Chapter 4

Transpiration Characteristics of Chinese Pines (*Pinus tabulaeformis*) in an Urban Environment

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Abstract Urban environments can significantly influence the transpiration of isolated plants. Therefore, optimal green space design, tree species selection, and tree maintenance require that the water use patterns of urban plants be quantified. In this study, the transpiration from individual Chinese pines (*Pinus tabulaeformis*) in the center of Beijing, China was measured continuously over a 2-year period. The response of whole-tree transpiration (E_t) to environmental factors was investigated in multiple time scales. Maximum sap flux density (J_s) ranged from 3.34E-05 to 8.2E-03 cm/s. E_t was much higher in summer (32.93 kg/day) than in winter (6.22 kg/day). E_t in the urban environment was much higher than that reported for Chinese pines with similar diameters at breast height (DBH) during 2000–2005 in suburban Beijing. Great differences were observed in the response of E_t to environmental factors at different time scales. At the diurnal scale, hourly mean J_s was linearly related to photosynthetically active radiation (PAR) and vapor pressure deficit (D), whereas at the daily scale, daily mean E_t was linearly related to PAR, air temperature (T_a), and soil water content (SWC), and was curvilinearly related to D. At the annual scale, E_t was similar in the growing seasons of 2008 (a wet year) and 2009 (a dry year), even though the annual precipitation (P) and irrigation times were significantly different (724.8 vs. 432.8 mm; 2 vs. 12).

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From this result, it can be concluded that urban soil water conditions affected by both P and irrigation practice were a major cause of interannual E_t variation.

Keywords Green space • Isolated tree transpiration • Sap flux density • Soil water content • Urban environment • Urban soil water

4.1 Introduction

Urbanization significantly influences local and regional climate, water resources, the atmosphere, and land use (Wu 2008). Urban green spaces including parks, street trees, gardens, agricultural areas, rehabilitated areas, fragmented natural areas in a city, natural areas surrounding a city, and other open areas are providers of urban ecosystem service (Niemelä et al. 2010). An urban green ecosystem can mitigate many of the environmental impacts of urban development by moderating climate, reducing atmospheric carbon dioxide, improving air quality, lowering rainfall runoff, and reducing noise levels (Nowak and Dwyer 2007). We see urban green areas as the most effective environmental protection tool and the foundation of the urban ecological framework (skeleton) or green infrastructure. Tree transpiration, in particular, cools the air and reduces storm water runoff (McPherson et al. 2005; Nowak and Dwyer 2007). At the same time, the transpiration pattern of trees in cities and surrounding areas may be significantly influenced by urban environmental changes (Gregg et al. 2003). Many metropolitan cities, including Beijing, expend great effort to improve tree cover. However, inappropriate green space design, tree species selection, and tree maintenance can increase water consumption. Furthermore, isolated urban plants are thought to be susceptible to "the clothesline effect," which causes high rates of evapotranspiration (Hagishima et al. 2007; van Bavel et al. 1962). Therefore, it is imperative to study the transpiration patterns and factors affecting transpiration in the urban environment.

Many studies have examined the factors affecting urban plant transpiration, which factors include plant density, irrigation, energy exchange with building walls, and pollutant concentrations (Hagishima et al. 2007; Heilman et al. 1989; Martin and Stabler 2002; Montague and Kjelgren 2004; Neighbour et al. 1988). These studies have focused primarily on responses of potted plants to a single feature of the urban environment. However, the effects of changes in the urban environment on the water use of trees in situ have seldom been studied.

Time scale is an important component in evaluating the factors influencing transpiration. Photosynthetically active radiation and vapor pressure deficit and soil moisture content affect transpiration on a daily time scale, whereas leaf area varies within and among species on seasonal and interannual time scales (Ohta et al. 2008; Phillips and Oren 2001). Diurnal and seasonal variations in tree transpiration have been broadly studied. However, knowledge regarding interannual variation is insufficient, especially about trees in urban environments with irrigation. Soil moisture changes are also a major cause of interannual variation in the transpiration period (Yoshifuji et al. 2007). Garden management techniques such as irrigation are being adopted in urban environments, especially in arid and semiarid areas or under dry weather conditions. Thus, in irrigated systems the interannual variations in soil water content do not correspond to the amount of precipitation. The effects of irrigation on interannual variations in transpiration are poorly understood.

