Effects of Chronic Exposures to Ozone on the Growth of Sunflower Plants

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Fourteen-day-old sunflower plants (*Helianthus annuus* L. cv. Russian Mammoth) were exposed to 0.1 or 0.2 ppm ozone (O_3) for 12 days in an artificially-lighted growth cabinet. Plants were harvested 0, 6 and 12 days after the start of exposure, and the growth analysis was performed. White fleck of injury developed on many leaves after the exposure to 0.1 or 0.2 ppm O_3 for 1-2 days, and subsequently withering of old leaves was accelerated. Twelve days after the start of exposure, the dry weight of whole plant was reduced by 11% and 32% of the control by 0.1 and 0.2 ppm O_3 , respectively. Root growth was markedly inhibited by O_3 , while leaf growth was slightly inhibited. Relative growth rate (RGR) and net assimilation rate (NAR) were reduced by 0.1 ppm O_3 for the first 6 days, but were not affected for the following 6 days. The RGR and the NAR were reduced by 0.2 ppm O_3 throughout the exposure period. For the last 6 days, the RGR was less affected by 0.2 ppm O_3 than the NAR, owing to the increase in leaf area ratio (LAR). Leaf weight ratio (LWR) was also increased by O_3 exposure, whereas stem weight ratio (SWR) and root weight ratio (RWR) were reduced. These changes in growth parameters suggest that the chronic exposures to low concentrations of O_3 should affect the net photosynthesis and the partitioning ratio of photosynthates in sunflower plants.

INTRODUCTION

Photochemical oxidants are the most important and widespread types of air pollutants in recent years. Injurious effects of the oxidants on agricultural and native vegetations have been investigated by many workers (see reviews¹⁻⁴). Ozone (O_3), which is a major component of photochemical oxidants, is probably more injurious to plants than any other air pollutants.^{5,6} Acute injuries induced by O_3 have been studied extensively. High concentrations of O_3 usually cause the visible symptoms of injury on leaves⁶⁻⁹ and affect the rates of photosynthesis, respiration and transpiration within a few hours.¹⁰⁻¹⁵

Chronic effects on plants of long-term exposures to relatively low concentrations of O_3 are considered to be more practical and important subjects at present. There has been an increasing number of studies concerning the chronic effects of O_3 on growth and yield of many plants. FEDER¹⁶ reported that the low concentrations of O_3 inhibited the flower formation of carnation and geranium plants. HEAGLE *et al.*¹⁷ documented that the exposure to 0.1 ppm O_3 for 67 days significantly reduced the

yield of a hybrid sweet corn. The results from TINGEY *et al.*¹⁸⁾ showed that 3-week exposure to 0.1 ppm O₃ could reduce the growth of soybean plants. Similar reduction in growth and/or yield have been also reported on many other plant species.^{19–24)} However, HARWARD and TRESHOW,²⁵⁾ reported that some understorey plants in the aspen zone significantly increased in the dry weight growth and the seed production by the exposure to 0.06 or 0.15 ppm O₃. From many other investigations, BENNETT *et al.*²⁶⁾ compiled evidences indicating the increase in growth of plants exposed to low concentrations of O₃, and showed in their own experiments that 12-day exposure to 0.03 ppm O₃ stimulated the growth of bean, barley and smart weed.

These conflicting results indicate that the chronic effects of low concentrations of O₃ on plant growth have not been clarified. Furthermore, almost all of these experiments were conducted to determine the effects of O₃ only by a single harvest procedure. The changes in growth and yield should be the results of many physiological and biochemical changes. In order to examine the chronic effects of O₃ on plant growth precisely, the effects on several growth parameters should be investigated.

In the present study, we exposed sunflower plants to 0.1 and 0.2 ppm O₃ continuously for 12 days, and detected the effects of O₃ on several growth parameters by means of the plant growth analysis. This procedure might provide the information concerning the physiological changes in O₃-exposed plants. Furthermore, we tried to give an explanation of the conflicting results reported by other workers.

