Ozone uptake by adult urban trees based on sap flow measurement

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A B S T R A C T
The O3 uptake in 17 adult trees of six urban species was evaluated by the sap flow-based approach under free atmospheric conditions. The results showed very large species differences in ground area scaled whole-tree ozone uptake (F03), with estimates ranging from 0.61 ± 0.07 nmol m−2 s−1 in Robinia pseudoacacia to 4.80 ± 1.04 nmol m−2 s−1 in Magnolia liliflora. However, average F03 by deciduous foliages was not significantly higher than that by evergreen ones (3.13 vs 2.21 nmol m−2 s−1, p = 0.160). Species of high canopy conductance for O3 (G03) took up more O3 than those of low G03, but that their sensitivity to vapour pressure deficit (D) were also higher, and their F03 decreased faster with increasing D, regardless of species. The responses of F03 to D and total radiation led to the relative high flux of O3 uptake, indicating high ozone risk for urban tree species.

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1. Introduction
The accelerating global urbanization caused severe air pollution (Wu, 2008). In Beijing, the air pollution problem has been exacerbated due to the wide-spread construction activities and increased number of vehicles (Hao et al., 2005; Chan and Yao, 2008). Air pollution affects human health, damages vegetation and various anthropogenic materials, and reduces visibility (McPherson et al., 1994). Trees in cities can improve the urban air quality by removing gaseous air pollution (Nowak and Dwyer, 2007). Therefore, great effort is made to increase and maintain urban trees.

Tropospheric ozone (O3; a list of all abbreviations is given in Table 1) is a potential risk factor in trees (Matyssek and Sandermann, 2003). Its negative effects include morphological and histological injuries, reduced photosynthesis, and altered water balance, among others (Landolt and Keller, 1985). Both the exposure-based approach and the flux-based approach are currently used to evaluate the risk of ozone damage to vegetation (Simpson et al., 2007). Since ozone injuries are more closely related to the ozone absorbed through the stomata than to ozone concentration in the atmosphere (Landolt and Keller, 1985; Musselman and Massman, 1998), the flux-based approach is better suited for the establishment of reliable critical levels as risk assessment tools for vegetation (Ferretti et al., 2007). The flux-based indices, AFsty (accumulated stomatal flux over threshold of y nmol m−2 s−1) (UNECE, 2004), can be used to serve this purpose.

O3 uptake by plants depends on both the ambient O3 concentration and the stomatal conductance (Wieser and Havranek, 1995; Nowak and Dwyer, 2007). At a given ambient O3 concentration, the rate of O3 uptake by leaves was effectively controlled by stomatal conductance, which is influenced by factors such as leaf characteristics, crown position, tree age, tree height, climate, and altitude (Beckett et al., 2000; Schafer et al., 2000; Wieser et al., 2000; Nunn et al., 2007). In urban settings, higher temperature (Landsberg, 1981), lower plant density (Hagishima et al., 2007), irrigation (Martin and Stabler, 2002), energy balance properties of urban surfaces (Montague and Kjelgren, 2004), and night illumination (Longcore and Rich, 2004) may allow for higher stomata aperture, hence, more O3 uptake. Considerable researches have been conducted to investigate ozone uptake by natural forests (Wieser et al., 2003, 2006; Nunn et al., 2007; Köstner et al., 2008; Braun et al., 2010). Fewer studies, however, have examined ozone uptake by urban trees.

O3 uptake by urban trees has been largely examined based on modeling approaches that integrate vegetation information with meteorological and ambient O3 concentration data (McPherson
et al., 1994; Nowak et al., 2000). These studies primarily focused on O₃ removal by urban trees (e.g., Nowak et al., 2000; Yang et al., 2005). While the modeling approach can provide important information on O₃ removal by urban trees at the city scale, variations in canopy resistance due to trees with different height and crown configurations, and heterogeneous ambient O₃ concentrations may introduce uncertainties into the estimates (Scott et al., 1998). Alternatively, O₃ uptake by urban trees can be measured based on the whole-tree ozone flux into the leaves that can be estimated by sap flow measurements, since transpiration and O₃ uptake are coupled through the activity of the stomata (Wieser et al., 2003). This method takes into account the presence of real boundary layer, and was previously used in heterogeneous and mountainous landscapes (Wieser et al., 2003, 2006; Matyssek et al., 2007, 2008).

Therefore, we chose this method to evaluate O₃ uptake by urban trees.

The objectives of this study are: (1) to quantify and compare whole-tree ozone uptake by different urban species; (2) to examine how O₃ flux of urban trees is regulated by the stomata and environmental conditions; and (3) to provide accurate quantification of O₃ risk assessment with species-specific flux data.

2. Method and materials

2.1. Study site and trees

The study was carried out at the 116,500 m² Beijing Teaching Botanical Garden (116°25′37″ to 116°25′50″ E, 39°52′20″ to 39°52′28″ N), located close to the urban core of the Beijing city, China. Annual average precipitation from 1978 to 2009 in Beijing is about 585 mm, with more than 70% occurring from June to August (Beijing Water Authority, 2010). Annual average temperature from 1978 to 2009 in Beijing is approximately 11–12 °C (State Statistical Bureau, 2011). The experimental site is a typical green space embedded in densely populated commercial and residential areas, with heavy pedestrian and motor vehicle traffic.

Four deciduous tree species (Ginkgo biloba, Aesculus chinensis, Magnolia liliflora, Robinia pseudoacacia) and two evergreen tree species (Pinus tabulaeformis, Cedrus deodora) were selected in this research. In terms of number of trees in Beijing, G. biloba and R. pseudoacacia are among the top five deciduous tree species, while P. tabulaeformis and C. deodora are among the top five evergreen tree species (Beijing Gardening and Greening Bureau, 2005). A. chinensis is becoming more and more popular in urban settings with prospects of aesthetic enhancement and economic values (Wei et al., 2008).

