulated O_3 exposure over a threshold of 40 ppb) indices have shown that relative yield loss (RYL), crop production loss (CPL), and associated economic cost loss (ECL) are second highest in India (Dingenen et al. 2009; Avnery et al. 2011). Several studies have reported the effect of O_3 on crop yield for the Indian region but most of these are based on model simulations of ozone (Dingenen et al. 2009; Avnery et al. 2011; Ghude et al. 2014) or based on limited observations of O_3 (Emberson et al. 2009; Rai et al. 2010; Debaje 2014; Sinha et al. 2015; Lal et al. 2017). Dingenen et al. (2009) have estimated annual loss of 13–28% for wheat and 6–8% for rice in India using a global chemistry transport model. Annual loss estimated by Avnery et al. (2011) for wheat ranged from 9 to 30% based on simulations of ozone using Model for OZone And Related chemical Tracers-2 (MOZART-2). Ghude et al. (2014) using a Weather Research and Forecasting model coupled with chemistry (WRF-chem), have estimated annual loss of wheat and rice by about 5% and 2.1%, respectively. Sinha et al. (2015) have calculated crop losses for two states of India (Punjab and Haryana) in the range of 11–41% for wheat and 19–26% for rice. Lal et al. (2017) have reported reduction in crop yield using ground-based measurement of surface O_3 from a network of 17 sites covering different parts of India. To monitor more precisely the impact of O_3 on crops a long term study using ground-based observation is needed.

In northern India, the two main crop-growing seasons are Rabi and Kharif. Cotton, rice, sugarcane, maize, and vegetables are mainly grown in Kharif season while Rabi season mainly includes wheat. In India, wheat is mainly grown from January to April

in Rabi season while rice is grown during July–October (Kharif season). In India, rice and wheat are the two most important staple crops, therefore the present study concerns only the crop-growing season of wheat and rice. The present study was conducted at a suburban site of Agra to determine the impact of O_3 on crop yield by determining the RYL, CPL, and associated ECL for rice and wheat during 2010–13 using M7 and AOT40 indices. In addition, a comparison of old and revised O_3 exposure relationships derived for Indian crop phenotypes was also done.

15.2 Site Description

Measurements for the present study were performed at Dayalbagh Educational Institute, Dayalbagh, Agra (27° 10′ N, 78° 05′ E) (suburban site) for the period 2010–13 (Fig. 15.2). The study site lies in the middle of Indo-Gangetic Plain (IGP) and is about 200 km southeast of Delhi. During summer (Mar–May) Agra is hot and dry while cool in the winter (Jan–Feb). 90% of the annual rainfall (650 mm) is observed during monsoon season (Jun–Sept). Strong surface winds are observed during summer and monsoon while winter is associated with a greater calm period. In winter maximum and minimum temperature ranges between 10 and 3 °C and in summer it ranges between 45 and 25 °C. Relative humidity at the site varies from 25 to 99%. There are no industrial activities in the surrounding area of the sampling site. Agricultural practices are carried out in the vicinity of the sampling site (~1 km). The seasonal crops that are mainly grown in this area are paddy, wheat, bajra, and vegetables.

Fig. 15.2 Site description map

15.3 Methodology

The O_3 levels were recorded using an online O_3 analyzer (Thermo Scientific 49i) which is based on UV absorption photometry (Beer–Lambert law). O_3 molecules absorb UV light at 253.7 nm and according to Beer–Lambert law concentration of O_3 is proportional to the absorbance. The detection limit of the analyzer is 0.5 ppb. Weekly calibration of the instrument was done by using an O_3 generator (built-in) and zero air generator (Kumari et al. 2018).