Basic data of urban green characteristics in Beijing were listed as follows: 658,914.07 ha forest area, 61,695 ha green area, 44.4 % urban green coverage, 22 parks, 315 public gardens, 100 boulevards, 100,000 m^2 roof green area, and 210 ha community green area (Statistical Yearbook of Beijing 2010; www.bjyl.gov.cn). During the past decades, both urban green coverage (22.3–44.4 %) and green area (26,680–61,695 ha) have notably increased (Statistical Yearbook of Beijing 2010). Trees are essential components of all urban green spaces. More than 2,056 species of vascular plants (He et al. 1993) and more than 61 million trees (Beijing Municipal Bureau of Landscape and Forestry 2005) are planted across the city. Chinese pine (*Pinus tabulaeformis*), a species endemic to China, has been planted widely in northern Chinese cities because of its wide adaptability and aesthetic value. It is one of the top five evergreen tree species in Beijing in terms of number of individuals and ecological importance value (Beijing Gardening and Greening Bureau 2005; Meng 2004). In this study, we monitored the diurnal, daily, seasonal, and annual patterns of transpiration of Chinese pines in the center of Beijing with the help of the thermal dissipation probe method (TDP). The influences of urban environmental changes on the transpiration of Chinese pine were evaluated at different time scales.

4.2 Materials and Methods

4.2.1 Site Description

Beijing, the capital of China, is one of the oldest and fastest developing capital cities in the world. It has a population of 16.33 million and a built-up area of 873 km^2 (Beijing Statistics Yearbook 2007). This study was conducted in the Beijing Teaching Botanical Garden, which covers an area of 11.65×10^4 m^2 and is in the Chongwen District in the center of Beijing. Beijing, situated in a warm temperate zone, has a typical continental monsoon climate. Mean annual precipitation is about 585.8 mm with more than 70 % of the annual total occurring between July and August. Mean annual temperature is about 11.8 °C, varying between 11 and 12 °C.

Table 4.1 Characteristics of the trees sampled for sap flow measurements

Year	Tree number	DBH (cm)	Height (m)	Sapwood area (cm^2)	LAI	Orientation of sensor	Number of sensors
2008	No. 1	17	5.9	163.56	2.07	South, north	2TDP30
	No. 2	16.2	5.7	147.52	2.36	South, north	2TDP30
	No. 3	18.7	5.8	200.60	2.82	South, north	2TDP30
2009	No. 1	17.1	5.9	165.63	1.79	South, north	2TDP30
	No. 2	17.55	5.7	175.10	2.08	South, north	2TDP30
	No. 3	20.3	5.8	239.17	2.23	South, north	2TDP30

LAI, leaf area index

4.2.2 Estimation of Sapwood Cross-Sectional Area, Leaf Area Index, and Transpiration

Sapwood cross-sectional area (A_s, cm^2) was estimated from sapwood cross-sectional area and diameter at breast height (DBH) data collected in the Beijing Teaching Botanical Garden and Jiu Feng mountain in suburban Beijing using the relationship:

$$A_s = 0.3786 \times (\mathrm{DBH})^{2.1419} \quad \left(n = 22; R^2 = 0.9772; p < 0.0001\right). \tag{4.1}$$

Whole-tree leaf area index (LAI) was measured using a plant canopy analyzer (LAI2000; USA), and it was measured every 2 or 3 days during leaf expansion and defoliation and once a week during other periods under diffuse light conditions on cloudy days or at dusk.

Three Chinese pine trees of uniform size that were 45 years old were selected for sap flow measurements. The characteristics of the sampled trees are summarized in Table 4.1. Thermal dissipation probes (Dynamax, USA) were horizontally inserted in the sapwood of the trunk at breast height on both the north and south side of every sampled tree. Based on an empirical relationship (Granier 1987), sap flux density was derived from the temperature difference between the upper, constant-heated probe and the lower, unheated probe, which acted as a reference. Measurements of sap flow were taken every 10 s, and 10-min averages were stored in a datalogger (CR1000; Campbell Scientific, UK). Sap flux density measurements made in stems were scaled to each individual tree by its A_s (Granier et al. 1992):

$$E_t = \sum_t \left(\left(\left(J_{s-\mathrm{north}} + J_{s-\mathrm{south}}\right) \times A_s \times 3600\right)/(2 \times 1000)\right). \tag{4.2}$$

4.2.3 Environmental Monitoring

An automated weather station located in the Teaching Botanical Garden was used to measure meteorological parameters, using an air temperature (T_a) and relative humidity (RH) probe (HMP45C; Vaisala, Helsinki, Finland), a wind (w) sensor

