

Original Research

# A Comparative Study on Phenotypic Plasticity of Seven Urban Street Tree Species in Two Contrasting Environments

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## Abstract

The stresses imposed by impermeable paved grounds are known to result in poor health and drastically depressed benefits of street trees, but not all trees respond similarly. In this study, we investigated anatomical and chemical traits to evaluate the phenotypic plasticity of seven common street species. Analyses were performed on wood cores and leaves collected from street sites and a forest park site in Hefei, eastern China. We found significant increases in the vessel size of *Sapium sebiferum* (Ss) for the street trees, and the vessel frequency of *Albizia julibrissin* (Aj) and *Koelreuteria bipinnata* Franch. var. *integrifoliola* (Kb), indicating higher water transport efficiency and drought resistance under impervious pavements, respectively. The specific leaf area tended to be higher in Kb, *Sapindus mukorossi* (Sm) and Ss in the street site, while it was lower in *Cinnamomum camphora* (Cc) and *Platanus acerifolia* (Pa) for the street trees. Stomatal traits showed little change between the street site and the park site. Cc exhibited lower chlorophyll and carotenoid concentration in street trees. Ss and Cc showed high plasticity in terms of anatomical and chemical properties, respectively, while *Acer buergerianum* was unresponsive. These results provide a physiological basis for future street species selection in eastern China.

**Keywords:** roadside tree, pavement, soil sealing, water stress, anatomical plasticity, leaf nutrient

## Introduction

Trees in urban areas play an irreplaceable role in supporting healthy urban communities, as they can

ameliorate urban heat-island effect [1], reduce air pollution [2], diminish noise [3] and enhance recreational and aesthetic values [4]. However, the effectiveness of these benefits depends on growth and the health status of urban trees, which can be constrained by a range of abiotic factors including soil moisture, soil nutrients, and air quality [5]. In urban environments, trees are often surrounded by impervious pavements in streets,

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parking lots and plazas, which may be problematic for trees via increasing daytime surface temperature [6] and limiting infiltration of rainfall into the soil [7]. These paved habitats are often associated with reduced tree physiological functions, growth and survival [8-10], which eventually degrades tree ecological benefits.

Although in street tree plantings there may be less limitation to growth of the canopy, the presence of prevailing impervious pavement results in limited water input and excessive water demand of street trees [11]. Water input to street trees is reduced by paved surfaces and compacted soil preventing or delaying water percolation into the root zone [12]. In addition, water demand is exacerbated because increased air temperature and decreased humidity accentuate atmospheric vapor pressure deficit, which will lead to either higher water loss or reduced carbon uptake [13]. Furthermore, heat and drought stress on urban plants could be exacerbated as the global climate continues to warm and dry [14]. Under such conditions, the growth and health status of trees depends on whether the capacity for trees to absorb and transport water could meet the requirements for water loss in transpiration. Hydraulic architectures of leaf and xylem are major determinants of water transport efficiency and can be linked to the trees' drought resistance [15]. Potential xylem hydraulic conductivity is mainly decided by the frequency and size of conduits (vessels or tracheids). In general, large conduits have higher water transport efficiency, but tend to cavitate earlier than small conduits [16]. Leaf and stomatal anatomical characteristics (e.g. stomatal size/density, vein density, the thickness of palisade and spongy mesophyll layers) that directly affect photosynthesis and water loss can also reflect plants' ability to withstand heat/drought stresses [17]. For example, by regulating stomata to be more densely packed but smaller under soil water deficits, *Eucalyptus globulus* can hence be able to attain higher gas diffusion through stomata [18]. High leaf vein density has also been suggested to associate with increased drought resistance, by providing alternative water flow pathways in a redundant network [19, 20]. As key elements in tree hydraulics, xylem and leaf anatomical traits have therefore been widely investigated across various species and environments [21, 22]. However, it is not clear that how these traits respond to urban impervious pavements.

Plant pigments (chlorophyll and carotenoid) are bound to harvest photosynthetic active radiation and play a functional role in protection of the photosystems [23]. Variation in pigment concentration and composition, which determines leaf color and thus decorative qualities, can be influenced by environmental factors, such as light, temperature, water and fertilization [24]. Non-structural carbohydrates (NSCs) in plants are used to lower the osmotic potential and maintain the normal turgor of cells in order to reduce harmful effects on plants [25]. Several studies found that, the NSCs increase in relatively

adaptive species in response to stressful environments (e.g., low temperature, drought), while it is depleted in the relatively susceptible species [26]. Environmental stress can also cause the accumulation of malondialdehyde (MDA) in plant cell membranes, which works as a marker to point out lipid peroxidation under stress conditions [27].

Previous research indicates that adjustment in the biochemical, physiological or morphological phenotype in response to changes in environmental conditions (phenotypic plasticity) can provide increased environmental tolerance/adaptability [28]. At present, tree species in urban streets are generally selected based on aesthetic values rather than stress resistance. When chronically exposed to water deficit, heat, air and soil pollution under impervious pavements, some species may thrive with a large margin of safety based on high phenotypic plasticity, while others may operate narrowly. However, due to logistic difficulties of investigation and sampling in working urban landscapes, until recently there have been a few studies about phenotypic plasticity across various street tree species grown under land pavements. In this study, we conducted a comparative study in seven urban street tree species, as a response to an impervious paved situation versus a park situation. This work aimed to: 1) evaluate the specific phenotypic plasticity of seven commonly planted subtropical tree species to cope with impervious pavements; 2) to distinguish anatomical and chemical responses to impervious pavements.