The trees selected for certain type of species had similar diameter at the breast height (DBH), height, projected canopy area (Aₖ), and sapwood cross-sectional area (Aₛ) (Wang et al., 2011). The size of the selected trees in terms of DBH was determined based on the field surveys conducted in Beijing in 2007. Comprehensive species field surveys were conducted in Beijing in July and August, 2003, and in August, 2007, covering an area of 670 km² (Zhao, 2010). The distribution of DBH for urban trees in Beijing in 2003 is shown in Fig.4. We chose the DBH size of the trees by considering the increase in DBH during the past five years.

We selected two or three individual trees of each species for sap flux measurement. Sap flux measurement in urban environment was challenging due to relatively long distance among trees, insufficient sample size, species

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**Table 1**

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition (Units)</th>
</tr>
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<tbody>
<tr>
<td>Aₛ</td>
<td>sapwood area (cm²)</td>
</tr>
<tr>
<td>Aᵢ</td>
<td>sapwood area at depth i (cm²)</td>
</tr>
<tr>
<td>DBH</td>
<td>diameter at the breast height (cm)</td>
</tr>
<tr>
<td>Aₖ</td>
<td>canopy projected area (m²)</td>
</tr>
<tr>
<td>LAI</td>
<td>leaf area index</td>
</tr>
<tr>
<td>J₀</td>
<td>sap flux density in the outer 2 cm of sapwood (g cm⁻² d⁻¹)</td>
</tr>
<tr>
<td>Jᵢ</td>
<td>sap flux density at depth i (g cm⁻² d⁻¹)</td>
</tr>
<tr>
<td>Jₐ</td>
<td>sap flux density across the active sapwood (g cm⁻² d⁻¹)</td>
</tr>
<tr>
<td>Eᵣ</td>
<td>canopy transpiration (mm d⁻¹)</td>
</tr>
<tr>
<td>σᵢ</td>
<td>error estimate at depth i</td>
</tr>
<tr>
<td>σᵣ</td>
<td>error estimate in the outer 2 cm of sapwood</td>
</tr>
<tr>
<td>Gₛ</td>
<td>canopy conductance for O₃ (mmol m⁻² s⁻¹)</td>
</tr>
<tr>
<td>FO₂</td>
<td>canopy O₃ uptake rate (nmol m⁻² s⁻¹)</td>
</tr>
<tr>
<td>AOT40</td>
<td>accumulated exposure (O₃ accumulated over a threshold of 40 ppb)</td>
</tr>
<tr>
<td>AFO₂0.16</td>
<td>accumulated stomatal ozone flux over thresholds</td>
</tr>
<tr>
<td>[O₃]</td>
<td>O₃ concentration of the ambient air (ppb)</td>
</tr>
<tr>
<td>D</td>
<td>vapor pressure deficit (kPa)</td>
</tr>
<tr>
<td>Rₑ</td>
<td>total radiation (W m⁻²)</td>
</tr>
<tr>
<td>Tₑ</td>
<td>air temperature (°C)</td>
</tr>
<tr>
<td>SWC</td>
<td>soil water content (%)</td>
</tr>
<tr>
<td>ρ</td>
<td>density of water (998 kg m⁻³)</td>
</tr>
<tr>
<td>Gᵥ</td>
<td>universal gas constant adjusted for water vapor (0.462 m¹ kPa K⁻¹kg⁻¹)</td>
</tr>
</tbody>
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**Fig. 1.** The relationship between sapwood depth, sapwood area and diameter at the breast height (DBH) for G. biloba, P. tabulaeformis, R. pseudoacacia, and C. deodora.
diversity, suitable sites, convenient power, and granted permission (Pataki et al., 2011). Hereby, it was not feasible to study many trees of each species over a long time period. Moreover, a careful literature survey on previous studies shows that 1 to 8 individuals are adequate to indicate transpiration characteristics and their response to environmental variables of homegarden tree species, irrigated grapevines, natural rain forest, wet tropical forest, deciduous forest etc. in diverse environments (Granier et al., 1996; Pataki and Oren, 2003; Lu et al., 2003; O’Brien et al., 2004; Burgess, 2006; Costa et al., 2006; Fernandez et al., 2009).

2.2. Environmental measurements

An automated weather station was very close to the trees selected for the study. The station was located at an open area, with minimized influences from nearby trees, buildings, and other obstacles. Environmental parameters, including air temperature, air relative humidity, wind speed, total radiation, and rainfall, were monitored by the meteorological station (HMP45C temperature/humidity sensors, Vaisala, Inc., Helsinki, Finland; 034B wind sensor, Met One Instruments, Grants Pass, Oregon, USA; CMP-11 pyranometer, Kipp and Zonen, Delft, Netherlands; TE525MM tipping bucket rain gauge, Campbell Scientific, Inc., Logan, UT). Vapour pressure deficit (D) was calculated from air temperature and relative humidity data (Campbell and Norman, 1998). Three soil water probes (ECH2O, Decagon Devices, Inc., Pullman, WA, USA) were placed at the depth of 30 cm among the sampled trees to monitor soil water content. These environmental parameters were continuously monitored and recorded every 10 min.

Ambient ozone (O3) concentrations were monitored around the selected species and recorded every hour using Model 49i gas analyzer (Thermo Fisher Scientific Inc., Massachusetts, USA). The gas analyzer was calibrated every week.

