Characteristics of tree growth and leaf damage under different O$_3$ concentrations

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Abstract: *Pinus bungeana, Platycladus orientalis, Koelreuteria paniculata* and *Ginkgo biloba* were taken to research. 3 open-top chambers with O$_3$ concentration gradient were set up to study the characteristics of tree growth and leaf damage under different O$_3$ concentrations. The results showed that with the increase of O$_3$ concentration, the growth of different tree species were inhibited, but the diameter between different tree species was not significantly different. The plant height of different tree species the plant height of different tree species increased from 0.05m to 0.06m under NF O$_3$ concentration, from 0.01m to 0.03m under NF40 O$_3$ concentration, but from 0.01m to 0.02m under NF80 O$_3$ concentration. The diameter of different tree species at 50cm increased from 0.90cm to 1.40cm under NF O$_3$ concentration, from 0.70cm to 1.00cm under NF40 O$_3$ concentration, and from 0.60cm to 0.80cm under NF80 O$_3$ concentration. Under NF O$_3$ concentration, the leaves of different tree species performed well, without any damage symptoms. With the increase of O$_3$ concentration, leaves were withered and died. Leaves wilted under NF40 O$_3$ concentration, but died and fallen under NF80 O$_3$ concentration. *Pinus bungeana* and *Platycladus orientalis* were good at resisting O$_3$ pollution, while *Koelreuteria paniculata* and *Ginkgo biloba* were worse. The damage of O$_3$ concentration to plants is more sensitive to broad-leaved trees.

Keywords: O$_3$ concentration; Plant growth; Leaf damage; Growth characteristics.

1. Introduction
In recent years, with the rapid development of global economy and industrialization, the amount of nitrogen oxides, carbon monoxide and hydrocarbons discharged into the atmosphere have increased, which leads to the changes of photochemical O$_3$ (O$_3$) concentration in the troposphere (Karnosky et al.,2004). At the same time, the change of land coverage caused by human activities leads to the decrease of O$_3$ absorption performance on the surface, which leads to the increase of O$_3$ concentration near the surface. It was found that with the rapid development of human activities and industrialization, the near-surface O$_3$ concentration is increasing at the rate of 0.3% to 2% every year, and it was predicted that the
O$_3$ concentration in the troposphere will double by 2100 (Prentice et al., 2001; Liang Jing et al., 2010), by 2025, the average concentration of O$_3$ near the surface of East Asia will reach 70ppb, becoming the most serious O$_3$ pollution area in the world (Lelieveld and Dentener, 2000; Akimoto, 2003). O$_3$ in the near-surface layer, as an important factor affecting global climate change and a secondary pollutant endangering human health and the growth of animals and plants, has been widely concerned (Sitch s et al., 2007; Selin N E et al., 2009). The harm of O$_3$ to the environment has been studied by scholars as early as the last century. When the O$_3$ concentration in the atmosphere $\geq$0.1ppm, the growth of plants is inhibited and early senescence occurs. At first, leaf pores are damaged, and then small spots are produced between the smallest veins on the upper surface of leaves, and their colors can range from light brown to dark brown, even light purple or light red. In severe cases, most of the surfaces of leaves are brown, yellowish or bronze, and the cells in sponge tissue under the leaves will also be damaged. O$_3$ fumigation experiment shows that high concentration O$_3$ can affect photosynthetic rate and physiological and biochemical characteristics of leaves of wheat, rice, rape and other plants, and finally affect biomass (Zhang Hongxing et al., 2014); Lippert et al. (1996) studied the photosynthesis of Picea abies seedlings under the increase of O$_3$ concentration, and found that the photosynthesis of the seedlings decreased obviously. Utriainen and Holopainen (2001) also pointed out that high concentration O$_3$ also inhibited the growth of Pinus sylvestris. Some scholars have also carried out O$_3$ fumigation experiments on the seedlings of Fagus sylvatica, and pointed out that the growth of the seedlings slowed down when O$_3$ treatment with 80 kg kgN·hm$^{-2}$·yr$^{-1}$ was added (Thomas et al., 2006); Wan Wuxing et al. (2013) studied the sensitivity of plants polluted by O$_3$ in the outer suburbs of Beijing, and found that the leaves of different plants had O$_3$ burn characteristics from white to yellow-brown and then to black. Most of the above studies are carried out in natural state, and there are few studies on the damage characteristics and performance of different O$_3$ concentrations to plants under artificial control. Therefore, in this study, Pinus bungeana, Platycladus orientalis, Koelreuteria paniculata and Ginkgo biloba were selected as the research objects, and three O$_3$ gradients were set up to observe the growth status and leaf injury characteristics of plants under different O$_3$ concentrations, and explain the harm of increased O$_3$ concentration to plants, so as to provide reference for O$_3$ prevention and control.

