# Effect of elevated ozone and carbon dioxide interaction on growth and yield of maize

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## Abstract

The effect of elevated tropospheric ozone and carbon dioxide interaction were evaluated on the growth and productivity of high quality protein maize (HQPM-1) at the research farm of the Indian Agricultural Research Institute, New Delhi. Maize plants were exposed from emergence to maturity for two years to different ozone levels in non filter air (NF), charcoal filter air (CF), non-filter air with elevated $CO_2$ (NF+$CO_2$), elevated ozone (EO and EO1), elevated ozone with elevated $CO_2$ (EO+$CO_2$) and ambient control (AC) in open top chambers. Elevated ozone significantly decreased growth attributes of leaf and shoot biomass and leaf area index and the yield attributes. Highest values of all the growth and yield attributes were observed in CF treatment. The photosynthetic rate decreased by 24 to 37% and from 41 to 56% under EO (ambient + 25-35 ppb $O_3$) over NF at tasseling and silking stage respectively. The yield increased by 21 to 31% in the sub ambient ozone levels in the CF treatment over non-filtered control whereas it decreased by 13 and 20 % under EO in both the years respectively. The presence of higher levels of ozone EO1 (ambient + 45-50 ppb $O_3$) however made the plant weak and more susceptible to pest attack, resulting in a complete loss in yield. The presence of elevated carbon dioxide along with elevated ozone in the EO+$CO_2$ treatment increased the yield by 9 to 10% over EO alone. Elevated $CO_2$ was able to counter the negative effect of O3 on growth and yield parameters of maize to a certain extent.

**Keywords**: tropospheric ozone, carbon dioxide, maize, growth and yield

## Introduction

Two aspects of global climate change that directly impact plant productivity are increasing atmospheric $CO_2$ and tropospheric $O_3$ concentration (Ainsworth et al, 2008). Atmospheric concentrations of $CO_2$ have been steadily rising and is projected to continue rising to at least 550 ppb by 2050 (Keeling et al, 2009).The production of elevated levels of surface $O_3$ levels is also of particular concern because it is known to have adverse effects on human health, vegetation, and a variety of materials (EEA, 2010b). Background $O_3$ is predicted to continue increasing by 0.5-2% per year over the next century, mainly due to increases in precursor emissions from anthropogenic sources (Solomon et al, 2007). The IPCC Fourth Assessment Report projects an increase in tropospheric $O_3$ across the globe of 20-25% by 2050 (Jaggard et al, 2010).There is a high interest in quantifying surface $O_3$ concentrations and associated trends, due to its significant impact on crop growth and vegetation. The concern for ozone is more as higher ozone levels are not limited to urban areas and its precursors can be transported hundreds of miles into rural areas where agricultural activities occur (Bhatia et al, 2012).

The responses of C3 plants to rising atmospheric $CO_2$ levels are considered to be largely dependent on effects exerted through altered photosynthesis. In contrast, the nature of the responses of C4 plants to high $CO_2$ remains controversial because of the absence of $CO_2$-dependent effects on photosynthesis. Unlike C3 crops for which there is a direct enhancement of photosynthesis by elevated $CO_2$, C4 crops will only benefit from elevated $CO_2$ in times and places of drought stress (Leakey, 2009). The sensitivity of photosynthesis to other environmental variables including high surface ozone levels has not been well documented in assessing plant responses to the new changing environment in case of C4 plants.

Carbon dioxide and $O_3$ have strong impacts on growth and productivity of crop plants. $CO_2$ typically stimulates plant productivity (Ainsworth and Long, 2005), whereas $O_3$ is phytotoxic to a range of plant species (Wittig et al, 2009). $O_3$ effects on plants are initiated in leaves when the gas enters through the stomata and disrupts cellular processes, resulting in suppression of growth and yield of many crops. As the $CO_2$ content of the air rises, C3 and C4 crops may exhibit increases in photosynthesis and biomass production, while increasing the efficiency at which they use water to produce that biomass (Leakey et al, 2009). In comparison with the beneficial effects of elevated $CO_2$, rising $O_3$ may have negative impacts like suppressed photosynthesis, accelerated senescence, decreased growth and lower yields (Booker et

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al, 2009). $CO_2$ can also have interactive effects with O3 on anti-oxidant production (Erice et al, 2007).