![Fig. 2. Daily sap flux density (\( J_o \)) for each tree in the selected species from November 1, 2008 to October 31, 2009. Days of missing data was filled by multiple regression or curve estimation considering the change of leaf area and soil water content (grey colour).](image)
2.3. Sap flow measurements and scaled transpiration

Instantaneous sap flux density, flow per unit sapwood cross-sectional area \( \bar{J}_s (g \text{ H}_2\text{O cm}^{-2} \text{ s}^{-1}) \), is estimated by thermal dissipation probes (Dynamax, Houston, TX, USA) since April, 2008, which continuously measure the temperature difference between heated and unheated probes \( \Delta T \) (Granier, 1987). The \( \Delta T \) data were recorded as 10 min means (CR1000 data logger, Campbell Scientific Ltd., UK). Errors may be caused by uncertainties in the baseline position (Oishi et al., 2008). During conditions of zero sap flux density, such as during prolonged rain events or after several night time hours, the temperature difference between upper and lower thermocouples represents the steady state temperature difference due solely to the dissipation of heat into non-transporting sapwood (Phillips et al., 1997). We selected the highest temperature difference between heated and unheated probes during times of zero flux \( \Delta T_{\text{exp}} \) as a baseline day by day, from which any sap flow causes a decrease in \( \Delta T_{\text{exp}} \) (Granier, 1987; Phillips et al., 1997). Deviation from the baseline is used to estimate \( J_s \) (Granier, 1987).

Both axial and radial variations in sap flux density across the active sapwood \( \bar{J}_s (g \text{ H}_2\text{O cm}^{-2} \text{ d}^{-1}) \) should be considered to reduce the errors that may occur when scaling-up sap flux density measurements to the whole-tree or stand scale (Oren et al., 1998; Oren et al., 1999a; Lu et al., 2000; Delzon et al., 2004; Ford et al., 2004; Tateishi et al., 2008). In our study, for \( P. \) tabulaeformis No.3 and \( C. \) deodara No.3, radial variations in \( J_s \) were measured by 80 mm long probes with thermocouples mounted at the 15 mm, 50 mm, and 90 mm (Dynamax, Houston, TX, USA). However, these were not feasible in each studied tree due to the following reasons: 1) it was too expensive. We had 17 selected trees, and three sets of sap flow measurement systems due to the low plant density of selected species; 2) we used three 100 Ahr batteries, rather than altering selected trees, and three sets of sap flow measurement systems due to the low plant density of selected species; 3) the local government has strict regulations on trees in urban areas, which confined our experiments on trees. Therefore, we used a simplified function for scaling radially detailed in Pataki et al. (2011).

Direct measurements at multiple sapwood depths are required to calculate radial variations in \( J_s \) (Lu et al., 2000; Delzon et al., 2004; Ford et al., 2004; Tateishi et al., 2008). In our study, for \( P. \) tabulaeformis No.3 and \( C. \) deodara No.3, radial variations in \( J_s \) were measured by 80 mm long probes with thermocouples mounted at the 15 mm, 50 mm, and 90 mm (Dynamax, Houston, TX, USA). However, these were not feasible in each studied tree due to the following reasons: 1) it was too expensive. We had 17 selected trees, and three sets of sap flow measurement systems due to the low plant density of selected species; 2) we used three 100 Ahr batteries, rather than altering the current for safety reasons, which limited the probes increase; and 3) the local government has strict regulations on trees in urban areas, which confined our experiments on trees. Therefore, we used a simplified function for scaling radially detailed in Pataki et al. (2011).

\[
\begin{align*}
\text{Angiosperm} & \quad J_s/J_0 = 1.033 \times \exp \left[-0.5 \left( \frac{x-0.09963}{0.4263} \right)^2 \right] \quad (1) \\
\text{gymnosperm} & \quad J_s/J_0 = 1.257 \times \exp \left[-0.5 \left( \frac{x-0.3724}{0.65620} \right)^2 \right] \quad (2)
\end{align*}
\]

where \( J_s/J_0 \) is the ratio of sap flux at the actual to the outermost sapwood depth, \( x \) is the relative sapwood depth based on previously published values.
where the sapwood area (cm²), respectively, at depth 2.4. Sapwood depth and sapwood area 0.1714 for gymnosperms (Pataki et al., 2011). The error at each sapwood increment study species at the same location and applied that relationship to our study trees we determined the relationship between tree diameter and sapwood area for each we did not core trees at the end of the three With other ongoing studies (long-term water use by urban tree species) at the site, was then propagated to obtain the total error in estimating whole-tree transpiration (Pataki et al., 2011).

To estimate the error at each 2-cm-sapwood increment (σi), we used the following equation (Pataki et al., 2011):

\[ σ_i = J_i \sqrt{σ_j^2 + (\sigma_R)^2} \]

where \( J_i \) is sap flux in the outer 2 cm of xylem, \( σ_j \) is the standard deviation in \( J_0 \), and \( σ_R \) is the error of the radial trends regression estimate, 0.2583 for angiosperms and 0.1714 for gymnosperms (Pataki et al., 2011). The error at each sapwood increment was then propagated to obtain the total error in estimating whole-tree transpiration (Pataki et al., 2011).

2.4. Sapwood depth and sapwood area

A destructive harvest is required to determine the exact proportion of a particular sensor’s length that extends into non-conductive sapwood (Oishi et al., 2008). With other ongoing studies (long-term water use by urban tree species) at the site, we did not core trees at the end of the three—year round experiment. Alternatively, we determined the relationship between tree diameter and sapwood area for each study species at the same location and applied that relationship to our study trees (Fig.1). Trees of various diameter at the breast height (DBH) rank in G. biloba (n = 33), R. pseudoacacia (n = 23), P. tabulaeformis (n = 22), and C. deodara (n = 15) were cored at 1.30 m from the ground at the Beijing Teaching Botanical Garden right before we started the sap flux measurement. Sapwood depth was visually estimated. As there are only a few trees for A. chinensis and M. liliflora in our study site, its sapwood depth was determined by removing cores from the nearby trees with DBH difference less than 2 cm.