## Experimental

### Study Site and Tree Species

Study sites were in the central urban area of Hefei, which is a conurbation located in the Middle East of China (31°48'~31°58'N, 117°11'~117°22'E). The built-up area of this city is approximately 441 km<sup>2</sup> (green area is 46%), with a resident population of about 7.97 million in 2017 (Hefei Municipal Bureau of Statistics). It has a subtropical monsoon climate with cold winter and hot summer. The mean annual air temperature averages 17.1°C, and annual precipitation totals 950 mm. Seven tall urban street broadleaved tree species were selected in the present study due to their widespread presence in urban areas in Hefei, especially in roadsides and parks [29]. They are *Acer buergerianum* Miq. (Ab), *Albizia julibrissin* Durazz. (Aj), *Cinnamomum camphora* (L.) presl (Cc), *Koelreuteria bipinnata* Franch. var. *integrifoliola* (Merr.) T. Chen (Kb), *Platanus acerifolia* Willd. (Pa), *Sapindus mukorossi* Gaertn. (Sm), *Sapium sebiferum* (L.) Roxb (Ss).

Seven 'street sites' were selected along streets, each of which supported one of the seven study species. In the street sites, trees were grown in belts or grids embedded in impervious pavement. A 'park site' was

selected as a control in several open areas where the soil was covered by grass in a nearby 1003.01 hectares central city park (Hefei Dashushan National Forest Park). Experimental measurements were performed on six individuals per species at each site ( $n = 6$ ) on July 2019. All selected individuals were >20-yr old, with similar height and diameter for each species (Table 1).

### Xylem Anatomy

In July 2019, wood cores (20-30 cm in length and 5.15 mm in diameter) of target trees were extracted from the stem at 1.3 m height by using a Hagl f CO300 increment borer (Hagl f Sweden AB, L ngsele, Sweden). All wood cores were sampled from the same orientation to avoid sunshine effects. The wood core samples were then placed in a 50: 50 mixture of ethanol and water and stored at 5 C. Transverse sections approximately 10-20  $\mu\text{m}$  thick were cut using a rotary microtome (Leica RM2265, Leica Microsystems, Germany). The slice was stained with safranin, then dehydrated in a graded alcohol series, cleared with xylene and permanently fixed with Canada balsam. Images were captured of the outermost rings of xylem using a digital camera (DS-Filc, Nikon Corporation, Japan) coupled to a positive fluorescent microscope (Eclipse E200, Nikon Corporation, Japan). For each image, the following parameters were measured using a NIS Elements D software: vessel length ( $V_L$ ,  $\mu\text{m}$ ), vessel width ( $V_W$ ,  $\mu\text{m}$ ), vessel perimeter ( $V_P$ ,  $\mu\text{m}$ ), cross-sectional area of vessel ( $V_A$ ,  $\mu\text{m}^2$ ), vessel frequency ( $V_F$ , the number of vessels per  $\text{mm}^2$ ), and double fiber wall thickness ( $F_T$ ,  $\mu\text{m}$ ).

### Leaf and Stomata Anatomy

On a sunny morning in 15 July 2019 (10 days after rain), three to six branches were cut from the sunny portion of the canopy of each selected tree individuals. Then thirty to forty fully developed leaves were collected and kept on dry ice for later anatomical and chemical measurement. Area of five to ten leaves was determined using a portable leaf area meter (Li-3100A, Li-Cor, USA), then oven dried for 48 h at 65 C to determine dry weight. For each individual, SLA was calculated as the ratio of leaf area to dry weight.

For leaf anatomy measurement, five to ten leaves were fixed in formalin-acetic acid-alcohol (FAA) solution for at least 24 h. Transverse thin sections were obtained by a Leica RM2265 rotary microtome, stained with safranin and fast green dye, and photographed under proper magnification by a Nikon Eclipse E200 microscope to measure leaf thickness ( $L_T$ ), upper and lower epidermis thickness ( $UE_T$  and  $LE_T$ ), palisade tissue thickness ( $P_T$ ) and spongy tissue thickness ( $S_T$ ). For vein density ( $V_D$ ), leaf samples were bleached with 5% sodium hydroxide until the veins were exposed, then were rinsed in distilled water and stained with 1% safranin solution, and photographed under a Nikon Eclipse E200 microscope. Vein length per leaf area was measured using ImageJ (<http://rsb.info.nih.gov/ij/>).

To measure stomata anatomy, leaf epidermises on the adaxial side were taken centrally in the leaf midway. Mounted sections were observed using a Nikon Eclipse E200 light microscope. For each epidermal peel, 20 stomata were sampled to measure stomatal length ( $S_L$ ) and width ( $S_W$ ) and 3 fields (300  $\mu\text{m} \times 300\mu\text{m}$ ) were sampled for stomatal density ( $S_D$ ).

Table 1. Characteristics of species and sites in the present study. DBH: diameter at breast height (means $\pm$ SE).

Species	Code	Site	DBH (cm)	Grid size (cm)	Pavement material
<i>Acer buergerianum</i>	Ab	Park	23.9 $\pm$ 0.8		
		Street	19.2 $\pm$ 1.0	65 $\times$ 65	Concrete
<i>Albizia julibrissin</i>	Aj	Park	28.5 $\pm$ 2.6		
		Street	21.8 $\pm$ 0.6	Strips of 45 cm width	asphalt
<i>Cinnamomum camphora</i>	Cc	Park	30.8 $\pm$ 2.0		
		Street	27.4 $\pm$ 1.1	130 $\times$ 130	asphalt
<i>Koelreuteria bipinnata</i> . var. <i>integrifoliola</i>	Kb	Park	22.1 $\pm$ 1.5		
		Street	28.3 $\pm$ 1.2	30 $\times$ 30 cm	Concrete
<i>Platanus</i> $\times$ <i>acerifolia</i>	Pa	Park	48.6 $\pm$ 2.7		
		Street	32.7 $\pm$ 0.8	130 $\times$ 130	asphalt
<i>Sapindus mukorossi</i>	Sm	Park	18.7 $\pm$ 1.1		
		Street	21.6 $\pm$ 0.3	80 $\times$ 80	asphalt
<i>Sapium sebiferum</i>	Ss	Park	28.0 $\pm$ 2.1		
		Street	28.8 $\pm$ 2.2	100 $\times$ 100	Concrete

