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Ozone uptake by adult urban trees based on sap flow measurement

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ABSTRACT

The O_3 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 (F_{O_3}), 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 liliiflora*. However, average F_{O_3} 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 O_3 (G_{O_3}) took up more O_3 than those of low G_{O_3}, but that their sensitivity to vapour pressure deficit (*D*) were also higher, and their F_{O_3} decreased faster with increasing *D*, regardless of species. The responses of F_{O_3} to *D* and total radiation led to the relative high flux of O_3 uptake, indicating high ozone risk for urban tree species.

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 (O_3; 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.

O_3 uptake by plants depends on both the ambient O_3 concentration and the stomatal conductance (Wieser and Havranek, 1995; Nowak and Dwyer, 2007). At a given ambient O_3 concentration, the rate of O_3 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 O_3 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.

O_3 uptake by urban trees has been largely examined based on modeling approaches that integrate vegetation information with meteorological and ambient O_3 concentration data (McPherson

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Table 1
Abbreviations used in the text.

Abbreviation	Definition (Units)
A_S	sapwood area (cm^2)
A_i	sapwood area at depth *i* (cm^2)
DBH	diameter at the breast height (cm)
A_c	canopy projected area (m^2)
LAI	leaf area index
J_O	sap flux density in the outer 2 cm of sapwood ($g\ cm^{-2}\ d^{-1}$)
J_i	sap flux density at depth *i* ($g\ cm^{-2}\ d^{-1}$)
J_S	sap flux density across the active sapwood ($g\ cm^{-2}\ d^{-1}$)
E_T	tree transpiration ($kg\ d^{-1}$)
E_C	canopy transpiration ($mm\ d^{-1}$)
σ_i	error estimate at depth i
σ_o	error estimate in the outer 2 cm of sapwood
σ_R	error estimate of the J_i/J_O ratio
G_{O_3}	canopy conductance for O_3 ($mmol\ m^{-2}\ s^{-1}$)
F_{O_3}	canopy O_3 uptake rate ($nmol\ m^{-2}\ s^{-1}$)
AOT40	accumulated exposure (O_3 accumulated over a threshold of 40 ppb)
$AF_{st}0,1.6$	accumulated stomatal ozone flux over thresholds of 0,1.6 $nmol\ m^{-2}\ s^{-1}$ ($mmol\ m^{-2}$, projected area) estimated during the growing season
$[O_3]$	ozone concentration of the ambient air (ppb)
D	vapor pressure deficit (kPa)
R_S	total radiation ($W\ m^{-2}$)
T_a	air temperature (°C)
SWC	soil water content (%)
ρ	density of water (998 $kg\ m^{-3}$)
G_V	universal gas constant adjusted for water vapor (0.462 $m^3\ kPa\ K^{-1}kg^{-1}$)

et al., 1994; Nowak et al., 2000). These studies primarily focused on O_3 removal by urban trees (e.g., Nowak et al., 2000; Yang et al., 2005). While the modeling approach can provide important information on O_3 removal by urban trees at the city scale, variations in canopy resistance due to trees with different height and crown configurations, and heterogeneous ambient O_3 concentrations may introduce uncertainties into the estimates (Scott et al., 1998). Alternatively, O_3 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 O_3 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 O_3 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 O_3 flux of urban trees is regulated by the stomata and environmental conditions; and (3) to provide accurate quantification of O_3 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 m^2 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 liliiflora*, *Robinia pseudoacacia*) and two evergreen tree species (*Pinus tabulaeformis*, *Cedrus deodara*) 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. deodara* 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 (A_c), and sapwood cross-sectional area (A_s) (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 km^2 (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

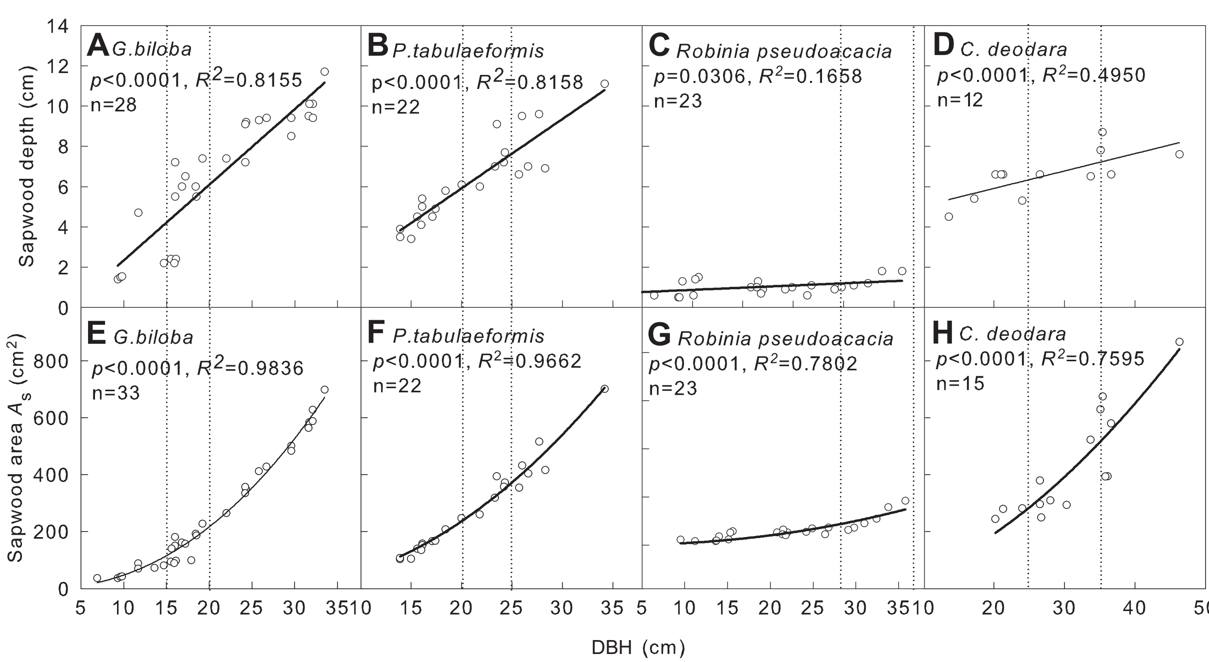

Fig. 1. The relationship between sapwood depth, sapwood area and diameter at the breast height (DBH) for *G.biloba*, *P. tabulaeformis*, ***R. pseudoacacia***, and *C. deodara*.