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Transpiration rates of urban trees, *Aesculus chinensis*

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Abstract

Transpiration patterns of *Aesculus chinensis* in relation to explanatory variables in the microclimatic, air quality, and biological phenomena categories were measured in Beijing, China using the thermal dissipation method. The highest transpiration rate measured as the sap flux density of the trees took place from 10:00 am to 13:00 pm in the summer and the lowest was found during nighttime in the winter. To sort out co-linearity, principal component analysis and variation and hierarchical partitioning methods were employed in data analyses. The evaporative demand index (EDI) consisting of air temperature, soil temperature, total radiation, vapor pressure deficit, and atmospheric ozone (O_3), explained 68% and 80% of the hourly and daily variations of the tree transpiration, respectively. The independent and joint effects of EDI variables together with a three-variable joint effect exerted the greatest influences on the variance of transpiration rates. The independent effects of leaf area index and atmospheric O_3 and their combined effect exhibited minor yet significant influences on tree transpiration rates.

Key words: horse chestnut; sap flux density; microclimate; air pollutants; leaf area index

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Introduction

Trees provide a broad range of aesthetic and environmental benefits (Nowak and Dwyer, 2007). They are an essential part of the urban infrastructure creating open and green spaces for residents and modulating heat, noise, and pollutant flows. The trees need to be regularly maintained as much of the urban area is paved, preventing proper replenishment of plant nutrients and water. In the meantime, water conservation is essential to satisfy the multiple demands of the urban environment (Wei et al., 2003). For optimal tree species selection and urban landscaping designs, the transpiration patterns of urban trees need to be quantified.

Horse chestnut is a common species in urban environments around the world and in addition to its landscaping values it is known for timber production and medicinal uses (Pittler and Ernst, 1998; Oleksyn et al., 2007; Wei et al., 2008). In China, horse chestnut (*Aesculus chinensis*), the tree and its lumber, has been historically linked to Buddhism and Buddhist temples and are more and more popular in urban settings with prospects of aesthetic enhancement and forestry (Wei et al., 2008), where trees are exposed to the microclimates, atmospheric pollutants, and biological phenomena. How well are the trees adapted to their urban ambience? The transpiration characteristics of trees are physiological responses that reflect the well-being of growing trees and may be used in assessing how well horse chestnut adapts in Beijing.

The transpiration of tree stands has been investigated (Phillips and Oren, 2001; Zeppel et al., 2006; Ohta et al., 2008; Limousin et al., 2009). In natural forests, trees in a stand are exposed to comparable climate and other environment elements. The soil water content governed by annual precipitation and its distribution patterns affects the transpiration rates (Yoshifuji et al., 2007; Ohta et al., 2008). The transpiration behaviors of urban trees *in situ* are subject to influences of the microclimatic conditions. The soil water content will not necessarily be affected by the precipitation patterns because impervious pavement may prevent natural recharge and irrigation. The seasonal variation of urban tree transpiration is not as predictable as trees in natural settings.

Tree transpiration responds to climatic changes such as global radiation, vapor pressure deficit, soil moisture, rainfall, and temperature (Granier et al., 1996; Mellander et al., 2004; Oguntunde, 2005; Burgess, 2006). Urban centers are the major producers of air pollutants that may harm plant growth (Wu, 2008). When excised leaves,

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seedlings, and saplings are exposed to sulfur dioxide (SO_2), nitrogen dioxide (NO_2), and ozone (O_3) in smog chambers and when mature forest trees are under high ambient O_3 concentrations, the vegetation experiences a greater extent of water losses (Temple, 1986; Neighbour et al., 1988; McLaughlin et al., 2007). The enhanced transpiration may be attributed to cuticular changes (Turunen and Huttunen, 1990) and stomata modifications (Landolt and Keller, 1985; Temple, 1986). Will urban trees respond to interactions of air pollutants and climatic changes in the same manner?

We studied the diurnal, daily, seasonal and annual patterns of transpiration of horse chestnut trees (*Aesculus chinensis*) in Beijing for 18 months using the thermal dissipation technique. It was hypothesized that the transpiration of urban trees was affected collectively by explanatory variables in the microclimate, air pollution, and pheno-phases of trees categories. The ordinary regression analyses in this case would have difficulty illustrating the complex interactions of explanatory variables with tree transpiration (Xia et al., 2008). Instead, we employed principal component analysis (PCA) (O'Brien et al., 2004) and the partitioning method (MacNally, 1996; Heikkinen et al., 2004; Teodoro et al., 2008) to evaluate how explanatory variables affect the transpiration of urban trees. Through PCA of the explanatory variables, we determined the net effect of factors on the transpiration of horse chestnut (O'Brien et al., 2004). The partitioning method was used to segregate the independent and joint effects among explanatory variables or between variable groups that provided further assessments of the potential causal-effect relationships (Borcard et al., 1992; MacNally, 1996).

Specifically, the outcomes answer the following research questions: (1) What are the transpiration patterns of horse chestnut at different time scales, especially at the annual scale? (2) How does the transpiration of horse chestnut respond to the multiple environmental variables? (3) Which environmental variables are the most important in affecting the transpiration of horse chestnut? (4) What is the role of phenology in influencing the transpiration of horse chestnut?

1 Materials and methods

1.1 Descriptions of study site and trees

The experimental plot was located at the Beijing Teaching Botanical Garden, Beijing, China (116°25′37″E–116°25′50″E, 39°52′20″N–39°52′28″N). It was in the densely populated central city area, covering an area of 116.5×10^3 m^2, and had a typical warm temperate continental monsoon climate. The mean annual precipitation was about 586 mm with more than 70% of the annual total occurring between June and August and the mean annual temperature between 11 and 12°C (Beijing Water Authority, 2010; State Statistical Bureau, 2011).

Aesculus chinensis is a deciduous, sun-adapted species with moderate to fast growth rate. Three trees of uniform size and comparable physiological characteristics were selected (Table 1). The selected trees were healthy, vigorous, and free from obvious defect. They were located among turf grass, shrubs and trees and planted at a spacing of about 2 m.