### Leaf Chemical Analyses

Oven-dried leaf samples were ground to fine powder in a ball mill to determine soluble sugar (Ss) and starch (St) concentration. Ss was extracted using an ethanol technique and determined using the anthrone colorimetric assay [30]. St was determined using a total starch assay kit (Megazyme International Ireland Ltd, Wicklow, Ireland). Non-structural carbohydrates (NSCs) concentration was calculated as the sum of Ss and St.

Photosynthetic pigments were extracted using 10 ml of 80% acetone from 0.1g fresh leaf samples and centrifuged at 4000g for 5 min. The supernatant's absorbance levels were detected at 663, 646 and 470 nm. The contents of chlorophyll a (Chl a), chlorophyll b (Chl b), carotenoid (Car) and total pigment content (Pigs) were calculated according to [31].

For the measurement of malondialdehyde (MDA) content, 0.5 g fresh leaf materials was homogenized with 1.5 mL 5% trichloroacetic acid (w/v), then centrifuged at 3000 rpm for 10 min. 2 mL of supernatant were added to 2 mL of 0.6% thiobarbituric acid in 5% trichloroacetic acid, then kept in water bath for 20 min, and centrifuged at 3000 rpm for 10 min. The aqueous phases were then measured at 450, 532, and 600 nm, respectively. MDA contents were calculated according to [32].

### Statistical Analysis

The site effect and its interaction with species on all parameters were analysed by two-way ANOVA. Intraspecific traits between the street site and the park site were compared by independent samples *t*-tests. Principal component analyses (PCA) were conducted

Table 2. Significance (p-values) of terms from two-way ANOVA analysis for the effects of site, species and their interactions on anatomical and chemical traits.

Parameter	Code	Site	Species	Site×Species
Vessel frequency	$V_F$	0.024	<0.001	0.003
Vessel area	$V_A$	0.035	<0.001	ns
Vessel width	$V_W$	0.037	<0.001	ns
Vessel length	$V_L$	0.020	<0.001	ns
Vessel perimeter	$V_P$	0.025	<0.001	ns
Double Fiber wall thickness	$F_T$	0.022	<0.001	ns
Specific leaf area	SLA	ns	<0.001	<0.001
Leaf vein density	$V_D$	<0.001	<0.001	0.001
Leaf thickness	$L_T$	ns	<0.001	ns
Upper epidermis thickness	$UE_T$	ns	<0.001	0.004
Lower epidermis thickness	$LE_T$	ns	<0.001	ns
Palisade tissue thickness	$P_T$	ns	<0.001	ns
Spongy tissue thickness	$S_T$	0.017	<0.001	ns
Stomatal length	$S_L$	ns	<0.001	ns
Stomatal width	$S_W$	ns	<0.001	0.043
Stomatal density	$S_D$	ns	<0.001	ns
Stomatal pore area index	SPI	ns	0.005	ns
Leaf soluble sugar	Ss	0.001	<0.001	0.022
Leaf starch	St	0.009	<0.001	0.001
Leaf nonstructural carbohydrates	NSCs	<0.001	<0.001	0.001
Malondialdehyde	MDA	ns	<0.001	ns
Chlorophyll a	Chl a	ns	<0.001	0.002
Chlorophyll b	Chl b	ns	<0.001	0.001
Carotenoid	Car	ns	<0.001	0.004
Pigments	Pigs	ns	<0.001	0.001

on the wood anatomical traits, leaf anatomical traits, stomatal traits and leaf chemical traits, respectively. For each variable, we determine phenotypic plasticity index (PPI) based on the following expression:  $PPI = (\text{species mean } 1 - \text{species mean } 2) / (\text{the larger species mean})$  [33]. All analyses were performed using R v.3.5.0 (R Development Core team, 2018).

## Results and Discussion

### Wood Anatomical Traits

As shown in Table 2, site and species significantly influenced wood anatomical traits, but there was no significant interaction between sites and species for all wood anatomical traits except for vessel frequency ( $V_F$ ) (Table 2). *Sapium sebiferum* (Ss) increased vessel area ( $V_A$ ), vessel length ( $V_L$ ), vessel width ( $V_W$ ) and vessel perimeter ( $V_P$ ), and increased fiber cell wall thickness ( $F_T$ ) in the street site compared with the park site (Fig. 1). *Platanus acerifolia* (Pa) decreased  $V_W$  in the street site.  $V_F$  of *Koelreuteria bipinnata* var. *integrifoliola* (Kb) significant increases in street trees. In contrast, *Sapindus mukorossi* (Sm) decreased  $V_F$  in the street site. In *Albizia julibrissin* (Aj) and *Cinnamomum camphora* (Cc), all wood anatomical traits did not differ significantly between sites.

Wood anatomical traits were respectively subjected to principal component analysis (PCA) according to sites and species (Fig. 5a). The first principal component (PC1) accounted for 83% and the second component (PC2) for 12% of the variation in the dataset. The wood anatomical traits of Cc at the street site were significantly separated from those at the park site on both PC1 and PC2 axis ( $p < 0.01$ ). We also found significant difference of Kb between the sites on PC2 axis ( $p < 0.05$ ).

