Chapter

# Vigor and Health of Urban Green Resources under Elevated $O_3$ in Far East Asia

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## Abstract

Conservation of urban greens is an essential action for city residents, however, declining symptoms and/or traces in the annual ring of trees grown are found in parks and forest stands in a city as well as its suburb with a high level of ozone ($O_3$). Urban greens, including roof-green, provide comfortable conditions for the people and a moderate environment in a city. They are exposed to severe environments; heat, drought, air-pollutions, etc. even with intensive management of the people. How can we proceed with the conservation and wise use of urban greens? We should know the ecophysiological responses of urban trees to such a global environment as well as a local one. Defensive capacities of urban greens should be analyzed in terms of damages caused by biotic and abiotic stresses, and it is important to understand their interactions from the viewpoint of plant-insect/disease. There is a concern that some green areas are suffering from an outbreak of insects and diseases, reducing the vigor and health of urban greens. We discuss these based on specific examples, such as man-made forests, in cities in far east Asia for considering our approach to how to keep urban green resources.

**Keywords:** urban green, plant-insect interaction, ground-level Ozone ($O_3$), nitrogen dioxide ($NO_2$), heat island

## 1. Introduction

Air pollution has been considered as the most serious environmental problem for human health, associated with some million deaths worldwide per year. Among them, SOx was eliminated by desulfurization equipment in factories, however, nitrogen oxides ($NO_x = NO+NO_2$) have not well regulated. As $NO_2$ is one of the precursors of $O_3$, emission of $NO_2$ in Asia is estimated to be about four times higher than that of Europa and the U.S.A. [1–5]. Carbon dioxide ($CO_2$) increases global warming and increasing tropospheric $O_3$ are important global environmental issues today [18]. Cities have to cope with the challenges derived from poor air quality impacting the well-being of human health and citizen.

China has implemented various policies and measures to control air pollution and promote urban greening as well as forest rehabilitation since 1999 [7]. In 2004, China officially launched the construction of national forest cities, and gradually promoted and organized the construction of forest cities on a large scale across the country as proposed by the Chinese leader, Mr. JP Xi (2016). In 2019, forest city construction was included in Chinese Law as a legal guarantee for land greening and its protection. Urban greens, such as avenue trees and park trees, provide comfortable conditions for city residents, and a moderate environment in megacities in China [8] and in Japan [9, 10], and in small cities in Europe [11]. To efficiently reduce $O_3$ in cities, it is important to define suitable urban forest management, including proper species selection, with a focus on the reduction ability of $O_3$ via flux data [12, 13], and other air pollutants, such as PM [14–17], biogenic emission rates, allergenic effects [18] and maintenance requirements.

An epidemiological investigation is the most objective and practical method to determine the degree of $O_3$ damage by investigating the typical characteristics of $O_3$ damage to plants in the natural environment [19, 20]. The highest $O_3$ concentrations primarily occurred in July and August in northern China and the central part of Japan [21–23], and in September or April and May in southern China [23–26], in April–June in northern Japan [21]. Ozone causes cellular damage in plants, reducing stomatal control, lower $CO_2$ assimilation rates, and the occurrence of visible leaf injury [9, 27, 28]. These effects often accelerate senescence, diminish green leaf area and biomass, allocation of photosynthates to roots [29] and reduce photosynthetic capacity [28, 30, 31]. The investigation of visible injury of $O_3$ to the urban forest can not only judge whether the current concentration of $O_3$ in the air has reached the level harmful to the urban plants (e.g., [32]), but also determine the situation of urban exposure to $O_3$ pollution, and provide objective evidence for plant sensitivity evaluation [29].

Plants of green-roof are exposed to severe environments; heat, drought, PM, air-pollutions, etc. even with intensive management of the people [11, 33, 34]. There are many factors reducing the vigor and health of trees in avenue, parks, and suburban forests, etc. With the aggravation of $O_3$ pollution in urban air, the number of injured plant species in urban vegetation increased significantly, and the vitality of urban green resources was affected. Study shows that most plant functional types suffer a substantial decline in LAI as $O_3$ level increases [35]. Studies on the effects of $O_3$ on plants commonly used the following methods: manipulative exposure experiment: $O_3$-FACE) and epidemiological investigation (e.g., [9]). The effects of single or mixed pollutants on plant functional traits were studied through controlled experiments, such as OTC or artificial fumigation, to judge the resistance/sensitivity of plants to single pollutants [36] and multiple stresses.

We should know more about the negative effects of elevated $O_3$ on environmental conditions for plants as well as residents in big cities and surrounding areas through supporting service of ecological services; that is, plant primary productivities and nutrient cycling [37]. Moreover, we should consider biodiversity conservation, including plant-insect interactions for our future resources (e.g., pollination) as affected by elevated $O_3$ (e.g., [38–43]).

For accessing the methods of improving environmental conditions in cities and the vicinities, we state the role of urban green, declining symptoms, ecosystem vigor and health of big cities, especially under increasing ground-level $O_3$ and its dynamics. We showed the effects of environmental changes derived from elevated $O_3$ and other environmental factors on the heath and vigor of green infrastructure. Based on this evidence, we discussed a plausible understanding of the construction and maintenance of urban greening. Moreover, to attain the international Sustainable Development Goals (SDGs), the interactions in urban and suburban greens should be better understood to maintain the green infrastructure.

## 2. Role of urban green

### 2.1 A cool island

Urban greenness is essential for people's daily lives, while its contribution to air quality control is unclear. Green-roof is recently popular in big cities for moderating heat island phenomena through canopy transpiration, offering shade, and water management [44] even in cool climate regions. Some green-roof consist of vegetable garden for fun people and to inspire motivation of management. The mitigation effects of green spaces in urban areas are clearly observed as a role of the cool island [45, 46]. These imply the accumulation of a cold air mass in the park and its gravitational flow-out into the surrounding area. This practice of urban greenness is also found in Sapporo, northern Japan **(Figure 1).**

The expansion of an urban tree canopy is a commonly proposed nature-based solution to combat the excess urban heat-island problem. The influence of trees on urban climates via shading is driven by the morphological characteristics of trees, whereas tree transpiration is predominantly a physiological process dependent on environmental conditions and the built environment. The heterogeneous nature of urban landscapes, unique tree species (including vegetable crops) assemblages (**Figure 2**), and land management decisions make it difficult to predict the magnitude and direction of cooling by transpiration [48].