Table 1 Characteristics of *A. chinensis* trees used in the experiment

Year	Tree	DBH* (cm)	Projected canopy area (m^2)	Sapwood area (cm^2)	Leaf area index (m^2/m^2)
2008	1	10.60	17.71	72.08	2.12
	2	12.40	18.08	82.94	2.14
	3	11.90	11.21	79.94	1.34
2009	1	16.20	18.08	107.37	2.16
	2	19.15	22.42	115.17	1.79
	3	16.50	16.60	111.71	1.41

* Diameter at breast height.

The sapwood area (A_s, cm^2) was estimated from drilled cores of tree stems. With other ongoing studies and a small number of *A. chinensis* trees at the site, nearby trees with diameter at breast height (DBH) difference less than 2 cm were alternately cored in May, 2008 and May, 2009. Tree height was measured by a laser altimeter in May, 2008 and May, 2009, respectively. Leaf area index (LAI) was measured by a LAI-2000 plant canopy analyzer (Li-Cor Inc., Lincoln, Nebraska, USA) every two or three days during leaf expansion and defoliation, and once a week in other periods under diffuse light conditions on cloudy days or at dusk from May, 2008 to April, 2011.

1.2 Environmental variables

An automated weather station was set up adjacent to the selected trees for continuous recording of microclimatic and air pollutant data. It was located in an open area away from influences of trees, buildings and other barriers to ensure the accuracy of measurements. An air temperature (T_a) and relative humidity (RH) probe (HMP45C, Vaisala Inc., Helsinki, Finland), and wind speed (w) sensor (034B Met One Windset, Campbell Scientific Inc., Logan, UT) were installed on a 10 m high standard mast. A pyranometer (CMP-11, Kipp and Zonen, Delft, the Netherlands) was installed on a 1.5 m high standard mast. Precipitation (P) (TE525MM, Campbell Scientific Inc., Logan, UT) was measured by pluviometer installed at the height of < 2 m. Soil temperature (T_s) probes were placed at depths of 10, 30, 50, and 80 cm of the soil profile (Model 109, Campbell Scientific Inc., Logan, UT, USA). Soil water monitoring probes (ECH_2O, Decagon Devices Inc., Pullman, WA, USA) were placed at the depth of 30 cm. All meteorological data were synchronized to scan and record at the same time interval as the sap flow measurements. Vapor pressure deficit (D) was calculated using the temperature and RH (Campbell and Norman, 1998).

Ambient nitrogen oxides (NO, NO_2, and NOx), sulfur dioxide (SO_2), ozone (O_3), and particulate matter with diameters of 2.5 μm or less ($PM_{2.5}$) concentrations were monitored amongst the trees using TEI Model 42i, 43i, 49i gas analyzers (Thermo Environmental Instruments Inc., Franklin, MA, USA), and a tapered element oscillating microbalance (TEOM, Series 1400, Rupprecht & Patashnick

Co. Inc., Albany, NY, USA), respectively. The pollutant concentrations were recorded hourly.

A journal was kept to note the irrigation practices. There were two regular irrigations to saturate the soil water condition: one at the end of March when spring began and the other at middle of November before the ground was frozen. In between, the soil water, whenever deficient, would be replenished by irrigation. During the study period, trees were irrigated 2 and 12 times for 2008 and 2009, respectively.

1.3 Sap flow measurements

Sap flux density was measured by installing thermal dissipation probes (TDP-30; Dynamax Inc., Houston, TX, USA) into the tree trunks. The probes consisted of a pair of 30 mm long needles, each containing a copper-constantan thermocouple. The upper needles were continuously heated at constant power, while the lower needles were left unheated to act as a reference (Granier, 1987). Because the sapwood thickness of the trees we used was less than 3 cm, one probe at breast height was adequate. All probes were installed on the north side of trees to avoid direct solar heating. The probes and adjacent portions of stem were wrapped with an aluminized plastic bubble-wrap to minimize spurious temperature gradients caused by radiant heating of the stem, as well as to protect against water running down the trunk (Zhao et al., 2005). Sap flux density (J_s, g $H_2O/(m^2 \cdot sec)$) was determined according to the following equation (Granier, 1987):

$$J_s = 119 \times \left(\frac{\Delta T_m - \Delta T}{\Delta T}\right)^{1.231}$$

where, ΔT_m (°C) is the temperature difference between the heated and the unheated needles when xylem sap flow is zero, and ΔT (°C) is the actual temperature difference between the two needles (Granier, 1987). The temperature was read at 10 sec intervals and averaged and recorded every 10 min by a CR1000 datalogger (Campbell Scientific Inc., UK). The data collected from May 1, 2008 to October 31, 2009 included two growing seasons and one dormant season in between.

Anywhere from 1 to 8 individual trees had been chosen for transpiration measurements under various landscape settings (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). In this experiment, J_s of each tree was independently measured and therefore represented a replicate of the measurements. Besides, J_s, climatic and air pollution variables were obtained from real-time continuous measurements and the recorded data were integrated and averaged over a time scale of 10 min. The continuous recordings captured the entire transpiration process and were more reliable and less susceptible to measurement errors. Three trees in this case would be adequate to cover the experimental requirements and overcome the measurement errors.

Total sap flow F (g/sec) for each tree was calculated by multiplying J_s with sapwood cross-sectional area at breast height (A_s, cm^2) (Granier et al., 1992). Canopy transpiration (E_c, mm/day) was obtained by dividing F by projected canopy area (A_c, m^2).

1.4 Statistical analyses

Statistical analyses were performed using SPSS 11.5 (SPSS Inc., USA), R statistical package (MacNally and Walsh, 2004), and Sigmaplot 10.0 (Systat Software Inc., San Jose, California). A paired samples t test was performed in SPSS 11.5 with a significance level of p = 0.05 for comparing annual sap flux density, daily sap flux density, and daily canopy transpiration in 2008 with those in 2009. Pearson correlation analysis was conducted using SPSS 11.5 to determine the interrelationships of the recorded environmental variables at the hourly scale.