AOT40 and M7 are the two commonly used metrics for quantifying the impact of O_3 on crop yield (Aunan et al. 2000; Dingenen et al. 2009; Ghude et al. 2014). M7 index is the seasonal mean of O_3 concentration during 09:00–16:00 h and AOT40 is an O_3 exposure metric in which O_3 levels of more than 40 ppb during solar radiation hours (07:00–18:00) are considered. M7 metric gives equal importance to all measurements and quantifies the yield losses due to O_3 concentrations <40 ppb, while AOT40 gives more importance to O_3 concentration >40 ppb (Tuovinen 2000). Hence, M7 is a better metric for estimating yield loss at lower O_3 levels while at higher O_3 levels AOT40 performs better (Hollaway et al. 2012). Therefore, a comparison of both the indices will be helpful in determining better crop yield responses to O_3.

$$\text{AOT40} = \sum_{i=1}^{n}([O_3]_i - 40) \quad \text{for } [O_3] > 40 \text{ ppb during daylight hours only} \quad (15.1)$$

$$\text{M7} = \frac{1}{n}\sum_{i=1}^{n}[O_3]_i \quad \text{for } 09:00 - 16:00 \text{ LT} \quad (15.2)$$

The O_3-exposure dose-response functions for relative yield (RY) for rice and wheat crops on the basis of field studies are given in Table 15.1.

The data of crop production (CP) from 2010 to 2013 has been taken from Directorate of Economics and Statistics, Department of Agriculture and Cooperation (2014).

Table 15.1 O_3 exposure-relative yield equations for wheat and rice

Crop	O_3-exposure-relative yield relationship	Reference
Wheat	$RY = e^{-(M7/137)^{2.34}}/e^{-(25/137)^{2.34}}$	Lesser et al. (1990)
	$RY = -0.0000161 * \text{AOT40} + 0.99$	Mills et al. (2007)
Rice	$RY = e^{-(M7/202)^{2.47}}/e^{-(25/202)^{2.47}}$	Adams et al. (1989)
	$RY = -0.0000039 * \text{AOT40} + 0.94$	Mills et al. (2007)

$$RYL_i = 1 - RY_i \tag{15.3}$$

RYL_i is relative yield loss for the respective year.

$$CPL_i = (RYL_i * CP_i)/(1 - RYL_i) \tag{15.4}$$

CPL_i is crop production loss for the respective year.

$$ECL_i = CPL_i * MSP_i \tag{15.5}$$

ECL_i is economic cost loss and MSP_i is minimum selling price for the respective year.