### Leaf Anatomical Traits

Specific leaf area (SLA) was significantly higher at the street sites than the park site in Kb, Sm and Ss (Fig. 2). In contrast, in Cc and Pa, SLA significantly decreased in street trees. Vein density ( $V_D$ ) in Aj, Cc, Kb and Ss significantly increased at the street site compared with the park site. Upper epidermis thickness ( $UE_T$ ) in Cc, Ss, and lower epidermis thickness ( $LE_T$ ) in Kb showed significantly decrease in street trees. For leaf thickness ( $L_T$ ), palisade tissue thickness ( $P_T$ ) and spongy tissue thickness ( $S_T$ ), there was no significant difference between sites in all species. According to PCA (Fig. 5b), we found significant differences of leaf anatomical traits between the street site and the park site in Ss ( $p < 0.05$  on PC1 axis;  $p < 0.01$  on PC2 axis), Cc ( $p < 0.05$  on PC2 axis) and Kb ( $p < 0.01$  on PC2 axis).

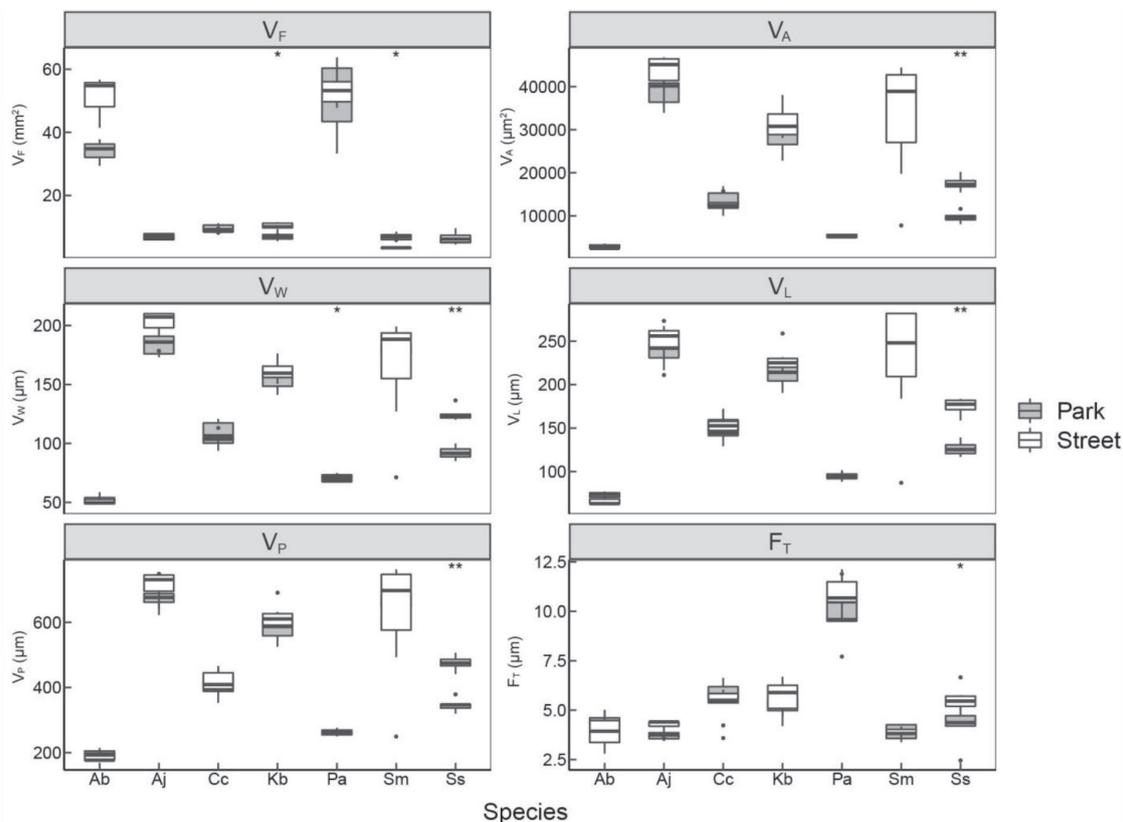


Fig. 1. Box-plots of wood anatomical properties for seven species at a park site (gray boxes) and street sites (white boxes). See Table 1 for species codes. \* and \*\* at the top of each box denote significant differences between the two sites for a species at  $p < 0.05$  and  $p < 0.01$ , respectively.