To determine the collective effects of explanatory variables on tree transpiration, firstly, we extracted PCA factor scores from the data representing all variables, reducing thirteen variables to four factors. Secondly, we generated and saved factor scores from the PCA analysis and matched these data with sap flux observations. Thirdly, the PCA factors affecting sap flux were estimated through stepwise multiple linear regressions. Finally, a four-parameter sigmoid function representing important physiological responses was built to indicate the collective effects of environmental factors on tree transpiration. For comparing the explanatory capacities of PCA factors with individual environmental variables to tree transpiration, the relationships between individual environmental variables and sap flux were also estimated using curve estimation analyses performed with Sigmaplot 10.0.

Variation partitioning outlines the relative importance of individual and joint contributions of explanatory variable groups toward the variance of a dependent response variable (Borcard et al., 1992). We conducted variation partitioning following previous publications (Anderson and Gribble, 1998; Heikkinen et al., 2004; Heikkinen et al., 2005). Variation partitioning would partition the variance of sap flux density into eight fractions: namely, the individual effects of climate, air pollutants, and LAI denoted as a, b, and c, respectively, the joint effects of climate and air pollutants, climate and LAI, and LAI and air pollutant denoted as d, e, and f, respectively, the joint effects of three explanatory variable groups denoted as g, and finally the unexplained variance denoted as h.

Hierarchical partitioning estimates the independent and joint contributions of each environmental variable to tree transpiration by considering all possible models in a multivariate regression (MacNally, 1996). This analysis was conducted with the R statistical package (MacNally and Walsh, 2004), using the "hier.part package" (R 2.3.1 R development core team, 2004). The maximum number of predictor variables that can be entered in this partition routine is 12. Moreover, hierarchical partitioning depends on monotonic relationships between the response and predictor variables (Heikkinen et al., 2004). We log-transformed the daily averaged vapor pressure deficit to improve the linearity of relationships between it and tree transpiration.

2 Results

2.1 Environmental variables

The microclimatic characteristics fluctuated daily as well as seasonally and the overall patterns of 2008 and 2009 were similar (Fig. 1). The annual averages of T_a, w, T_{s10}, R_s, and D were approximately 13.6°C, 1.05 m/sec, 14.2°C, 142.44 W/m^2, and 0.92 kPa, respectively. The daily averages and ranges of T_a, w, T_{s10}, R_s, and D of 2008 were not significantly different from those of 2009 (Table 2). The annual rainfall of 2008, 724.8 mm, however, was 67.5% higher than that in 2009, 432.8 mm. The annual averages of NO, NO_2, O_3, SO_2, and $PM_{2.5}$ were 18.55 ppb, 20.42 ppb, 20.20 ppb, 12.73 ppb, and 74.17 μg/m^3, respectively. The seasonal trend for atmospheric O_3 ran opposite of the other air quality parameters.

Table 2 Daily measurements of microclimatic and air quality variables in 2008 and 2009

Variable	2008		2009	
	Mean	Range	Mean	Range
T_a (°C)	13.79	–8.61~30.34	13.51	–9.36~31.18
T_{s10} (°C)	13.85	–1.15~28.21	14.62	–1.55~29.57
w (m/sec)	1.12	0.22–3.11	0.99	0.19–4.07
R_s (W/m^2)	142.21	10.96–313.36	142.67	1.76–322.82
D (kPa)	0.86	0.11–2.55	0.98	0.11–3.34
P (mm)	1.98	0.00–52.70	1.19	0.00–55.60
SWC_{30}* (%)	26.43	19.36–36.07	30.96	22.32–38.76
NO (ppb)	19.95	0.00–156.25	17.14	0.00–192.70
NO_2 (ppb)	17.90	1.92–68.80	22.94	5.15–67.59
O_3 (ppb)	18.63	0.70–102.20	21.76	0.30–74.86
SO_2 (ppb)	15.34	0.18–83.80	10.11	0.00–61.91
$PM_{2.5}$ (μg/m^3)	89.79	0.43–279.16	58.54	0.93–239.49

* Soil water content at 10–30 cm layer.

2.2 Temporal variations of transpiration

The sap flux density (J_s) of *A. chinensis* fluctuated diurnally when the trees were actively growing. It started rising in early morning to reach the apex around midmorning, remained at high levels until early afternoon, and then gradually returned overnight to the early morning (Fig. 2a). The maximum J_s took place at 10:00 to 13:00 and minimum J_s took at 03:00 to 06:00 of each day, respectively. When the trees went into dormancy in winter, there was little J_s for day or night.

Daily canopy transpiration (E_c) of *A. chinensis* averaged 0.79 mm/day and varied between 0.01 and 2.53 mm/day over one year, and during the growing season it averaged 1.47 mm/day. During the spring, the average daily E_c rose rapidly from 0.33 mm/day in March to 1.64 mm/day in May. The highest and lowest E_c were in June (1.65 ± 0.12 mm/day) and February (0.09 ± 0.01 mm/day), respectively (Fig. 2b). The E_c of the growing season of April through October, 251.79 mm, was considerably higher than that of the non-growing season of November through March, 26.03 mm.

The canopy transpirations throughout the growing season varied according to the pheno-phases (Fig. 2c). As the trees entering the annual growing phase, there were steadily increasing water demands. The E_c rose from (0.31 ± 0.06) mm/day at bud sprouting through bud opening, leaf emergence, leaf exposure, and flower bud occurrence to reach its peak at the seeding phase of (1.61 ± 0.15) mm/day. Afterwards, E_c gradually reverted back to the initial level. During the leaf emergence and leaf expansion stage, LAI was the most important factor affecting E_c (see insert in Fig. 2c).

The average daily sums of sap flux density ($\sum J_s$) in 2008, 235.38 g H_2O/(cm^2·day), did not vary significantly from that in 2009, 223.67 g H_2O/(cm^2·day) (Fig. 2d).