2. Research method

2.1. Situation in the study area
Located at the foot of Xiangshan Mountain, Beijing Botanical Garden is the largest comprehensive botanical garden in Beijing, which can be used for recreation, science, education and scientific research. The whole park covers a large area, 18km away from the urban area. It is located at 39 48 ′ N, 116 28 ′ E, with an altitude of 76m and belongs to temperate continental climate. The average annual temperature is 11.6 ℃, with an average temperature of -3.7 ℃ in January and 26.7 ℃ in July. Extreme high temperature 41.3 ℃, extreme low temperature 17.5 ℃, annual precipitation 634.20 mm, relative humidity 43%~79%. There are more than 6000 types of plants in Beijing Botanical Garden, including trees, shrubs and flowers, aquatic, terrestrial plants with different temperature zones, and a small number of fruit trees. Common tree species here are Pinus tabulaeformis, Platycladus orientalis, Pinus koraiensis, Cedrus deodara, Pinus bungeana, Eucommia ulmoides, Salix babonica, Ginkgo biloba, Sophora japonica, etc. The main shrubs are Ligustrum lucidum, Berberis amurensis, Buxus sinica, Sabina procumbens, Forsythia suspensa, Jasminum nudiflorum, etc.

2.2. Controlled experiment: different O$_3$ concentrations
Open-top (OTC) gas simulation method was adopted, with a total of 3 gas chambers, one of which was the existing OTC, and the other two were designed as simple plastic gas chambers (the length, width and height were 2.6m, 1.5m and 2.2m, respectively). 3 OTCs with different O$_3$ concentrations—NF (normal ambient air O$_3$ concentration), NF40 (normal ambient air O$_3$ concentration add 40 nmol·l$^{-1}$) and NF80 (normal ambient air O$_3$ concentration add 80 nmol·l$^{-1}$), were set up for artificial control pot experiment. The reason and basis for setting different O$_3$ gradient concentrations in this way was that
related studies have found that the threshold value of O$_3$-induced plant damage in conifers such as pine trees was between 150 ppb to 2 times the environmental concentration, while the threshold value of O$_3$-induced plant damage in broad-leaved trees such as ginkgo, poplar and birch was between 60 ppb to 1.4 and 1.7 times the environmental concentration (Zhang, 2011). The environmental O$_3$ concentration in Beijing and Guangzhou was 60 nmol·mol$^{-1}$ (Wang, et al., 2016). Meanwhile, this study refers to the experimental settings of Xinyue (2016) and Niu Junfeng (2012), and set three O$_3$ gradients under the atmospheric O$_3$ concentration in Beijing, adding 40 nmol·mol$^{-1}$ (NF40) to the O$_3$ environmental concentration (NF) After that, it was doubled (NF80), which exceeded the threshold of O$_3$-induced plant damage, but not much. The three O$_3$ concentration gradients gradually increased, and in the controllable range of O$_3$ damage to plants, they also had significant effects on the growth and physiological characteristics of different tree species, so they were set as follows. From August 2016 to October 2017, the experiment was carried out from 9:00 to 16:00 every day. O$_3$ fumigation was carried out on NF40 and NF80 OTCs every two days, and the O$_3$ concentration was controlled by adjusting the O$_3$ amount of O$_3$ generator. The O$_3$ monitor was used to measure the real-time O$_3$ concentration, temperature and humidity data in the gas chambers, and the normal watering management was carried out during the whole experiment. Atmospheric O$_3$ concentration data of normal environment (NF) was obtained from the ambient air quality monitoring station set up in Beijing Botanical Garden in Beijing Environmental Protection Monitoring, where is 300m away from the experimental site.