2.5. Estimation of canopy conductance

Urban trees generally have open, well-ventilated, aerodynamically rough canopies. Therefore, a strong coupling of canopy surface to the atmosphere can be assumed (Jarvis and Menaughton, 1986; Schafer et al., 2000). We validated this assumption for our selected deciduous tree species. Using a gas exchange system (LI-6400, Li-cor, USA), we measured the stomatal conductance (\( G_C \)) of 9 healthy mature leaves from 3 branches in the outer middle canopy of each tree at noon (12:00-13:00) for three days per month from May to October. For comparison, averaged stomatal conductance at the leaf level was obtained by relating \( G_C \) around 12:00 from May to October to the tree’s foliage area. Finally, the average calculated stomatal conductance values were compared to values obtained from gas exchange measurements for the same tree during the same time period. The difference between these two averages wasn’t significant for both G. biloba and A. chinensis (Table 4; \( p = 0.513 \) for G. biloba; \( p = 0.792 \) for A. chinensis). These results indicated that the boundary layer resistance was low under urban tree canopy, and the canopy surface is aerodynamically well coupled to the atmosphere. Therefore, the whole-tree canopy conductance (\( G_C \), mmol H₂O m⁻² s⁻¹) of the selected trees can be calculated based on a simplified equation (Köstner et al., 1992):

\[ G_C = \frac{(E_{pG}T_A)}{D} \]

\( E_p \) is the canopy transpiration obtained by dividing \( E_p \) by projected crown area (Granier, 1987); \( p \) is the density of water [998 kg m⁻³]; \( G_p \) is the universal gas constant adjusted for water vapor (0.462 m² kPa K⁻¹ kg⁻¹); \( T_A \) is the air temperature (°C); and \( D \) is vapour pressure deficit (kPa). We selected a subset of the data to calculate \( G_C \) based on the following rules: 1) data collected during rainfall and 2 h after, were excluded to avoid the discrepancy between evaporation and tree transpiration (Granier et al., 2000); 2) data were excluded when global radiation, or vapour pressure deficit, or stand transpiration were too low (<5% of the maximum value), because of the large relative uncertainties in computing \( G_C \) under these conditions (Granier et al., 2000); 3) data were excluded when \( D < 0.6 \) kPa for \( G_C \) estimation, to keep errors in \( G_C \) estimates to less than 10% (Ewers and Oren, 2000); and 4) only data collected during the leaf-on periods were included for the selected deciduous species. Days with leaf-on after full expansion for G. biloba, A. chinensis, M. liliflora, R. pseudoacacia were DOY115-305, DOY 118-306, DOY
118-306, respectively. The critical level for trees is defined for a six month growing season (UNECE, 2004). Hence, only data collected during DOY 122-305 (from May 1 to October 31) were used for the selected species for comparisons with critical level.

Unlike the intermittent measurements, the continuous sap flow and environmental recordings over a rather small time scale are more reliable and less susceptible to measurement errors. Therefore, the variations of ozone uptake based on this method would be representative on how the environmental variables influence the ozone uptake by urban trees. Response functions of GC to vapour pressure deficit (D) and total radiation (Rs) were derived from boundary line analysis (Webb, 1972; Jarvis, 1976; Dye and Olbrich, 1993; Rico et al., 1996; Martin et al., 1997), using the maximum of Gc of 2–3 trees per species for different D classes (step width: 0.2 kPa) and Rs classes (step width: 50 W m\(^{-2}\)). How Gc responds to changes in D can be described by the following function (Oren et al., 1999b):

\[
Gc = -m \ln(D) + b
\]

where m and b were estimated using least squares regression with SigmaPlot 10.0 (Systat Software Inc., San Jose, California). The relationship between \(G_c\) and ln(D) provided the best fit for the deciduous species. For the evergreen species, the slope of the regression, quantifies stomatal sensitivity to D. The parameter b, the intercept, is the reference conductance (Gref) at D = 1 kPa.

2.6. Calculation of O\(_3\) uptake

The canopy O\(_3\) uptake was calculated according to the flux equation below, by assuming zero O\(_3\) concentration at the mesophyll surface (Laik et al., 1989):

\[
F_{O3} = |O_3|/G_{O3}
\]

where \(F_{O3}\) is the whole-tree canopy O\(_3\) uptake rate scaled to ground surface area, \(|O_3|\) is the ozone concentration of the ambient air (Wieser et al., 2000); \(G_c\) is the canopy conductance to water vapour, and 0.633 is the conversion factor representing the ratio of the diffusion coefficients of ozone to water vapour in air (C. Wieser and Havranek, 1995).

The concentration-based critical levels (Cle) and flux-based critical levels (Clef) are typically used to indicate the risk of ozone damage to vegetation (Simpson et al., 2007). The Cle for crops, natural vegetation, and forest trees has been derived from a linear relationship between the accumulated exposure (\(E_0\) accumulated over a threshold of x ppb, AOT\(_x\)) or the accumulated flux (accumulated \(O_3\) flux above a threshold y, AFS\(_y\)) and relative yield or percentage reduction in biomass (UNECE, 2004). New critical levels (AOT\(_{405}\) ppm h and AF\(_{x}\) 1.6 4 mmol m\(^{-2}\)) for ozone effects on trees have been proposed recently (UNECE, 2004). In this study, we used these two new critical levels to evaluate the potential risk of ozone damage on urban trees.

2.7. Data processing

2.7.1. Gap filling

Missing data is a common problem when conducting sap flow studies over long periods of time. In order to estimate annual water loss and compare species differences for the studied species, it was necessary to devise gap filling procedures for sap flux during the study period. Previous studies have used a multiple regression approach by regressing daily sap flux against daily PAR and D (Wullschlegler and Norby, 2001), or a trignometric regression approach that accounts for independence in climate data (Hubbard et al., 2010).

