Impact of emission mitigation on ozone-induced wheat and rice damage in India

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In this study, we evaluate the potential impact of ground level ozone (O_3) on rice and wheat yield in top 10 states in India during 2005. This study is based on simulated hourly O_3 concentration from the Weather Research and Forecasting model coupled with Chemistry (WRF-Chem), district-wise seasonal crop production datasets and accumulated daytime hourly O_3 concentration over a threshold of 40 ppbv (AOT40) indices to estimate crop yield damage resulting from ambient O_3 exposure. The response of nitrogen oxides (NO_x) and volatile organic compounds (VOC) mitigation action is evaluated based on ground level O_3 simulations with individual reduction in anthropogenic NO_x and VOC emissions over the Indian domain. The total loss of wheat and rice from top 10 producing states in India is estimated to be 2.2 million tonnes (3.3%) and 2.05 million tonnes (2.5%) respectively. Sensitivity model study reveals relatively 93% decrease in O_3-induced crop yield losses in response to anthropogenic NO_x emission mitigation. The response of VOC mitigation action results in relatively small changes of about 24% decrease in O_3-induced crop yield losses, suggesting NO_x as a key pollutant for mitigation. VOC also contribute to crop yield reduction but their effects are a distant second compared to NO_x effects.

Keywords: AOT40, chemical transport model, crop damage, ozone, yield loss.

GROUND level ozone (O_3) is mostly produced by a chain reaction involving photochemical oxidation of volatile organic compounds (VOC) in the presence of nitrogen oxides (NO_x) in the lower troposphere[1]. A substantial body of evidence exists describing the potential for ground level O_3 to damage human health, crops and ecosystem[2]. Field experiments have demonstrated that elevated ground level O_3 when exposed for longer duration can impact crops directly causing phytotoxic responses to yield or biomass[3–7]. Furthermore, because O_3 is a secondary pollutant with regional distribution[8,9], crop yield losses occur over many important agricultural regions world wide[10].

Impacts of ground level O_3 on major crop yield losses have been indicated to threaten food security leading to economic loss[11–14]. Current O_3 exposure impact assessment study[15] evaluated the global losses of major agricultural commodities of 79–121 million metric tonnes costing of 11–18 billions USD, and projected economic damage of about 12–35 billions USD by 2030. Recent observational[16,17] and model[14,18–20] based impact assessment studies on local to regional scale have assessed the magnitude of crop losses and indicated that a substantial economic benefit may be expected from a reduction in air pollution[18–20]. A recent study by the World Meteorological Organization/United Nations Environment Programme (WMO/UNEP) identified Asian region to be vulnerable to O_3 pollution and therefore could benefit from improved human health and increased crop production of staple crops from the effort of mitigating shortlived climate pollutant such as NO_x and VOC.

Few recent local to regional scale studies in India indicated the prevalence of elevated ground level O_3 concentration over important agriculture regions[21] including one of the most fertile agricultural lands of the Indo-Gangetic Plain. Due to rapid urbanization, industrialization and expanding economy[22], ground level O_3 (ref. 23) as well as tropospheric column ozone is increasing over India[24,25], and projected to increase in future[26]. This may increase the vulnerability of major agricultural crops in India. A recent study[14] quantified the potential impact of ground level O_3 on major crops (wheat, rice, cotton and soybean) in India and showed a nationally aggregated yield loss of 6.1 million tonnes (equivalent to 1.3 billion USD), which is sufficient to feed about 35% of population living below poverty line in India. All these and earlier studies were aimed at providing estimates of O_3-induced crop damage and relatively little attention has been paid to the important role of mitigating air quality to improve agricultural productivity. These benefits are likely to be important in India which is particularly vulnerable to short-lived climate pollutants. As such, it is imperative that our knowledge on O_3 impacts on agriculture across India needs to be improved by identifying the critical mitigation action.

One of the major requirements of air quality management for a particular region is to understand the relative

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role of precursor's emission, particularly, dominant pollutants such as NO_x and VOC. The aim of this paper is to explore the relative role of precursor species for targeting the critical mitigation action towards improving food security. In an earlier work[14], we estimated O_3-induced fractional loss of wheat and rice for the entire country as well as for the top 10 wheat and rice producing states in India. The objective of this work is to expand our earlier work by exploring the response of anthropogenic NO_x and VOC mitigation action on O_3-induced crop damage for the top 10 wheat and rice producing states in India. The model runs were obtained in the frame of the current emission scenario in India[14,27]. Our estimate can help policymakers to examine future mitigation strategies for crop protection.