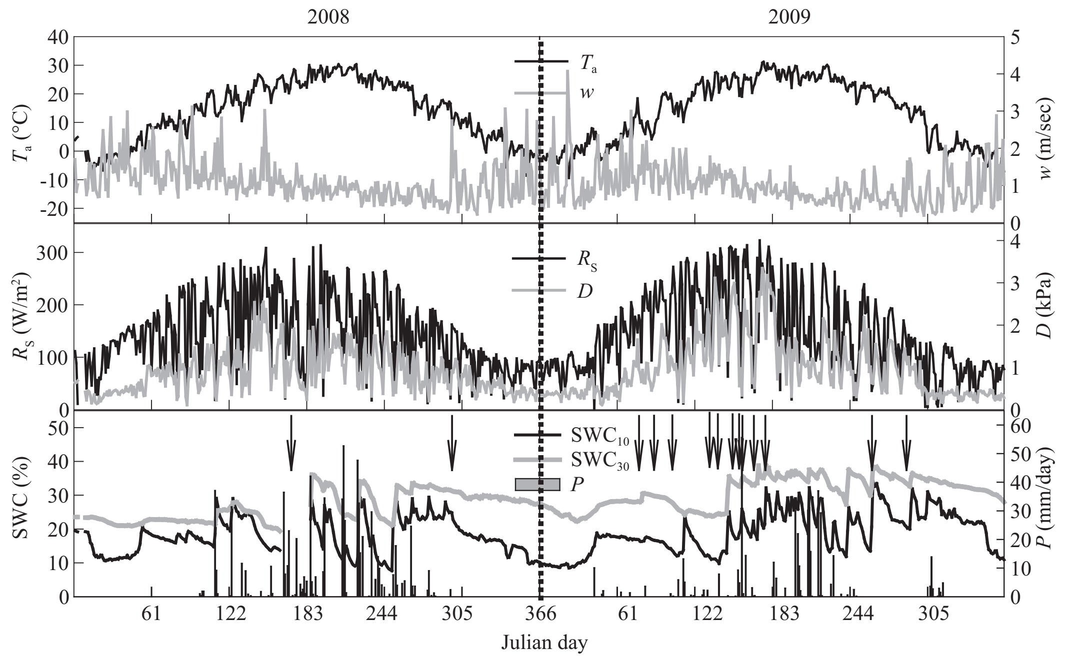

Fig. 1 Daily trends of microclimatic parameters from January 1, 2008 to December 31, 2009. T_a: air temperature; w: wind velocity, R_s: total radiation; D: vapor pressure deficit; SWC_{10}: soil water content at 0–10 cm layer; SWC_{30}: soil water content at 10–30 cm layer, and P: precipitation. Downward arrows show the irrigation dates.