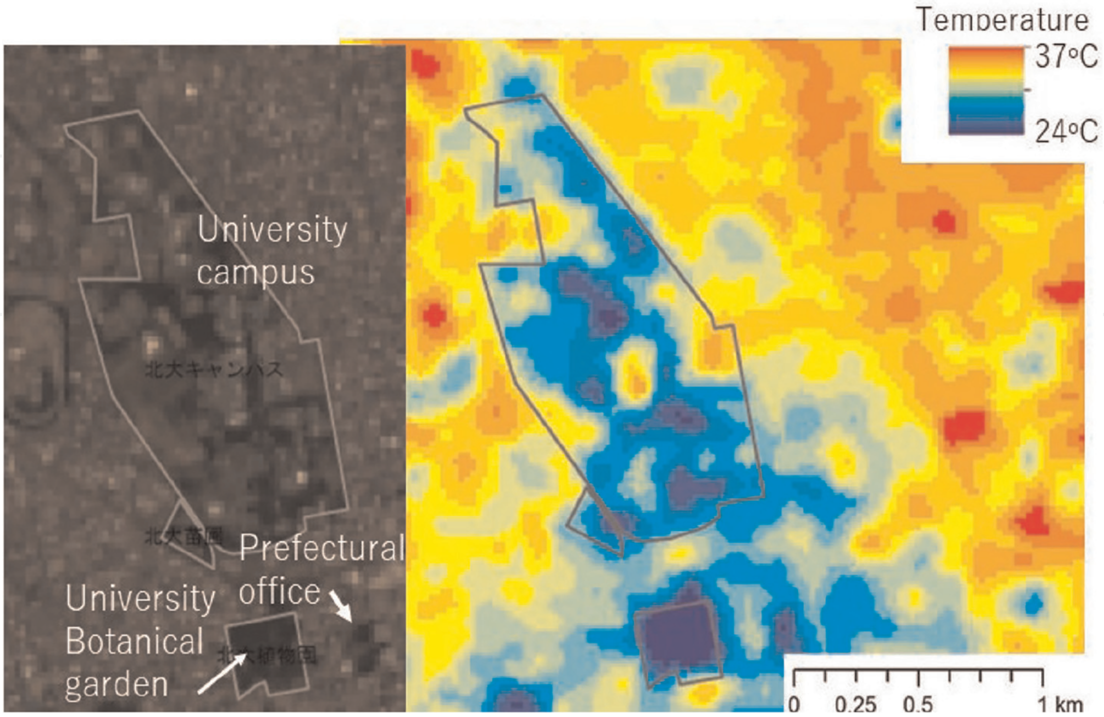


**Figure 1.**
*Thermal image in Sapporo city center with green areas and their vicinity via the Landsat data (12 July 2015), offered Dr. H. Tani and the courtesy of Kyoritsu Publisher, Tokyo [47].*

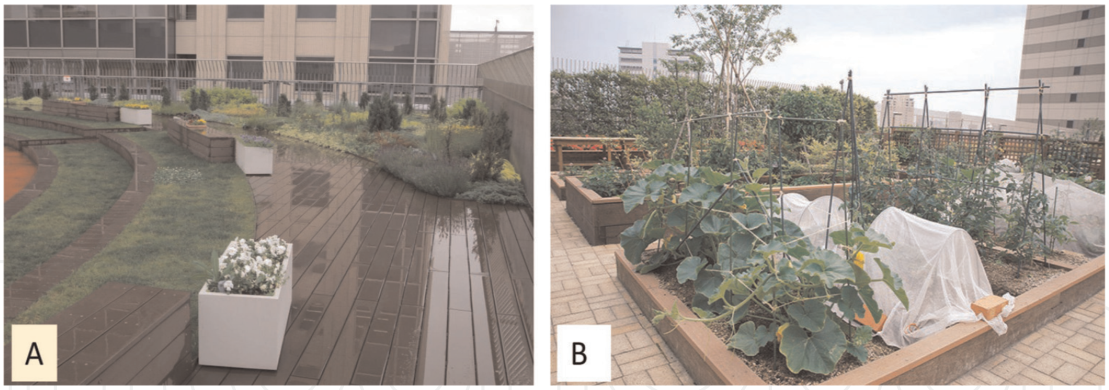


**Figure 2.**
*Roof green with perennial plants and shrubs in Sapporo where we have heavy snow (A), and vegetable garden with small shade trees near the railway station in Tokyo (B) taken by T. Koike.*

The Bowen ratios showed clearly the essential role of evaluation of transpiration capacity of urban tree canopy for moderating heat in a city. In this sense, we should keep the vigor and health of the green area in urban and suburban regions with high $O_3$ tolerance and also with $O_3$-sensitive plant species.

Ozone is a strong oxidative gas, and is not a substrate of plant physiological processes, but is an intensive stressor. We employ $O_3$-sensitive plants, such as morning glory (*Ipomoea nil*), as a biological indicator for avoiding $O_3$ stresses in a city [49]. As green area (trees and shrubs) has a high capacity for improvement of $O_3$ that is detected by flux monitoring [12, 50, 51], the green area has higher removal capacity (3.4 g $m^{-2}$ $yr.^{-1}$ on average) than green roofs (2.9 g $m^{-2}$ $yr.^{-1}$ as average removal rate), with lower installation and maintenance costs [13]. To overcome present gaps and uncertainties, they proposed a novel species air quality index (S-AQI) of suitability to air quality improvement for tree/shrub species. We recommend city planners to select species with an S-AQI > 8, that is, with high $O_3$ removal capacity, $O_3$-tolerant (e.g., [34, 52, 53]), non-emitting species of BVOC as a precoucer of $O_3$ [18], resistant to pests and diseases [38], tolerant to drought and non-allergenic plants. Consequently, green roofs can be used to supplement urban trees in improving air quality in cities.

### 2.2 The decline of urban and suburb green resources

With the effective promotion of national energy conservation and emission reduction measures, air pollution in China has been reduced [54].

Similar to most already-industrialized countries, China is now shifting away from $SO_2$-dominated to NOx- and $O_3$-dominated air pollution [55]. According to the bulletin on ecological and environmental conditions of China in 2019, the average $O_3$ concentration in China in 2019 was the highest in the past 5 years (148 $\mu g \cdot m^{-3}$), 20% higher than that in 2015, and the range of areas with high $O_3$ concentration was also expanding. Measurements from the national network for monitoring air pollutants show severe and worsening $O_3$ pollution in many areas, particularly the densely populated regions like Beijing-Tianjin-Hebei metropolitan area, YRD, PRD, etc. [56] (**Figure 3**). Beijing and its surrounding areas are typical composite pollution areas in North China, and the pollution degree has an obvious suburban

**Figure 3.**
*Representative cities and districts in east Asia YRD Yangtze River Delta PRD: Pearl River Delta economic zone.*

gradient in somewhat [57–59], and plants have been threatened by high $O_3$ concentration [23, 60].

Although ground-level ozone ($O_3$) concentrations are expected to increase over the twenty-first century, especially in east Asia, with increasing $NO_2$ [4, 5].