15.4 Result

Figure 15.3 shows the monthly variation of hourly average O_3 for the period January 2010–December 2013. The highest values of O_3 were observed during summer with mean O_3 mixing ratios 48 ± 26.7 ppb. During summer season high temperature, high solar radiation, and low humidity favor the photochemical production of O_3.
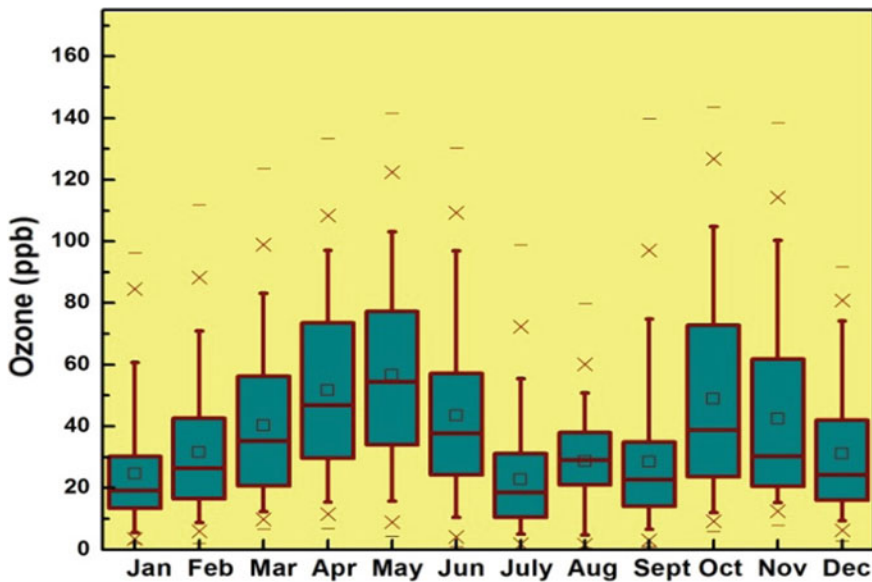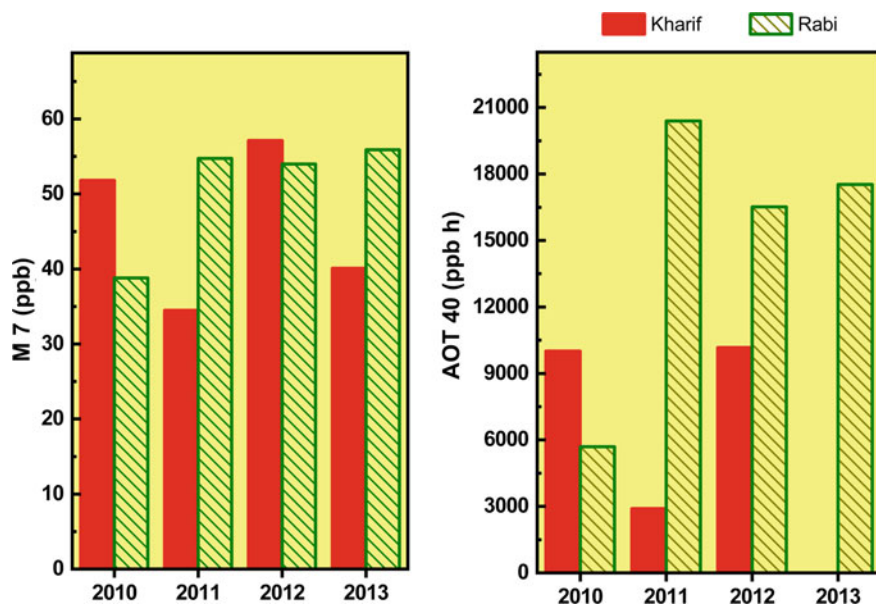

Fig. 15.3 Monthly mean values of O_3 during 2010–13

Fig. 15.4 Yearly M7 and AOT40 values for Kharif and Rabi crops

In winter O_3 levels were low (28.3 ± 19.3 ppb) due to low boundary layer and less solar radiation. The monsoon season is characterized by the lowest mean O_3 mixing ratios (19.8 ± 14 ppb).

The cumulative AOT40 and average M7 values for wheat and rice crops for Kharif and Rabi seasons have been calculated using Eqs. (15.1) and (15.2) (Fig. 15.4). M7 value in Kharif season followed the trend 2012 (57.1 ± 20.4 ppb) > 2010 (51.8 ± 22.8 ppb) > 2013 (40.1 ± 12 ppb) > 2011 (34.5 ± 19.6 ppb). However, Rabi crop showed only slight inter-annual variation in M7 values and the trend observed was 2013 (55.9 ± 25 ppb) > 2011 (54.7 ± 9.6 ppb) > 2012 (54 ± 18.1 ppb) > 2010 (38.8 ± 14.5 ppb).

AOT40 indices show maxima during Rabi season and minima during Kharif season. During Kharif season the highest AOT40 value was observed in 2012 ($10,168.3 \pm 3510.3$ ppb h) while the lowest value (2896.44 ± 1406.1 ppb h) was observed in 2011. AOT40 of Kharif season for 2013 was not calculated as data was missing for that period. For Kharif crop, the lowest AOT40 value was observed in 2011 because during July–Oct 2011 relatively higher rainfall was observed as compared to other years. However, in Rabi season the trend in AOT40 values was 2011 ($20,399.4 \pm 6087.1$ ppb h) > 2013 ($17,533.4 \pm 4821.5$ ppb h) > 2012 ($16,514.5 \pm 4420.9$ ppb h) > 2010 (5696.2 ± 1138.1 ppb h).