MATERIALS AND METHODS

Plant material. Sunflower seeds which were obtained from the plants bred in our institute were dipped into water for 12 hr and then sterilized by dipping into 1 g l⁻¹ Benlate solution (Dupont, Delaware, U.S.A.) for 30 minutes, followed by rinsing with running tap water for 2 hr. Three seeds were directly sown in each plastic pot (11 cm in diameter and 20 cm high) containing a mixture of vermiculite, peat moss, perlite and fine gravel (4 : 4 : 2 : 1, v/v). As basal fertilizers, 5 g of Magamp K (N : P₂O₅ : K₂O = 6 : 40 : 5, W. R. Grace Co., Tennessee, U.S.A.) was added to each pot, and the medium was adjusted to pH 6.4 with magnesia lime (about 15 g pot⁻¹). Plants were fertilized regularly (1–3 times week⁻¹) with 100–200 ml of 0.1% Hyponex solution (N : P₂O₅ : K₂O = 6.5 : 6 : 19) plus Hoagland's No. 2 micro nutrients²⁷⁾ and watered regularly or daily as needed.

After sowing the pots were brought into a controlled environment growth cabinet (170 × 230 × 190 cm³, Koito Co. Ltd.) to grow plants under the following environmental conditions. Air temperature in the cabinet was 25 ± 0.5°C, and relative humidity was 75 ± 5%. Light source consisted of twenty-four 400 W stannous halide lamps (Yoko Lamp, Toshiba), and long wavelength (>800 nm) of the emitted radiation was eliminated through a heat absorbing glass filter. Light intensity was about 420 μE m⁻² sec⁻¹ (ca. 115 W m⁻², 30 klux) at plant height. Light/dark cycle was 14/10 hr. Fresh air was led into the cabinet after being passed through activated charcoal and catalyst-bearing (containing MnOx and CuO) filters to remove ambient air pollutants. Air velocity in the cabinet was 0.2–0.4 m sec⁻¹, and ventilation rate was 75 m³ hr⁻¹ (ca. 10 times hr⁻¹). The concentration of carbon dioxide (CO₂) in the cabinet was continuously monitored and regulated at 400 ± 4 ppm throughout the experimental period with a controlling system equipped with a infrared CO₂ gas analyzer (URA-2S, Shimadzu). In the growth cabinet, plants were rotated on a turntable to minimize

possible position effects.

Seedlings were selected for uniformity and thinned to a single plant per pot 7 days after sowing. Twelve-day-old plants were transferred to another controlled environment growth cabinet for O₃ exposure (Koito Co. Ltd.). The size and the environmental conditions in this cabinet were the same as those in the cabinet where plants had been grown previously, except for the high ventilation rate up to 800 m³ hr⁻¹ (ca. 110 times hr⁻¹) to minimize the effects of unknown pollutants which might be produced by photochemical reactions in the cabinet.

Exposure to O₃. Fourteen-day-old plants were exposed to O₃ for 12 days. O₃ was generated by a silent electrical discharge in dry oxygen and mixed with the filtrated fresh air, and the mixture was led into the cabinet. The concentration of O₃ in the cabinet was monitored continuously and regulated by a controlling system based on a chemiluminescent O₃ analyzer (Model 806, Kimoto). Growth experiments consisted of three separate experiments. The concentration of O₃ in each experiment was 0.0 ppm (control), 0.1±0.002 ppm or 0.2±0.004 ppm. Environmental conditions inside the cabinet were almost identical among the three experiments except for the O₃ concentration and were kept constant during the growth experiments.

Harvests and growth analysis. Plants were harvested just before the start of O₃ exposure (0 day) and also harvested 6 and 12 days thereafter. The extents of visible injury and withering in each leaf were visually assessed in 5% increments of leaf area. Area of each leaf was measured by an automatic planimeter (Model 3100, LI-COR Co. Ltd.). Total number of leaves and plant height were recorded. Then plants were divided into leaf laminae, stem, root, flower bud and withered leaves, which were dried at 80–90°C for 3–5 days and then weighed. Stem part included leaf petioles.