### 2.2.1 Forest stand scale

In the $O_3$-sensitive beech forest as suggested by screening data of 18 tree seedling-scale by OTCs [34] (**Table 1**), we revealed earlier autumn senescence caused by elevated $O_3$ had already started, which was not found in the $O_3$-tolerant oak forests [12]. Ozone flux-based risk assessment was performed with the use of flux towers of carbon sequestration capacity in old temperate forests in Japan; pure forests of Siebold's beech vs. mixed evergreen and deciduous forests dominated by Konara oak (*Quercus serrata*).

Higher phytotoxic $O_3$-dose above a threshold of 0 uptake (POD-0) with higher canopy stomatal conductance (Gs) was observed in the beech forest than that in the oak forest. Light-saturated gross photosynthesis declined earlier in the late growing season with increasing POD-0.

The Tanzawa mountain range is located in the southwestern part of the region of Tokyo metropolis of Japan, and provides recreation activities to the residents of big cities. Dominate tree species are Siebold's beech forests are distributed in the high-elevation areas but have declined significantly. Recent ozone monitoring data suggest

| $O_3$ Sensitivity | Leaf habit | Leaf growth | Species |
|---|---|---|---|
| **High (sensitive to $O_3$)** | Broad-leaved | Deciduous | *Populus maximowiczii, Populus nigra,* **Siebold's beech** (*Fagus crenata*), Japanese zelkova (*Zelkova serrata*) |
| | | Evergreen | *Castanopsis sieboldii* |
| | Coniferous | Deciduous | Japanese larch (*Larix kaempferi*) |
| | | Evergreen | Japanese red pine (*Pinus densiflora*) |
| **Moderate** | Broad-leaved | Deciduous | **Japanese white birch** (*Betula platyphylla* var. *japonica*),*Quercus serrata* |
| | | Evergreen | *Quercus myrsinaefolia*, Camphora (*Cinamomum camphora)* |
| | Coniferous | Evergreen | Nikko fir (*Abies homolepis*) |
| **Low (tolerant to $O_3$)** | Broad-leaved | Deciduous | **Mizunara oak** (*Quercus mongolica* var. *crispula*) |
| | | Evergreen | *Lithocarpus edulis, Machilus thunbergii* |
| | Coniferous | Evergreen | Japanese black pine (*Pinus thunbergii*), Sugi cedar (*Cryptomeria japonica*), Hinoki cypress (*Chamaecyparis obtuse*) |

*Adaptation from Yamaguchi et al. [34]. Bold means materials in Shi et al. [61] in section 4.*

**Table 1.**
*Classification of Japanese forest tree seedlings to $O_{3-}$ sensitivity obtained from the OTC.*

that high ozone concentrations (<100 ppb) may be a possible chronic cause of the loss of beech vitality started in 1980 days to date [62, 63].

### 2.2.2 Street landscape

Recently, efficient use of internet data offered an outline of the health and vigor of urban green in relation to air quality data (Air Quality Index: $PM_{2.5}$, $PM_{10}$, $SO_2$, $NO_2$, CO, and $O_3$) from 206 monitoring stations from 27 provincial capital cities in China [23–26]. Over 90% of air quality variation could be explained by socio-economics and geo-climates, suggesting that air quality control in China should first reduce efflux from social economics, while geo-climatic-oriented ventilation facilitation design is also critical. Pooled-data analysis at the national level showed that street-view greenness was responsible for 2.3% of the air quality variations in the summer and 3.6% in the winter; however, when separated into different regions, the explaining power increased to 16.2% at best. For different air quality components, greenness had the most significant associations with $NO_2$, CO, and $O_3$, and the street-view/bird-view ratio was the most powerful indicator of all greenness parameters. Large inter-city variations were observed in all the greenness parameters, and the weak associations between all street-view parameters and bird-eye greenspace percentage (21–73%) indicate their representatives of different aspects of green infrastructures.

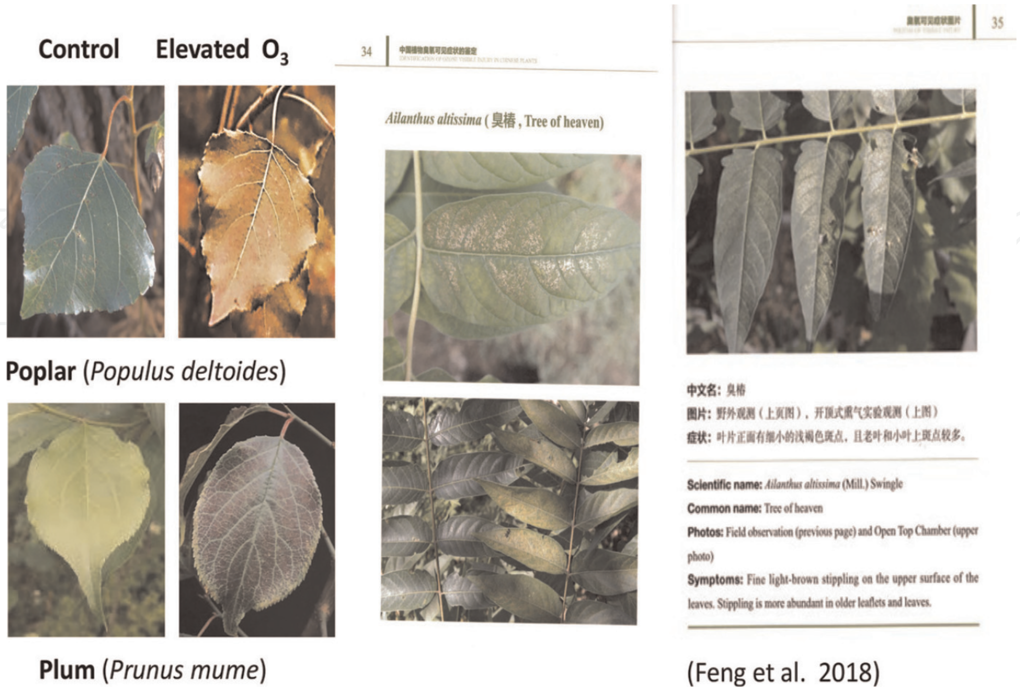
Another assessment is shown in the traditional method of dendrochronology [64]. Urban tree growth is often affected by higher temperatures, reduced water availability, small and compacted planting pits like many avenue trees, as well as pollution inputs. Despite these reducing growth conditions, recent studies found a better growth of urban trees compared to trees at rural sites with high $O_3$, and enhanced growth of trees in recent times as shown in poplar [65]. Sakhalin fir (*Abies sachalinensis*) trees growing in urban vs. rural (or suburb) sites in Sapporo, northern

Japan analyzed the growth differences between growing sites and the effects of the pollution (e.g., $NO_X$, $SO_2$, and $O_X$, etc.) on tree growth (cf. **Table 1**). When exhaust gas of diesel cars circulates between urban areas and suburbs, the following chemical reactions occur: in the urban area; NO (from diesel cars) + $O_3 \rightleftharpoons$ (Ultraviolet ray) $\rightarrow NO_2$ [65]. Moreover, environmental conditions seem to positively affect tree growth, though with the exception of $O_3$, which had strong negative correlations with growth.