Independent samples *t*-test at a confidence interval of 95% was performed to ascertain the significant difference in inter-annual M7 and AOT40 values. For AOT40 value no statistically significant difference was observed between all the years in Kharif season. However, in Rabi season AOT40 values in 2010 were found to be

statistically significantly different. M7 showed a significant difference for the year 2012 with 2010, 2011, 2013, and between 2010 and 2011 in Kharif season while in Rabi season all the years showed a significant difference in M7 values except between 2010 and 2011.

On comparing the observed AOT40 and M7 values with the values reported for other sites in India (Fig. 15.5), the observed value of AOT40 (15,036 ppb h) for wheat for the study site (average of 2010–13) is comparatively lower as compared to AOT40 value (27,553 ppb h) reported for an urban site of Pune by Beig et al. (2008) for the time period 2003–06. However, a study conducted at a suburban site Mohali (Sinha et al. 2015) for 2012 has reported 17,111 ppb h AOT40 which is higher than the value reported in the present study but the M7 value (51.7 ppb) reported at Mohali and study site are comparable. At two rural sites of India, Debaje et al. (2010) and Singh et al. (2015) have reported AOT40 values for wheat. Debaje et al. (2010) have reported 3745 ppb h for Ahmednagar considering Jan–Mar (2007) as the crop-growing season and Singh et al. (2015) have reported 11,600 ppb h for Varanasi considering Dec-Mar as crop-growing season. Both the studies report comparatively lower AOT40 values as compared to the present study.

Beig et al. (2008) have reported O_3-exposure-related study for the period 2003–06 at an urban site of Pune and reported a value of 1442 ppb h for rice while the study conducted at a rural site of Varanasi (Sarkar et al. 2015) reported a comparatively higher AOT40 value (11,200 ppb h). However, for the present study site, an average AOT40 7690 ppb h was observed (average of 2010–12) which is comparatively
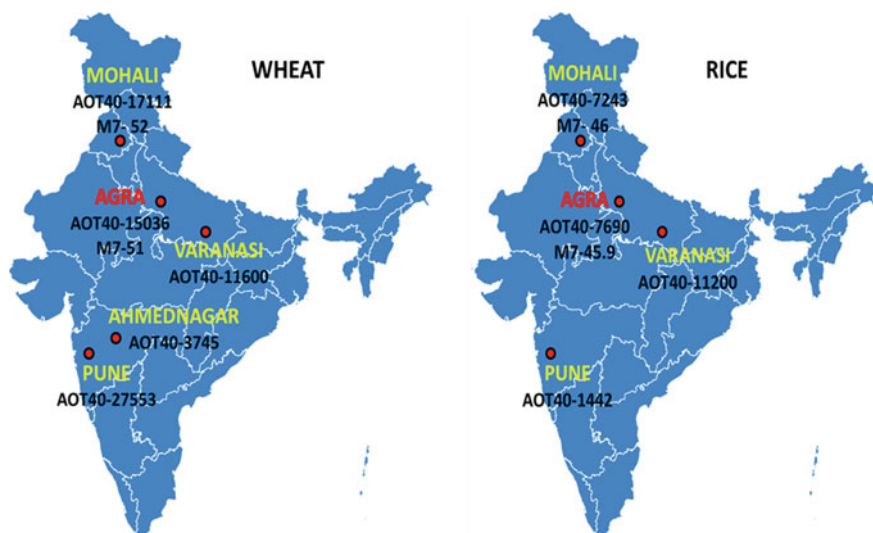

Fig. 15.5 Comparison of AOT40 (in ppb h) and M7 (in ppb) values for wheat and rice crop reported at different sites of India (Mohali (Sinha et al. 2015); Varanasi (Singh et al. (2015) for wheat), (Sarkar et al. (2015) for rice); Ahmednagar (Debaje et al. 2010); Pune (Beig et al. 2008) and Agra (present study))

lower than the values reported for Varanasi but higher than the value reported for Pune. Sinha et al. (2015) have tried to find the impact of O_3 exposure on rice using M7 indice and found value (M7-46 ppb) comparable to the present study (average 2010–13).