Relative growth rate (RGR), net assimilation rate (NAR), leaf area ratio (LAR), specific leaf area (SLA), leaf weight ratio (LWR), stem weight ratio (SWR) and root weight ratio (RWR) were calculated according to the following formulae:²⁸⁾

$$\begin{aligned} \text{RGR} &= \frac{1}{W} \cdot \frac{dW}{dt} = \frac{\ln W_2 - \ln W_1}{t_2 - t_1} \\ \text{NAR} &= \frac{1}{\bar{F}} \cdot \frac{dW}{dt} = \frac{(W_2 - W_1) \cdot (\ln \bar{F}_2 - \ln \bar{F}_1)}{(t_2 - t_1) \cdot (\bar{F}_2 - \bar{F}_1)} \\ \text{LAR} &= \bar{F}/W \\ \text{SLA} &= \bar{F}/F \\ \text{LWR} &= F/W \\ \text{SWR} &= S/W \\ \text{and RWR} &= R/W \end{aligned}$$

where W_i and $\bar{F}_i$ are the dry weight of whole plant and the leaf area at time t_i (i : 1 and 2), respectively. F , S and R are the dry weight of leaves, stem and root, respectively.

RESULTS

Visible injury caused by O₃ exposure

The symptom of visible injury was first noted as white fleck^{4,6)} within 2 days after the start of exposure to 0.1 or 0.2 ppm O₃, and was most notable on the tip or the edge of upper surface of leaf laminae, especially of matured leaves. As the ex-

Table 1 Effects of O₃ exposure on some characteristics of sunflower plants.^{a)}

	O ₃ concentration (ppm)		
	0.0 (control)	0.1	0.2
Visible injury (%) ^{b)c)}	1.2 ± 0.4	9.5 ± 5.2 ^{***d)}	46.8 ± 7.3 ^{***}
Withering (%) ^{b)}	1.1 ± 0.4	3.4 ± 0.5 ^{***}	12.0 ± 2.6 ^{***}
Withered leaves (mg dry wt)	68.2 ± 23.8	206.5 ± 38.2 ^{***}	695.2 ± 139.7 ^{***}
Flower bud (mg dry wt)	17.3 ± 6.9	16.0 ± 5.8	10.6 ± 3.8 ^{**}
Number of leaves	24.4 ± 1.2	23.7 ± 1.8	26.6 ± 2.2 ^{**}
Plant height (cm)	48.2 ± 3.4	47.1 ± 3.0	42.8 ± 3.8 ^{**}

^{a)} Plants were harvested 12 days after exposure started. Mean of 12 plants and standard deviation are indicated for each sample.

^{b)} Percentage of the total leaf dry weight.

^{c)} Including the yellow coloring and withering of leaves.

^{d)} Significance of difference from control (t-test), ^{**}*P* < 0.01, ^{***}*P* < 0.001.

posure continued, the symptom spread on the expanded leaves and appeared even on the upper young leaves. Furthermore, O₃ exposure accelerated the withering of lower old leaves, which was apparently similar to that of naturally senescent leaves. With increase in concentration of O₃, the degrees of visible injury and of withering of leaves increased. Effects of O₃ exposure on these characteristics were summarized in Table 1.

Effects of O₃ on dry matter production

As shown in Fig. 1, dry weight growth of whole plant was significantly reduced (*P* < 0.001) by the exposure to 0.1 or 0.2 ppm O₃ for 6 days. At the final harvest, the dry weight of plants exposed to 0.1 and 0.2 ppm O₃ was smaller by 11% and 32%

Fig. 1 Effect of O₃ exposure on the increase in dry weight of whole plant. Dry weight of withered leaves was excluded. O₃ exposure was started 14 days after sowing and continued for 12 days thereafter. Each symbol is the mean of 12 plants and vertical bars indicate ± standard deviation of the mean.

○: 0 ppm (control), ◐: 0.1 ppm, ●: 0.2 ppm O₃ exposure treatment.

Fig. 2 Effect of O_3 exposure on the increase in dry weight of stem. Symbols and conditions are the same as in Fig. 1.