Three potted seedlings of *Pinus bungeana*, *Platycladus orientalis*, *Koelreuteria paniculata* and *Ginkgo biloba* were placed in each gas chambers, and the seedlings are all 3 years old. The 3-year-old trees are in the early stage of growth and development, which makes the research results more remarkable (Xu et al., 2008; Li et al., 2018). *Pinus bungeana*, *Platycladus orientalis*, *Koelreuteria paniculata* and *Ginkgo biloba* are common landscaping tree species in Beijing. The area of *Platycladus orientalis* ranks second among all tree species in Beijing, and *Pinus bungeana*, as a pine, has strong ability to absorb pollutants and is insensitive to O$_3$. *Koelreuteria paniculata* and *Ginkgo biloba* are sensitive to O$_3$. Choosing these tree species can highlight the results of plant growth and physiological characteristics under different O$_3$ concentrations. The flower pot for seedlings was 40cm in diameter and 50cm in height. Seedling size, crown width, basal diameter and plant height of *Pinus bungeana*, *Platycladus orientalis*, *Koelreuteria paniculata* and *Ginkgo biloba* in different chambers were basically the same. The plant heights of *Pinus bungeana*, *Platycladus orientalis*, *Koelreuteria paniculata* and *Ginkgo biloba* were about 1.3m, 1.35m and 1.4m, respectively.

2.3. Measurement of plant growth status

Potted seedlings of four kinds of trees were distributed and placed in three OTCs, and three trees were placed in each air chamber, 36 test trees in total; There was little difference among different seedlings. The height and diameter at 50cm of each seedling in different OTCs were measured with diameter at breast height ruler at the beginning. After fumigating with O$_3$ for 14 months, the plant height and diameter at 50cm of each seedling in different OTCs were measured again, and the changes in plant height and diameter at 50cm of each seedling under different O$_3$ concentrations were calculated.

2.4. Observation of damage degree of leaves

Observe the leaves of plants and record the change degree of leaf color. Grading was carried out according to the size, quantity and greening degree of the leaf damaged spots, which were observed once every two weeks and recorded, and the injury grade was made according to this (Liu et al., 2015).

Table 1. Leaves damage grade

| Leaves injury rate /% | Damage grade |
|----------------------|--------------|
| 0—15                 | 1            |
| 15—30                | 2            |
| 30—50                | 3            |
| 50—75                | 4            |
| >75                  | 5            |
3. Results and analysis

3.1. Changes of tree height under different O\textsubscript{3} concentrations

The changes of plant height of trees with different O\textsubscript{3} concentrations under artificial control are shown in Figure 1, and different tree species showed the phenomenon of inhibiting tree growth when O\textsubscript{3} concentration rises. Under the control of different O\textsubscript{3} concentrations NF, NF40 and NF80, at the beginning of the experiment, the plant height of Pinus bungeana trees were 1.30m, 1.33m and 1.31m respectively, and at the end of the experiment, they were 1.36m, 1.34m and 1.32m respectively. During the whole experiment, the plant height of Pinus bungeana increased by 0.06m under NF O\textsubscript{3} concentration, but only increased by 0.01m under NF40 and NF80 O\textsubscript{3} concentration. Under NF O\textsubscript{3} concentration, the plant height of Platycladus orientalis increased from 1.36m to 1.41m, which increased by 0.05m, while under NF40 and NF80 O\textsubscript{3} concentration, the plant height only increased by 0.03m and 0.01m; the plant height of Koelreuteria paniculata increased by 0.06m under NF O\textsubscript{3} concentration, but only by 0.02m under NF40 and NF80 O\textsubscript{3} concentration. The plant height of Ginkgo biloba increased by 0.06m under NF O\textsubscript{3} concentration, but only by 0.03m and 0.02m under NF40 and NF80 O\textsubscript{3} concentration. It can be seen that the plant height of different tree species increased at NF O\textsubscript{3} concentration, ranging from 0.05m to 0.06m, while that of different tree species also increased at NF40 O\textsubscript{3} concentration, but the range of increase was very limited, with the added value ranging from 0.01m to 0.03m. Under NF80 O\textsubscript{3} concentration, the plant height of different tree species increased even less, only by 0.01m to 0.02m. This shows that the increase of O\textsubscript{3} concentration is not conducive to the growth of plants, and can inhibit the growth of trees in a certain range. From different tree species, the inhibition of O\textsubscript{3} concentration on trees is not obvious, but there are significant differences among tree species (Table 1, $P<0.05$).