Methodology

In this study, we used regional WRF-Chem (Version 3.2.2). We evaluated the risk of crop damage due to O_3 for two major crops in India (wheat and rice) based on the accumulated daytime hourly ozone concentration above a threshold of 40 ppbv (AOT40) during crop growing season for which exposure-response functions are available. We considered the top 10 wheat and rice producing states in India for which the response of anthropogenic NO_x and VOC mitigation action was examined. The estimates of district-wise annual crop production for wheat and rice were obtained from the Special Data Dissemination Standard–Directorate of Economics and Statistics (SDDS-DES), Ministry of Agriculture (Government of India).

We simulated hourly ground level O_3 concentration over India at a horizontal resolution of 0.5° × 0.5° and a vertical resolution of surface to 50 hPa for the year 2005. Meteorological initial and boundary conditions were based on the National Centers for Environmental Prediction Final (NCEP/FNL) meteorological reanalysis fields. The varying chemical boundary conditions were based on Model for Ozone and related Chemical Tracers (MOZART-4)[28]. The model gas–phase–chemical mechanism was from MOZAR-4 coupled to the Goddard Chemistry Aerosol Radiation and Transport (GOCART) aerosol scheme. Anthropogenic emissions of carbon monoxide (CO), sulphur dioxide (SO_2), non-methane volatile organic compounds (NMVOCs), NO_x, particulate matter (PM10, PM2.5), and black carbon (BC)/organic carbon (OC) were taken from the Intercontinental Chemical Transport Experiment-Phase B (INTEX-B) inventory[29]. The fire emissions from the Fire Inventory from NCAR (FINNv1)[30] and biogenic emissions of trace species were calculated online using the model of emissions of gases and aerosols from nature (MEGAN)[14,31,32].

This district-wise crop data was converted to grid format using geographic information system (GIS)-based statistical methodology to match the 0.5° × 0.5° resolution of WRF-Chem. AOT40 exposure metrics (eq. (1)) over 90 days of crop growing period and its concentration response (CR) relationships (eqs (2) and (3))[6,14,33] were used to calculate the yield reduction of wheat and rice at different O_3 exposure levels. We adopted the AOT40 based CR function given in Van Dingenen[34] for wheat (eq. (2)) and rice (eq. (3)) which were scaled such that the relative yield is equal to 1 at zero exposure. We considered 90 days from 15 June to 15 September as a *kharif* growing season for rice, and December to February as *rabi* growing season for wheat. As rice is also cultivated during *rabi* season in many parts of India, we considered exposure during *rabi* seasons depending upon seasonal rice production fields and fraction of total rice production during both the seasons.

$$\text{AOT40 (ppmh)} = \sum_{i=1}^{n} ([\text{O}_3]_i - 0.04) \quad \text{for } \text{O}_3 \geq 0.04 \text{ ppmv}, \tag{1}$$

$$\text{For wheat RY} = -0.0161 \times \text{AOT40} + 0.99. \tag{2}$$

$$\text{For rice RY} = -0.0039 \times \text{AOT40} + 0.94. \tag{3}$$

$$\text{CPL} = \frac{\text{RYL}}{(1-\text{RYL})} \times \text{CP}. \tag{4}$$

Using modelled hourly ground level daylight (i.e. >50 W/m^2 global radiation) O_3 concentrations, we calculated crop production loss (CPL) for each grid cell for wheat and rice using eqs (1)–(4). CP is the actual annual crop production for 2005 and relative yield loss (RYL) = 1 – relative yield (RY). The state-wise crop production loss is estimated by summing all grid cells within the top 10 rice and wheat producing states in India.

In order to assess the response of anthropogenic NO_x and VOC mitigation action on O_3 induced crop damage in India, we did two additional simulations for surface O_3; one with no anthropogenic NO_x emissions and the other with no anthropogenic VOC emissions (reduction scenario). However, we allowed natural emissions such as biogenic emissions of NO_x and VOC and emissions from the biomass burning. We then assessed the yield reductions for both cases and compared them with initial simulations (baseline scenario).