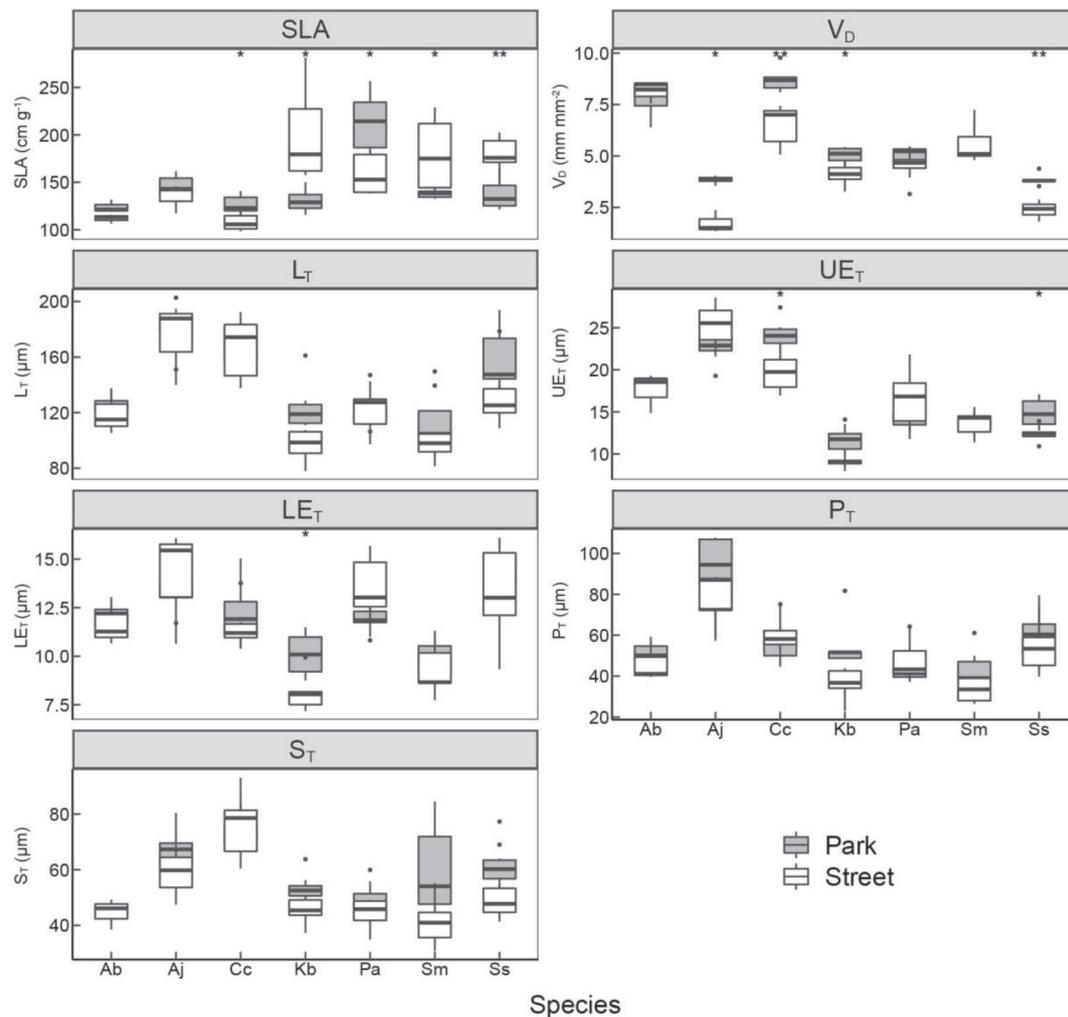


Fig. 2. Box-plots of leaf anatomical properties for seven species at a park site (gray boxes) and street sites (white boxes). See Table 1 for species codes. \* and \*\* at the top of each box denote significant differences between the two sites for a species at  $p < 0.05$  and  $p < 0.01$ , respectively.

### Stomatal Anatomical Traits

Stomatal length ( $S_L$ ) and stomatal density ( $S_D$ ) did not vary significantly between the street site and the park site in all species (Fig. 3). Stomatal width ( $S_W$ ) showed significantly increase in street trees of Aj. In Cc and Pa, stomatal pore index (SPI) significantly increased in the street sites. Based on the results of PCA (Fig. 5c), there was only significant difference of stomatal anatomical traits between the two sites in Cc ( $p < 0.05$  on PC2 axis).

### Leaf Chemical Traits

Leaf soluble sugar content (Ss) was significantly higher at the street sites than at the park site in Cc and Kb (Fig. 4). Leaf starch content (St) significantly increased in the street site in Cc and Aj, but decreased in Pa. In all species, non-structural carbohydrates (NSCs) tended to be higher in the street sites than in the park site, but the differences were only statistically

significant in Cc. At the street site, the chlorophyll-a content (Chl a), chlorophyll-b content (Chl b), carotenoid content (Car) and total pigment content (Pigs) in Cc were significantly lower than those at the park site. In Aj, Pigs also showed significantly decrease in street trees, while other species showed no significant change between the sites. There was no significant difference of malondialdehyde (MDA) between the sites in all species. According to PCA (Fig. 5d), the leaf chemical traits of Cc at the street site were significantly separated from those at the park site on both PC1 and PC2 axis ( $p < 0.01$ ). We also found significant difference of Aj between the sites on PC2 axis ( $p < 0.01$ ).

### Plasticity of Anatomical and Chemical Traits

These seven tree species exhibited different anatomical and chemical plastic responses between the park site and the street site (Fig. 6). The mean PPI