In our study, due to power-off or equipment maintenance, there were 20, 23, 144, 60, 73 missing days during the one year period (365 days), and 13, 13, 14, 74, 0, 12 missing days during the growing period (183 days) for G. biloba, A. chinensis, M. lilii, R. pseudoacacia, P. tabulaeformis, and C. deodara. As for daily \(J_0\), we estimated daily \(J_0\) for missing days by multiple regression or curve estimation to measured sap flux densities and climate data collected on site. Photosynthetically active radiation (PAR), vapor pressure deficit (D), and soil water content (SWC) were the best predictors of daily \(J_0\), accounting for approximately 60% of the observed variability (Table 2). Canopy leaf area index was close to maximum during this period. As for hourly canopy conductance (\(G_c\)), a filter was employed to studied species to make nearly all individuals have the same gap, except R. pseudoacacia with a two-month gap. For R. pseudoacacia, Jarvis-style model was built (\(R^2 = 0.5476\) for R. pseudoacacia 1, \(R^2 = 0.5235\) for R. pseudoacacia 2, \(R^2 = 0.7248\) for R. pseudoacacia), and used for the \(G_c\) gap. These data, along with known estimates for the other hours, were used to calculate accumulative ozone uptake and compare species difference for the studied species during the growing season.

2.7.2. Statistical analyses

Statistical analyses were performed by SPSS 11.5 (SPSS Inc., Chicago, USA). Paired sample \(t\) tests were conducted to test whether there were statistically significant differences at \(p < 0.05\) in average stomatal conductance obtained from sap flow measurements and gas exchange measurements of the deciduous species. Independent \(t\) tests were used to test whether there were significant differences at \(p < 0.05\) in the average \(G_c\), \(F_{O3}\), annual average AF\(_{x}\) between deciduous species and evergreen species, as well as \(J_0\) at the North and South aspect of trunk in P. tabulaeformis. One-
way ANOVA was used to test whether there were significant differences at p < 0.05 in $J_0$ at the different aspect of trunk in C. deodara and R. pseudoacacia, as well as the average $G_0$, $F_0$, and annual average $A_{Fst}$ among species.

3. Results

3.1. Sap flux scaling

The daily sap flux density in the outer 2 cm of sapwood ($J_0$) for studied trees showed a seasonal change pattern, with flux densities increasing in April as canopy leaf area started growing, reaching a broad plateau between May and August, and then declining in September (Fig. 2). The high $J_0$ of summer coincided with the rapid growth season, strong solar radiation, and ample water supply, typical environment of trees in temperate ecosystems. During the winter months, even the $J_0$ of evergreen trees was markedly damped (Fig. 2). In order to conduct species comparisons for the studied species from 1st, May to 31th, October in 2009, gap filling procedures for sap flux densities were devised. A. chinensis and P. tabulaeformis exhibited high $J_0$ (139.11 ± 21.12; 141.30 ± 20.61 g cm$^{-2}$ d$^{-1}$); G. biloba and C. deodara showed intermediate values (124.84 ± 9.03; 111.32 ± 22.92 g cm$^{-2}$ d$^{-1}$); and M. liliiiflora and R. pseudoacacia had much lower densities (97.27 ± 12.48; 86.85 ± 13.83 g cm$^{-2}$ d$^{-1}$).

Axial variation was substantial in the selected trees in P. tabulaeformis, C. deodara, and R. pseudoacacia (Fig. 3A–C). Due to more exposure to sun in the south aspect, the anatomy of the xylem structure and under branch height, there was apparent relationship between sap flux density and aspect in P. tabulaeformis and C. deodara, but no apparent relationship with R. pseudoacacia (Wang et al., 2010). Hourly $J_0$ over 24 h at different aspects were highly correlated (Fig. 3D–F). Therefore, mean $J_0$ could be accurately estimated based on the measurement obtained on one aspect. Daily means of $J_0$ at the different aspect of trunk were similar (Fig. 3G–I; for P. tabulaeformis, Independent $t$-test, $p = 0.972$; for C. deodara, one-way ANOVA, $p = 0.913$; for R. pseudoacacia, one-way ANOVA, $p = 0.422$). This similarity in urban trees was different from findings from natural forests (Oren et al., 1999a), which maybe because every aspect of trunk in urban trees exposes to similar radiation and humidity conditions, due to the low density of trees.

$J_s$ (sap-flux density across the active sapwood) and $E_T$ (tree transpiration) estimated with the method proposed by Pataki et al. were shown in Table 3 (Pataki et al., 2011). The differences in tree transpiration among species were relatively large, with estimates ranging from 4.56 ± 1.42 kg tree$^{-1}$ d$^{-1}$ in M. liliiiflora to 35.09 ± 14.44 kg tree$^{-1}$ d$^{-1}$ in C. deodara. The highest $J_s$ was found in A. chinensis, while the highest $E_T$ was found in C. deodara. The coefficient of variation (= standard deviation/mean), as well as the difference between the coefficient of variation for $J_0$ and $J_s$ were also similar to the pattern in the Pataki paper, which was about 25% for $J_0$ and 50% for $J_s$ (Pataki et al., 2011).

3.2. Ozone load

Daily average concentration of ambient $O_3$ exhibited a seasonal cycle with maxima of 75 ppb during the summer and minima of 1 ppb during the winter (Fig. 5). The maximum $O_3$ concentration occurred in the summer when the air temperature was high and the photochemical reaction was active. During our study period (from November 1, 2008 to October 31, 2009), the hourly average $O_3$ concentration was 22 ppb, with the maximum of 138 ppb. Most of the hourly average concentrations of $O_3$ approximated 84%, were within the range of 0–40 ppb. Approximately 7% of the hourly average concentrations of $O_3$ were greater than 60 ppb. The accumulated ozone exposure over a threshold of 40 ppb or nl l$^{-1}$ (AOT40) during the growing season (from May 1, 2009 to October 31, 2009) was 20.12 ppm h at the study site.