Results

Wheat and rice crops in India and distribution of surface O_3

Figure 1 *a* and *b* shows the geological distribution of wheat and rice production among the Indian states. This

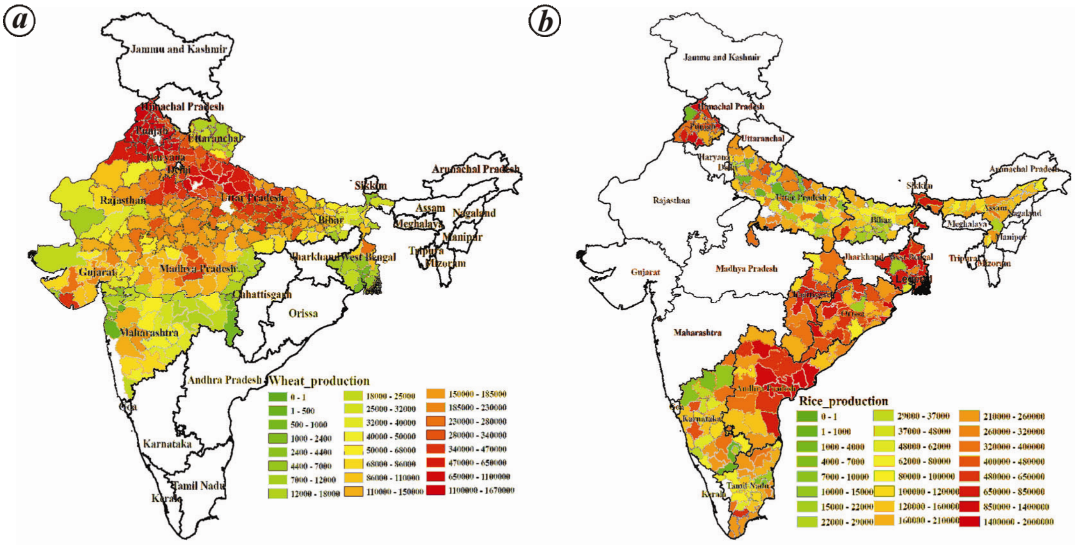

Figure 1. District-wise production output (in tonnes) for (***a***) top 10 wheat producing states and (***b***) top 10 rice producing states in India in 2005.

difference in wheat and rice productivity within India is largely a function of micro-climates, soil quality and local resources. Rice is a dominant crop of the country. The dominant regions of rice cultivation can be distinguished as coastal Indian states along the eastern Assam and states along the foothills of Himalayas (Punjab, Haryana, Uttar Pradesh, West Bengal and Bihar). Wheat, the second most important crop after rice, is generally cultivated during *rabi* season in the central and northern part of India along the foothills of Himalayas.

Figure 2 shows the annual averaged daytime ground level O_3 levels over India. It can be seen that the location of higher O_3 concentration varies strongly between different geographical regions. Surface O_3 concentration is generally higher (40–50 ppb) over most of the important agricultural regions such as northern states of India along the foothills of Himalaya (Indo-Gangetic (IG) region), western Maharashtra, and eastern India where emission intensity of precursor gases is very high[27,32,35]. It can be seen that elevated O_3 concentration leads to increased exposure on rice cultivation in the states of Uttar Pradesh, Bihar and the coastal strips of eastern India and southern India, except Tamil Nadu where O_3 levels less than 30 ppb are seen.

Figure 3 *a* and *b* compares between the model calculated monthly AOT40 with the observed AOT40 from two measurements sites: Delhi[23] and Pune[21]. It also shows the comparison between model calculated diurnal variations of O_3 with the observations from the same two sites. The modelled values are interpolated to the location where the observations are taken. Although Delhi and Pune are not important agricultural sites for comparison, in the absence of any O_3 measurements from the rural agricultural site in India, this comparison provides an opportunity to validate the modelled data with observations.

