Uptake of O$_3$ by Various Street Trees

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Potted eleven street tree species (Aucuba japonica, Cinnamomum camphora, Daphniphyllum macropodum, Ginkgo biloba, Hedera rhombea, Ligustrum japonicum, Pasania edulis, Prunus yedoensis, Quercus acutissima, Rhododendron oomurasaki, Zelkova serrata) were treated with various concentrations of O$_3$ to investigate the heritable differences in the capacity of O$_3$ uptake. The rates of net photosynthesis and transpiration, and stomatal density were determined for every tree species. Some species showed a linear relationship between O$_3$ concentration and the uptake rate of O$_3$, while other species did not. The analysis using a gas phase diffusive conductance indicated that the nonlineality was assumed to be resulted from the stomatal closure. Concerning those nine tree species which showed the linear increase in O$_3$ uptake rate with O$_3$ concentration, the rate of O$_3$ uptake was ranked as follows: P. yedoensis = H. rhombea > Z. serrata > Q. acutissima > C. camphora = D. macropodum = G. biloba > A. japonica = R. oomurasaki. Those tree species with higher uptake rates of O$_3$ were not characterized with higher stomatal frequency but with higher gas phase conductance for water vapor. This result suggested that the heritable differences in the rates of O$_3$ uptake are determined by the interspecific differences in stomatal conductances.

INTRODUCTION

The atmosphere in urban and suburban areas in Japan are polluted by photochemical oxidants.1) Ozone (O$_3$), a major component of oxidants, reduces the activity of plants grown in these areas.

On the other hand, there is a considerable interest in the role of plants in cleaning atmosphere by absorbing air pollutants. O$_3$ that enters leaves through stomata is dissolved on moist surfaces of mesophyll cells.2) The driving force for the absorption of O$_3$ is a function of the concentration gradient from the leaf exterior to the interior as well as the resistance to gaseous flow along the diffusion pathway.3)

It might be beneficial to find species which could absorb air pollutants, if vegetation does constitute an important sink for air pollutants, as suggested by Bennett and Hill,4) Hallgren et al.,5) Leuning et al.,6) and Roberts.7) Street trees are the dominant vegetation in urban and suburban areas where levels of air pollution tend to be highest. The present study was, therefore, designed to investigate the foliar uptake of O$_3$ by several important street tree species.
MATERIALS AND METHODS

Plant materials
Eleven tree species (*Aucuba japonica*, *Cinnamomum camphora*, *Daphniphyllum macropodum*, *Ginkgo biloba*, *Hedera rhombea*, *Ligustrum japonicum*, *Pasania edulis*, *Prunus yedoensis*, *Quercus acutissima*, *Rhododendron oomurasaki*, *Zelkova serrata*) are used as the experimental materials. Nurseries of these tree species were cultivated in plastic pots (11 cm diameter, 15 cm deep) filled with a mixture of vermiculite, peatmoss, perlite, and gravel (2:2:1:1, v/v). Each pot contained 5 g of Magamp-K and 15 g of magnesia lime. These potted trees were grown in a phytotron greenhouse at 25°C and a relative humidity of 70%. Potted trees were watered daily and were fertilized with Hyponex solution (1 g/l) once a week.

Stomatal frequency
The impressions were made of the lower (abaxial) and upper (adaxial) epidermis using thin films of cellulose acetate and the stomatal frequency was determined under a light microscope.

Fumigation system
The fumigation was performed in an assimilation chamber (20×10×5 cm deep) at 25°C, 70% R.H., which was set in a controlled environment room. Illumination system of the controlled environment room was applied for the light source of the assimilation chamber. Illumination system was consisted of twenty four 400 W stannous halide lamps (Yoko Lamp, Toshiba). The light was filtered through heat absorbing glass filter, which removed radiation above 800 nm. The quantum flux density inside the assimilation chamber was ca. 500 µEinstein m⁻²s⁻¹. Prior to the fumigation, the plant was illuminated for more than one hour to open stomata. After the preillumination period, O₃ was generated by a silent electrical discharge in dry oxygen and was introduced into the controlled environment room. Concentrations of O₃ within the room were monitored continuously by a Kimoto Model 806 chemiluminescent detector of O₃. The outputs from the analyzer were fed to an analogous recorder equipped with a PID controller which regulated the pollutant flow through mass flow controllers.

Gas exchange measurement
Fully expanded leaves were accommodated into the assimilation chamber. A cross flow fan stirred the chamber air. Air contained O₃ was continuously sucked by a pump through the suction pipe. Air flow rate was monitored by a rotameter and was adjusted to 10 l/min.