3.3. Ozone uptake

The seasonal variations of daily average canopy conductance to $O_3$ ($G_0$), whole-tree $O_3$ uptake rate ($F_0$), and accumulative

![Fig. 5. Seasonal course of daily mean ambient ozone concentration ($O_3$), ground area scaled canopy conductance for ozone ($G_0$), canopy $O_3$ uptake rate ($F_0$), and accumulated stomatal ozone flux ($A_{Fst}$) of six tree species in urban environment from November 1, 2008 to October 31, 2009. Jarvis-style model was built and used to fill the canopy conductance gap in R. pseudoacacia (grey colour).](image)
stomatal O₃ flux (AFₙ0) of the 17 selected trees were shown in Fig. 5. The highest levels of GO₃ and FO₃ were observed in summer months, while the lowest levels were observed in winter months (Fig. 5). During the growing season, the average GO₃ (p = 0.004), FO₃ (p = 0.002), and annual average AFₙ0 (p = 0.013) differed significantly among studied species. A. chinensis and M. lilii had the high FO₃ (4.01 ± 0.61; 4.80 ± 1.04 mmol m⁻² s⁻¹), while R. pseudoacacia had the lowest FO₃ (0.61 ± 0.07 mmol m⁻² s⁻¹). The other studied species showed intermediate values. In particular, the

Table 5
Average canopy conductance for O₃ (GO₃, mmol m⁻² s⁻¹), canopy O₃ uptake rate (FO₃, mmol m⁻² s⁻¹), and accumulated stomatal ozone flux over thresholds of 0.16 nmol m⁻² s⁻¹ (AFₙ0,16, mmol m⁻²) estimated during the growing season (from May 1 to October 31).

<table>
<thead>
<tr>
<th>Species</th>
<th>GO₃ mmol m⁻² s⁻¹</th>
<th>FO₃ mmol m⁻² s⁻¹</th>
<th>AFₙ0,16 mmol m⁻²</th>
</tr>
</thead>
<tbody>
<tr>
<td>G. biloba</td>
<td>80.27 ± 0.84</td>
<td>3.09 ± 0.01</td>
<td>15.77 ± 0.02</td>
</tr>
<tr>
<td>A. chinensis</td>
<td>104.16 ± 16.61</td>
<td>4.01 ± 0.61</td>
<td>19.15 ± 3.16</td>
</tr>
<tr>
<td>M. lilii</td>
<td>129.10 ± 29.22</td>
<td>4.80 ± 1.04</td>
<td>20.97 ± 5.63</td>
</tr>
<tr>
<td>R. pseudoacacia</td>
<td>17.35 ± 2.14</td>
<td>0.31 ± 0.07</td>
<td>3.43 ± 0.41</td>
</tr>
<tr>
<td>P. tabulaeformis</td>
<td>58.08 ± 9.16</td>
<td>5.11 ± 1.28</td>
<td>11.12 ± 1.66</td>
</tr>
<tr>
<td>C. deodara</td>
<td>62.76 ± 5.21</td>
<td>2.24 ± 0.17</td>
<td>11.29 ± 1.02</td>
</tr>
</tbody>
</table>

Notes: To make nearly all individuals have the same gaps, a filter was employed to select the maximum AFₙ0 (p = 0.002) differed significantly from those of deciduous species (G. biloba, A. chinensis, M. lilii, R. pseudoacacia) by contrast was not significantly higher than those of evergreen species (P. tabulaeformis and C. deodara) (82.94 vs 60.42 mmol m⁻² s⁻¹ p = 0.322; 3.13 vs 2.21 nmol m⁻² s⁻¹ p = 0.160; 14.74 vs 11.20 mmol m⁻²; p = 0.364) (Table 5).

3.4. Effects of environmental factors on ozone uptake

O₃ uptake was determined by interaction of canopy conductance and ambient O₃ concentration. The resulting O₃ uptake rate (FO₃) followed a close pattern to ambient O₃ concentration (Fig. 6). At a given ambient O₃ concentration, FO₃ was effectively controlled by canopy conductance to O₃ (GO₃) and, hence, by vapour pressure deficit (D) and total radiation (Rₛ). D and Rₛ were correlated. At the range of D between 0.8 kPa and 1 kPa, Rₛ was the dominant factor of GO₃ response, so while both D and Rₛ increased, so did GO₃ (Fig. 6). When D was approaching 1 kPa and beyond, D became the dominant factor, the increase of D leading to a decrease in GO₃, despite of the increase of Rₛ because of the need to protect the hydraulic system (Fig. 6).

An analysis of hourly data confirmed that the high D led to varying degrees of decline in GO₃, and thus contrasting reduction in FO₃, especially with more pronounced reductions in G. biloba, A. chinensis, and M. lilii (Fig. 6A). At low D, however, GO₃ was
high and thus allowed a high O₃ flux even at low O₃ concentrations (Fig. 6A). Using equation (6), we analyzed data selected from the boundary line analysis for each species. All the least-square regressions between GC and D were significant (p < 0.0001), with the regression coefficient of determination (R²) ranging from 0.97 to 0.99. The sensitivity of GC to D (the slope m in equation (6)) increases linearly with Gref (the b in equation (6)) for study species (Table 6). The slope of this linear relationship was 0.50 (R² 0.99). Furthermore, the thresholds at which GC began to decrease also occurred at higher D values (1.2 kPa) for G. biloba, A. chinensis, and M. liliiiflora than that for other species (1.0 kPa) (Table 6). Hence, the higher was the Gref, the more sensitive to M. liliiiflora to 0.99. The sensitivity of M. liliiiflora to the increase of O₃ begins to decrease faster with increasing D, regardless of species (Fig. 6A). It’s important to note that sensitivities were estimated based on data of GC in the range in which GC decreases exponentially with D, but not on all the data. For all the data, the reduction in GC was less sensitive to the increase of D.