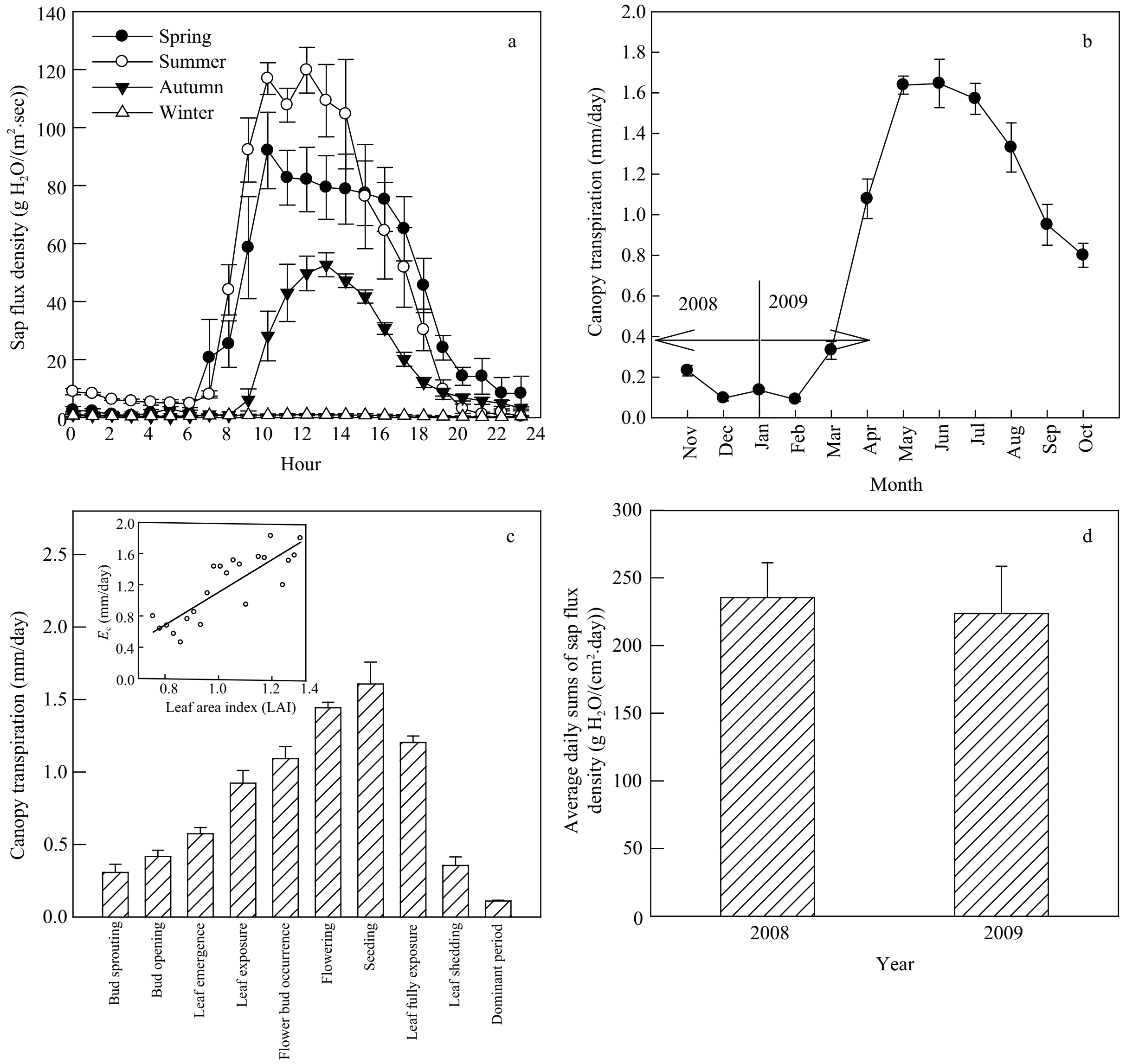

Fig. 2 Temporal trends of transpiration of *A. chinensis* grown in Beijing, May 1, 2008 through October 31, 2009. (a) diurnal sap flux density (J_s) of typical days in spring, summer, autumn and winter; (b) daily canopy transpiration (E_c) during a 12-month period; (c) daily E_c during different phenological periods; (d) daily sums of sap flux density ($\sum J_s$). The inserted scatter graphic in c indicates the variation of E_c with the increase of leaf area index (LAI). Error bars indicate standard error of three replicates.

However, the growing season E_c in 2008, 1.19 mm/day, was significantly lower than that in 2009, 1.33 mm/day. This was due to the increase in the ratio of sapwood area to canopy area (A_s/A_c) of young *A. chinensis* trees in 2009.

2.3 Tree transpiration vs. explanatory variables

Most microclimatic and air quality variables exhibited similar temporal variation patterns (Table 3). For example, T_a, RH, T_{s10}, R_s, D, and atmospheric O_3 all followed the same temporal trend. The interrelationships among the climatic variables and between the climatic and air quality variables were apparent. The primary incidence heat energy, R_s, triggered the rise of T_a and in turn caused the rises in T_{s10} and D that represented changes taken place in the heat sinks. While atmospheric O_3, a product of atmospheric photochemical reaction, was positively correlated with climatic variables, other air pollutants such as NO, NO_2, SO_2, and $PM_{2.5}$ was inversely correlated with climatic variables. Yet, both soil water content (SWC) and P did not appear to correlate with one another and other variables.

The factor loadings in the PCA mirrored the interrelationships exhibited by the explanatory variables (Table 4). Four PCA axes explained 71.3% of the variance in tree transpirations caused by variables characterizing the urban environment. The first axis explaining 32.4% of the variance was positively correlated with T_a, T_{s10}, R_s, D, and O_3 and indicated that sunny, dry, and warm climate conditions would create high evaporation-transpiration demands and cause strong photochemical reactions. As a result, this axis is referred to hereafter as the evaporative demand index (EDI). The second axis explained an additional 17.9% of the variance and was positively correlated with the pollutants NO, NO_2, SO_2 and $PM_{2.5}$ and collectively they indicated the extent of pollutant emissions, and is referred to hereafter as the air quality index. The third axis explained an additional 12.3% of the data variance and was correlated to RH, w, thus is referred to hereafter as the air

Table 3 Correlation coefficients of the hourly averages of climatic and air quality variables

Variable	T_a	RH	w	T_{s10}	SWC_{30}	R_s	P	D	NO	NO_2	O_3	SO_2	$PM_{2.5}$
T_a	1.00	0.24	*x*	0.94	*x*	0.35	*x*	0.69	–0.40	–0.41	0.50	–0.42	*x*
RH		1.00	–0.55	0.40	*x*	–0.35	*x*	–0.41	*x*	*x*	*x*	*x*	0.32
w			1.00	*x*	–0.22	0.31	*x*	0.27	–0.32	–0.39	0.26	*x*	–0.32
T_{s10}				1.00	*x*	*x*	*x*	0.54	–0.37	–0.44	0.41	–0.47	*x*
SWC_{30}					1.00	*x*	*x*	*x*	*x*	*x*	*x*	*x*	*x*
R_s						1.00	*x*	0.61	*x*	–0.23	0.37	*x*	*x*
P							1.00	*x*	*x*	*x*	*x*	*x*	*x*
D								1.00	–0.30	–0.35	0.54	–0.25	*x*
NO									1.00	0.62	–0.33	0.51	0.41
NO_2										1.00	–0.35	0.59	0.35
O_3											1.00	–0.35	*x*
SO_2												1.00	0.43

RH: relative humidity. *x* donates absolute value of correlation efficient less than 0.2.

Table 4 First four principal components describing the hourly average sap flow of *A. chinensis* trees in Beijing, May 1, 2008 to October 31, 2009

Category	Principal component			
	1 EDI	2 Air quality	3 Air humidity	4 Rain
Eigenvalue	4.212	2.328	1.595	1.129
Variance (%)	32.402	17.904	12.271	8.686
Cum. variance (%)	32.402	50.306	62.577	71.263
Component loadings*				
T_a (°C)	0.864	–0.238	0.368	–0.036
RH (%)	–0.075	0.038	0.902	–0.085
w (m/sec)	0.113	–0.352	–0.691	–0.236
T_{s10} (°C)	0.734	–0.319	0.538	–0.010
SWC_{30} (%)	–0.030	–0.127	0.257	0.850
R_s (W/m)	0.654	0.028	–0.460	0.092
P (mm)	–0.056	–0.130	0.197	–0.389
D (kPa)	0.878	–0.096	–0.285	0.071
NO	–0.257	0.745	0.071	0.221
NO_2	–0.329	0.741	0.060	0.260
O_3	0.646	–0.266	–0.132	–0.061
SO_2	–0.245	0.805	–0.131	–0.165
$PM_{2.5}$	0.137	0.706	0.369	–0.224

* Component loadings equal the correlations between each variable and the principle component.

humidity index. The fourth axis further explained 8.7% of the data variance and was correlated to SWC and P thus referred to hereafter as the rain index.

The outcomes of multiple linear regression analysis between transpiration of *A. chinensis* and PCA components showed that its transpiration was mainly affected by the variables in EDI. Introduction of other variables did not significantly increase the explanation capacity. The best-fit models were obtained with a three-parameter sigmoidal function that explained 68.2% and 80.3% of the variation in J_s and E_c, respectively (Fig. 3). This curve approached asymptotes at both ends beyond which EDI had little influence on sap flow (Fig. 3).