In the present study, AOT40 for the initial three months of agricultural crop growth period was determined (Kharif-July–Sept; Rabi-Jan–Mar) as a value of 3000 ppb h has been set as a critical value for exposure of agricultural crops to O_3 (Dingenen et al. 2009). It was found that AOT40 lies above the critical value in Rabi season in all years except 2010 while no such trend was observed in Kharif season. This observation indicates that the O_3 levels exceed the critical level during the Rabi crop-growing season.

To calculate relative yield AOT40 and M7 for the respective period have been used (Fig. 15.6). The relative yield obtained from AOT40 and M7 for wheat were highest in 2010 (0.9; 0.96) and lowest in 2011 (0.66) using AOT40 and in 2013 (0.9) using M7. For rice RY calculated from AOT40 was similar in 2010 and 2012 (0.9) and the highest value was observed in 2011 (0.93). For M7 metric also the highest value was observed in 2011 (0.99). However, the RY values obtained from M7 metric for both the crops were higher than the values obtained from the AOT40 metric.

A number of studies have reported the crop yield responses by using AOT40 and M7. Sinha et al. (2015) have used both the indices for estimating rice and wheat yield loss and found 5.2 and 4.1 times higher relative yield loss by AOT40. Similarly, Lal et al. (2017) have also reported higher RYL values derived from AOT40 metric than M7 for rice and wheat. In the present study, the RYL values obtained from AOT40 for the study period was 3.9 and 3.2 times higher than M7 values for rice and wheat, respectively.

Crop production loss (CPL) using AOT40 and M7 has been calculated using Eq. (15.4). The crop production loss for wheat during the study period 2010–2013 ranges from 0.06 to 0.27 million tons based on AOT40 metric and 0.02 to 0.05 million tons for M7 metric with the highest loss observed in the year 2011. For rice, crop production loss ranges from 993 to 1290 tons (AOT40) and 118 to 351 tons (M7).

To evaluate the economic cost loss (ECL) for wheat and rice (using Eq. 15.5) minimum selling prices (MSP) for respective years were taken from the database of Commission for Agriculture Costs and Prices (Directorate of Economics and Statistics 2014). For wheat, the ECL calculated on the basis of AOT40 was highest in 2011 (345.4 million rupees) and lowest in 2010 (64.8 million rupees) while on the basis of M7 the highest ECL was observed in 2013 (75.3 million rupees). ECL for rice was maximum in 2011 (1.4 million rupees) and minimum in 2010 (1.0 million rupees) by AOT40 while for M7 the highest value was observed in 2012 (0.44 million rupees).