Together with rice and wheat, maize provides at least 30% of the food calories to more than 4.5 billion people in 94 developing countries (Von Braun et al, 2010). In India, maize is the third most important cereal crop after rice and wheat having an area of 8.5 million hectare and a production of 21.28 million tons in 2010-11 (USDA, Maize Report, 2011-12). Although there has been a lot of research on the interactive effects of elevated $CO_2$ and $O_3$ on C3 crops like rice and wheat, there are few reports on how C4 crops like maize will respond to elevated $CO_2$ and $O_3$ interactions in the future. In view of maize being an important cereal crop the present investigation was conducted to quantify the impact of elevated $O_3$ and elevated $CO_2$ interaction on growth and productivity of maize.

## Materials and Methods

### *Location, climate and soil characteristics*

The experiment was conducted during 2008 and 2009 kharif season using open-top chambers (3 meter diameter and 2.5 meter height) in the farm of Indian Agricultural Research Institute (IARI), New Delhi, which is situated at 28°40'N and 77°12'E, at an altitude of 228 m amsl. The climate of the region is subtropical, semi-arid. Average rainfall is 75 cm annually and mean maximum and minimum temperatures from June to November are 38°C and 19°C. The alluvial soil of experimental site had a pH 8.61, EC 0.158 $dSm^{-1}$ and was sandy loam in texture having 0.32% organic carbon and bulk density of 1.42 g $cm^{-3}$. The $NH_4$-N and $NO_3$-N were observed to be 12.54 and 25.09 kg $ha^{-1}$, respectively.

### *Treatments and crop management*

Experiment was carried out growing HQPM-1 maize variety, with seven treatments arranged in a randomized block design with three replications in open top chambers (OTCs). The treatments were non filtered air (NF: 5-10% less than ambient $O_3$), charcoal filtered air (CF: 80-85% less than ambient $O_3$), elevated ozone [(EO: NF + 25-35 ppb $O_3$), (EO1: NF + 45-50 ppb $O_3$)], elevated ozone with elevated carbon dioxide (EO+$CO_2$: NF + 25-35 ppb $O_3$ + 500±50 ppm $CO_2$), non-filtered air with elevated carbon dioxide (NF+$CO_2$: NF + 500±50 ppm $CO_2$) and ambient open plot control (AC). HQPM-1 is high quality protein maize, a hybrid of maize, well identified for cultivation across the country having quality protein and shows resistance to major diseases like Maydis leaf blight (MLB) and Turcicum leaf blight (TLB). Sowing of HQPM-1 at 60 × 20 cm spacing, in each OTC chamber was done on June 21, 2008 and June 25, 2009. Maize was grown as per recommended management practices. Maize was harvested at maturity on November 6, 2008 and November 13, 2009. The OTCs were fitted with an inert PVC pipe of 10 cm diameter (adjustable height) with many small holes which released either charcoal filtered air (CF), non-filtered air (NF) or elevated ozone along with non-filtered air (EO) at the crop canopy level. Air was blown into the OTCs through a fan that provided uniform air speeds. The ventilation rates were kept at 3 air changes per minute to keep the leaf boundary layer resistances down and the chamber temperature was 0.5 to 1.0°C higher than ambient. In the EO treatment 25 to 35 ppb of additional ozone was maintained over the non-filtered air levels. $O_3$ was applied for 7 hours $d^{-1}$ (09.30-16.30 h) in the elevated $O_3$ chambers.

### *Ozone generation and measurement*

Additional $O_3$ was generated from oxygen with the help of reaction with UV radiation < 200 nm using ozone generators (Systocom, Varanasi, India). Air was sampled from the middle of each OTC at the crop canopy level and fed to an $O_3$ analyzer (Model APOA-370, Horiba, Germany) for measuring the ozone concentrations daily from 9.30 to 16.30 h. The light intensity inside and outside the OTCs was measured using a portable light meter (Metravi 1332), temperature and relative humidity were measured with a portable temperature-humidity probe. Charcoal filters adsorbed ozone from ambient air blown inside the OTCs and lowered the ozone concentrations by 80-85% of the ambient air. The non-filtered (NF) treatment was the control treatment and a 5% decrease in concentration than the ambient ozone levels was observed in this treatment. The seasonal ozone concentrations during the experiment period i.e. in the month of June to November 2008 and 2009 are shown in Figure 1. The peak average concentrations were observed during September and October months.