A further analysis on the hourly data showed that only small changes occurred for both GC and O₃ concentration, and thus for FO₃, with the increase of Rₖ (Fig. 6B). For G. biloba, A. chinensis, and M. liliiiflora, in turn for FOG, tended to increase with the increase of Rₖ, and then decrease rapidly after approximately 400 W m⁻² at which the stomata presumably became light saturated. However, the O₃ uptake by the other studied species remained largely constant with the increase of Rₖ during most of the time.

4. Discussion

4.1. Whole-tree O₃ uptake of contrasting species

The sap flow based approach for estimating ozone uptake at the whole-tree or the stand level covered the effect of boundary layers on ozone flux (Wieser et al., 2003). Both average canopy O₃ uptake rate and accumulated O₃ uptake estimated during the growing season (from May, 1 to October, 31) of the studied species in urban environment were comparable with values obtained in a Pinus canariensis forest in Canary Islands (Wieser et al., 2006), Norway spruce (Picea abies) and cembran pine (Pinus cembra) at six rural sites between 580 and 1950 m a.s.l (Wieser et al., 2000), and in turn for FOG, tended to increase with the increase of Rₖ, and then decrease rapidly after approximately 400 W m⁻² at which the stomata presumably became light saturated. However, the O₃ uptake by the other studied species remained largely constant with the increase of Rₖ during most of the time.

The studied species in urban environment exhibited higher O₃ uptake in summer months, when higher temperature, radiation, vapor pressure deficit, and precipitation occurred. The seasonal variation in FOG, in our study was similar to that observed in a pine forest at high elevation (Matyssek et al., 2007, 2008). However, our results were different from that observed in a Pine forest in Canary Island (Mediterranean type climate) (c.f. Luis et al., 2005; Wieser et al., 2006). Due to the combination of strong fog impact on air humidity and access to deep soil water reserves, O₃ uptake did not show a significant reduction when the air and soil were dry, hence no clear seasonal trend was observed in a pine forest in Canary Island (c.f. Luis et al., 2005; Wieser et al., 2006).

There were very large species differences in ground area scaled whole-tree ozone uptake (F O₃), with estimates ranging from 0.61 ± 0.07 nmol m⁻² s⁻¹ in R. pseudosasa to 4.80 ± 1.04 nmol m⁻² s⁻¹ in M. liliiiflora. This was mainly due to the influence of management, disturbance, species composition, and many other aspects of decision-making in urban forests as compared to their natural counterparts (Patali et al., 2011). However, average FO₃ by deciduous foliages was not significantly higher than that by evergreen ones (3.13 vs 2.21 nmol m⁻² s⁻¹, p = 0.160). In contrast, Wieser et al. (2003) found that when scaled to the ground surface area, the O₃ uptake by evergreen foliages (Norway spruce, Cembran pine) was significantly higher than that by deciduous ones (European larch), which was due to differences in stomatal behavior, leaf area index, and canopy structure.

Notably, we found the annual O₃ uptake by trees estimated by our sap flow measurements in Beijing was 0.78 g m⁻² (i.e., an average of AF₃O during growing season 16.20 nmol m⁻² × 48 g mol⁻¹ × 1000 = 0.78 g m⁻²), which is much lower than values estimated from the Urban Forest Effects Model (e.g., McPherson et al., 1994; Yang et al., 2005; Nowak and Dwyer, 2007; Table 7). Nowak and Dwyer (2007) found that the average annual O₃ removal rate by canopy cover in several USA cities was about 2.96 g m⁻² (i.e., total pollution removal 9.3 g m⁻² × the ratio of O₃ to total pollution removal 31.8% = 2.96 g m⁻²). Yang et al. (2005) found that the annual O₃ removal rate per canopy area in Beijing was approximately 5.50 g m⁻² (i.e., 27.5 g m⁻² × 20% = 5.50 g m⁻²). McPherson et al. (1994) showed that annual O₃ removal rate by tree canopy cover in Chicago was 2.86 g m⁻². Since the length of the season over which estimates were made (in-leaf, daytime, yearly) were same, this large discrepancy between estimates from our field data and those from modeling may be due to the following reasons. First, the canopy resistance (Rc) of approximately 1.74 cm s⁻¹ used in UFORE model was significantly smaller than 2.81 cm s⁻¹, the average Rc of the selected species measured in our study (Table 7). This difference in canopy resistance may be the primary cause of the large discrepancy. In modeling approaches, canopy resistance has been typically calculated either based on a multi-layer canopy deposition model, or derived from literature on individual trees and forests (Baldocchi et al., 1987; McPherson et al., 1994; Nowak and Crane, 2000; Yang et al., 2005). Second, leaf area index that was used to calculate canopy stomatal resistance and canopy cuticle resistance in UFORE model was much higher than that in our study (Table 7). Third, ambient O₃ concentrations measured in our study were lower than those used in modelling (Table 7). Fourth, while sap flow measurements only estimate the O₃ flux into the leaves, modeling methods calculate the total dry deposition that includes both stomatal O₃ uptake and adsorption onto non-transpiring external tree surfaces.

### Table 6
Stomatal sensitivity to vapor pressure deficit (D) estimated as the slope of the relationship between canopy conductance and ln(D) (Oren et al., 1996b), applied to those data in which gc decreased exponentially with D (see Fig. 6A).