(034B Met One Windset; Campbell Scientific, Logan, UT, USA), a quantum sensor (PAR Lite; Kipp and Zonen, Delft, Netherlands), a soil temperature (T_s) probe at a depth of 10 cm (109; Campbell Scientific), and a rainfall (P) gauge (TE525MM; Campbell Scientific). Soil moisture content was measured at depths of 10 and 30 cm (SWC_{10}, SWC_{30}) using soil moisture sensors (ECH_2O; Decagon Devices, Pullman, WA, USA) in the center of the sampled Chinese pine trees. All these meteorological data were sampled and recorded at the same frequency as the sap flow measurements. Vapor pressure deficit (D) was calculated using the 10-min averages of temperature and relative humidity as follows:

$$D = \mathrm{a} \times \exp(\mathrm{b}T_{\mathrm{a}}/(T_{\mathrm{a}} + \mathrm{c})) \times (1 - \mathrm{RH}) \tag{4.3}$$

where a, b, and c are fixed parameters equal to 0.611 kPa, 17.502, and 240.97 °C, respectively (Campbell and Norman 1998).

4.2.4 *Statistical Analyses*

Statistical analyses were performed using SPSS 11.5 (SPSS, Chicago, IL, USA) and Sigmaplot 10.0 (Systat Software, San Jose, CA, USA). A paired-samples t test was performed in SPSS with a significance level of $p = 0.05$ for the comparison of mean E_t. The relationships between E_t and T_a, PAR, D, and SWC on both the diurnal and daily scale were investigated using curve estimation analyses performed with Sigmaplot. Linear regression analyses were conducted to study the influences of climate variables on E_t at multiple time scales using the stepwise procedure in SPSS with a significance level of $p = 0.05$.

4.3 Results and Discussion

4.3.1 *Urban Environmental Conditions*

Table 4.2 summarizes the daily variation in environmental parameters during 2008 and 2009. There was no significant difference between the air temperature (T_a), wind speed (w), soil temperature (T_{s10}), or photosynthetically active radiation (PAR) in 2008 and 2009. The annual average T_a, w, T_{s10}, and PAR were approximately 13.6 °C, 1.05 m/s, 14.2 °C, and 231.7 mol/m^2/s, respectively. The vapor pressure deficit (D) varied from 0.11 to 3.34 kPa and showed a seasonal trend (Fig. 4.1). D increased from around 0.57 kPa in March to a maximum of around 3.3 kPa in June before falling to less than 0.5 kPa at the end of the season in November (Fig. 4.1). The atmosphere was very dry in spring, and D often exceeded 2.0 kPa. Moreover, D during May and June in 2008 (1.37 and 1.02 kPa) was

Table 4.2 Average daily values of urban environmental factors and irrigation times in Beijing in 2008 and 2009

Parameter average value (range)	2008 (n = 366)	2009 (n = 365)
T_a (°C)	13.79 (−8.61 to 30.34)	13.51 (−9.36 to 31.18)
T_{s10} (°C)	13.85 (−1.15 to 28.21)	14.62 (−1.55 to 29.57)
w (m/s)	1.12 (0.22–3.11)	0.99 (0.19–4.07)
PAR (μmol/m^2/s)	242.86 (17.10–574.08)	220.61 (4.02–554.12)
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$_{10}$ (%)	17.72 (7.68–29.42)	19.16 (8.50–34.19)
SWC$_{30}$ (%)	26.43 (19.36–36.07)	30.96 (22.32–38.76)
Frequency of irrigation (times)	2	12

significantly lower than in 2009 (1.83 and 2.10 kPa), which was the result of the lower air relative humidity (RH) and higher T_a during that period in 2009.

The year 2008 was the wettest year since records began to be kept in 1999, whereas 2009 was a dry year in which rainfall was below average (Statistical Bureau, 1999–2009). Rainfall in 2008 was 67.5 % higher than in 2009 (724.8 vs. 432.8 mm), but the time of local irrigation was only one-sixth of that in 2009 (2 vs. 12 times). As a consequence, the soil layer was 1.4 % wetter in 2009. In correspondence with the precipitation and irrigation, the soil moisture conditions varied greatly (Fig. 4.1). Moreover, soil water content at a depth of 10 cm was always lower and fluctuated more than that at a depth of 30 cm.

4.3.2 Transpiration Pattern of Chinese Pines at Multiple Time Scales

The diurnal patterns of sap flow density (J_s) in Chinese pines under sunny weather over four seasons are illustrated in Fig. 4.2a. Maximum J_s varied considerably among seasons, ranging from 3.34E-05 to 8.2E-03 cm/s. Diurnal J_s exhibited a broad peak pattern in summer and a narrow peak pattern in both spring and autumn, whereas the diurnal pattern was not pronounced in winter. In comparison with the J_s pattern in summer, in spring and autumn the timing of the onset and peak of J_s were delayed, whereas that of its decline was advanced. The diurnal pattern of sap flow indicated that sap flux density in the Chinese pine had no significant "noon depression" phenomenon. Noticeable sap flow in Chinese pine was evident in the nighttime, which may alleviate plant water stress.