### *Carbon dioxide generation and Monitoring*

The enhanced $CO_2$ concentrations were maintained inside the OTCs using high pressurized cylinders containing $CO_2$ with the help of dual stage regulators and gas flow meter. $CO_2$ was supplied from the cylinders to the OTCs through 6 mm polyurethane tubing and mixed with the ambient air at the outlet of the air blowers and subsequently distributed evenly inside the OTCs. $CO_2$ levels inside the chambers

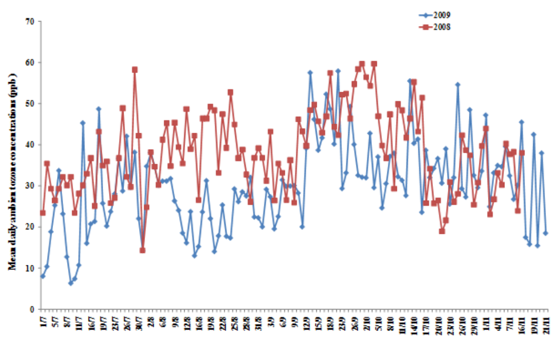


Figure 1 - Mean daily ambient ozone concentrations in ppb during crop growth period in 2008 and 2009.

were monitored using a $CO_2$ gas monitor, Industrial Scientific, USA (CDU-440).

***Measurement of photosynthetic rate and stomatal conductance***

Single-leaf net photosynthetic rates and stomatal conductance were measured with portable photosynthesis systems (LI-6400-40 Portable Photosynthesis System) at tasseling (33 and 32 DAS) and silking growth stages (66 and 55 DAS) during crop growth period in the first and second year respectively. The measurements were made on the third fully expanded mature leaf from the top of each plant on cloud free days between 10.00 and 11.00 AM local time on three randomly selected plants in each chamber.

***Plant sampling and analysis***

Plant samples were collected at tasseling, silking and milking growth stages on 33, 66, and 98 DAS in the first year and on 32, 55, and 81 DAS in second year of study respectively. Root, shoot and leaf dry weight and length parameters and leaf area index were recorded at different growth stages. Yield related parameters such as number of cobs, thickness of cobs, number of rows per cobs, number of grain per row, cob length, number of grain per cob, 100 grain weight and grain yield were recorded after the final harvest.

## Results and Discussion

***Ozone levels in ambient air***

The daily average ozone concentrations measured during the experiment period i.e. from the month of October to March are shown in Figure 1. Elevated O3 exposure began in July when the maize was in the three-leaf stage and ended in October when it was ripe. The daily average $O_3$ concentration during the entire crop growth period in ambient air was 38 ppb in 2008 and 31 ppb in 2009. Higher concentration of ambient $O_3$ was observed during September to October in 2008.

***Impact of different treatments on photosynthetic rate and stomatal conductance***

The highest photosynthetic rate was observed in CF treatment and the lowest in EO1 treatment in both the years (Figure 2). The photosynthetic rate decreased by 24 to 37% and from 41 to 56% under EO (ambient + 25-35 ppb $O_3$) over NF at tasseling and silking stage respectively. The decrease in stomatal conductance under the elevated ozone treatments led to a decline in the photosynthetic activity. More decrease in the photosynthetic activity was observed at tasseling stage in EO1 treatment. The stomatal conductance ranged from 0.12 gs to 0.28 gs at tasseling stage and from 0.03 gs to 0.53 gs at silking stage in first year (Figure 3). The stomatal conductance ranged from 0.12 gs to 0.26 gs at tasseling stage and from 0.02 gs to 0.60 gs at silking stage in second year. There was a decline in stomatal conductance in both the elevated $CO_2$ treatments. Under elevated $CO_2$ no significant increase in photosynthetic activity was observed in our study in NF+$CO_2$ treatment over NF alone. However, Leakey et al (2009) observed an overall 10% increase in $CO_2$-induced leaf photosynthetic rate in maize. Higher levels of ozone and carbon dioxide levels might have led to a closure of stomatal pores, thereby reducing the conductance.