Earlier studies in the US and Europe have tried to develop a crop-specific O_3-exposure-response relationship using NCLAN and EOTCP as an indicator of reduction in crop yield since the 1980s (Heck et al. 1982). Further Mills et al. (2007) derived O_3-exposure-relative yield functions using AOT40 on the basis of existing literature. But all these studies were conducted on European and US-specific crops and no specific relations have been developed for Asia specific crops. Therefore,
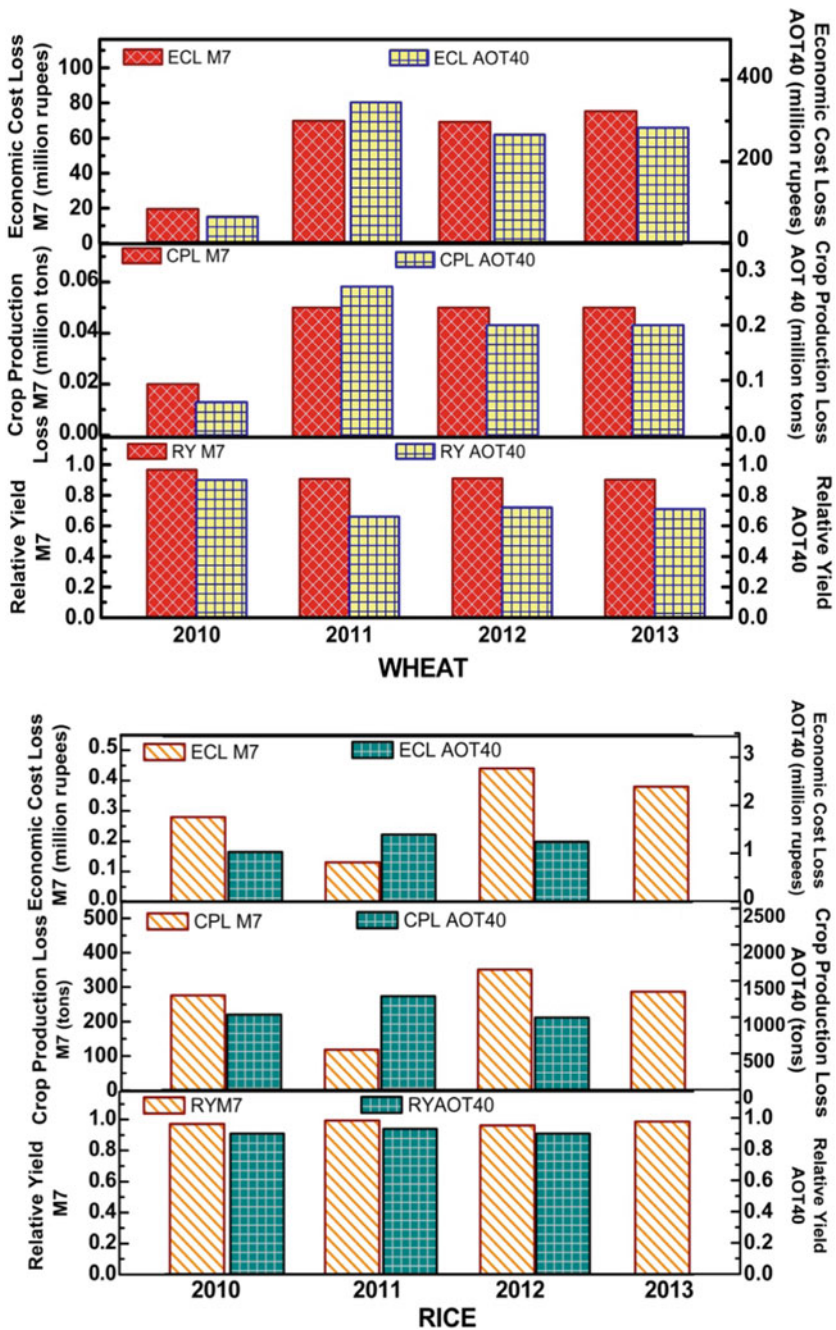
Fig. 15.6   Assessment of the impact of O$_3$ on wheat and rice crops during 2010–13

for determining the influence of O_3 exposure on Indian specific crop-exposure-yield relationships are needed.

Sinha et al. (2015) have tried to develop relative yield relationships for Indian crop species (Table 15.2). In the present study, a comparison of both the exposure-yield functions has been done to determine the variation in relative yield using old exposure-response relationships and revised relationships derived by Sinha et al. (2015) (Fig. 15.7). It was found that for wheat (AOT40) RY derived by Mills et al. (2007) overestimate the RY as compared to RY derived for Indian cultivars by Sinha et al. (2015). On comparing RY values of wheat on the basis of AOT40 a variation of 4–10% was found which is comparatively smaller than the variation found using M7 value (6–44%). The largest variation using M7 was observed in the year 2011.