The total transpiration from May 1, 2008 to April 30, 2009 amounted to 6,547.87 kg. Figure 4.2b illustrates the annual variation in E_t. The annual pattern

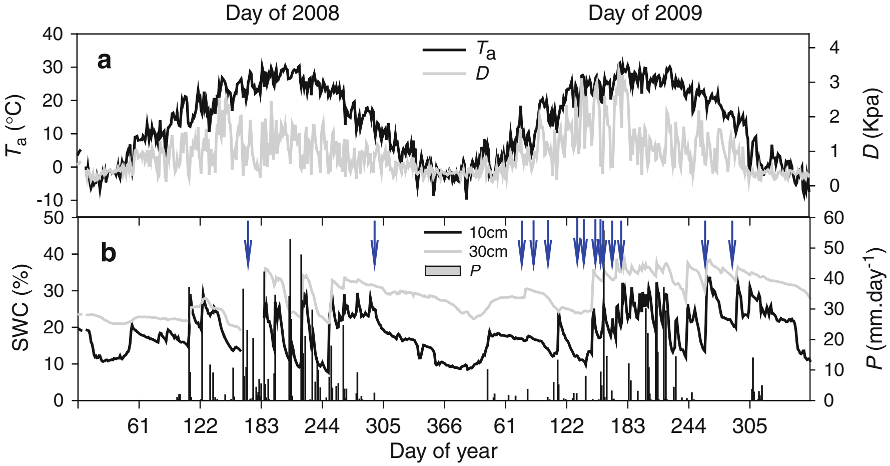

Fig. 4.1 Climatic data from 2008 to 2009. Reading from the top: daily air temperature (T_a; *black line*), mean vapor pressure deficit (*D*; *grey line*), precipitation (*P*; *bars*, right scale), soil water content (SWC) in the 0–10 cm soil layer (SWC_{10}; *black line*) and SWC in the 10–30 cm soil layer (SWC_{30}; *grey line*). Some data are missing because of power failure. *Arrows* indicate times of irrigation. Note that the Chinese pines received much less irrigation in 2008 than in 2009

of E_t was similar in 2008 and 2009. As shown in Fig. 4.2c, E_t increased rapidly from March 7 (8.46 kg/day), reached its peak on July 18 (54.94 kg/day), and then gradually decreased. Figure 4.2d illustrates the seasonal patterns of daily mean whole-tree transpiration. Strong seasonality was observed with E_t, which was much greater in the summer (June to August; 32.93 kg/day) than in winter (December to February; 2.78 kg/day), which may be attributed to the lower soil moisture content, vapor pressure deficit, and reduced radiation received in winter. Such seasonality in tree water use is generally observed in temperate and tropical systems (Melanie et al. 2006). Furthermore, E_t was much higher during the growing season (April to October) than during the nongrowing season (November to March). The nongrowing season E_t of Chinese pine cannot be neglected, as it accounts for about 8 % of the annual E_t and maintains the existing living cells. This finding is consistent with the results of Ceschiaa et al. (2002), which revealed that, during the nongrowing season, maintenance respiration of adult beech (*Fagus sylvatica*) trees ranged between 7.2 and 528 μmol/m^3/s at breast height and in the upper crown, respectively.

Statistical analysis showed that both the monthly E_t and average E_t (33.16 vs 31.61 kg/day) during the growing season (May to October) did not differ significantly in 2008 and 2009 (Fig. 4.3). Such maintenance of interannual variation of E_t was also observed in a pine forest and in an eastern Siberian larch forest (Ohta et al. 2008; Phillips and Oren 2001). However, there were obvious annual variations in tree water use observed in an open woodland of two co-occurring