***Impact of different treatments on Leaf area index (LAI)***

Observations pertaining to leaf area index (LAI) at different growth stage (33, 66, and 98 and 32, 55, and 81 DAS first and second year, respectively) are presented in Table 1. Different ozone treatments significantly affected LAI of maize crop. During crop growth period, LAI recorded marked improvement between tasseling and silking stage and there after LAI declined. Maximum LAI was observed at silking stage in both the years. This might be due to the fact that, the leaves were fully functional and expanded at this stage than at the other stages. Highest LAI was recorded in CF treatment at all the stages during both the seasons. Maximum LAI was observed in CF (4.64 and 5.35) followed by NF+$CO_2$ (4.20 and 5.00) at silking stage in first and second year respectively. Lower LAI values were recorded in EO, EO1 treatments than all other treatments. On an average, maize produced more LAI in second year compared to first year. At

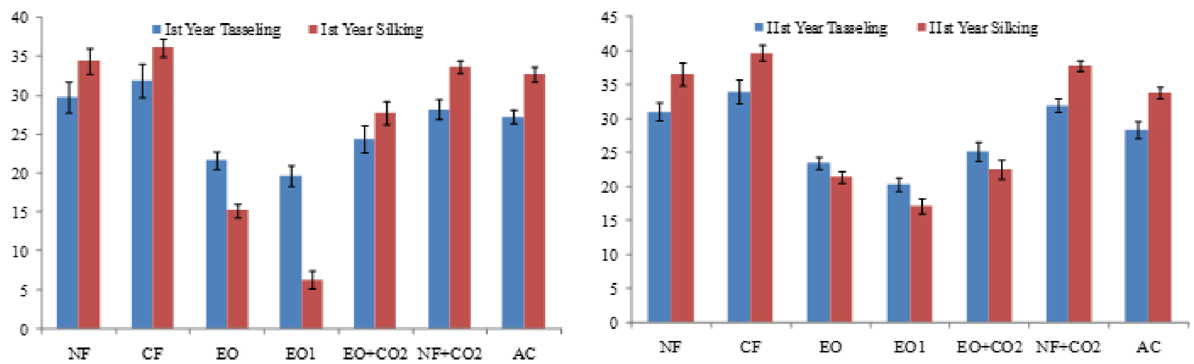


Figure 2 - Effect of different treatments on photosynthetic rate (μmol $m^{-2}$ $s^{-1}$) in maize.

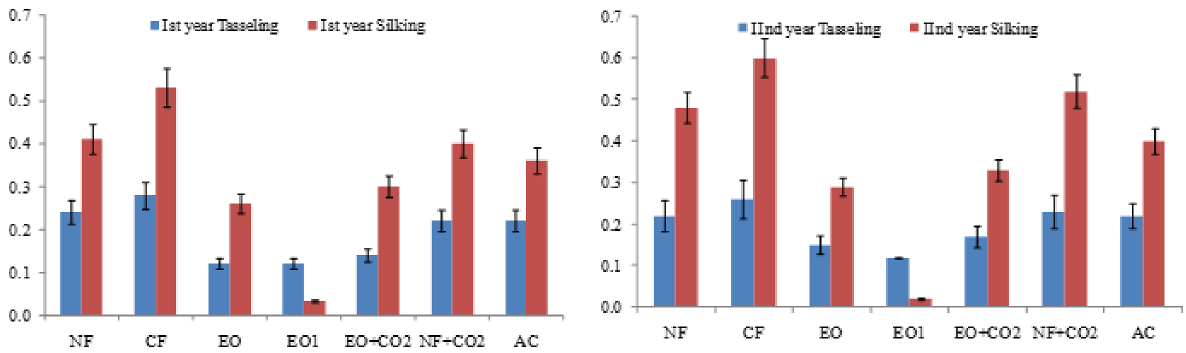


Figure 3 - Effect of different treatments on stomatal conductance (gs) in maize.

silking stage significant difference was observed in EO and EO1 over the NF control in both the years. There was a 12-15% and 13-15.4% decrease in LAI under EO and EO1 treatment over the NF control throughout the crop growth period in first and second year, respectively (Table 1). At milking stage EO recorded a LAI of 2.85 and 2.15 in first and second year respectively and LAI was lowest at 2.00 in EO1 in the second year. Kharel and Amgain (2010) observed that elevated ozone reduced the LAI of plants. There was 9-14% increase in LAI in CF over the NF control treatment throughout the crop growth period in both the years.