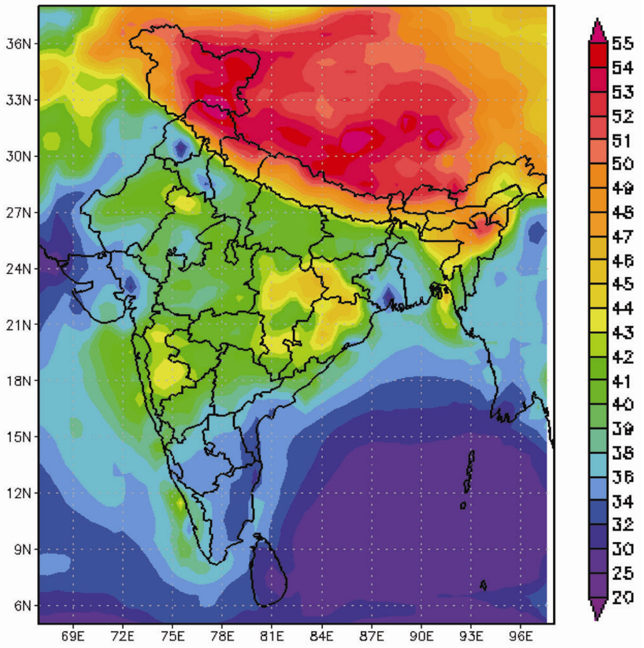

Figure 2. Figure annual averaged daytime surface ozone concentration (in ppbv) for 2005.

It can be seen that in general, the model produces reasonably good monthly variability in the AOT40 values at both sites. Agreement between modelled and observed AOT40 is in general satisfactory for Delhi compared to Pune where the model tends to overestimate monthly AOT40 during December–March period. We find excellent agreement between the model and observations of diurnal variation in ground level O_3 for Delhi. However, for Pune, model underestimated O_3 in the afternoon and overestimated O_3 during night and morning hours.

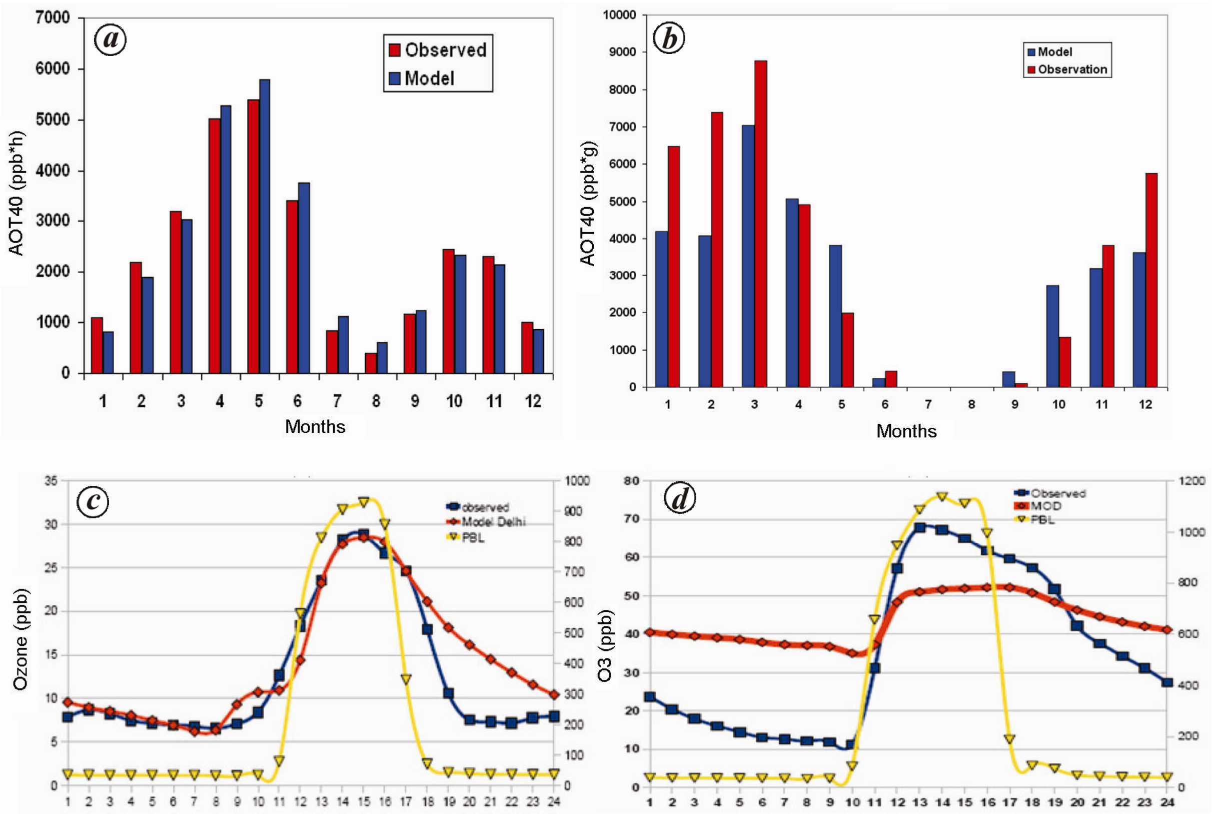

Figure 3. Comparison between modelled and simulated monthly AOT40 for (***a***) Delhi (average for 2001–2004) and (***b***) Pune (average for 2003–2006). Comparison between modelled and simulated mean diurnal variation of ground level ozone for (***c***) Delhi and (***d***) Pune. Yellow line in figure shows the mean diurnal variation of planetary boundary layer (PBL) height.