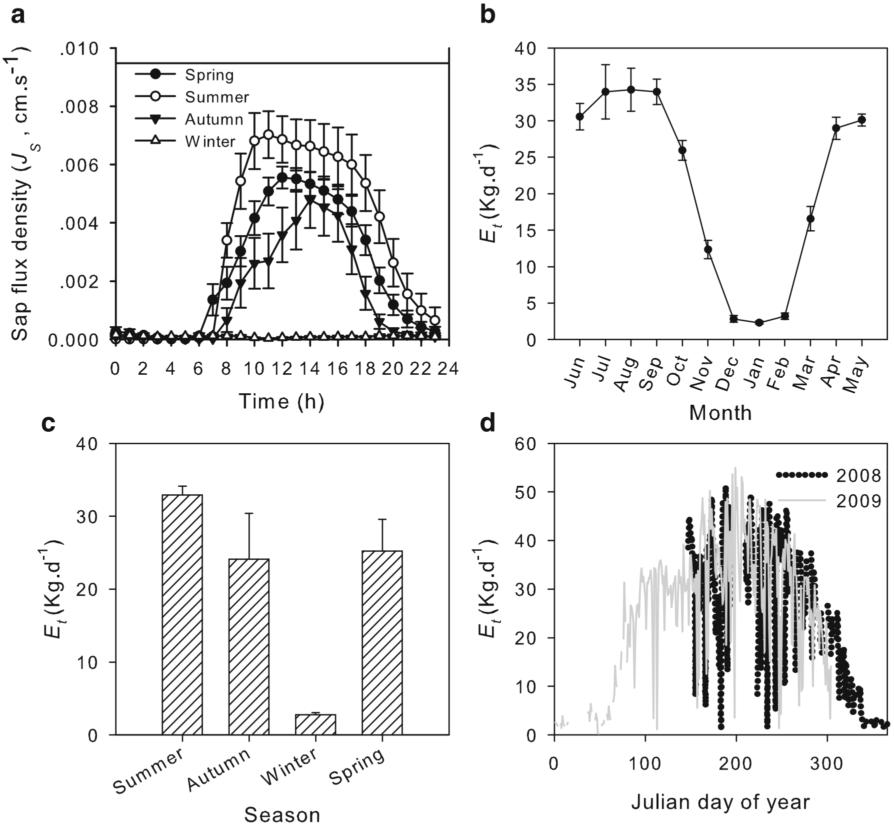

Fig. 4.2 Diurnal (**a**), monthly (**b**), seasonal (**c**), and annual (**d**) patterns of daily mean whole-tree transpiration (E_t) in Chinese pines. All points represent mean values of three sampled trees

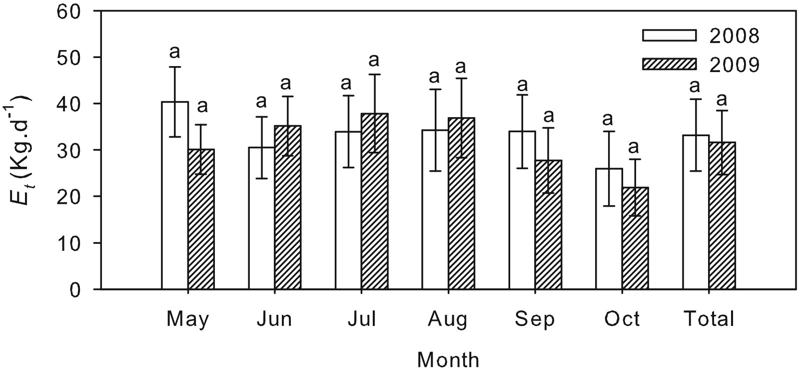

Fig. 4.3 Mean E_t (kg/day) for each month and the whole growing season in 2008 and 2009. Letters indicate significant differences between years ($p < 0.05$). *Vertical bars*, standard error

Table 4.3 Chinese pine tree transpiration in suburban and central Beijing

	Results		Biological factors		
Time/soil/site	J_{s-max} (cm/s)	E_t (kg/day)	DBH (cm)	Height (m)	References
2005 cinnamon mixed forest	0.0025–0.0040	4.58–9.88	13.31–19.31	10.5–13.8	Liu (2008)
2002 cinnamon mixed forest	0.0001–0.0015		11.3	9	Nie et al. (2005)
2004 loess mixed forest	0.0030		21.5	12.8	Ma et al. (2006)
2001 loess mixed forest	0.00041–0.00080		18.1, 20.4	12.2,14.5	Ma and Wang (2002)
2001 brown mixed forest	0.0011	19.59	20.5	12.8	Ma et al. (2003)
2005 cinnamon sparse woods		4.0	14.8–15.4	6.7–7.2	Wang et al. (2008)
2008 cinnamon sparse woods	0.0082	33.17	16.2–18.7	5.7–5.9	Our results
2009 cinnamon sparse woods	0.010	31.60	17.1–20.3	5.7–5.9	Our results

species (a coniferous *Callitris* species and a broad-leaved *Eucalyptus* species), in a 19-year-old *Acacia mangium* plantation and in a Mediterranean *Quercus ilex* forest (Limousin et al. 2009; Ma et al. 2008; Melanie et al. 2006).