![Figure 1. Tree height variation in different O\textsubscript{3} concentrations](image-url)
Table 1 is the variance analysis of plant height of trees with different \( \text{O}_3 \) concentrations. After repeated two-factor analysis, the results showed that the difference of plant height of trees with different \( \text{O}_3 \) concentrations was statistically significant (\( P < 0.05 \)). The values of F-crit among tree species and \( \text{O}_3 \) concentrations were 3.74 and 2.76 respectively, which were lower than the F values of 4.87 and 39.11 respectively. This showed that the changes of plant height of trees with different \( \text{O}_3 \) concentrations were significant among tree species and \( \text{O}_3 \) concentrations.

Table 2 Variance analysis of tree height in different \( \text{O}_3 \) concentrations

| Difference source | SS   | df | MS   | F    | P-value | F crit |
|-------------------|------|----|------|------|---------|--------|
| Tree species      | 0.005| 2  | 0.003| 4.87 | 0.025   | 3.74   |
| \( \text{O}_3 \) concentrations | 0.14 | 7  | 0.023| 39.11| <0.001  | 2.76   |
| Errors            | 0.007| 14 | 0.0005|      |         |        |
| Sum               | 0.15 | 23 |      |      |         |        |

3.2. Variation in tree diameter with different \( \text{O}_3 \) concentration

The diameter changes of trees at 50cm under different \( \text{O}_3 \) concentrations are shown in Figure 2. The diameters of \textit{Pinus bungeana} at 50cm were 3.00cm, 3.40cm and 3.00cm under the control of different \( \text{O}_3 \) concentrations NF, NF40 and NF80 at the initial stage of the experiment, and 4.10cm, 4.10cm and 3.60cm at the end of the experiment. During the whole experiment, the diameter of \textit{Pinus bungeana} increased by 1.10cm at 50cm under NF \( \text{O}_3 \) concentration, but only increased by 0.70cm and 0.60cm at 50cm under NF40 and NF80 \( \text{O}_3 \) concentration. The diameter of \textit{Platycladus orientalis} at 50cm under NF \( \text{O}_3 \) concentration increased by 0.09cm from 2.90cm at the beginning of the experiment to 3.80cm at the end of the experiment, but only increased by 0.70cm and 0.60cm at 50cm under NF40 and NF80 \( \text{O}_3 \) concentration. The diameter of \textit{Koelreuteria paniculata} increased by 1.40cm at 50cm under NF \( \text{O}_3 \) concentration, and increased by 0.80 cm and 0.70 cm; at 50cm under NF40 and NF80 \( \text{O}_3 \) concentration. The diameter of \textit{Ginkgo biloba} at 50cm increased by 1.20cm under NF \( \text{O}_3 \) concentration, but only increased by 1.00cm and 0.80cm under NF40 and NF80 \( \text{O}_3 \) concentration. It could be seen that the diameters of different tree species at 50cm have increased at NF \( \text{O}_3 \) concentration, ranging from 0.90 cm to 1.40 m, while the diameters of different tree species at 50cm have also increased at NF40 \( \text{O}_3 \) concentration, but the range of increase is very limited, with the increase value ranging from 0.70 cm to 1.00 cm. Under NF80 \( \text{O}_3 \) concentration, the diameter of different tree species at 50cm have increased even less, only by 0.60 cm. This showed that the increase of \( \text{O}_3 \) concentration can inhibit the growth of trees. From different tree species, the inhibition of \( \text{O}_3 \) concentration is not obvious, and there is no significant difference in diameter between different tree species (Table 4-2, \( P > 0.05 \)).