Fig. 3 Effect of O_3 exposure on the increase in dry weight of root. Symbols and conditions are the same as in Fig. 1.

Fig. 4 Effect of O_3 exposure on the increase in dry weight of leaves. Symbols and conditions are the same as in Fig. 1.

Fig. 5 Effect of O_3 exposure on the increase in leaf area. Symbols and conditions are the same as in Fig. 1.

than that of control plants, respectively.

The effects of O_3 on dry weight growth of stem, root and leaf laminae are shown in Figs. 2, 3 and 4, respectively. Six-day exposure to 0.1 or 0.2 ppm O_3 was sufficient to reduce the dry weight growth of each organ. Compared with the control plants, the stem dry weight at the final harvest revealed 13% and 38% reductions for plants exposed to 0.1 and 0.2 ppm O_3 , respectively. Drastic reduction in the dry weight growth of root was caused by O_3 exposure. At the final harvest, the root dry weight of 0.1 ppm O_3 -exposed plants was smaller by 15% than that of control plants, while a 50% reduction was caused by 0.2 ppm O_3 . Leaf growth was also reduced by O_3 ex-

Table 2 Effects of O₃ exposure on the relative growth rate (RGR) and the net assimilation rate (NAR) of sunflower plants.^{a)}

	Exposure duration (days)	O ₃ concentration (ppm)		
		0.0 (control)	0.1	0.2
RGR	0-6	0.276	0.235	0.224
(mg mg ⁻¹ day ⁻¹)	6-12	0.189	0.196	0.154
NAR	0-6	1.232	1.149	1.058
(mg cm ⁻² day ⁻¹)	6-12	1.185	1.274	0.844

^{a)} Dry weight of withered leaves was excluded to calculate these values.

posure. Although the withering of lower leaves was accelerated, the growth reduction of leaf dry weight caused by O₃ exposure was less than that of stem or root. The exposure to 0.2 ppm O₃ reduced leaf dry weight by 18%, and 0.1 ppm O₃ reduced by only 6% ($P < 0.05$) even when the exposure was continued for 12 days. A slight reduction in leaf area growth was also detected in the O₃-exposed plants (Fig. 5). At the final harvest, the leaf area of plants exposed to 0.1 and 0.2 ppm O₃ was smaller by 9% and 14% than that of control plants, respectively.

The exposure to O₃ did not influence the number of leaves emerged, irrespective of the withering of old leaves, except that 12-day exposure to 0.2 ppm O₃ stimulated the development of new leaves (Table 1). Flower bud was observed on the top of stem of almost all plants at the final harvest. The exposure to 0.2 ppm O₃ reduced the dry weight of flower bud by 39% of the control value, though 0.1 ppm O₃ had no significant effect (Table 1). Stem elongation expressed as plant height was depressed by O₃ exposure (Table 1), but the suppression was not so remarkable as the reduction in dry weight growth of stem.

Effects of O₃ on growth parameters

The data presented in the previous section (Figs. 1-5) were subjected to the growth analysis. Table 2 shows the changes in RGR and NAR of plants in each treatment. For the first 6 days of exposure, the RGR of sunflower plants was reduced in 0.1 and 0.2 ppm O₃ by 15% and 19% of that of the control, respectively. For the following 6 days, the exposure to 0.2 ppm O₃ resulted in the same extent of reduction in RGR as before, whereas 0.1 ppm O₃ caused a slight increase. The change in NAR caused by O₃ resembled with the change in RGR. The NAR of plants exposed to 0.1 ppm O₃ was smaller than that of the control plants for the first 6 days but somewhat larger for the following 6 days. The exposure to 0.2 ppm O₃ reduced the NAR during the exposure period for 12 days. By the way, the reduction in NAR amounted to 29% of the control value and was larger than that in RGR for the last 6 days.