The presence of elevated $CO_2$ along with elevated O3 in EO+$CO_2$ treatment increased the LAI as compared to EO and EO1 alone. The results suggest that an elevated $CO_2$ levels were able to overcome the decrease in LAI due to EO levels to some extent. The LAI increased by 4% under EO+$CO_2$ as compared to the EO alone treatment. Feng et al (2007) also reported that elevated $CO_2$ could significantly ameliorate or offset the detrimental effects of elevated $O_3$ by reducing the $O_3$ flux in wheat leaves. Uprety et al (2010) observed higher leaf area index in elevated $CO_2$ treatments as compared to control. The LAI increased with increase in the age of the crop and reached maximum at silking stage in first and second year, respectively. The intercepted photosynthetically active radiation was at its maximum at this time. It has earlier been observed by researchers that the mechanisms leading to chronic $O_3$ damage are due to decreased photosynthetic productivity, decrease in green leaf area, and plant productivity (Ashmore, 2005; Fuhrer, 2009).

### *Impact of different treatments on growth attributes*

Above ground biomass was measured in term of length and dry matter of the shoot. The shoot length and dry matter of maize was recorded at 33, 66, and 98 days after sowing (DAS) in first year and on 32, 55, and 81 DAS in the second year (Table 1). Shoot length increased up to milking stage in both the years. On an average, shoot length was more in first year as compared to second. The shoot length of maize was significantly affected by elevated $O_3$ concentration in both years. Significant reductions took place in shoot length under EO1 treatment. There was a 17% and 27% decrease in shoot length in EO over the NF control treatment at silking stage in first and second year respectively. At the time of harvesting EO and EO1 recorded shoot length (169.47 and 103.54 cm) in first and second year as compared to other treatments. Filtration of ozone led to an increase in plant shoot length in the CF treatment as compared to the NF control treatment. The growth of the plants shoot was best in the CF treatment in both years where the concentration of ozone was much lower than in ambient air. There was a 14% and 17% increase in shoot length in CF over the NF control throughout the crop growth period in first and second year respectively.

The presence of elevated $CO_2$ along with elevated $O_3$ increased the shoot length as compared to EO alone. The shoot length was also more in case of NF+$CO_2$ treatment over the NF control. The results suggest that an elevated $CO_2$ along with elevated $O_3$ was able to counteract some of the negative impacts of elevated $O_3$ concentrations on plant growth. Since elevated $CO_2$ increased photosynthesis and other growth parameters, increasing $CO_2$ levels in the future might counteract some of the negative effects of ozone on the growth of vegetation. Feng et al (2007) also observed reduced shoot growth under elevated $O_3$ in wheat.

In the first year of the study after the milking stage the crop was infested with aphid pest. The plants under the EO1 treatment which had higher concentration of ozone (ambient + 45-50 ppb) were very badly infested with aphid and could not recover from the aphid infestation. The whole of the crop under EO1 treatment had a premature senescence and perished giving no yield. This showed that plants grown under higher ozone concentration became weak and could not withstand the insect attack. Among the other treatments, CF recorded consistently highest dry matter accumulation at all the growth stages of the crop, followed by NF+$CO_2$. No significant difference was observed in dry matter in the ambient open plot air control (AC) and NF treatments. At other growth stages, differences among the treatments were sig-

Table 1 - Growth parameters of maize at different stages.