Reason for this is not clear and needs to be studied further. Uncertainties in emissions of O_3 precursors at this location may be one reason.

Crop production losses and response of NO_x and VOCs mitigation action

Figure 4 *a* and *b* shows the total (by weight in tonnes) and fractional (in %) O_3-induced crop losses (baseline scenario) for top 10 dominant wheat and rice producing states in India respectively. The number along the states in Figure 4 represents the order by their production amount. Almost all fractions of total annual wheat production come from the cultivation of these crops during *rabi* season, whereas for rice cultivation, it is through *kharif* and *rabi* (10% of total production) season. In 2005, the aggregated wheat and rice production from top 10 states in India amounts to 65.5 and 82 million tonnes respectively. The total loss of wheat and rice from these states is estimated to be 2.2 million tonnes (3.3%) and 2.05 million tonnes (2.5%) respectively. The crop production loss for rice is highest in Punjab – 0.85 million tonnes (more than 41% of total) followed by Andhra Pradesh – 0.33 million tonnes (16% of total) Uttar Pradesh – 0.25 million tonnes (12% of total), West Bengal – 0.23 million tonnes (11% of total) and Orissa – 0.16 million tonnes (8% of total). This suggests that these states are more vulnerable to crop production loss due to exposure to relatively high O_3 concentrations. It can be seen in Figure 4 that the overall pattern for yield loss due to ground level O_3 is similar in terms of loss by weight and fraction for top ten rice producing states.

The highest crop production loss for wheat, of the order of 0.61 million tonnes (28% of total), is estimated in Uttar Pradesh where wheat production is also highest during the study period. It can be seen in Figure 4 that wheat loss is more in Madhya Pradesh (0.49 million tonnes, 22% of total), Rajasthan (0.23 million tonnes, 11% of total) and Maharashtra (0.22 million tonnes, 8% of total) although Punjab and Haryana are second and third most wheat producing states in India. It is interesting to note that although Uttar Pradesh, Punjab and Haryana are the largest wheat producing states in India fractional yield loss of wheat appears to be significantly less (<1%) compared to other low wheat producing states In India. For example, O_3-induced fractional loss of wheat in Maharashtra (which is eighth largest wheat producing state) is greatest (~17%) followed by Madhya Pradesh (~8%), Gujarat (~8%), West Bengal (~6%) and