4.3.3 Comparison of Chinese Pine Transpiration in a Suburban Versus an Urban Environment

Table 4.3 summarizes transpiration in Chinese pine trees in a suburban area and in the center of Beijing (Liu 2008; Ma et al. 2006; Ma and Wang 2002; Ma et al. 2003; Nie et al. 2005; Wang et al. 2008). Both daily E_t and the maximum J_s observed in this study were much higher than those reported for Chinese pines with similar DBH in the suburban area of Beijing. The results suggest that the urban environment may promote plant water loss. The significant differences in transpiration between Chinese pine in the suburban and urban area may be attributable to the following factors: (1) increased Beijing urban air temperatures (Xiao et al. 2007) may enhance plant water loss (Wang et al. 2005); (2) low plant density could increase transpiration in both potted plants (Hagishima et al. 2007) and trees (Jimenez et al. 2008) because of the "clothesline effect" (van Bavel et al. 1962); (3) SWC is a very important factor for Chinese pine transpiration, particularly when the soil water is in deficit (Liu 2008), and the increased transpiration in urban areas could be attributable to a large increase in E_t in response to higher SWC; and (4) the

Table 4.4 Multiple linear regression analysis of the relationships between transpiration and meteorological conditions (T_a, RH, PAR, D, and w) at multiple time scales

Growing stage	Time scale	Main driving factors	R^2	p
Whole period	10 min	$y = -1.02\text{e-}06 + 3.379\text{e-}06\text{PAR} + 0.001D$	0.731	0.000
	1 h	$y = -2.60\text{e-}05 + 3.349\text{E-}06\text{PAR} + 0.001D$	0.740	0.000
	1 day	$y = -0.940 + 0.056\text{PAR} + 0.752T_a$	0.817	0.000
	1 month	$y = 4.891 + 1.212T_a$	0.941	0.000
Growing period	10 min	$y = -0.001 + 3.927\text{e-}06\text{PAR} + 0.000T_a$	0.741	0.000
	1 h	$y = -0.001 + 3.955\text{E-}06\text{PAR} + 0.000T_a$	0.747	0.000
	1 day	$y = 3.783 + 0.057\text{PAR} + 0.524T_a$	0.665	0.000
	1 month	$y = 11.603 + 0.922T_a$	0.651	0.001
Dormant period	10 min	$y = 0.000 + 0.001D + 1.339\text{e-}06\text{PAR}$	0.531	0.000
11/2008 to 3/2009	1 h	$y = 0.000 + 0.002D + 1.378\text{e-}06\text{PAR}$	0.544	0.000
	1 day	$y = -1.377 + 1.012T_a + 0.046\text{PAR}$	0.791	0.000
	1 month	$y = -12.004 + 36.825D$	0.955	0.004

trees sampled in this study were shorter than the trees reported in the suburban area. A previous study reported that taller trees had lower mean canopy stomatal conductance (G_s, ~ 60 mmol/m^2 leaf area s^{-1}) than shorter trees (G_s, ~320 mmol/m^2 leaf area s^{-1}) (Schäfer et al. 2000).

4.3.4 Relationships Between the Transpiration of Chinese Pine and Urban Environmental Factors

Table 4.4 summarizes the relationships between the transpiration of Chinese pines and various climatic factors, including T_a, RH, PAR, D, and w, on multiple time scales. The sap flow rate in Chinese pines was highly related to the meteorological factors, but varied substantially with both growing season and time scale. For example, the trunk sap flow of the whole period was significantly correlated with PAR and D on both the 10-min scale and the 1-h scale, whereas the sap flow mainly depended on PAR and T_a on the daily scale and on T_a on the monthly scale. Similarly, the trunk sap flow of both the growth period and the dormant period was dependent on different climatic parameters at different time scales. The results suggest that the driving factors of E_t on the 10-min scale were the same as those on the 1-h scale. The E_t values at the 10-min, 1-h, and daily scales were highly correlated with PAR, whereas on the monthly scale, E_t was mainly affected by T_a (whole period and growth period) or D (dormant period).

The diurnal variation pattern of J_s closely matched that of PAR and D, and the correlation between J_s and PAR was generally better than that between J_s and D. For instance, on Julian day 118, the correlation coefficient (R^2) between J_s and PAR and J_s and D was 86 % and 71 %, respectively. PAR and D together explained 94.5 % of the variation in J_s. The diurnal pattern of J_s in the dormant period was very different from that in the growing period in that J_s was negatively related to