| Parameter | Treatments NF | CF | EO | EO1 | EO+$CO_2$ | NF+$CO_2$ | AC | LSD p=0.05 |
|---|---|---|---|---|---|---|---|---|
| | | | | Tasseling Stage | | | | |
| **first year** | | | | | | | | |
| shoot length (cm) | 26.80 | 40.51 | 25.89 | 25.41 | 26.32 | 26.65 | 25.30 | 5.39 |
| shoot DW[$] (g) | 12.89 | 14.35 | 10.56 | 10.36 | 10.64 | 14.01 | 13.90 | 1.09 |
| leaves DW (g) | 21.04 | 25.39 | 13.95 | 13.65 | 16.59 | 21.76 | 20.67 | 3.21 |
| leaf area index | 2.72 | 2.96 | 2.35 | 2.30 | 2.40 | 2.63 | 2.40 | 0.27 |
| **second year** | | | | | | | | |
| shoot length (cm) | 23.36 | 34.50 | 20.57 | 20.16 | 22.39 | 25.18 | 23.01 | 4.50 |
| shoot DW (g) | 10.71 | 13.24 | 8.59 | 8.48 | 8.95 | 11.62 | 9.33 | 1.01 |
| leaves DW (g) | 19.26 | 23.08 | 11.33 | 10.00 | 12.87 | 20.39 | 18.48 | 0.61 |
| leaf area index | 2.90 | 3.15 | 2.40 | 2.40 | 2.50 | 3.05 | 2.70 | 0.33 |
| | | | | Silking Stage | | | | |
| **first year** | | | | | | | | |
| shoot length (cm) | 182 | 210 | 152 | 137 | 164 | 192 | 178 | 14.86 |
| shoot DW (g) | 241 | 290 | 151 | 123 | 193 | 250 | 219 | 19.87 |
| leaves DW (g) | 25.13 | 27.72 | 18.46 | 15.14 | 20.59 | 26.81 | 23.47 | 3.15 |
| leaf area index | 4.08 | 4.64 | 3.20 | 2.80 | 3.41 | 4.20 | 3.67 | 0.64 |
| **second year** | | | | | | | | |
| shoot length (cm) | 185 | 198 | 145 | 131 | 168 | 191 | 182 | 10.61 |
| shoot DW (g) | 168 | 186 | 132 | 119 | 156 | 173 | 163 | 17.90 |
| leaves DW (g) | 18.25 | 22.83 | 14.07 | 8.70 | 15.31 | 20.46 | 17.01 | 2.41 |
| leaf area index | 4.93 | 5.35 | 3.70 | 2.95 | 4.10 | 5.00 | 4.75 | 0.57 |
| | | | | Milking Stage | | | | |
| **first year** | | | | | | | | |
| shoot length (cm) | 204 | 242 | 169 | 0 | 187 | 225 | 195 | 24.51 |
| shoot DW (g) | 262 | 307 | 179 | 0 | 210 | 285 | 242 | 53.40 |
| leaves DW (g) | 22.35 | 27.51 | 15.22 | 0 | 17.63 | 24.19 | 21.88 | 2.34 |
| leaf area index | 3.43 | 3.87 | 2.85 | 0 | 3.22 | 3.52 | 3.30 | 0.32 |
| **second year** | | | | | | | | |
| shoot length (cm) | 142 | 197 | 104 | 79.65 | 120 | 170 | 132 | 15.32 |
| shoot DW (g) | 212 | 247 | 159 | 102 | 174 | 235 | 202 | 24.12 |
| leaves DW(g) | 15.42 | 19.65 | 12.79 | 6.94 | 13.80 | 16.35 | 14.08 | 2.11 |
| leaf area index | 3.15 | 3.60 | 2.15 | 2.00 | 2.45 | 3.30 | 3.00 | 0.90 |

[$]DW - dry weight

nificant with respect to dry matter accumulation, the highest being in CF and the lowest in EO1.

Dry matter accumulation increased with the advancement in the age of the crop. Among the stages, maximum dry matter accumulation occurred between tasseling and silking stage. On an average, maize produced more shoot dry matter in first year as compared to second year. Karberg et al (2005) reported that the elevated $O_3$ decreased dry matter via decreasing net photosynthesis, oxidative damage to cell membranes, especially chloroplasts. Thus in our experiment EO and EO1 concentration affected and altered the carbon allocation to the shoot and the total dry matter. Wang et al (2008) observed that total dry matter significantly decreased with increase in ozone concentration in *Brassica napus* plants. Sudhakar et al (2008) also reported 20% less dry matter in tomato plants when exposed to elevated ozone. Kharel and Amgain (2010) observed that elevated ozone reduced total above-ground biomass by 16.6% in mungbean. The presence of elevated $CO_2$ along with EO increased the dry matter as compared to EO alone.