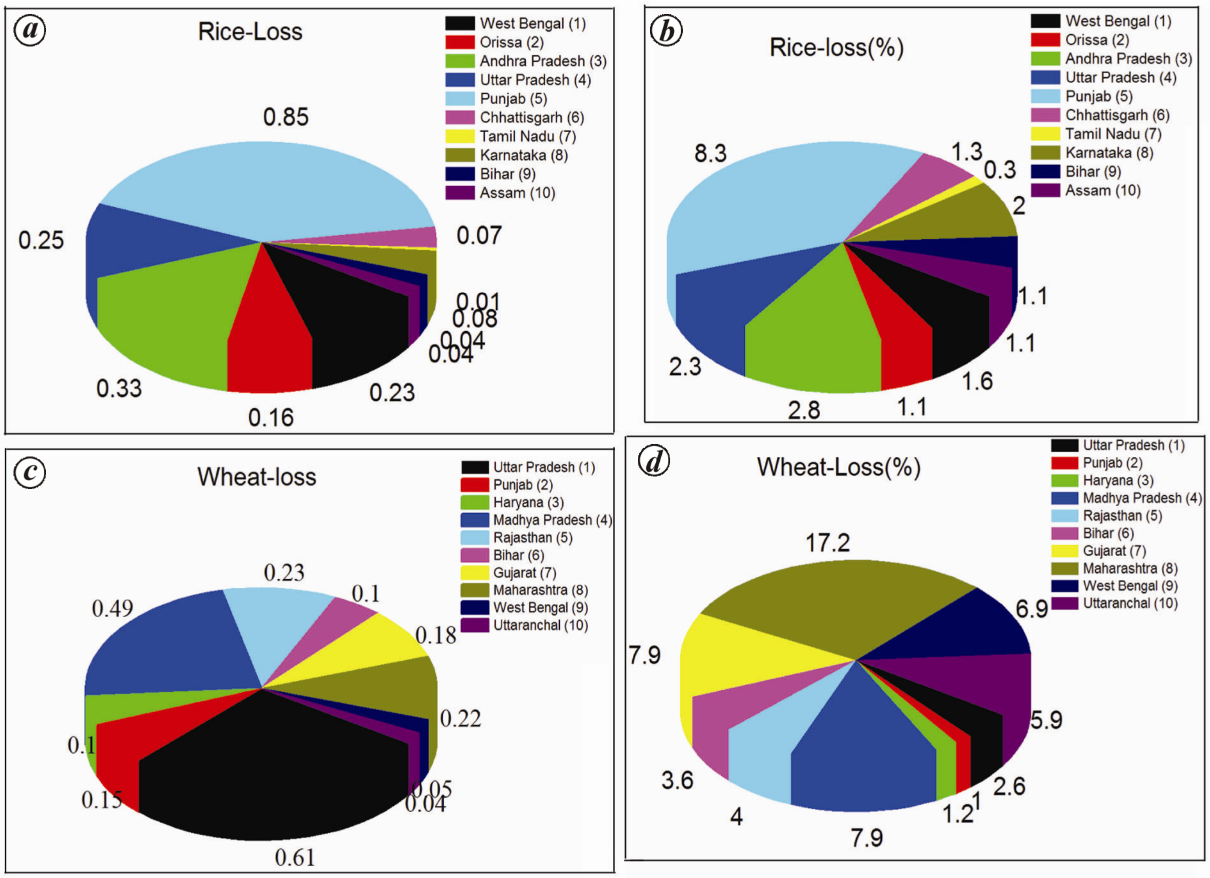

Figure 4. Estimated crop production losses (by weight) for (***a***) rice and (***b***) wheat for 10 highest ranked states in India during the year 2005. Number (along the states) 1 is the highest producing state for wheat and rice while number 10 is the lowest producing state. Right panel of each figure shows fractional loss.

Uttaranchal (~5%). This suggests that these states are more vulnerable to wheat production losses due to ozone exposure, relative to top 3 wheat producing states in India.

In order to evaluate the impact of emissions mitigation of O_3 precursors (NO_x and VOC) on O_3-induced crop yield loss we performed two simulations; one with no-anthropogenic NO_x emissions and other with no-anthropogenic VOC emissions from India. These simulations were performed to mitigate the surface O_3 over the entire Indian domain including rice and wheat fields. Figure 5 *a* shows the aggregated O_3-induced yield losses for wheat and rice for baseline (purple), NO_x (red) and VOC (yellow) emission reduction scenario. This is also shown for top 10 wheat and rice producing states in India in Figures 5 *b* and *c* respectively. The overall reduction in crop yield for two crops in baseline simulations amounts to 4.3 million tonnes (2.2 million tonnes for wheat, 2.1 million tonnes for rice) in 2005. It can be seen in Figure 5 that simulations with no-anthropogenic NO_x emissions result in small losses of 0.24 million tonnes for wheat and 0.05 for rice and aggregated losses (combined rice and wheat) of about 0.3 million tonnes. The impact of simulations with no-anthropogenic NO_x emissions results in relatively 93% (97% for rice and 89% for wheat) decrease in O_3-induced crop yield losses compared to the baseline scenario. On the other hand, the impact of reductions in anthropogenic VOC emissions results in crop losses of about 3.2 million tonnes (1.62 million tonnes for wheat, 1.6 million tonnes for rice). The response of VOC mitigation action results in relatively small changes of about 24% (22% for rice and 26% for wheat) decrease in O_3-induced crop yield losses with respect to baseline scenario. Overall, the emission reduction scenario primarily reflects that O_3 production in India and subsequent crop yield loss is largely NO_x-sensitive (small sensitivity to VOC). The mitigation response of anthropogenic NO_x emissions exhibits significant decrease in O_3-induced crop yield losses for most of the top 10 wheat and rice producing states in India (Figure 5 *b* and *c*). This further demonstrates that NO_x emission control could effectively mitigate O_3-induced production losses and significantly benefit crop production output. The dominant sectors contributing to NO_x emissions are: transportation (32%); power (including diesel generators) (36%); and industry (14%). NO_x emission controls, if implemented nationwide, could effectively mitigate O_3-induced crop-yield losses and significantly improve the food security of India.