Table 3 is the variance analysis of diameter at 50cm of trees with different \( \text{O}_3 \) concentrations. After repeated two-factor analysis, the results show that the diameter at 50cm of trees with different \( \text{O}_3 \) concentrations has no statistical significance among tree species (\( P=0.08, P > 0.05 \)), but has statistical significance among \( \text{O}_3 \) concentrations (\( P=0.001, P < 0.05 \)), and the F-crit value is between tree species and \( \text{O}_3 \) concentrations. The F-crit is larger than the f value (4.42) among tree species and smaller than the f value (18.98) among \( \text{O}_3 \) concentrations, which indicates that the diameter change at 50cm of trees with different \( \text{O}_3 \) concentrations is not significant among tree species, but significant among \( \text{O}_3 \) concentrations, which also indicates that the increase of \( \text{O}_3 \) concentration has little effect on the diameter change among different tree species.
Figure 2 Variation of 50cm diameter of trees in different O₃ concentrations

Table 3. Variance analysis of 50cm diameter of trees in different O₃ concentrations

| Difference source   | SS   | df  | MS   | F      | P-value | F crit |
|---------------------|------|-----|------|--------|---------|--------|
| Tree species        | 0.14 | 1   | 0.14 | 4.42   | 0.08    | 5.99   |
| O₃ concentrations   | 3.61 | 6   | 0.60 | 18.98  | 0.001   | 4.28   |
| Errors              | 0.19 | 6   | 0.03 |        |         |        |
| Sum                 | 3.94 | 13  |      |        |         |        |

3.3. Characteristics of leaves damage with different O₃ concentrations

The change characteristics of tree leaves with different O₃ concentrations are shown in Figure 3. The leaves of different tree species were in good condition under NF O₃ concentration, and the leaves did not have any injury symptoms. With the increase of O₃ concentration, leaves withered and died, leaves wilted under NF40 O₃ concentration, and leaves wilted, died and fallen under NF80 O₃ concentration. The changes of leaf injury characteristics of trees with different O₃ concentrations under manual control are shown in Table 3. The sensitivity of different tree species to the increase of O₃ concentration were quite different: under NF O₃ concentration, the leaves of different tree species do not have any yellowing
and death, and the leaves basically grow normally, and the leaf injury rates were equal to level 0, all of which were in the level of no injury. Under the O$_3$ concentration of NF40, the leaves of different tree species began to turn yellow and wilted, especially in Koelreuteria paniculata and Ginkgo biloba. The injury rates of Pinus bungeana and Platycladus orientalis were 1% and 10% respectively, and the injury grades were all Grade 1. The leaf injury rates of Koelreuteria paniculata and Ginkgo biloba were 78% and 53%, and the injury grades were 5 and 3 respectively. Under NF80 O$_3$ concentration, a large number of tree species died, especially Koelreuteria paniculata, and Pinus bungeana and Platycladus orientalis were relatively light. The leaf injury rates of Pinus bungeana and Platycladus orientalis were 8% and 16% respectively, and the injury grades were grade 1 and 2 respectively. The leaf injury rates of Koelreuteria paniculata and Ginkgo biloba were 92% and 76%, respectively, and the injury grades were 5. This showed that Pinus bungeana and Platycladus orientalis have stronger ability to resist O$_3$ pollution, and Pinus bungeana is stronger than Platycladus orientalis; Koelreuteria paniculata and Ginkgo biloba have weak ability to resist O$_3$ pollution, and Koelreuteria paniculata has the weakest ability to resist O$_3$ pollution.