2.4 Key driving environmental variables of sap flow

At different time scales, the transpiration rates were affected by variables in EDI in different manners (Fig. 4). At the hourly scale (Fig. 4a), R_s accounted for 37.6% of the variance in which the independent and joint contributions were 25.1% and 12.5%, respectively. The independent contribution referred to sole involvement of an explanatory variable and joint contribution referred to involvement of this variable in combinations with other explanatory variables. D and T_a accounted for independently 10.7% and 7.3% and jointly 15.6% and 11.2%, respectively of the variances associated with hourly J_s. Contributions of T_{s10} and O_3 to the variance of the hourly J_s were similarly separated (Fig. 4a). At the daily scale, D, T_a, R_s, and T_{s10} accounted for 23.3%, 23.2%, 21.9%, and 21.5% of the variance associated with E_c, respectively (Fig. 4b).

Atmospheric O_3 accounted for 6.9% and 10.0% of the variances associated with the average hourly and daily transpiration rates of *A. chinensis*, respectively (Fig. 4). The adverse effect of atmospheric O_3 on plants is customarily characterized in terms of an accumulated ozone exposure dose over a 40 ppb threshold (AOT40) that is expressed in ppm/hr. The cumulative O_3 exposure of trees in the 2009 growing season was considerably lower than that in the 2008 growing season. The most intense exposure to O_3 took place approximately from Julian day number (JDN) 200 through 263, beyond which the atmospheric O_3 levels subsided below the 40 ppb threshold (Fig. 5a). From JDN 1 to 200, the cumulative $\sum J_s$ in 2009 were essentially the same as those in 2008. From JDN 200 to 263, the cumulative $\sum J_s$ of 2008 increased and deviated from those of 2009 (Fig. 5b). At the end, the cumulative $\sum J_s$ of 2008 and 2009 came back in agreement (Fig. 5b). They showed periods when trees were experiencing stresses due to atmospheric O_3 exposure (JDN 200 to 263) and trees were recovering from O_3-induced stresses (JDN > 263).

2.5 Role of phenology

The progression of phenophases was in sync with changes of the leaf area index. When the variance of daily sap flux densities was decomposed, variations in climatic variables (T_a, T_{s10}, R_s, D, RH, and SWC_{30}), air pollutant variables (NO, NO_2, O_3, SO_2, and $PM_{2.5}$), and LAI accounted for 75.2%, 45.1%, and 41.6%, of the variance, respectively (Fig. 6). The amount of variation captured by all of the selected explanatory variables collectively was 75.7% (Fig. 6). The three groups of explanatory variables combined effect, fraction g, accounted for the largest portion of variance of daily sap flux densities. The independent effect of climatic variables on daily sap flux densities, fraction a, was relatively large (18.8%), while the independent effects

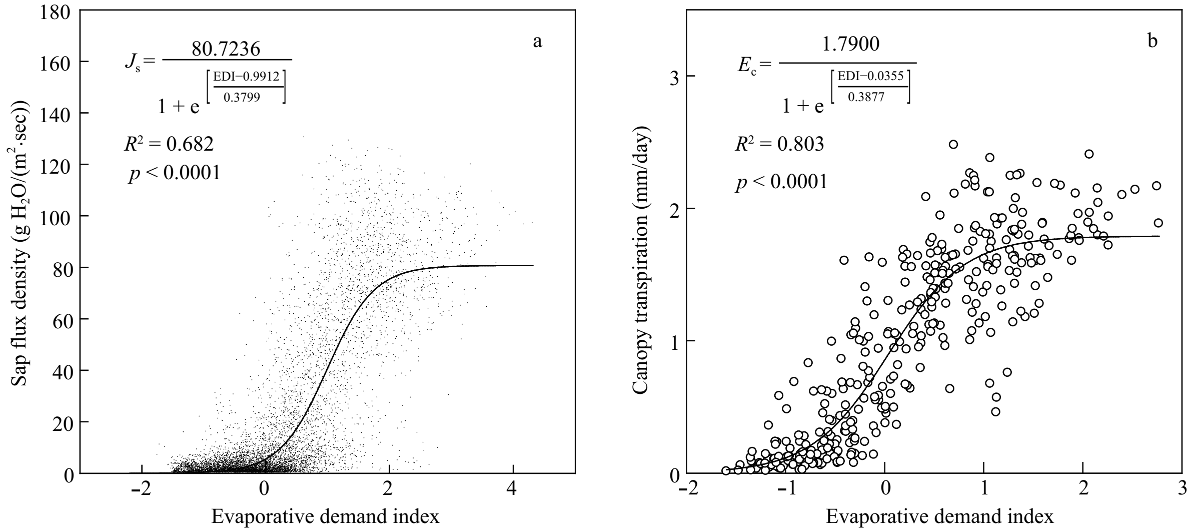

Fig. 3 Evaporative demand index (EDI) vs. transpiration characteristics of *A. chinensis* in Beijing during May 1, 2008 to October 31, 2009. (a) hourly sap flux density (J_s); (b) daily canopy transpiration (E_c).