***Impact of different treatments on yield attributes***

Data on yield attributes of maize after final harvesting of crop viz. number of cobs per plant, thickness of cob, number of rows per cob, number of grains in a row, cob length, test weight, number of grains in a cob and grain yield as influenced by ozone and CO2 levels is presented in Table 2. There was no difference obtained within the treatments with respect to the number of cobs except under the elevated levels of ozone.

The thickness of cob was lowest in EO (10.56 cm) in the first year and EO1 (6.9 cm) in the second year. The highest thickness was recorded in CF (11.48 cm and 12.3 cm) treatment in both of the years and was significantly different from the other treatments. The CF treatment also had more number of grains per row and number of rows per cobs followed by NF+$CO_2$, NF, control, EO+$CO_2$, EO, and EO1. The same trend was shown by cob length in all treatments. Significant difference was obtained in number of grains in a row among all the treatments except the ambient control and the non-filtered control treatment (Table

Table 2 - Growth parameters of maize at different stages.

| Parameter | Treatments | | | | | | | LSD |
|---|---|---|---|---|---|---|---|---|
| | NF | CF | EO | EO1 | EO+$CO_2$ | NF+$CO_2$ | AC | p=0.05 |
| **first year** | | | | | | | | |
| No of cobs plant$^{-1}$ | 2.00 | 2.00 | 1.67 | 0 | 2.00 | 2.00 | 2.00 | 0.26 |
| Thickness of cob (cm) | 10.64 | 11.48 | 10.56 | 0 | 10.9 | 11.03 | 10.5 | 0.49 |
| No of rows cob$^{-1}$ | 10.8 | 11.6 | 10.1 | 0 | 10.7 | 11 | 10.3 | 0.61 |
| No. of grain row$^{-1}$ | 26.6 | 28.9 | 25.4 | 0 | 25.8 | 27.4 | 26.4 | 1.2 |
| Cob length (cm) | 7.14 | 9.4 | 6.81 | 0 | 7.07 | 7.82 | 7.18 | 1.06 |
| 100 grain wt (g) | 15.01 | 16.88 | 14.6 | 0 | 14.8 | 15.45 | 15.14 | 0.6 |
| No. of grains cob$^{-1}$ | 287 | 335 | 257 | 0 | 276 | 301 | 272 | 20.8 |
| **second year** | | | | | | | | |
| No. of cobs plant$^{-1}$ | 1 | 1 | 1 | 1 | 1 | 1 | 1 | ns |
| Thickness of cob (cm) | 10.5 | 12.3 | 8.6 | 6.9 | 9.8 | 11.0 | 9.5 | 0.9 |
| No. of rows cob$^{-1}$ | 9.7 | 10.7 | 8.8 | 8.2 | 9.1 | 9.9 | 9.5 | 0.43 |
| No. of grain row$^{-1}$ | 32 | 35 | 26 | 22 | 28 | 32 | 31 | 3.2 |
| Cob length (cm) | 14.5 | 16.2 | 11.7 | 10.2 | 13.0 | 15.1 | 14.1 | 1.23 |
| 100 grain wt (g) | 33 | 36 | 31 | 30 | 32 | 33 | 32 | 2.1 |
| No. of grains cob$^{-1}$ | 307 | 375 | 225 | 199 | 258 | 315 | 291 | 19 |

2). No significant difference in 100 seed test weight was observed in NF+$CO_2$ and NF treatments and EO and EO+$CO_2$ treatments. The lowest weight was obtained in EO in first year and EO1 in second year which showed significant difference with all the other treatments at 5% level of significance. The yield contributing characters viz., number of grains per row and number of rows per cobs and test weight were negatively influenced by the EO concentration. Accelerated senescence observed under elevated $O_3$ shortened the seed formation and thereby reduced average seed number and ultimately the seed yield.