| Tree species       | NF    | NF40 | NF80 |
|-------------------|-------|------|------|
| Pinus bungeana    | ![Image](image1) | ![Image](image2) | ![Image](image3) |
| Platycladus orientalis | ![Image](image4) | ![Image](image5) | ![Image](image6) |
| Koelreuteria paniculata | ![Image](image7) | ![Image](image8) | ![Image](image9) |
| Ginkgo biloba     | ![Image](image10) | ![Image](image11) | ![Image](image12) |

**Figure.3** Leaf changes of trees with different O$_3$ concentrations
Table 4. Damage characteristics of different O$_3$ exposure effects in leaves

| Tree species          | O$_3$ concentration | Damage characteristics                                                                 | Damage ratio /% | Damage grade |
|-----------------------|---------------------|----------------------------------------------------------------------------------------|-----------------|-------------|
| Pinus bungeana        | NF                  | Leaves were not damaged, and no symptoms of etiolation and death                        | 0               | 0           |
|                       | NF40                | Leaves were basically unchanged, and they were no symptoms of etiolation and death      | 1               | 1           |
|                       | NF80                | A few of leaves showed yellowing symptoms, and the old leaves were yellowing and died   | 8               | 1           |
| Platycladus orientalis| NF                  | Leaves were not damaged, and there were not yellowing and died                          | 0               | 0           |
|                       | NF40                | Very few leaves turn yellow, and some old leaves had etiolation                       | 10              | 1           |
|                       | NF80                | A few old leaves began to show symptoms of etiolation and death                        | 16              | 2           |
| Koelreuteria paniculata| NF                  | Leaves were not damaged, and no symptoms of etiolation and death                      | 0               | 0           |
|                       | NF40                | Almost all leaves wilted and some leaves died                                           | 78              | 5           |
|                       | NF80                | A large number of leaves withered and died                                              | 92              | 5           |
| Ginkgo biloba         | NF                  | Leaves were not damaged, and there were not yellowing and died                          | 0               | 0           |
|                       | NF40                | Leaves turned yellow, and the tip of them began to wither                               | 53              | 3           |
|                       | NF80                | The leaves of the whole plant wither in a large area, and the degree of etiolation was further serious | 76              | 5           |

4. Discussion

High concentration O$_3$ stress inhibited the growth of trees, resulting in the decline of tree biomass and the change of distribution ratio between aboveground and underground parts (Niu, 2012; Wittig et al., 2009). Under the control of atmospheric carbon dioxide, one-year-old hybrid poplar (*Populus tremula*×*P. tremuloides*) has been growing for 2 years at 1.5 times of atmospheric O$_3$ concentration. The results show that the height of one-year-old experimental seedlings has decreased by 20% and 17%, respectively, and the stem dry weight has decreased by 5%, and the root dry weight has decreased by 20% (Niu, 2012; Häikiö et al., 2007); The leaf area growth of Betula pendula seedlings decreased by 36%, and the plant height and basal diameter growth decreased by 15% and 20%, respectively, under the treatment of 1.4-1.7 times atmospheric O$_3$ concentration for six consecutive growth seasons (May 1996-October 2001) (Niu, 2012; Oksanen, 2003); The research on 3-year-old Pinus sylvestris seedlings also showed that the basal diameter growth, stem dry weight accumulation and root dry weight accumulation of the experimental seedlings decreased by 9%, 17% and 19%, respectively, under 1.5-1.6 times atmospheric O$_3$ concentration (Niu, 2012; Utriainen and Holopainen, 2001). Meta-analysis results show that the current near-surface O$_3$ (40 ppb) causes the ratio of underground biomass to aboveground biomass of forest tree species to decrease by about 3% in the middle and high latitudes of the northern hemisphere (Wittig et al., 2009). This study also shows that the increase of O$_3$ slows down the growth rate of plant height and diameter of *Pinus bungeana* and *Koelreuteria paniculata*, and plants grow faster under normal environmental O$_3$ concentration. There are differences in the growth and
slowing down speed of different tree species diameters, which is due to the different sensitivity of different plants to O₃, and the sensitivity is influenced by the plant characteristics and environmental factors (Zhang, et al., 2014; Xu, et al., 2007), which is consistent with the research results of Wan et al. (2013).