### *2.2.3 Foliar $O_3$ symptoms*

Symptoms of $O_3$ injury had been observed at different levels in several plant species. The presence of foliar symptoms does not necessarily imply that there are significant effects on growth, yield or reproduction. Visible injury symptoms in bio-indicator plants are more perceptible and comprehensible for laymen than air pollution concentrations, which may help to enhance the environmental awareness to the general public. Therefore, it is an effective way to monitor the $O_3$ risk in urban and regional areas by investigating the typical characteristics of $O_3$ injury on plants as well as the street view [23–26]. These studies have identified sensitive species that could contribute to further investigated under controlled conditions.

The growth and physiological response of plants exposed to high concentrations of $O_3$ for a long time can reflect the degree of atmospheric $O_3$ pollution. Ozone levels in Beijing area were high enough to induce foliar symptoms by the year of 2021 at least, injury has been observing in different species [8, 60, 66, 67]. Visible injury was investigated on July and August in the main parks, mountainous and plain areas. The typical symptoms of the $O_3$ foliar injury are dark stipple, mottling and tip burn [66]. Some examples of typical symptom are illustrated as an atlas (**Figure 4**).



*Ailanthus altissima* (臭椿, Tree of heaven)

中文名：臭椿
图片：野外观测（上页图），开顶式熏气实验观测（上图）
症状：叶片正面有细小的浅褐色斑点，且老叶和小叶上斑点较多。

**Scientific name:** *Ailanthus altissima* (Mill.) Swingle
**Common name:** Tree of heaven
**Photos:** Field observation (previous page) and Open Top Chamber (upper photo)
**Symptoms:** Fine light-brown stippling on the upper surface of the leaves. Stippling is more abundant in older leaflets and leaves.

**Figure 4.**
*Examples of damaged leaves of trees in a big city polluted with ozone. Photos of poplar and plum are cited from Nouchi [49], and tree of heaven is cited from Feng et al. [52, 53], the handbook for diagnosing $O_3$ damages of Chinese avenue and park trees.*

Sensitive plants exposed to $O_3$ pollution usually show symptoms of visible leaf injury (ICP-Forest; [68]); most of them were surveyed on the basis of the Forest Health Expert Advisory System [69]. In recent years, foliar $O_3$ symptoms on plants were studied in Beijing, Hebei, Nanchang, and the surrounding areas of field investigations following the procedures for $O_3$ symptoms ([8, 60, 66, 67, 70]; and [71]).

Symptoms were more frequent in rural areas and mountains in northern Beijing, downwind from the city, and less frequent in city gardens [8]. *Ailanthus altissima* (Tree of heaven) is considered as the best bio-indicator tree for the Beijing area, because it is a native tree species with wide distribution, and symptoms of $O_3$ injury are easy to characterize. Similar investigations of $O_3$ damage symptoms on plant leaves were also carried out in Hebei Province. *Buxus megistophylla* was most frequently investigated and its injury symptoms of it were easy to be characterized, which will good to be used as an indicator species for ambient $O_3$ pollution in this region [71]. The other investigation in Nanchang city in Jiangxi province, which can represent subtropical urban areas in China, find that the $O_3$ concentration of suburban regions was significantly higher than in urban and exurban regions [70] (cf. **Figure 2**). The highest average $O_3$ concentration occurred in June at 40 ppb (AOT40 = 35.5 mg $m^{-3}$ $h^{-1}$), well over the threshold considered (19.6 mg $m^{-3}$ $h^{-1}$) to exert negative influences on the growth of wild plants. *Cerasus yedoensis*, *Phoebe shearer*, *P. bournei,* and *Litsea cubeba* might work as bio-indicators of ozone pollution in Nanchang [70].

Ozone stress in plants is recognized as a visible symptom of leaves at various levels of $O_3$ in the atmosphere [32, 52, 53 and 72]. How can we obtain a bigger scale from individual tree scale to town scale? A typical example is recently reported in China with the use of big internet data [23–26]. They could identify the association between greenness and air pollution from a street view scale, which can favor urban greenness management and evaluation in other regions where street-view data are available. Urban forests play a vital role in terms of environmental quality related to particulate matter (PM including black carbon: BC) and studies on this area are increasing [73, 74]. The PM analyzes were divided into vertical and lateral directions at the stand scale [14]. The PM removal capacity of different vegetation types was usually in the following order: coniferous forest > evergreen forest > deciduous forest as related to foliar shape and longevity. Therefore, multi-scale analyzes on the effects of PM could help to better understand the roles of urban forests as a complex system.

## 3. Ozone and other environmental stress factors

The singly or combined effects of elevated $O_3$ on woody plants and surroundings were investigated using manipulative exposure experiment OTCs or $O_3$-FACE. Feng et al. [52, 53] integrated the results of 46 current $O_3$ fumigation experiments on 61 woody plants in OTCs in China. Net photosynthetic rate, growth index, and biomass of woody plants are affected by elevated $O_3$, showed varying degrees of reduction (**Figure 5**). Drought, high nutrients, temperature stress, and tropospheric $O_3$ pollution often co-occur in urban areas, adversely affecting urban plant health. Another experimental comprehensively analyzed the adsorption and absorption capacity of 537 species of plants in common urban forests in China to six kinds of air pollutants, namely, $SO_2$, NOx, freon (F), chlorine (Cl), $O_3$ and PM, six tree species with strong comprehensive tolerance to air pollutants were selected [75].

Identify possible indicators for $O_3$ sensitivity in woody plant species that could be useful for improving risk assessment and selecting appropriate species for urban