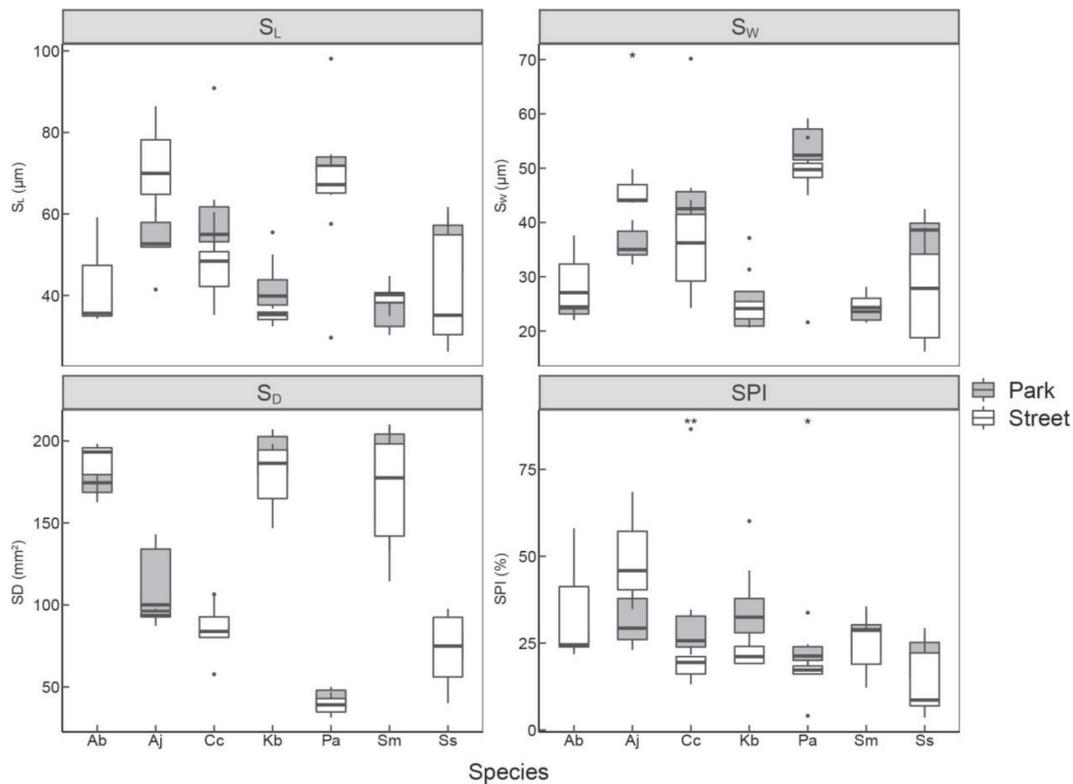


Fig. 3. Box-plots of stomatal anatomical properties for seven species at a park site (gray boxes) and street sites (white boxes). See Table 1 for species codes. \* and \*\* at the top of each box denote significant differences between the two sites for a species at  $p < 0.05$  and  $p < 0.01$ , respectively.

values of chemical features were higher than those of anatomical features. Ss and Cc showed high plasticity in terms of anatomical and chemical properties, respectively.

Our study provides evidence that land pavement along roadside significantly influenced wood anatomy, leaf anatomy, stomatal anatomy and leaf chemistry of trees grown at the street sites in comparison to the park site. We also observed marked differences in phenotypic plasticity of anatomical and chemical traits across the seven street tree species, even though they had been grown in the same conditions in a long-term.

Recent pioneer studies have concluded that impervious pavement alters water relations of urban trees by analyzing plant hydraulic conductivity [10, 34, 35]. However, few studies have focused on the corresponding effects of hydraulic infrastructure on the water transport efficiency under land pavement. In our study, we found inter-specific differences in wood anatomy of the study species. Among the seven species, *Sapium sebiferum* (Ss, Chinese tallow tree), which is native to eastern Asia and known to be invasive elsewhere, showed the highest phenotypic plasticity in wood anatomy, in terms of increased vessel size in newly formed xylem. This result was consistent to previous studies that, as an invasive species, Ss can tolerate wide environmental variation and obtain an advantage in changing environments, which would contribute to invasion success [36, 37]. Larger vessels

will result in increases in xylem hydraulic conductivity [38]. Although we did not measure it in this study, we could expect that Ss grown at the street site are able to transport water more efficiently and to better support tree growth [39-41]. A reverse pattern was observed in *Platanus acerifolia* (Pa), where vessel width ( $V_w$ ) were found to be smaller at the street site, suggesting more restriction in water transport. *Platanus* spp., which is widely planted as street trees, has been reported to be higher water use compared to other urban tree species in Los Angeles [42]. According to previous studies, it was generally thought that there was a tradeoff between the hydraulic efficiency associated with larger vessels and their vulnerability to cavitation [16, 43]. In our study, Ss grown under pavements appears to improve the hydraulic conductivity, rather than the vulnerability to cavitation. In addition, we found significantly increase of vessel frequency ( $V_f$ ) in *Koelreuteria bipinnata* var. *integrifoliola* (Kb) at the street site. The increased  $V_f$  can ensure some vessels remain active while others might be affected by cavitation [44], indicating xylem hydraulic adaptation of Kb to minimize drought induced cavitation risk and to avoid hydraulic failure under land pavement [45].

A leaf with a large area per unit mass (specific leaf area, SLA) could imply a higher potential for photosynthesis and growth; in contrast, a low SLA is better able to store water and associated with adaptability to high water stress [46, 47]. In