As RGR is the product of NAR and LAR, effect of O₃ on LAR should be investigated (Fig. 6). The exposure to 0.2 ppm O₃ increased the LAR by 28% of the control value at the final harvest. LAR was further divided into SLA and LWR. The SLA was only slightly increased by O₃ exposure (data not shown), whereas the LWR of plants pronouncedly increased with prolonged duration of exposure and with increased concentration of O₃ (Fig. 7): At the final harvest, the exposure to 0.2 ppm

Fig. 6 Effect of O₃ exposure on the leaf area ratio (LAR). Symbols and conditions are the same as in Fig. 1.

Fig. 7 Effect of O₃ exposure on the leaf weight ratio (LWR). Symbols and conditions are the same as in Fig. 1.

Fig. 8 Effect of O₃ exposure on the stem weight ratio (SWR). Symbols and conditions are the same as in Fig. 1.

Fig. 9 Effect of O₃ exposure on the root weight ratio (RWR). Symbols and conditions are the same as in Fig. 1.

O₃ increased LWR by 21% of the control value, while 0.1 ppm O₃ increased LWR by 5% ($P < 0.05$). We also calculated the ratio of dry weight of stem or root to that of whole plant (Figs. 8 and 9). The exposure to 0.1 ppm O₃ for 12 days only slightly reduced both SWR and RWR, whereas 0.2 ppm O₃ significantly reduced SWR and RWR by 9% and 28%, respectively.

DISCUSSION

Dry matter production in sunflower plants was significantly reduced by the exposure to both 0.1 and 0.2 ppm O₃ for 12 days (Fig. 1). These findings support the

previously reported results that the chronic exposures to low concentrations of O_3 inhibited plant growth and yield.¹⁶⁻²⁴⁾ In addition, results of growth analysis in the present investigation suggested that several physiological functions participating in the plant growth were altered by O_3 through the course of exposure period. The reduction in RGR caused by O_3 exposure appeared to be derived from the effect of O_3 on NAR. It has been well documented that the exposures to high concentrations of O_3 inhibit the net photosynthesis and stimulate the respiration in several plants.^{10-12,14,15)} The reduction in NAR represented in the present study suggests that chronic exposures to low concentration of O_3 could also induce the inhibition of net photosynthesis and/or the acceleration of respiration in plants. The reduction in NAR by exposure to 0.09 ppm O_3 has been reported with other herbaceous plant species.²⁹⁾

However, for the last-half period of 0.1 ppm O_3 exposure in the present experiments, the NAR was recovered or rather accelerated in the similar manner to the change in RGR. A similar result was reported by OSHIMA *et al.*,³⁰⁾ who observed the reduction in RGR of the parsley plants caused by the exposure to 0.2 ppm O_3 for the first several weeks, followed by the higher RGR than that of control plants. Such changes in NAR and RGR might be at least partly responsible for the stimulative effects of O_3 on plant growth reported by several workers.^{25,26)} During the exposure to O_3 , plants might have adapted to the given environmental condition. Although the mechanisms of O_3 phytotoxicity have not yet been defined, there were some studies that O_3 in high concentrations could affect the activities of several enzymes.^{31,32)} TANAKA and SUGAHARA³³⁾ reported that poplar plants exposed to 0.1 ppm SO_2 increased in superoxide dismutase activity and thereby became tolerant to acute toxicity of SO_2 . In the plants adapted to low concentrations of O_3 , the enzymes which participate in the defense of O_3 toxicity might be also induced or activated during the exposure period. Studies on the enzymes relating to O_3 tolerance should be prerequisite to know the mechanisms of adaptation to O_3 .