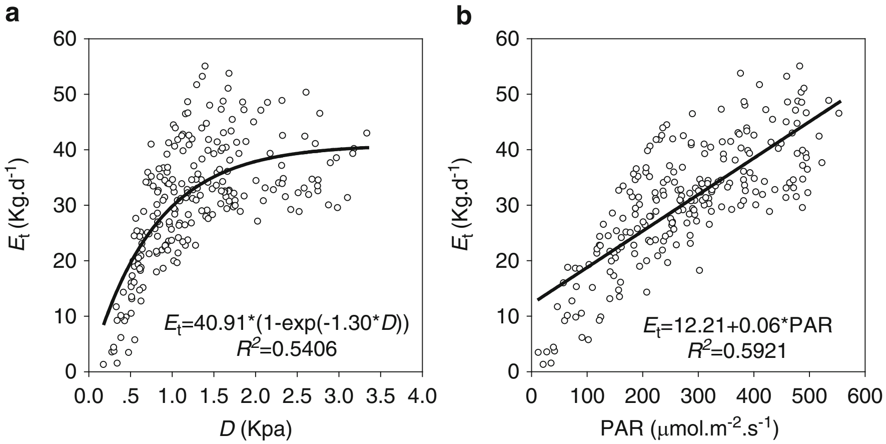

Fig. 4.4 Relationship between E_t and (**a**) vapor pressure deficit (D) and (**b**) photosynthetically active radiation (*PAR*) on the daily scale

PAR and D (e.g., $J_s = 0.0001–1.5083\text{e-}007\text{PAR}$, $R^2 = 0.56$, $p < 0.0001$; $J_s = 0.0002–0.0002D, R^2 = 0.56, p < 0.0001$ on Julian day 8). The results suggest that the shape of the diurnal flux in trees was mainly controlled by PAR, which might be caused by stomatal sensitivity to PAR. The research results are consistent with these on xylem water fluxes in ten tree species and two liana species (Phillips et al. 1999).

The day-to-day variation in E_t of Chinese pine was largely a function of daily differences in PAR, D, and SWC during the growing season. Increases in average daily D led to plateau-like increases in E_t [$E_t = 40.91(1 - \exp(-1.30 \times D)$, $R^2 = 0.54, p < 0.0001$] (Fig. 4.4a), indicating stomatal closure, which is consistent with studies on individual 30-year-old *Pinus sylvestris* L. trees (Wang et al. 2005), ten tree species (Phillips et al. 1999), and in a tropical rainforest (Granier et al. 1996), whereas these results differ from a study on large red maple trees (Wullschleger et al. 2000). Increases in the average daily PAR led to near-linear increases in E_t ($E_t = 12.21 + 0.06\text{PAR}, R^2 = 0.59, p < 0.0001$) (Fig. 4.4b). Daily PAR, however, had to exceed 100 μmol/m^2/s before rapidly increasing rates of E_t. A similar relationship was found by Wullschleger et al. in large red maple trees and by Zimmermann et al. in ten tree species (Phillips et al. 1999; Wullschleger et al. 2000).

When the rainy days were excluded, E_t was significantly correlated with SWC$_{10}$ with medium explanatory power and with SWC$_{30}$ with less explanatory power (Fig. 4.5a). Specifically, three representative patterns between E_t and SWC$_{10}$ were identified (Fig. 4.5b–d). First, between days 195 and 214, it rained at an interval of a few days and SWC remained high (>19.5 %). During this time, the correlation between E_t and SWC was not significant. This result suggests that with sufficient soil water, E_t might be more sensitive to other variables, such as vapor pressure deficit, D, rather than SWC. Second, between days 164 and 183, after a first occurrence of 55 mm of rainfall, SWC increased to 20 % and then dropped again.