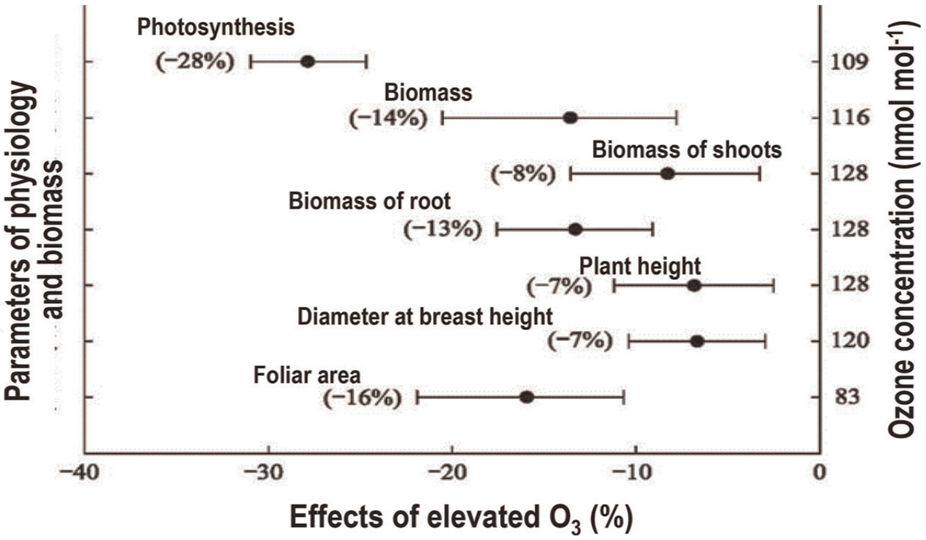


**Figure 5.**
*Effects of elevated $O_3$ concentrations on net photosynthetic rate, growth index, and biomass of woody plants in China (Adapted from a meta-analysis by [52, 53]).*

greening in areas with high $O_3$ levels. It seems feasible to plant tree species that are less sensitive to $O_3$ exposure, particularly in urban areas.

### 3.1 Heat

The combined impacts of air warming and $O_3$ on phenology and its functional traits are still not well illustrated for urban trees and roof green, including root crops (radish) on mini-farmland on buildings (cf. **Figure 2**) are still poorly understood. The reduction in the growth of radish (*Raphanus sativus* var. *sativus*) caused by elevated $O_3$ was accelerated by elevated temperature [72, 76]. This reduction discourages people's motivation for cultivation on a farm on rooftop (cf. **Figure 2**). Spring phenological and function in leaves of *Populus alba* and lian qiao (*Forsythia suspensa*) under ambient air (15.8°C, 35.7 ppb), increased air temperature (IT, ambient air temperature + 2°C) in a combination of two levels of $O_3$ ($EO_3$, ambient $O_3$ + 40 ppb), and their combined treatments (17.7°C, 74.5 ppb) [23–26]. Compared to $EO_3$, the combined treatment advanced the spring pheno-phase, increased growth, and induced a higher photosynthetic rate and antioxidative enzyme activities, which indicated that the positive effects of increased temperature alleviated the inhibition of growth induced by $O_3$. We expect that high temperatures open many stomata and increase the transpiration rate to a certain threshold. Therefore, it was expected that the amount of $O_3$ absorbed would also increase because the stomatal conductance would increase. In Italy, among three species with different water requirements (poplar>beech> oak), fast-growing plant species with high water requirements show more susceptible to $O_3$ and drought stress via the use of $^{13}C$ in leaves [77].

### 3.2 Nitrogen deposition

With the rapid industrial development and modern agricultural practices, increasing N deposition can cause nutrient imbalance. With remarkably high levels of $NO_2$ in east Asia [4, 5], $O_3$ could adversely affect the productivity of forest tree species, but risk assessments of $O_3$ impact were still limited [78]. We analyzed risk assessment of

$O_3$ on suburb forest tree species based on two previous studies via OTC [79], that is, the growth data in potted seedlings of Siebold's beech (*Fagus crenata*) and of three representative conifers, cypress (*Cryptomeria japonica*), pine (*Pinus densiflora*) and Japanese larch (*Larix kaempferi*). From deciduous leaf habit, N deposition increased in the $O_3$ sensitivity of beech while unchanged that of larch ([79], **Figure 6**). Based on the results, we conclude that the area with a high risk of $O_3$ impact does not necessarily correspond to the area with high $O_3$ exposure under different N levels.

Japanese larch and its hybrid larch ($F_1$; *Larix gmelinii var. japonica* × *Larix kaempferi*) are an important afforestation species in northeast Asia. We investigated whether N loading mitigates the negative $O_3$ impacts on two larch species [80]. Although N loading mitigated the negative effects of $O_3$ on Japanese larch, N loading did not mitigate $O_3$-induced inhibition of growth and photosynthetic capacity in the $F_1$. Elevated $O_3$ also reduced leaf nitrogen/phosphorus (N/P) ratio by elevated $O_3$, with significant effects in $F_1$, particularly under N loading. To avoid the negative effect of increasing $O_3$, we will plant Japanese larch but not $F_1$ at N rich site and/or accumulation of the N deposition site.

Larch species are associated with ectomycorrhizal (ECM) fungi, which play a critical role in nutrient acquisition for their hosts [4, 81, 82]). In this study, we investigated species richness and diversity of ECM fungi associated with a hybrid larch ($F_1$) and its parents (Dahurian larch; *L. gmelinii var. japonica,* Japanese larch; *L. kaempferi*), under simulated N deposition (0 and 100 kg $ha^{-1}$ $yr.^{-1}$) with/without phosphorous (P) (0 and 50 kg $ha^{-1}$ $yr.^{-1}$) planted in immature volcanic ash (Vitric Andosols) with low nutrient availability. $F_1$ showed heterosis in relative biomass, which was most apparent under high N treatments. Except for Dahurian larch, effects of the nutrient addition to ECM fungal community in $F_1$ were intermediate. $F_1$ was tolerant to high N loading, which was due to a consistent, relatively high association with *Suillus* sp. and *Hebeloma* sp. [81].

A recent trial was carried out for analyzing the combined effects of $O_3$ (low and two times ambient $O_3$), elevated $CO_2$ (ambient vs. 700 ppm), and 3 levels of soil N supply on Siebold's beech seedlings grown in climatized chambers [83]. They found that elevated $CO_2$ ameliorated $O_3$-induced reductions in photosynthetic activity, whereas the negative effects of $O_3$ on photosynthetic traits were enhanced by soil

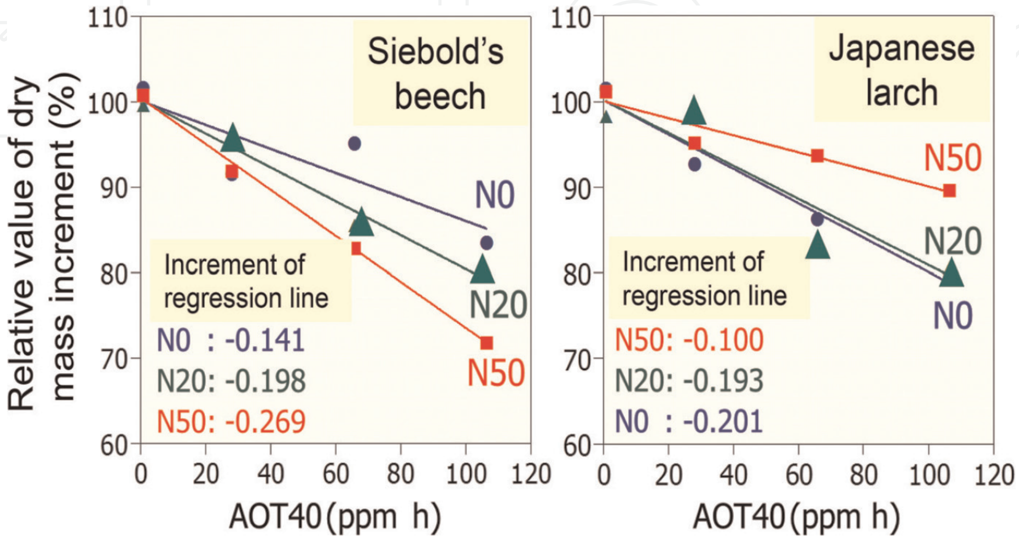


**Figure 6.**
*Contrasting sensitivity of Siebold's beech vs. Japanese larch to elevated $O_3$ (as shown in AOT40) with increasing nitrogen loading to the soil (Re-illustrated from [79]).*