Higher levels of O3 exposure resulted in lowered immunity of maize to aphid attack. There was a complete yield loss observed in maize under higher concentration of elevated $O_3$ (ambient+45-50 ppb ozone) subsequently (Figure 4). Elevated O3 impacted the crop growth parameters significantly and this led to a lowering in the economic yield of maize. No grain yield was obtained in the EO1 treatment of the study in the first year, as the maize plant was badly infested with aphid insect and died. However a decline of grain yield by 35% was obtained in the second year of the study in the EO1 treatment. The grain yield was lowered by 13% and 20% under EO levels and it increased by 31% and 21% on filtration of $O_3$ in the charcoal filter treatment in first and second year of study, respectively. Cereals are highly sensitive and have shown decreased yields with increasing $O_3$ levels (Rai and Agrawal, 2008; Singh et al, 2010). There is abundant evidence that current ambient $O_3$ in many areas of the world are high enough to induce significant yield losses in crops such as wheat (Wang et al, 2007b), soybean (Morgan et al, 2003), and rice (Ainsworth et al, 2008). Estimated reductions of global yields ranging from 2.2-5.5% for maize, to 3.9-5% and 8.5-14% for wheat and soybean, respectively have been reported by (Avnery et al, 2011a). The deleterious effects of $O_3$ on the grain yield have often been attributed to premature leaf senescence, decrease photosynthesis and consequent reductions in assimilate availability, and alterations in assimilate partitioning (Black et al, 2000; Feng et al, 2007, 2008). Ozone exposed plants experienced an early senescence (Fuhrer et al, 1997). Ozone filtration had an influence in increasing the seed yield of maize. No significant difference was observed in grain yields in the ambient air control (AC) and NF treatments. Ozone concentration were always higher in the EO and EO1 treatment over the NF control. So, it could be inferred that higher levels of ozone had a negative impact on seed yield. It can be concluded that all seed yield related parameters were significantly affected by elevated levels of $O_3$. The removal of $O_3$ from ambient air also increased the yield as seen in all the parameters under the CF treatment.

There was an increase in all the yield parameters under EO+$CO_2$ treatment as compared to EO alone. The grain yield increased by 9-10% with elevated $CO_2$ and elevated $O_3$ in combination over EO alone. Elevated $CO_2$ ameliorated the negative effect of $O_3$, thus there was an increase observed in all the yield

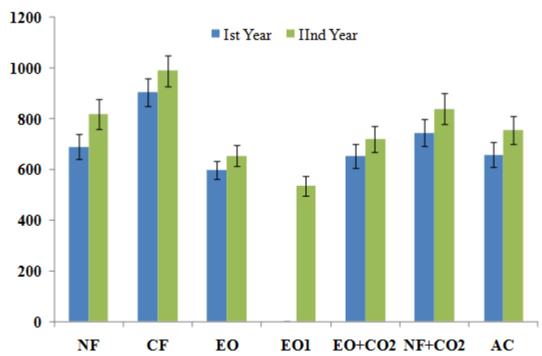


Figure 4 - Average grain yields (g m$^{-2}$) of maize after final harvesting.

parameters under EO+$CO_2$ treatment as compared to elevated $O_3$ treatment in both the years. Fiscus et al (2002) observed that in soybean (*Glycine max)* seed yield decreased under EO and increased under elevated $CO_2$. This protective effect of $CO_2$ was due to increased photosynthetic rate, dry matter production and more allocation of carbohydrate to the grain. Piikki et al (2008) observed an increase in grain yield due to increasing grain number per unit ground area in case of elevated $CO_2$. Elevated $O_3$ reduced number of seeds per plant (13.17%), seed dry weights (19.67%), test weight (g 1000 seeds$^{-1}$), (10.28%), total above-ground biomass (16.60%), harvest index (6.25%) and shelling percentage (5.07%) in mungbean (Kharel and Amgain, 2010).

***Conclusions***

Ambient ozone levels affected the productivity and growth of crops. Charcoal filtration of ozone from ambient air had a positive impact on all the growth and yield parameters in maize. The productivity increased under charcoal filtered treatment where the ozone concentrations were 80 to 85% lower than in ambient air. Elevated carbon dioxide along with elevated ozone was able to offset some of the negative impact of elevated ozone alone. Higher levels of ozone significantly affected above ground biomass in maize and declined yield. The study provided evidence that there are indeed interactive effects of $O_3$ and $CO_2$ and these may be antagonistic in nature. The present investigation also highlights the importance of clean non-toxic atmospheric environment necessary for the healthy growth of plants.

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