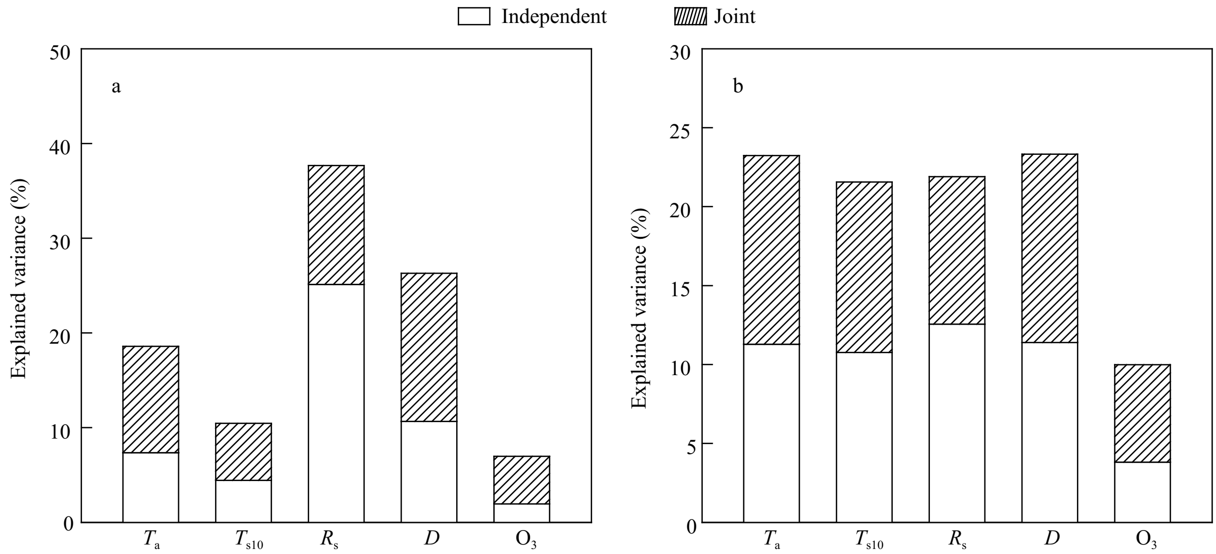

Fig. 4 Independent and joint effects of explanatory variables composing the evaporative demand index (EDI) on the variance of *A. chinensis* transpiration, May 1, 2008 to October 31, 2009. (a) hourly sap flux density (J_s); (b) daily canopy transpiration (E_c).

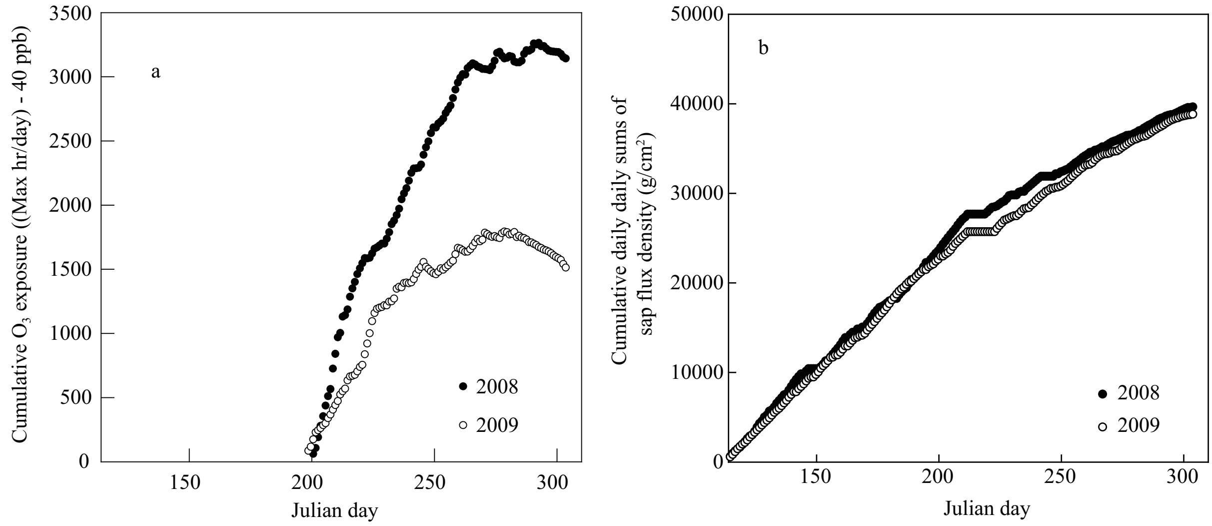

Fig. 5 Accumulated atmospheric O_3 exposure and transpiration of *A. chinensis* in Beijing. (a) accumulated > 40 ppb atmospheric O_3 exposure, we have used here a daily running sum of maximum hourly O_3 concentration per day minus 40 ppb; (b) cumulative daily sums of sap flux density ($\sum J_s$).

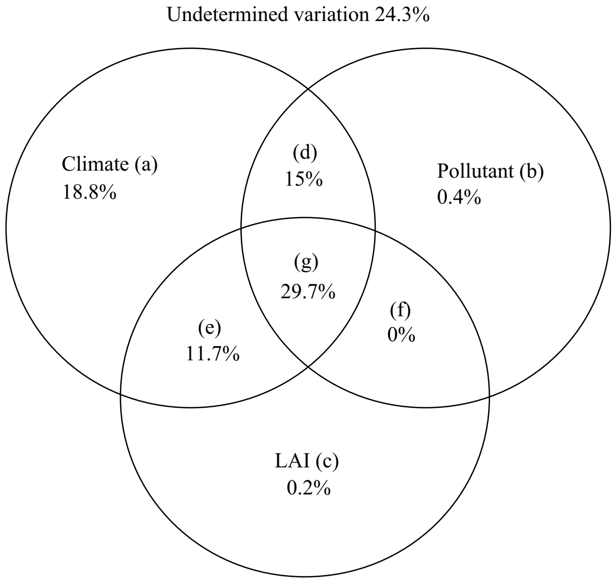

Fig. 6 Schematic depiction of relative effects of explanatory variables in climate, LAI, and pollutant groups on daily sap flux density. Fragments a, b, and c indicate independent effects and fragments d, e, f, and g indicate joint effects of respective overlapping groups.

of LAI and air pollutant variables, respectively fractions b and c, were minor. For the two-factor combinations, the combined effects of climatic and pollutant variables, fraction d, and climatic and LAI variables, fraction e, were notable. However, the combined effect of pollutant and LAI variables, fraction f, was not found.