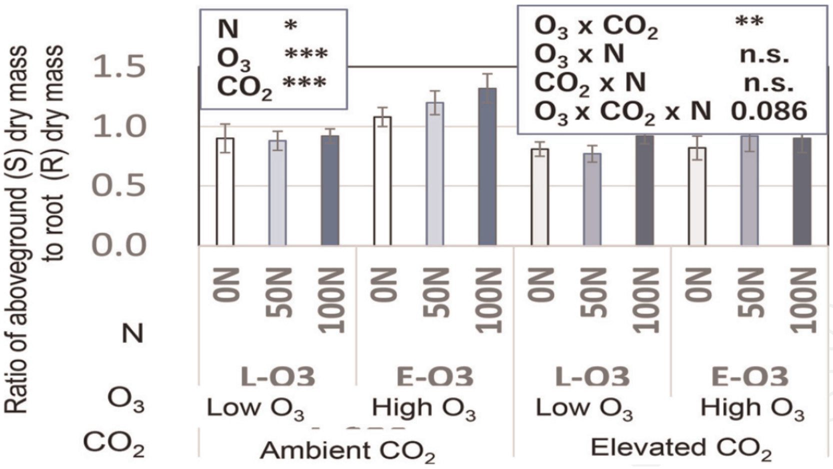


**Figure 7.**
*Ratio of aboveground mass (S) to root mass (S/R) of Siebold's beech seedlings raised under different $O_3$, $CO_2$, and three levels of N roading (Adapted from [83]).* $^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$, *n.s. not significant, the actual p-values are shown when* $0.05 \leq p < 0.10$.

nitrogen supply. Although we observed two- or three-factor interactions of gas and soil N in leaf photosynthetic traits, the shoot-to-root dry mass ratio (S/R) was the only parameter for which a significant interaction was detected (**Figure 7**) among seedlings. $O_3$ caused a significant increase in S/R under ambient $CO_2$, whereas no similar effects were observed under elevated $CO_2$.

## 4. Biological stresses on urban green

Elevated ground-level $O_3$ induces adverse effects in plants. Vigor and health of plants under elevated $O_3$ are discussed through biological stresses: (i) the composition and diversity of plant communities by affecting key physiological traits [38, 84, 85]; (ii) foliar chemistry and the emission of volatiles (mainly BVOC) [43], thereby affecting plant–plant communication, plant-insect interactions, and the composition of insect communities [38, 42, 43, 85]; and (iii) plant–soil-microbe interactions (e.g., [81]) and the composition of soil communities by disrupting plant litterfall [61] and altering root exudation, soil enzymatic activities, decomposition, and nutrient cycling [86, 87]. The community composition of soil microbes is consequently changed, and alpha diversity is often reduced. The effects depend on the environment and vary across space and time.

### 4.1 Plants' defense capacity under elevated ozone with elevated $CO_2$

Most carbon-based defense chemicals are synthesized from photosynthates [88]. As found in birch [89, 90] and cauliflower [20], we expect plant defense will increase at elevated (E) $CO_2$ and decrease at elevated (E) $O_3$. Aspen-FACE in the northcentral U.S.A. provided a combination of $CO_2$ (560 ppm) and $O_3$ (x ambient 1.5 times) [91] and showed performance of forest tent caterpillar (*Malacosoma disstria*) larvae. $ECO_2$ reduced N and increased tremulacin (a glycoside in poplar plants) levels, whereas $EO_3$ increased early season N and reduced tremulacin as compared to controls. With respect to insects, $ECO_2$ had almost no effect on larval performance. Larval performance improved in $EO_3$, but this response was negated by the addition of $ECO_2$ (i.e.,

$CO_2$ + $O_3$ treatment). The tent caterpillars will have the greatest impact on aspen under current $CO_2$ and $EO_3$, due to increases in insect performance and reduced in tree growth, whereas the insect will have the least impact on aspen under high $CO_2$ and low $O_3$ levels, due to moderate changes in insect performance and enhances tree growth.

## 4.2 Outbreak of insect and disease, a role of symbiosis

Defense capacities of plants are mostly originated from photosynthates, as a result, defense traits (leaves, branches, bark, etc.) of plants under elevated $O_3$ are lower. Consequently, trees and shrubs under elevated $O_3$ are attacked by diseases, insects, and wild animals [38, 62]. Outbreaks of sawfly and repeated sawfly attacks are fatal for the weakened beech trees. Another indirect biotic factor is the increased population of sika deer (*Cervus nippon*), which eat up ground vegetation and destroys related community balance. Sika deer is not fond of eating plants containing high levels of C-based defense chemicals (such as phenolics and lignin) [92]. Therefore, individuals whose defense levels have decreased due to $O_3$ are grazed.

The factors affecting beech decline in the Tanzawa mountains are complicated, however, further scientific research activities in various fields are required to understand the phenomena and to recover the beech forest vegetation [62, 63].

Colonization and species abundance of ECM fungi were revealed in 2-year-old hybrid larch ($F_1$) under the combination of elevated $CO_2$ and $O_3$ in OTC ($O_3$ $< 6$ nmol $mol^{-1}$, $EO_3$: 60 nmol/mol; ambient and elevated $CO_2$ [380 vs. 600 mmol $mol^{-1}$]). After two growing seasons, ECM colonization and root biomass increased under elevated $CO_2$ [81]. Additionally, $O_3$ impaired ECM colonization and species richness, and reduced stem biomass. Concentrations of aluminum (Al), iron (Fe), molybdenum (Mo), and phosphorous (P) in needles were reduced by $O_3$, while potassium (K) and magnesium (Mg) in the roots increased. No effects of combined fumigation were observed in any parameters except the P concentration in needles. The tolerance of $F_1$ to $O_3$ might potentially be related to a shift in ECM community structure. Special ECM to larch (*Suillus* sp.) could keep infection even under $EO_3$, so we can expect *Suillus* sp. as a candidate for improving larch rhizosphere [81].