The increase of O₃ concentration can inhibit the growth of trees, and also damage the leaves of trees. The visible injury symptoms of leaves are caused by O₃ entering into tissue cells through the open stomata of the lower epidermis of leaves and reacting with substances on the cell wall and plasma membrane (Fu, et al., 2014; Karnosky D F et al.,2007). When plant leaves are damaged by O₃, the most typical feature is that some yellow-brown or brown spots appear on local leaves (Donnelly et al, 2001; Fowler et al, 2008), some of these patches are yellow-brown and some are brown, and different tree species show different color patches. With the growth of plants with high O₃ concentration, the symptoms of leaf injury will gradually spread to the whole leaf, which will lead to an increase in the number of epidermal necrotic plaques and the area of injured plaques, until the necrotic plaques cover the upper surface of the whole leaf, but the lower surface of the leaves is not affected much, and everything is normal. If the plants are exposed to high O₃ concentration for a long time, the leaves of the whole tree will lose water in a large area until they die, eventually causing the leaves to fall off. Liu et al. (2015) set up three gradient O₃ observation chambers, and found that under the condition of high concentration O₃ (200 ppb-300 ppb), the old leaves were damaged first, then the mature leaves, and the new leaves were less damaged; At the same time, it was found that Pinus tabulaeformis was basically harmless at O₃ concentration of 200ppb, but slightly damaged at O₃ concentration of 300ppb, which indicated that Pinus tabulaeformis had strong O₃ resistance, which was consistent with the result that Pinus bungeana, as the representative of conifers, was lightly damaged by O₃ in this study. In European studies, it was found that with the increase of O₃ concentration, more than half of the 65 species showed wilting leaves, yellow leaves and withering in severe cases, but conifers had strong tolerance and low sensitivity to injury (Lie et al., 2014; Timonen et al.,2004); In this study, the leaf injury rates of Pinus bungeana were 1% and 8% under the O₃ concentration of NF40 and NF80, respectively, both of which were grade 1, which indicated that the leaf injury degree of Pinus bungeana was low and proved the strong O₃ tolerance of conifers. The leaf injury rates of Koelreuteria paniculata under the O₃ concentrations of NF40 and NF80 are 78% and 92%, respectively, both of which are of Grade 5, indicating that Koelreuteria paniculata is extremely sensitive to O₃ and has poor tolerance to O₃, which is determined by the characteristics of tree species. As a broad-leaved tree species, Koelreuteria paniculata grows faster and has a higher O₃ absorption rate than conifers such as Pinus bungeana (Mannines et al., 2003), so it is sensitive to O₃.

5. Conclusion

Different tree species inhibit tree growth when O₃ concentration increases. Plant height and diameter at 50cm increase slowly when O₃ concentration increases, and there is no significant difference in diameter between different tree species when O₃ concentration increases. Under the concentration of NF O₃, the leaves of different tree species all performed well without any injury symptoms. With the increase of O₃ concentration, leaves withered and died, leaves wilted under NF40 O₃ concentration, and leaves wilted, died and fallen under NF80 O₃ concentration. Pinus bungeana and Platycladus orientalis have stronger ability to resist O₃ pollution, while Koelreuteria paniculata and Ginkgo biloba have weaker ability to resist O₃ pollution. The damage of O₃ concentration to plants is more sensitive to broad-leaved trees.

Acknowledgements

This work was financially supported by Youth fund of Beijing Academy of Agricultural and Forestry Sciences(QNJJ202017), President fund of Beijing Academy of Forestry and Pomology Sciences(201903), National Natural Science Foundation of China (31500352),Hunan forestry science and Technology Innovation Fund Project (XLK202103-1, HNGYL-2020-1),and Forestry Science and Technology Plan Project in Hunan (Construction and monitoring of large sample plot of natural forest).
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