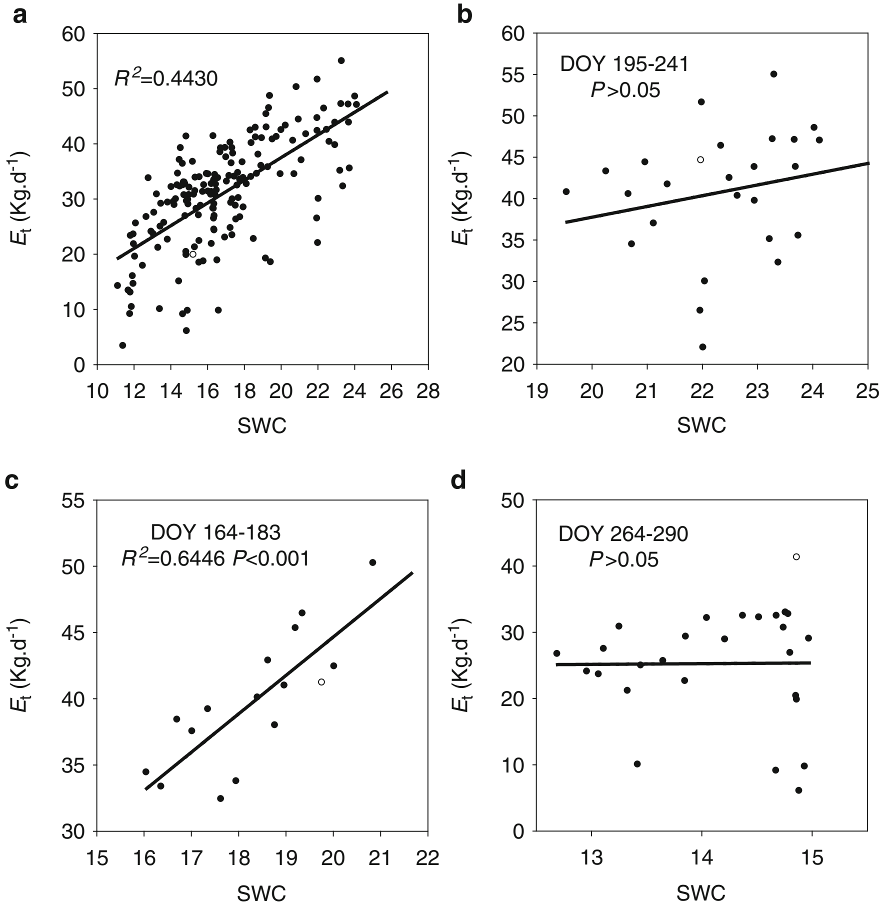

Fig. 4.5 Correlations between E_t and SWC_{10} (**a**) excluding rainy days during (**b**) Julian days (DOY) 195–241, (**c**) Julian days 164–183, and (**d**) Julian days 264–290 on the daily scale

The correlation between E_t and SWC was significant, indicating that the transpiration was affected greatly by SWC. Third, between days 264 and 290, no rainfall occurred and SWC remained low (<15 %). The correlation between E_t and SWC was not significant, which suggests that soil moisture was not the key factor regulating transpiration during this period. PAR and SWC together explained 74.3 % of the variation in E_t.

Meteorological factors affect instantaneous variability, whereas SWC determines the general level of tree sap flow (Huang et al. 2009; Liu 2008; Phillips and Oren 2001). SWC was a very important factor for E_t in the Chinese pine, particular after a rainfall followed by no rain for a few days. However, in a related study in a mixed forest of Chinese pines in suburban Beijing, sap flow showed a trend of accelerated growth when SWC increased from 4 % to 14 %, whereas the

Table 4.5 *t* test of characteristics of three sampled trees between 2008 and 2009

Parameter	May to October in 2008	May to October in 2009	*t*	df	Sig. (two-tailed)
A_s (cm^2)	170.56	193.30	−2.103	2	0.170
A_c (m^2)	21.77	22.78	−2.831	2	0.105
LAI	2.42	2.03	3.657	2	0.067

A_c indicates canopy area

increase slowed down when SWC was greater than 14 % (Liu 2008). This slowing trend in sap flow was not observed in this study, which may be attributable to the soil water availability of the study site.

According to previous studies, the factors affecting interannual variability in transpiration are mainly growing season length, soil drought (Yoshifuji et al. 2007), leaf area dynamics (Phillips and Oren 2001), rainfall (Limousin et al. 2009), and compensatory mechanisms linking annual rainfall, leaf area index, and tree water use (Melanie et al. 2006). In our study, the sampled tree characteristics, including A_s, A_c, and LAI, and most environmental factors were similar in the two different years (Tables 4.2 and 4.5), whereas precipitation differed significantly in 2008 and 2009. Because of irrigation, soil water content was not exclusively affected by the amount of precipitation, and irrigation effectively offset soil drought (Fig. 4.1). Therefore, there was no significant decrease in soil moisture content in the dry year of 2009. These results indicate that soil moisture content was the most important variable among the factors determining E_t of Chinese pine at an interannual scale. Similarly to this, the annual evapotranspiration of eastern Siberian forests is relatively steady as a result of inflow from the deeper thawing layer affecting the soil moisture content (Ohta et al. 2008).

4.4 Conclusions

In this study, the water use patterns of Chinese pines in the center of Beijing were studied at multiple time scales. The results showed that water use of Chinese pines in the urban environment is mainly driven by photosynthetically active radiation and vapor pressure deficit at the diurnal scale and by soil water content at the seasonal and annual scale. Despite the drastic interannual variability in rainfall, E_t was almost the same in 2008 and 2009, suggesting that Chinese pine may be an appropriate species for the urban landscape of Beijing in the predicted future climate of reduced rainfall and higher air temperature. In comparison with suburban Beijing, the urban environment may significantly promote water loss in Chinese pines. Because of the significant correlation between transpiration and soil water content, it is appropriate to plant Chinese pines along roadsides or in plazas rather than on turf with regular irrigation.

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