The rate of O₃ uptake of leaves was determined by measuring O₃ concentrations using a Kimoto Model 806 chemiluminescent detector of O₃ at the inlet and outlet of the chamber. The adsorption of O₃ onto the surface of assimilation chamber and on the measuring circuit system was determined at various concentrations of O₃ and eliminated from the uptake of O₃ in tree species. Net photosynthetic rate was determined by measuring CO₂ concentrations at the inlet and outlet of the chamber with an infrared CO₂ analyzer (Fuji, Model ZAP). Transpiration rate was determined by measuring the water vapor concentrations of the air entering and leaving the chamber using
Estimation of diffusive conductance

The conductance to water vapor diffusion through the boundary layer and internal gas phase of the leaf \((G_{sv})\) was estimated from the rates of transpiration and leaf temperature using the following equation.

\[
J_{sv} = \frac{(c_{sv}^e - c_{sv}^{in})}{G_{sv}}
\]

where \(J_{sv}\) is the transpiration rate, \(c_{sv}^e\) and \(c_{sv}^{in}\) are the concentrations of water vapor in the bulk air and at the transpiring site of interior leaf cells (assumed to be the saturated water vapor concentration at leaf temperature), respectively.

RESULTS

Stomatal frequency

Every tree species tested in the present experiment had no stomata on the adaxial leaf surface, indicating that these tree species were hypostomatous (Table 1). The number of stomata ranged from 65 mm\(^{-2}\) in H. rhombea to 476 mm\(^{-2}\) in Q. acutissima.

Interspecific difference in photosynthetic rate

The rate of net photosynthesis in nine street tree species is listed in Table 2. There were significant differences in the rate of net photosynthesis. P. yedoensis showed the highest rate of net photosynthesis of 19.27 µmol CO\(_2\) m\(^{-2}\)s\(^{-1}\). A. japonica and P. edulis were the least efficient.

Effect of O\(_3\) concentration on O\(_3\) uptake rate

The rate of O\(_3\) uptake increased linearly with increasing concentration of O\(_3\) (Fig. 1). The concentration of O\(_3\) was very low, so that no stomatal closure was detected during the exposure to O\(_3\) in any species shown in this figure. Furthermore, no detectable reduction of net photosynthetic rates or the decline of gas phase conductance was determined in these five tree species (data not shown).

| Table 1 Abaxial and adaxial stomatal frequencies of various street tree species. |
|-----------------|-----------------|-----------------|
|                 | Adaxial surface | Abaxial surface |
| Hedera rhombea  | 0               | 65±12           |
| Ginkgo biloba   | 0               | 109±13          |
| Aucuba japonica | 0               | 157±7           |
| Ligustrum japonicium | 0           | 172±12          |
| Pasania edulis  | 0               | 182±34*         |
| Prunus yedoensis| 0               | 230±28          |
| Daphniphyllum macropholium | 0     | 240±12          |
| Zelkova serrata | 0               | 262±2           |
| Cinnamomum camphora | 0          | 292±35          |
| Rhododendron oomurasaki | 0     | 347±35          |
| Quercus acutissima | 0           | 476±60          |

* Hair disturbed the strict counting of stomatal frequencies.
Table 2  Net photosynthetic rates in various street trees.

<table>
<thead>
<tr>
<th>Species</th>
<th>Net Photosynthesis* μmol CO₂ m⁻² s⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rhododendron oomurasaki</td>
<td>5.39</td>
</tr>
<tr>
<td>Aucuba japonica</td>
<td>7.07</td>
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<tr>
<td>Pasania edulis</td>
<td>7.27</td>
</tr>
<tr>
<td>Daphniophyllum macropodum</td>
<td>10.95</td>
</tr>
<tr>
<td>Hedera rhombea</td>
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<tr>
<td>Ligustrum lucidum</td>
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<tr>
<td>Ginkgo biloba</td>
<td>14.59</td>
</tr>
<tr>
<td>Cinnamomum camphora</td>
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</tr>
<tr>
<td>Quercus acutissima</td>
<td>18.50</td>
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<tr>
<td>Zelkova serrata</td>
<td>18.64</td>
</tr>
<tr>
<td>Prunus yedoensis</td>
<td>19.27</td>
</tr>
</tbody>
</table>

* Mean value of 2-4 measurements.

Fig. 1  O₃ uptake rates in various street tree species as a function of O₃ concentration. O₃ uptake rates were determined by a conventional open gas flow system. O₃ concentration shown in a figure is the effective concentration of O₃ coming out from the assimilation chamber.

Fig. 2  O₃ uptake rates and gas phase diffusive conductance for water vapor in L. lucidum as a function of O₃ concentration. The result shown in this figure is a typical example for those species which did not have a linear relationship between O₃ uptake rates and O₃ concentration.