### *4.2.1 Oak wilt disease*

Deciduous oak dieback in Japan has been known since the 1930s [93], but it has been spreading to the whole Japanese island, mainly facing to sea of Japan side where N deposition, as well as transboundary $O_3$ levels, was high [94]. N deposition [83] and $O_3$ bring an imbalance in S/R ratio [29] and physiological homeostasis. The symbiotic ambrosia fungus *Raffaelea quercivora* is the causal agent of oak dieback and is vectored by oak beetle (*Platypus quercivorus* [Murayama]). This is the first example of an ambrosia beetle fungus that kills vigorous trees. Future global warming will possibly accelerate the overlapping of the distributions of *P. quercivorus* and most *Quercus* sp. with the result that oak dieback will become more serious in Japan.

The Meiji Jingu (shrine) is an important green resource in a mega-city, Tokyo, Japan, and planned natural regeneration smoothly continued until around 1990, however, invasive palm seedlings started to prevent the regeneration of various

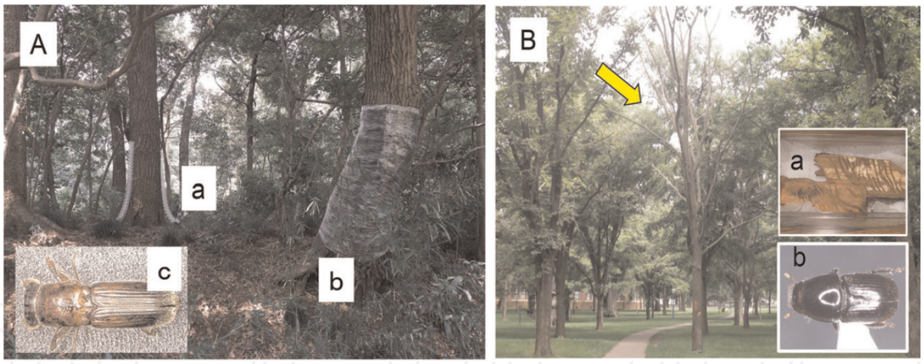


**Figure 8.**
*A: Inside view of tthe Meiji Shrine forest (courtesy of Ms. Harumi Ejiri-Noda). a: Insect trap with "continuous rotho" attached to the oak stem at holes for collecting adult beetle, b: Vinyl film inhibiting shatter-proof wrapped at damaged tree stem,c: Bark beetle (Platypus quercivorus), B: Dutch elm disease in the campus of Hokkaido University in Sapporo. Allow indicates declining individual elm tree infected with beetle. a: Trace under bark attacked by the beetle, b: Elm bark beetle (Scolytu esurient).*

broadleaved trees. Progress of "Heat Island phenomenon" may have enabled the overwintering capacity of invasive palm [95]. Since its seed dispersal depends on birds, seedlings of palm are found in many urban forests. Moreover, palm leaves are $O_3$ tolerant, while $O_3$ suppresses root growth [77], but the moist forest floor seems to allow them to continue to grow. However, mature oaks are declining with intensive infection of wilt disease (**Figure 8A**). How can we manage the serious damages? The Health and vigor of oaks seem to be declining even though most oaks have relative $O_3$ tolerance (cf. **Table 1**) but their root growth is usually suppressed. We hardly regulate the progress of oak wilt disease.

### *4.2.2 Die-back of elm tree*

A sudden increased mortality of *Ulmus davidiana* var. *japonica* (Japanese elm) trees occurred during 2014–2016 in Sapporo, northern Japan [96]. The estimated damaged tree age ranged between 36 and 186 years. Elm bark beetle (*Scolytus esuriens*) was regarded as a key insect for the spread of the disease. Fungi isolated from elm bark beetle and the wood of the galleries were identified as *Ophiostoma ulmi* and *Ophiostoma novo-ulmi*. Most declining trees with wilting branches were present around these beetle-attacked trees (**Figure 8B**). Therefore, Dutch elm disease caused this occurrence of Japanese elm dieback. This declining may be related to declining of tree vigor and health under degradation of the atmospheric environment with increasing nitrogen deposition and $O_3$ [80].

Higher leaf N content and lower plant defense (low condensed tannin) content in N loading and lower condensed tannin content in elevated $O_3$ were observed with $O_3$-FACE, suggesting that both N loading and elevated $O_3$ decreased the leaf defense and that N loading further enhanced the leaf quality as food resource of insect herbivores [19, 20, 89, 90]. Visible foliar injury caused by N loading might directly induce the reduction of the number of elm sawfly individuals.

Although elevated $O_3$ suppressed the plant defense capacity in leaves as found in white birch [41, 42, 97] and poplar [43], a significantly lower number of elm leaf beetle was observed in elevated $O_3$. Why did the number of leaf beetle in leaves in elevated $O_3$ decrease with lowered chemical defense?

### *4.2.3 Insect-plant interaction: $O_3$ as an environmental disturber*

Plant–insect interactions are basic components of biodiversity conservation. Ground-level $O_3$ usually suppresses not only plant activities and disrupts interaction webs among plants-insect [41]. $O_3$ mixing ratios in suburbs are usually higher than in the center of cities and may reduce photosynthetic productivity, as suggested by Gregg et al. [65] for poplar and Moser-Reischl et al. [64] for fir. As a result, carbon-based defense capacities of plants may be suppressed by elevated $O_3$ more in the suburbs than in the urban region. Contrary to this expectation, grazing damage by leaf beetles (found in birch, alder, elm, and poplar: [43]) has been severe in some urban centers in comparison with the suburbs. To explain differences in grazing damages between urban areas and suburbs, the disruption of olfactory communication signals by elevated $O_3$ via changes in plant-regulated biogenic volatile organic compounds (BVOC) and long-chain fatty acids with double bonds are considered (e.g., [41, 43]). Ozone-disrupted BVOCs of plants should be considered to explain insect herbivory activities in urban and suburban systems.

## 5. Construction and maintenance of urban greening

The green space in the city not only serves as a cool island but also provides relaxation. However, even with management, there is always a risk of decline due to air pollution, high temperatures, high vapor deficit, nutrient imbalance, etc. due to narrow planting holes and restriction of the root system. “Meiji Jingu” forest was designed to be maintained by natural regeneration created in the center of Tokyo metropolis [98], but the invasion of palms by the heat island and the decline of oak wilt disease are imminent (**Figure 8A**, **B**). Even if the roadside trees and rooftop greening can be managed sufficiently, the viewpoint of nutrient cycling is important for park trees [99]. Additionally, we should introduce a moderating method of application of ethylene-di-urea (EDU). This is considered a chemical that offers protection to the treated plants against $O_3$ [100–102].