Plants exposed to 0.2 ppm O_3 exhibited the smaller reduction in RGR than that in NAR for the last-half of exposure period (Table 2). The remarkable reduction in NAR induced by O_3 could be compensated by the increase in LAR (Fig. 6) resulting in smaller reduction in RGR. The increase in LWR and the reduction in SWR and RWR caused by O_3 indicated that low levels of O_3 had changed the partitioning ratio of photosynthate among leaves, stem and root (Figs. 7, 8 and 9). BENNETT and OSHIMA³⁴⁾ observed the reduction in RWR of the carrot plants by a long-term exposure to O_3 . Other investigators have demonstrated that O_3 could reduce the dry weight growth of root most severely, resulting in a reduction in RWR in plants.^{18,23,24,29,30)} It has been reported that the plants in deficiency of photosynthate showed larger reduction in dry weight growth of root than that of shoot.³⁵⁾ The reduction in RWR in O_3 -exposed plants might also result from the deficiency of photosynthate caused by O_3 . Another report indicated that O_3 reduced the proportion of dry weight of fruits to that of whole plant.³⁶⁾ Besides, present experiments also showed the reduction in dry weight growth of flower bud caused by O_3 exposure (Table 1). These results suggest the changes in partitioning ratio of photosynthate in O_3 -exposed plants. The change in the partitioning ratio was probably caused by the inhibition of translocation of photosynthate or by the enhancement of respiration in the dissimilation parts, i.e. root, stem and flower. Recently, TINGEY *et al.*³⁷⁾ have suggested the inhibitory effect of O_3 on translocation of photosynthate

in ponderosa pine. Accordingly, the increase in total number of leaves and the acceleration of senescence of old leaves in O₃-exposed plants (Table 1) should be further investigated in view of the changes in partitioning and translocation of photosynthate and other metabolites.

Retardation of stem elongation in O₃-exposed plants might be resulted from the reduction in dry weight growth of stem. On the other hand, ethylene production was reported in plants exposed to high concentrations of O₃.^{38,39)} It is known that ethylene inhibits stem elongation⁴⁰⁾ and accelerates senescence.⁴¹⁾ By exposure to low concentrations of O₃, plants might produce ethylene. Therefore, it is probable that retardation of stem elongation and acceleration of senescence caused by O₃ exposure in the present experiment can be explained by ethylene production.

SHIMIZU *et al.*⁴²⁾ investigated the effects of a long-term exposure to low concentrations of SO₂ on the growth of sunflower plants. They found that SO₂ altered the several growth parameters, which suggested some changes in physiological functions in plants. The method of growth analysis seems to be useful to analyze the changes in physiological functions resulting in the changes in growth and yield of plants exposed to an air pollutant and probably to pollutant mixture. However, in order to understand the precise mechanisms of the growth reduction of plants induced by chronic exposures to low concentrations of O₃ and the mechanisms of adaptation of these plants, more direct studies on the effects on physiological phenomena, such as photosynthesis, respiration, enzyme activity, translocation of photosynthate and hormonal balance must be studied. Studies on some of these problems are in progress in our laboratory.

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<和文抄録>

ヒマワリの生長に及ぼすオゾン長期暴露の影響

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一定の環境に制御した人工光型グロースキャビネットで、ロシアヒマワリを播種後14日めから12日間、0.1 ppm および 0.2 ppm のオゾン (O₃) に暴露し、植物の乾物生長に及ぼす O₃ の影響について検討した。O₃ 暴露開始日および6日め、12日めに植物を選出して葉面積、器官別乾重などを測定し、それをもとに生長解析法を用いて生長の各パラメータを算出した。0.1 ppm および 0.2 ppm O₃ によって著しい可視障害が葉面に発現し、下位葉の枯死が促進された。0.1 ppm および 0.2 ppm O₃ は暴露開始後12日めで、植物個体の乾重をおのおの対照より11%、32%減少させた。O₃ 暴露によって各器官とも乾重の増加が抑制されたが、その程度は根で最も大きく、葉で最も小さかった。また葉面積増加も葉乾重増加と同程度に O₃ によって抑制された。生長解析の結果、0.1 ppm O₃ は暴露前半の6日間に植物の相対生長率(RGR)や純同化率(NAR)を対照と比較して減少させたが、後半は減少させなかった。これに対して 0.2 ppm O₃ は暴露期間を通じ RGR や NAR を減少させたが、後半における RGR の減少率は NAR の減少率に比べて小さかった。また 0.2 ppm O₃ は植物の葉面積比(LAR)や葉重比(LWR)を対照より増加させたが、一方莖重比(SWR)や根重比(RWR)を減少させた。これらの結果から、低濃度 O₃ の長期間暴露は植物の純光合成速度や光合成産物の分配率に影響することが示唆された。