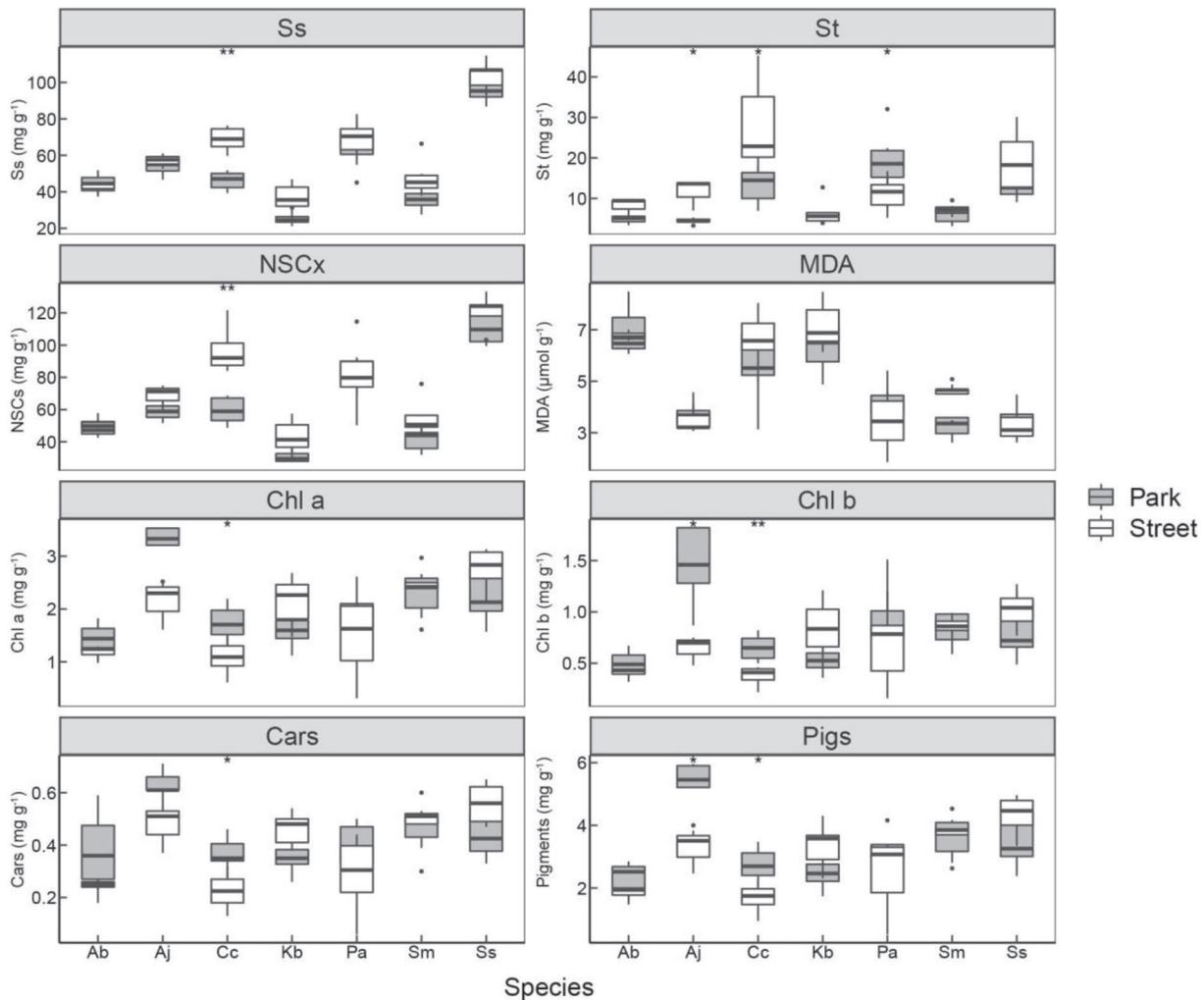


Fig. 4. Box-plots of leaf chemical properties for seven species at a park site (gray boxes) and street sites (white boxes). See Table 1 for species codes. \* and \*\* at the top of each box denote significant differences between the two sites for a species at  $p < 0.05$  and  $p < 0.01$ , respectively.

our study, Kb, *Sapindus mukorossi* (Sm) and Ss tended to have higher SLA in the street site, while *Cinnamomum camphora* (Cc) and Pa decreased SLA in street trees, indicating different strategies under land pavement. In addition, we found higher vein density ( $V_D$ ) of *Albizia julibrissin* (Aj), Cc, Kb and Ss in the street site compared with the park site. Similar results can be found in drought resistant plants which, when grown with reduced rainfall, exhibit increased  $V_D$  together with water use efficiency, since  $V_D$  has been associated with leaf hydraulic conductance, photosynthesis within and across species [48-50]. The increased  $V_D$  could result from declining leaf width or increasing vein numbers in response to altered vapor pressure deficit (VPD) [51,52]. Increased epidermal thickness is considered to be an efficient mechanism for water conservation which might decrease leaf transpiration resulting in a higher water use efficiency [53]. However, the epidermis of our studied species did not present this characteristic under pavement. In contrast, Cc and Ss in the street site had thinner upper and lower epidermal tissue ( $UE_T$  and

$LE_T$ ), which could benefit gas exchanges and improve  $CO_2$  distribution from the stomata throughout tree leaves [54]. There was limited variation of palisade and spongy tissue thickness between the sites for all species.

In this study, Cc in the street site displayed higher leaf soluble sugar (Ss), starch (St) and non-structural carbohydrate concentrations (NSCs) than those in the park site (Fig. 4). Increased NSCs probably is likely to indicate that the gross photosynthetic activity fully meets or exceeds the demand for carbon in growth and respiration [55]. It may result from enhanced photosynthesis due to the higher air temperature at the street site. However, we did not photosynthesis in the present study. If drought persists, then source limitation will occur and NSCs will decrease or will become inaccessible through mobilization and/or phloem failure before death. Malondialdehyde (MDA) concentration, which has been considered an indicator of oxidative damage to leaf structure and function, has been shown to be correlated with the stress of temperature/water to plants [56, 57]. Compared with the park site, MDA did