3 Discussion

3.1 Temporal variations of transpiration rates

We demonstrated how the transpiration rate of horse chestnut (*A. chinensis*) grown in the urban setting of Beijing varied seasonally. The daily canopy transpiration, E_c varied from 0.01 to 2.53 mm/day throughout the year with annual average of 0.79 mm/day and growing season average of 1.47 mm/day, comparable to those of other species in natural settings (Magnani et al., 1998; Wullschleger et al., 1998, 2000). Annual precipitation should be adequate to satisfy the water demand of *A. chinensis* planted in Beijing. However, the precipitation was not uniformly distributed, resulting sometimes in water deficiencies during the growing season. For example, the 2009 monthly canopy transpiration of April, May, September, and October exceeded the respective monthly precipitation. Supplemental irrigation would be necessary to safeguard the well-being of *A. chinensis* trees grown in Beijing.

At the diurnal scale, substantial nocturnal sap flow was observed especially in the early half of the evening (Fig. 2a) to refill the stem water deficit due to high daytime water loss (Snyder et al., 2003). The nocturnal sap flow was higher in summer compared to that in spring and autumn, consistent with the higher demands of stem water recharge in summer. At the phenological scale, E_c was much higher during the growing season than non-growing season (Fig. 2b). The non-growing season E_c accounted for 9.4% of the annual E_c that was essential for maintenance of living cells in dormant trees (Ceschiaa et al., 2002). The annual sap flux in 2008 (a relatively wet year) did not differ significantly from that in 2009 (a relatively dry year) (Fig. 2d). The annual sap flux of a pine forest and a Siberian larch forest were found not to vary substantially year by year (Ohta et al., 2008; Phillips and Oren, 2001). Others showed that the annual canopy water use of a *Callitris* spp. and *Eucalyptus* ssp. mixed woodland and a Mediterranean *Quercus ilex* forest varied yearly (Zeppel et al., 2006; Limousin et al., 2009). The discrepancies reflected the availability of water at each locale. In our study, the annual precipitations were 724.8 and 432.8 mm for 2008 and 2009, respectively. Precipitation supplemented with timely irrigations in this case kept adequate water in the soil profile to satisfy the transpiration needs of the *A. chinensis*. The average daily SWC were 26.43% and 30.96% in 2008 and 2009, respectively. As a result, the daily SWC of both years never reached the deficit level (< 20%) that would limit the transpiration of trees.

3.2 Roles of microclimate

The impacts of the urban environment on the transpiration of *A. chinensis* might be depicted by four composite factors each consisting of a set of explanatory variables with distinctive attributes, namely the evaporative demand index (EDI), air quality index, air humidity index, and rain index. The transpiration rates of forest trees might be adversely affected due to exposures to severe air pollution. Compared with the transpiration rates of trees in a tropical forest (O'Brien et al., 2004), the transpiration rates of *A. chinensis* grown in Beijing were influenced mainly by the explanatory variables in EDI in which atmospheric O_3 was included (Fig. 3). The low sap flows were characterized by combinations of high atmospheric humidity, low vapor pressures, low solar radiations, and cold temperatures. The sap flow increased exponentially as the environment became warmer, brighter, and less humid and approached a plateau beyond which EDI no longer affected the transpiration rate of the trees.

The explanatory variables of EDI affected the tree transpiration both independently and jointly. The joint effects of a variable were equal to or greater than its independent effect, indicating the co-linearity of the variables. Collectively T_a, T_{s10}, R_s, D, and O_3, accounted for greater percentages of the variances associated with hourly and daily sap flow than any of them individually (Fig. 4). The daily transpiration of trees was most closely related to D that regulated the extent of daily water uptake, and the hourly transpiration of trees was most closely related to R_s that regulated the diurnal changes of the transpiration flux in trees (Phillips et al., 1999).

3.3 Roles of air quality

The atmospheric O_3 concentration showed a relatively minor effect on increasing the transpiration of *A. chinensis* trees (Figs. 4 and 5). For the trees, the most intense exposure to potential O_3 stress occurred from JDN 199 to 263 and the 2008 exposure levels were markedly higher than those of 2009 (Fig. 5a). This was the time of the year the daylight was long, solar radiation was intense, and air temperature was high. Logically, the daily sap flux density would be high. The same climatic conditions however would enhance the photochemical reactions that generate atmospheric O_3. In 2008, the cumulative > 40 ppb O_3 exposures were near twice that in 2009. For the adverse impacts on daily sap flux density, the difference between 2008 and 2009 was relatively minor yet distinctively notable (Fig. 5b). At the end, the cumulative daily sap flux density in 2008 was not significantly different from that in 2009 (Fig. 5b).

Under ordinary circumstances, it would be difficult to distinguish whether the slight difference in tree transpiration during this period was attributable to the deterioration of air quality or to the hot and dry climate of summer and early fall. The statistical analysis procedures we employed, principle component analysis and partitioning method, took into account the co-linearity of variables and were able to sort out the contributions of each variable. It was unequivocal that *A. chinensis* trees in Beijing would increase the transpiration rate to cope with the poor air quality of the summer months. Trees that experienced long-term exposures to air pollution often exhibited leaf chlorosis, branch dieback, and eventually death (Gerosa et al., 2008). However, the adverse impacts, based on observations made in 2008 and 2009, appeared temporary.

4 Conclusions

(1) The transpiration of *A. chinensis* trees in the urban environment was governed by the microclimatic and air quality variables, namely air temperature, soil temperature at 10 cm depth, total radiation (R_s), vapor pressure deficit (D) and concentration of atmospheric ozone. The hourly transpiration was most significantly affected by R_s that controlled the diurnal changes in transpiration flux. The daily transpiration of trees was most significantly affected by D that determined the daily water uptake.

(2) Urban air quality had a minor effect on the transpiration of *A. chinensis* trees. When exposed to harmful levels of atmospheric O_3 in the summer months, they showed a temporary increase in transpiration rate in proportion to the severity of air pollution. The annual cumulative sap flux density of the trees however was not affected by the air quality.

(3) The transpiration of *A. chinensis* trees varied according to the pheno-phases. The leaf area index individually and in combinations with climatic variables accounted for 41.6% of the variance in daily sap flux densities.

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