However, the rate of O₃ uptake did not increase linearly with increasing concentration of O₃ in some tree species tested in the present experiment. A typical example for these tree species is shown in Fig. 2 for L. japonicum. The gas phase diffusive conductance, determined simultaneously, decreased with increasing concentration of O₃. For other species with no lineality of O₃ uptake rate with O₃ concentration showed a
similar decline in gas phase diffusive conductance.

It is a matter of course that the uptake rate of \( \text{O}_3 \) per unit \( \text{O}_3 \) concentration is designated as the slope of linear regression lines shown in Fig. 1. The uptake rates of \( \text{O}_3 \) per unit \( \text{O}_3 \) concentration determined by this method were 240.9, 164.1, 121.5, 144.6, and 101.3 nmol m\(^{-2}\)s\(^{-1}\) ppm\(^{-1}\) for \( P. \ yedoensis \), \( Q. \ acutissima \), \( C. \ camphora \), \( Z. \ serrata \), and \( G. \ biloba \), respectively. Thus \( P. \ yedoensis \), deciduous species, showed larger uptake rate of \( \text{O}_3 \) than any other species presented in Fig. 1.

**Effect of light intensity on \( \text{O}_3 \) uptake rate in \( P. \ yedoensis \)**

Figure 3 shows the effect of light intensity on the rates of net photosynthesis, \( \text{O}_3 \) uptake and gas phase conductance of \( P. \ yedoensis \). With increasing light intensity, the rate of net photosynthesis increased curvilinearly. The rate of \( \text{O}_3 \) uptake and gas phase conductance were also increased with increasing light intensity.

The rate of \( \text{O}_3 \) uptake per unit concentration of \( \text{O}_3 \) was estimated using the results shown in Fig. 3 (Fig. 4). The rate of \( \text{O}_3 \) uptake per unit \( \text{O}_3 \) concentration had a linear relationship with the gas phase diffusive conductance of water vapor determined at various light intensities.

**Relationship between gas phase conductance and \( \text{O}_3 \) uptake rate**

Figure 5 shows the relationship between gas phase conductance and \( \text{O}_3 \) uptake rate per unit \( \text{O}_3 \) concentration of various tree species. The results shown in this figure de-
monitored that gas phase conductance of various tree species correlates very well \((r=0.99)\) with O3 uptake rate per unit O3 concentration.

**DISCUSSION**

Gas phase resistance of leaves to diffusion of water vapor is composed of both boundary layer and stomatal diffusive resistances. The boundary layer resistance is determined by wind velocity and the effective length to flow of gases. The boundary layer resistance was held fairly constant in the present experiment by similar stirring of the air and by comparable effective length of between 10 and 15 cm. As a result, gas phase conductance, a reciprocal of gas phase resistance, should be solely related with stomatal diffusive conductance. Thus in this report, we designate the gas phase conductance as an indicator of stomatal aperture.

The rate of pollutant gas transfer from the atmosphere to the interior leaf cells is regulated by many factors. When once they are inside the leaf, these gases would diffuse into intercellular spaces and be absorbed on or in the water-covered surfaces of palisade or spongy parenchyma cell walls. Thus it is easily conceivable that the uptake rates of gases by plants would increase with increasing solubility of the pollutant to water. However, Hill\(^2\) reported that despite of the low solubility of O3 in water (the solubility of SO2 is 39.4 ml/ml H2O while that of O3 is only 0.26 ml/ml H2O at 20°C), the uptake rate of O3 was comparable with SO2. In the same report, he showed that the uptake rates of SO2 and O3 by alfalfa at 5 ppm were 85 and 50 \(\mu l\) min\(^{-1}\)m\(^{-2}\), respectively. This reported data suggested that O3 readily diffuses into stomatal cavities and reacts rapidly on the surface of leaf mesophyll cells by its reactive nature. This consideration and those reported results suggest that though the solubility of gases is an important factor for the uptake of gases, the metabolizing capacity of ions in mesophyll cells is a major factor controlling gas transfer from the atmosphere into the leaf.\(^6\)

Taylor et al.\(^1\) explained that the age-dependent O3 flux into leaves was regulated by both gas phase and liquid phase pathways. Furthermore, they suggested that the pathways for O3 diffusion into mesophyll cells were not identical with those for the diffusion of CO2 or water vapor. In their report, they assumed that O3 would not incorporate into leaves through the stomata in the dark. From this assumption they identified adsorption as the uptake of O3 determined in the dark. However, even in the dark, stomata partially open and O3 diffuses into leaves through partially open stomatal pores as shown in Fig. 3. This speculation would be supported even by the results reported by Taylor et al.\(^1\) that the rate of O3 uptake in the dark decreased with
the duration of exposure to 0.25–0.60 ppm and the uptake of O₃ in young leaves in the dark ceased to uptake O₃ when exposed for longer period.