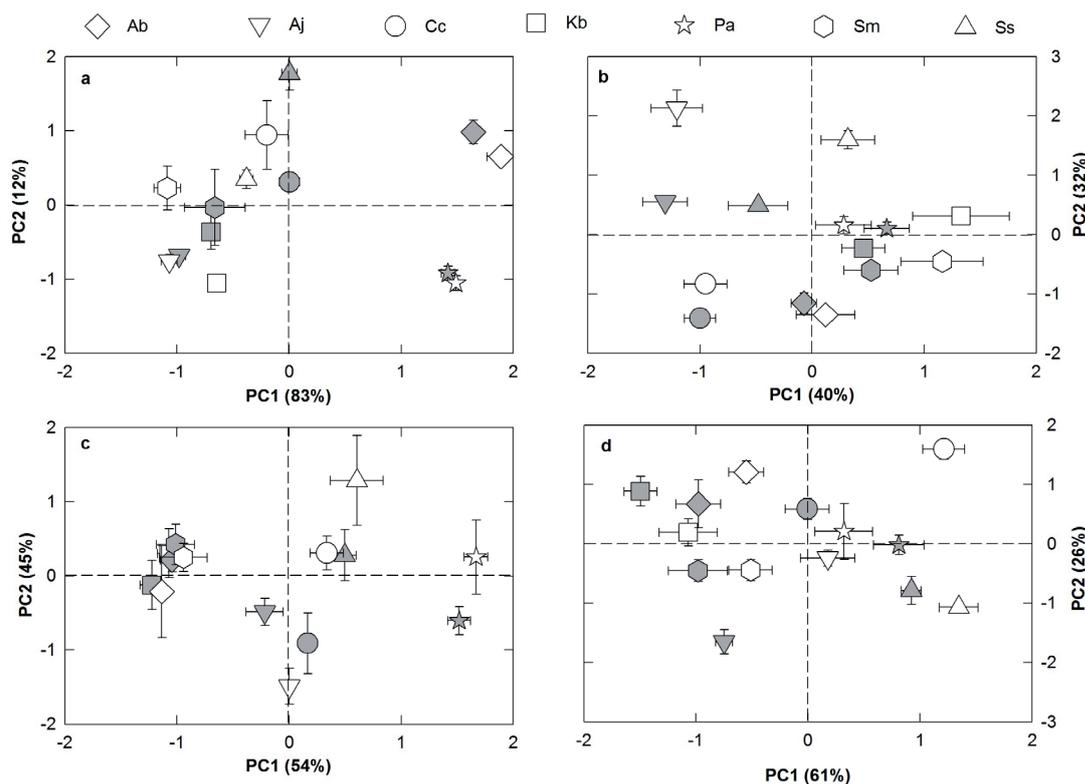


Fig. 5. Principal component analysis for a) 6 wood anatomical traits, b) 7 leaf anatomical traits, c) 4 stomatal traits and d) 8 leaf chemical traits for seven species at a park site (gray) and street sites (white). Different symbols indicate the seven tree species: Pa (five-pointed star), Ss (triangle), Ab (diamond), Cc (circle), Sm (hexagon), Aj (inverted triangle) and Kb (square). See Table 1 for species codes.

not change significantly at the street sites for all species. This result indicates that serious plasma membrane lipid peroxidation of the studied species may not happen under the drought/heat stress caused by land pavement in the street site [58].

In the present study, Cc exhibited lower chlorophyll a (Chl a), chlorophyll b (Chl b), carotenoid (Car) and

pigments (Pigs) concentration in the street site compared to the park site. Numerous studies have shown that drought and/or heat can decrease photosynthetic pigment content due to reduction of chlorophyll synthesis and inhibition of photosynthetic enzymes [59]. In addition, it may also result from decreased soil nutrient availability such as Mg and P, or the root uptake of nutrients [60] in paved soils. Reduced photosynthetic pigments can directly limit its photosynthetic potential and hence primary production. For the other species, we did not observe any significant change, indicating that photosynthetic pigment of Cc is more sensitive to impervious pavements.

Acers, which are commonly cultivated in urban areas across the temperate world due to its ornamental value, are generally thought to be moderately drought tolerant [61]. In our study, among the seven studied species, *Acer buergerianum* (Ab, trident maple) was the only species showed no significant change in all anatomical and chemical variables, exhibiting low phenotypic plasticity. However, Ab displayed the smallest xylem vessel size among the seven species, indicating the ability to avoid cavitation and decline in function.

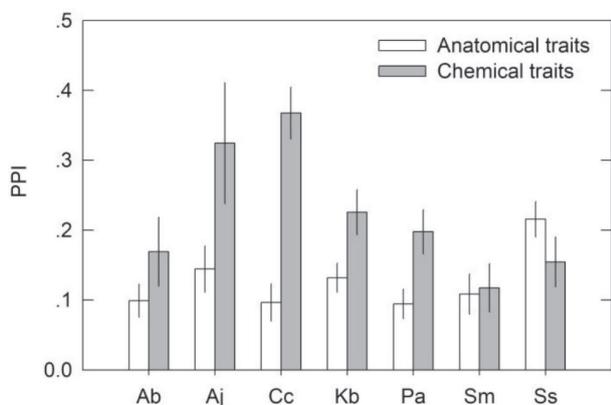


Fig. 6. Index of phenotypic plasticity (PPI) in response to pavements for 17 anatomical traits (white bars) and 8 chemical traits (grey bars) in seven urban tree species. Data are means±SE. See Table 1 for species codes.

## Conclusions

Land pavements in urban area are challenging environments for street trees. Our data indicates that land pavement could change the xylem structure, leaf structure and chemistry of the street species in urban area. Our findings suggested that the responses of anatomical and chemical traits to land pavement were species specific. Among species, street trees of *Sapium sebiferum*, *Albizia julibrissin* and *Koelreuteria bipinnata* var. *integrifoliola* appeared to increase vessel size and frequency. Stomatal traits showed little change between the street site and the park site. *Cinnamomum camphora* showed lower chlorophyll and carotenoid concentration, and higher leaf non-structural carbohydrates concentration in street trees. The study provides practical information for tree management in urban sites, but also suggests that key plant processes and responses such as xylem vessel size, non-structural carbohydrates and specific leaf area are fundamental for a full understanding of responses of urban trees to environmental stresses. However, data must be interpreted with caution, as several other confounding variables (eg., air/soil pollution) that might affect the physiology of urban trees were not explicitly investigated in this study. Further studies are still needed to explore the dependence of pavement on other soil and plant traits.

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## Conflict of Interest

The authors declare no conflict of interest.

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