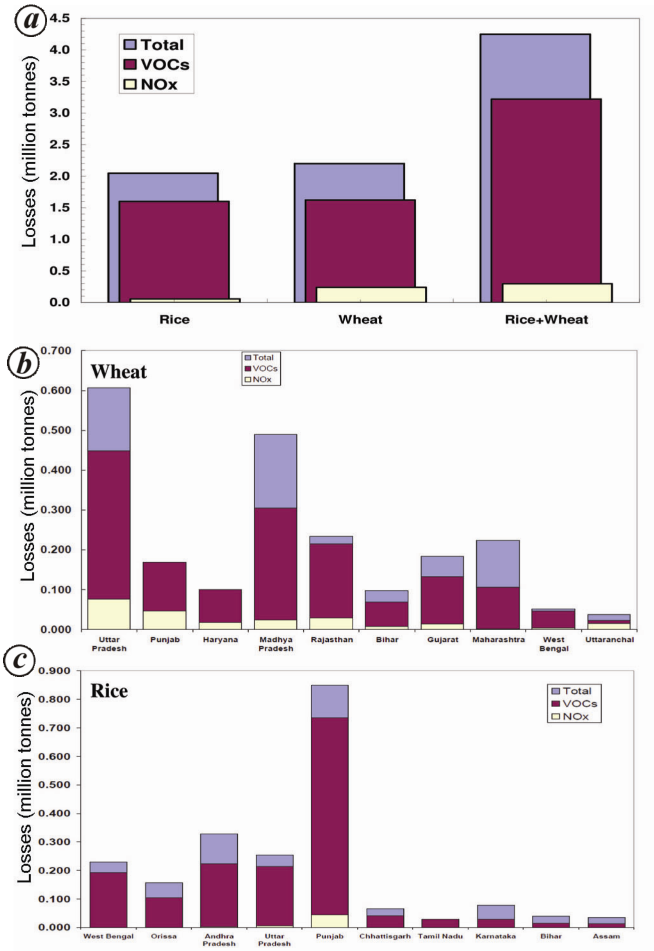

Figure 5. Change is crop production loss (million tonnes) for wheat, rice and combined for baseline scenario (total), simulations without anthropogenic NO_x emissions (NO_x) and simulations without anthropogenic VOC emissions (VOCs) during 2005. Change in crop production loss is shown for (***a***) total from top 10 wheat and rice producing states, (***b***) top 10 wheat producing states and (***b***) top wheat producing states in India.

Summary and conclusion

We have used the most suitable spatial crop distribution and production data available for India and the latest emission inventories. Using a regional chemistry transport model and AOT40 exposure indices (CR relationship), we have estimated the risk of crop damage caused by ground level O_3 pollution for top 10 wheat and rice producing states in India under the present-day emission scenario. Three model runs were analysed, baseline simulations with present anthropogenic NO_x and VOC emission, without anthropogenic NO_x and VOC emissions. Later two simulations were compared to assess the response of NO_x and VOC mitigation action on O_3 induced wheat and rice damage in India. Our assessment indicates significant production losses for wheat of about 2.2 million tonnes (3.3%) and for rice about 2.05 million tonnes (2.5%) due to O_3 exposure. Rice producing states that are vulnerable to relatively high O_3 exposure are Punjab (0.85 million tonnes), Andhra Pradesh (0.33 million tonnes), Uttar Pradesh (0.25 million tonnes) and West Bengal (0.23 million tonnes). Similarly, other wheat producing states vulnerable to high O_3 exposure are Uttar Pradesh (0.61 million tonnes), Madhya Pradesh (0.49 million tonnes), Rajasthan (0.23 million tonnes) and Maharashtra (0.22 million tonnes). Impact of anthropogenic NO_x mitigation action shows relatively 93% (98% for rice and 90% for wheat) decrease in O_3-induced crop yield losses compared to baseline scenario. On the other hand, impact of anthropogenic VOC emissions mitigation action results in small changes of about 24% (97% for rice and 89% for wheat) decrease in O_3-induced crop yield losses with respect to baseline scenario. This result provides first-hand and important information to policymakers to propose or implement emission control of O_3-precursors to ensure improved national food security.

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