Table 15.2 A comparison of old and revised O_3 exposure-related equations

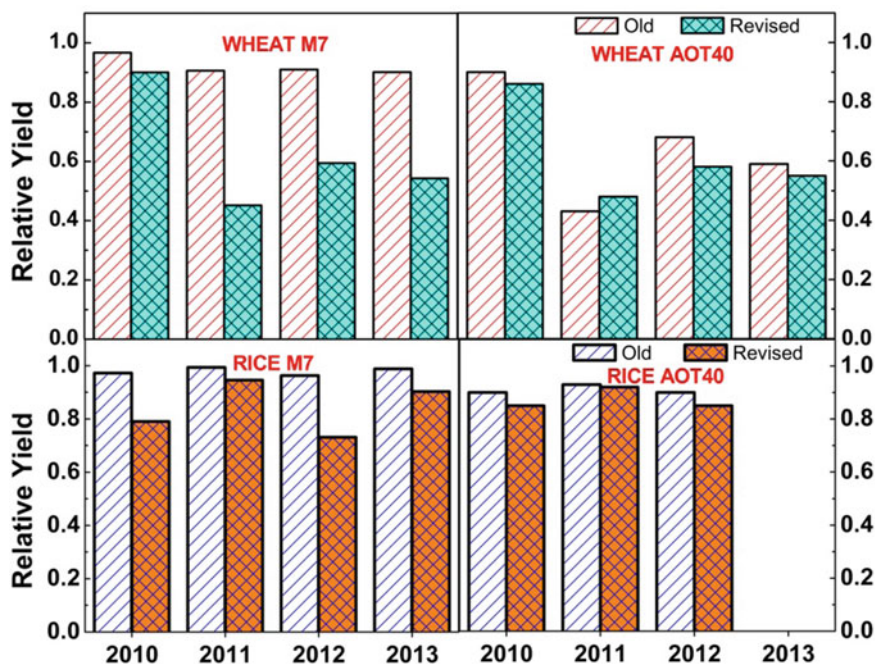| Crop	Metric	Old relation	Revised relation
Wheat	M7	$RY = e^{-(M7/137)^{2.34}}/e^{-(25/137)^{2.34}}$	$RY = e^{-(M7/62)^{4.5}}/e^{-(25/62)^{4.5}}$
	AOT40	$RY = -0.0000161 * AOT40 + 0.99$	$RY = -0.000026 * AOT40 + 1.01$
Rice	M7	$RY = e^{-(M7/202)^{2.47}}/e^{-(25/202)^{2.47}}$	$RY = e^{-(M7/86)^{2.5}}/e^{-(25/86)^{2.5}}$
	AOT40	$RY = -0.0000039 * AOT40 + 0.94$	$RY = -0.00001 * AOT40 + 0.95$

Fig. 15.7 Comparison of old and revised O_3 crop-exposure relationships

The magnitude of the overestimation of RY by earlier crop-exposure relations was comparatively less (AOT40-1–5% and M7-4–23%) for rice as compared to newly derived relations for both AOT40 and M7 metrics.

15.5 Conclusion

In this study, an estimation of O_3-induced crop yield losses for rice and wheat using two indices has been done. AOT40 indices showed maxima during Rabi season and minima during Kharif season. Similar variation has been found in M7 values but the magnitude of inter-annual variation was less as compared to AOT40 values. RYL for wheat and rice on the basis of AOT40 ranged 10–34% and 7–10%, respectively while on the basis of M7 relative yield losses ranged from 3 to 11% for wheat and 0.7 to 4% for rice. Using RYL an estimation of CPL has been done. CPL for wheat amounted to 0.02–0.05 million tons using M7 and 0.06–0.27 million tons using AOT40 was observed. CPL for rice was relatively smaller than wheat. For M7 it ranged from 118 to 351 tons and 993 to 1290 tons for AOT40. AOT40 and M7 metrics gave very different crop yield losses, as these two metrics are for US and European regions. Therefore, a comparison of US and European specific crops and Indian cultivars derived O_3 exposure relations has been done. It was found that old O_3 exposure-related relationships had over-estimated RY for both the crops in comparison to relationship derived for Indian cultivars. Studies on M7 and AOT40 metrics indicate that crop yield is potentially at a risk from rising O_3 levels. These studies can be helpful in better integration of the policies and abatement measures aimed at reducing air pollution. In addition, development of crop management practices for reducing the impact of O_3 like appropriate cultivar selection, withholding irrigation during the highest ozone episodes can be helpful for farmers to protect their crops from O_3.

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