<table>
<thead>
<tr>
<th>Species</th>
<th>Sensitivity(m)</th>
<th>gcref(b)</th>
<th>m/b</th>
<th>D threshold</th>
</tr>
</thead>
<tbody>
<tr>
<td>G. biloba</td>
<td>−233.57</td>
<td>451.75</td>
<td>−0.52</td>
<td>1.00</td>
</tr>
<tr>
<td>A. chinensis</td>
<td>−278.67</td>
<td>562.69</td>
<td>−0.50</td>
<td>1.20</td>
</tr>
<tr>
<td>M. liliiiflora</td>
<td>−416.6</td>
<td>873.20</td>
<td>−0.48</td>
<td>1.40</td>
</tr>
<tr>
<td>R. pseudosasa</td>
<td>−44.35</td>
<td>82.14</td>
<td>−0.54</td>
<td>0.80</td>
</tr>
<tr>
<td>P. tabuliformis</td>
<td>−116.34</td>
<td>241.43</td>
<td>−0.48</td>
<td>1.00</td>
</tr>
<tr>
<td>C. deodara</td>
<td>−160.19</td>
<td>302.53</td>
<td>−0.53</td>
<td>1.00</td>
</tr>
</tbody>
</table>

*D threshold is the value of leaves to air vapor pressure difference from which gc begins to decrease in an exponential form. Reference canopy conductance (gcref) is gc at D = 1 kPa.

### Table 7
Ozone removal/uptake values per square meter of tree canopy cover per year (g m⁻² year⁻¹) from the literatures.

<table>
<thead>
<tr>
<th>Site</th>
<th>O₃ concentration (ppb)</th>
<th>Tree cover (%)</th>
<th>Canopy resistance (cm s⁻¹)</th>
<th>LAI</th>
<th>Removal rate g m⁻² year⁻¹</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chicago</td>
<td>Hourly</td>
<td>27 (13–38)</td>
<td>11</td>
<td>1.74</td>
<td>4.30 28.6</td>
<td>McPherson et al., 1994</td>
</tr>
<tr>
<td>Beijing</td>
<td>Monthly</td>
<td>70(40–120)</td>
<td>17</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>USA cities</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Beijing</td>
<td>Hourly</td>
<td>22 (0–138)</td>
<td>2.81</td>
<td>2.34</td>
<td>0.85</td>
<td>Our results</td>
</tr>
</tbody>
</table>
which may lead to higher ozone removal. Fifth, deposition velocity in UFORE model was calculated as the inverse of the sum of the aerodynamic, quasi-laminar boundary layer and canopy resistances (Nowak and Crane, 2000), but in our study we only calculated canopy resistances, which would also contributed to the difference. In conclusion, this difference may suggest the necessity to consider the species-specific flux in O3 risk assessment.

4.2. Environmental control of ozone uptake in urban trees

Variations in O3 uptake are partly due to the variations in both ambient O3 concentrations and stomatal conductance. At our study site, there was a pronounced seasonal pattern in O3 concentrations. O3 concentrations were high in summer months, but much lower during the winter months. The resulting F03 showed a close pattern to ambient air O3 concentrations (Fig. 5). Stomatal control is a critical factor in limiting whole-tree ozone uptake (Emerson et al., 2000; Wieser et al., 2006; Nunn et al., 2007). The degree of stomatal opening that regulated the whole-tree ozone uptake in our selected trees was mainly influenced by the vapour pressure deficit and radiation. The relative high O3 uptake by urban trees may be due to the reasons below. On the one hand, at low D, stomata were widely open allowing a high flux of O3 into the leaves even at low O3 concentrations. Similar result was also found in a planted exotic species (Pseudotsuga menziesii) in South America, which replaced native vegetation resulting in increased vegetation water use (Fernandez et al., 2009). Secondly, the slope in the strong linear relationship between the sensitivity of GC to D (the slope m in equation (6)) and Gref (the b in equation (6)) for studied species was of 0.50 (Table 6). This value was much smaller than that for the mesic adapted species (0.60), much larger than that for desert species (0.42 and 0.38), but closer with that for plantation species (0.46) (Oren et al., 1999b; Fernandez et al., 2009). Thirdly, high water availability at our study site might increase O3 uptake. Chamber experiments with seedlings or twigs gave evidences that drought stress protected plants from O3 injury mainly by regulating stomatal aperture (Wieser and Havranek, 1993). In our study site, the soil water content were not in deficit condition for nearly all the studied species, except for R. pseudoacacia (Fig.7), which may not limit the stomata opening, and hence contributed to the relative high ozone uptake by urban trees.

4.3. Do ozone concentrations exceeding critical levels cause probable corresponding effects on urban trees?

Both the exposure-based and flux-based critical levels (AOT40 and AFst1.6) were used to evaluate the potential impacts of ozone on trees in our study site. Our results indicated that there was great potential O3 risk for trees in our study site, when using the exposure-based critical level. The AOT40 (accumulated exposure over a threshold of 40 ppb or nl l \(^{-1}\)) during the growing season at our study site was 20.12 ppm h, which far exceeded the AOT40 5 ppm h, the current critical level for ozone impacts on trees (UNECE, 2004).

When using the flux-based critical level, the AFst1.6 values for most of the studied species were above 4 mmol m\(^{-2}\) s\(^{-1}\), the current flux-based critical level for ozone impacts on trees (UNECE, 2004). These results indicated that urban trees species, including both deciduous species and evergreen species, are susceptible to O3 damage. However, AFst1.6 values observed for the four deciduous species ranged from 14.70 ± 5.13 mmol m\(^{-2}\) in M. liliiiflora to 0.15 ± 0.08 mmol m\(^{-2}\) in R. pseudoacacia, suggesting that the tolerating capacity to O3 was diverse. By contrast, AFst1.6 values observed for the two evergreen species approached the current flux-based critical level, indicating that they may be less susceptible to O3 damage. These results are similar to findings from previous studies that Mediterranean evergreen shrubs have a higher capacity to tolerate ozone stress than their deciduous relatives (Calatayud et al., 2010). In addition, our results suggest that the flux-based measurement is better suited for evaluating the risk of ozone impacts on urban trees than the exposure-based method. These results are also consistent with those from previous studies that ozone fluxes are more accurate than AOT40 exposure-based measurement in predicting ozone visible foliar injury (Gerosa et al., 2008).

Acknowledgments

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