### 5.1 Nutrient cycling

Effects of tree species on mineral soil, litter, and root properties are found to be inconsistent, and understanding general cross-site patterns and the possible mechanism is important for enhancing the forest ecological service through proper tree species selection. Leaf litterfall nutrient concentrations and their ratios are a common indicator of site nutrient status and a critical component of many ecosystems [87]. Concentrations of N and P in the leaf litter are related to foliar concentrations, but they are reduced by nutrient resorption during senescence as affected by $O_3$ [61, 84]. However, few studies have assessed how the timing of litter collection affects estimates of nutrient concentration [61, 84]. The emphasis on sampling senesced leaf tissue at a single point in time leads to biased estimates of nutrient concentrations, stoichiometry, and litterfall and resorption fluxes, especially for P than for N in birch, beech and maple at the Hubbard Brook Forest. In northeast China, mineral conditions of four tree species; larch (*Larix gmelinii*), pine (*Pinus sylvestris* var. *mongolica*), poplar (*Populus* spp.), and elm (*Ulmus pumila*) were compared in several minerals, the component of SOC and soil N concentrations. Elm could capture more mineral SOC and nutrients, poplar induced mineral soil P depletion, and pine litter was of more recalcitrance for decomposition [103].

The effects of elevated $O_3$ in different soil conditions (brown forest, volcanic ash, and serpentine soil) on foliar elements stoichiometry were investigated in *Betula platyphylla* var. *japonica* (white birch), (*Quercus mongolica* var. *crispula* (oak) and Siebold's beech (*Fagus crenata*) with a $O_3$-FACE [61]. Soil nutrients have distinct impacts on retranslocation rate of K, Fe, and P. A negative correlation between foliar N and the metal elements was found in white birch. From the differences of foliar contents as well as their retranslocation rate, Siebold's beech with determinate shoot growth pattern was rather more sensitive to $O_3$ stress on foliar contents, meanwhile oak was possibly susceptible to $O_3$ on dynamics of immobile elements. Mn and K can become indices in assessing the $O_3$ and soil effects.

Decomposition is directly related to nutrient cycling [104]. Litter decay dynamics of paper birch (*Betula papyrifera*) were assessed at the Aspen-FACE in the northcentral USA. Leaf litter was decomposed for 12 months under factorial combinations of ambient (360 ppm) vs. elevated $CO_2$ (560 ppm), crossed with 36 vs. 55 $nLO_3\ L^{-1}$. *In situ*, litterbags methods revealed that $CO_2$ enrichment regardless of $O_3$ produced poorer quality litter (high C/N, lignin/N, and condensed tannins) than did ambient $CO_2$ (low C/N, lignin/N, and condensed tannins). Substrate quality differences were reflected in the mass loss rates of litter (k-values), which were high for litter generated under ambient $CO_2$ (0.89 $yr.^{-1}$) and low for litter generated under elevated $CO_2$ (0.67 $yr.^{-1}$), which suggests regulating the storage of fixed C and the release of $CO_2$ from northern forest ecosystems. Additionally, revegetation should be needed in NE China where we have a limited amount of rainfall ($<$500 mm $yr.^{-1}$) after the thinning or harvest of the "restoring agricultural land forest" [7]. We should carefully select larch species, such as *Larix gmelnii* under salt stress and $EO_3$ [105].

### 5.2 EDU application

Increasing evidence on the antiozonate efficacy of EDU against the phytotoxic action of $O_3$ is becoming more readily available [100, 101]. EDU is a very promising antiozonant with its antiozonate action being observed when applied to roots in concentrations of 275.7 to 374.3 mg $L^{-1}$. The effect of ambient $O_3$ on visible foliar injury, growth, and biomass in field-grown poplar cuttings of an Oxford clone sensitive to $O_3$ irrigated with EDU or water for 3 years. Protective effects of EDU on $O_3$ visible injury were found but no increase in stem height and diameter was found [102]. EDU was more effective in some cultivars compared with others although this remains inexplicable [33]. Additionally, the biochemical mechanism of its antiozonate activity is still unclear [78].

## 6. Concluding remarks and future perspective

Urban vegetation or green infrastructure, as a cost-effective and nature-based approach, aids in meeting clean air standards, which should be taken into account by policy-makers. Nowadays, complex atmospheric pollution seriously threatens the vitality of suburb trees as well as urban trees (e.g., [23]). Continuous attention should be paid to the long-term changes of $O_3$ and related impacts on urban greening. On the basis of "matching site with trees," more attention should be paid to the relationship between plants and urban planting small environment [33]. Highly ranked tree species that can inclusively resist $O_3$ and other pollutants which will be the priority target of urban greening.

Recent high air pollution in many cities indicates the urgent need for policy action and for urban development based on local air quality management; the prospects of improving urban air quality through proper design and protection of vegetation within local planning strategies [106], such as selecting of non-emission species of BVOC as a precursor of $O_3$. In addition, we should make more effort to reduce the emission of CO, NOx, VOC, etc. as $O_3$ precursors [22, 64]. Elevated ground-level $O_3$ can adversely affect plants and inhibit their growth and productivity, threatening ecological health via pollination [38, 40, 41] food security, etc. Therefore, it is important to develop ways to protect plants against $O_3$-induced negative effects [13, 107]. Of course, we should choose tree species of non-emitter of BVOC as a precursor of $O_3$ as shown by screening experiments of tree species [18]. It would be effective to create a space where the wind can easily pass through the city plan to discharge $O_3$ [13, 46]. In addition, we expect that new studies should be green chemistry for the continuous support of green infrastructure for city residents.

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## Abbreviations

| | |
|---|---|
| AOT40 | Accumulated ozone exposure over a threshold of 40 ppb |
| BVOC | biogenic volatile organic compound |
| CO | Carbon oxide or Carbonic oxide |
| ECM | Ectomycorrhizal fungi |
| $ECO_2$ | Elevated $CO_2$ |
| $EO_3$ | Elevated $O_3$ |
| EPA | U.S.A. air pollutant emission |
| FACE | Free-Air $CO_2$ enrichment |
| Gs | stomatal conductance |
| ICP | International cooperative program on effects of air pollution on natural vegetation and crops |
| IT | Increased air temperature |
| LAI | Leaf area index (leaf area per unit land area; $m^2\ m^{-2}$) |
| LRTAP | National emissions reported to the convention on long-range transboundary air pollution |
| LandSat | Land Satellite |
| $NO_2$ | Nitrogen dioxide |
| $O_3$ | Ozone |
| $O_3$-FACE | Ozone in a free-air controlled environment |

| | |
|---|---|
| OTC | Open top chamber |
| PM | Particle matter |
| POD-0 | Phytotoxic $O_3$-dose above a threshold of 0 uptake |
| PRD | Pearl River Delta economic zone |
| S-AQI | Species air quality index |
| S/R ratio | shoot to root dry mass ratio |
| SDGs | Sustainable Development Goals |
| SOC | Soil organic carbon |
| SOx | Sulfur oxide complex |
| YRD | Yangtze River Delta |

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