The uptake of O₃ is strongly influenced by a number of complex environmental factors that regulates stomatal aperture, such as light, humidity, CO₂, water condition, and ABA. Among these factors, light intensity is the most ubiquitous and regulative factor fluctuated diurnally in the field. Our present results also clearly showed that the uptake rate of O₃ was strongly influenced by light and was increased with the increase of light intensity (Fig. 2).

Beside these environmental factors that affect on O₃ uptake rate, the morphological and physiological differences in stomatal frequency or response to O₃ seemed to influence the magnitude of uptake rates. However, in the present experiment, we could not observe the relationship between the O₃ uptake rate or the rate of net photosynthesis and stomatal density (Table 1, 2, Fig. 1). Q. acutissima had the greatest stomatal frequencies, but either rate of O₃ uptake or net photosynthesis was lower than P. yedoensis. These results suggest that the stomatal frequency may not be a factor regulating the uptake of gases from atmosphere.

In many species, the rate of O₃ uptake was found to increase linearly as the concentration of O₃ was increased over the ranges of concentration encountered in ambient air and low enough not to cause stomatal closure (Fig. 1). While, in other species tested in the present experiment, the rate of O₃ uptake did not increase linearly with increasing O₃ concentration (e.g. in L. japonicum, Fig. 2). The simultaneous determination of gas phase conductance and uptake rates of O₃ suggests that the non-lineality was induced by the decreased gas phase conductance.

Concerning those five tree species shown in Fig. 1 and additional four species mentioned below showing the linear increase in O₃ uptake rate with O₃ concentration, the rate of O₃ uptake can be ranked in the following order according to the slope of the linear regression line shown in the figure: P. yedoensis > H. rhombea > Z. serrata > Q. acutissima > C. camphora = D. macropodum = G. biloba > A. japonica = R. oomurasaki. This ranking was not coincident with the stomatal density as mentioned above.

The rate of O₃ uptake was markedly different between species. The O₃ uptake rate in P. yedoensis was more than double of the rate in G. biloba. However, we found a linear relationship between the gas phase conductance for water vapor and the uptake rates of O₃ per unit O₃ concentration in eleven tree species (Fig. 5). Furthermore, we also found a linear relationship between O₃ uptake rates per unit O₃ concentration and the gas phase conductance in P. yedoensis at various light intensities (Fig. 4). It is thus suggested that diffusion of gases might determine the uptake of O₃ and, in turn, the species differences in the rate are determined by species differences in the gas phase conductance.

There is a considerable effort to speculate the role of vegetation for the sink of atmospheric pollutants. For this purpose, we propose that the use of a commercially available diffusive resistance porometer is the best and the easiest way for the determination of gas phase diffusive conductance, since the uptake rate of atmospheric pollutants is mainly regulated by the gas phase diffusive conductance.

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REFERENCES


（和文抄録）

種々の街路樹のオゾン吸込み速度

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鉢植えの街路樹9種（Aucuba japonica, Cinnamomum camphora, Daphniphyllum macropodum, Ginkgo biloba, Hedera rhombea, Ligustrum japonicum, Pasania edulis, Prunus yedoensis, Quercus acutissima, Rhododendron oomurasaki, Zelkova serrata）に種々の濃度のオゾンを処理して、オゾン吸込み速度の植物種間差を調べた。光合成、蒸散速度、気孔密度についても調べた。今回実施した街路樹の中で、ある種は処理したオゾン濃度とオゾン吸込み速度との間に直接関係があったが、他の種ではオゾン吸込み速度がオゾン濃度の上昇に伴って飽和する傾向にあった。気層拡散コンダクタンスをオゾン吸込み速度と同時に測定した蒸散速度と気温から求めた結果、飽和圧のオゾン吸込み速度は気孔が閉鎖するために起こった現象であることが推察された。オゾン濃度の上昇に伴ってオゾン吸込み速度が直接的に増加する種の吸込み速度は以下のような順になった。
P. yedoensis = H. rhombea > Q. acutissima ≥ Z. serrata > C. camphora = D. macropodum ≥ G. biloba > R. japonicum

このオゾン取込み速度の順位と気孔密度の大小の順位とは異なっていた。種々の植物の単位濃度あたりのオゾン取込み速度と気層拡散コンダクタンスとの間には直線関係が見られた。以上の結果は、オゾン取込み速度の植物種間差は、気孔密度の大小によるのではなく、気層拡散コンダクタンスの大小によることを示唆するものである。すなわち、気層拡散コンダクタンスは、もっぱら気孔コンダクタンスによって決定されているので、オゾン取込み速度の植物種間差は気孔コンダクタンスの種間差によるものと思われる。