The effects of urban impervious surfaces on eco-physiological characteristics of *Ginkgo biloba*: A case study from Beijing, China

Yingshi Song, Feng Li, Xiaoke Wang, Chongqi Xu, Junying Zhang, Xusheng Liu, Hongxing Zhang

**A R T I C L E   I N F O**

Article history:
Received 22 July 2014
Received in revised form 10 October 2015
Accepted 12 October 2015
Available online 23 October 2015

Keywords:
Urban impervious surface
Eco-physiological characteristics
*Ginkgo biloba*

**A B S T R A C T**

Accelerated urbanization continues to convert natural lands to impervious surfaces, resulting in serious impacts to the environment, and affecting the growth of urban plants. In this study, we evaluated eight environmental factors, and nine eco-physiological characteristics of *Ginkgo biloba* planted on two types of impervious surface (totally impervious surface and partly impervious surface), and one non-impervious surface (grass land). Results showed that the primary effect of the impervious surfaces on the environment were increasing air temperature (*T*<sub>a</sub>) and soil temperature (*T*<sub>s</sub>), and decreasing relative humidity of air (*RH*) and soil moisture content (*SMC*). *G. biloba* net photosynthetic rate (*Pn*) on totally impervious surfaces (*TIS*), and partly impervious surfaces (*PIS*) was 39% and 22% lower than trees on an urban grass land (*GL*). *T*<sub>a</sub> and *G. biloba* also showed similar reductions. Compared to *GL*, F<sub>v</sub>/F<sub>m</sub> on *TIS* and *PIS* decreased 7% and 6%, respectively, and PSII decreased 32% and 41%, respectively. Water use efficiency (WUE), light use efficiency (LUE), and CO₂ use efficiency (CUE) of *G. biloba* growing on impervious surfaces were 20–40% less than those on the grass land. Redundancy analysis (RDA) indicated the combination of environmental factors explained 66% of the variation of *G. biloba* eco-physiological responses. This study revealed the eco-physiological responses and variation of *G. biloba* to different substrates. Results indicated it is vital to improve plant environmental quality, and enhance urban green ecological services. Our study provides a scientific reference for urban greening, and ecological land construction.

© 2015 Elsevier GmbH. All rights reserved.

**Introduction**

Cities are dominated by anthropogenic activities (Su et al., 2010), and a complex social-economic-natural ecosystem (Ma and Wang, 1984). The impervious surface is one of the primary changes imposed by human beings (Elvidge et al., 2007; Nowak and Greenfield, 2012). Driven by the increasing population and urbanization, natural lands have been transformed into anthropogenic impervious surfaces (Hartley et al., 2008), including roads, community squares, roofs (Razzagham et al., 2014), and parking lots (Burghardt, 2006; Xian et al., 2007). As a result, land without impervious cover is scarce in urban areas. Impervious surfaces provides us with level roads and can seal the soil to prevent the dust from diffusing into the air, but it produces serious impacts to the ecological environment (Schuier, 1994). The most direct effect of impervious surfaces is the urban heat island (Schuier, 1994; Zhao et al., 2011; Zhou and Wang, 2011). Due to thermal properties of impervious surfaces, temperatures in urban areas are higher than suburban areas (Takebayashi and Moriyama, 2009). The other important impact is urban water cycle processes. Most impervious surface materials are typically asphalt, cement, stone, brick, and even plastic, which are water-proof, and have little infiltration. This can increase the surface runoff (Haase and Nuissl, 2007), decrease groundwater recharge (Haase, 2009), and increase the threat of flooding. In addition, impervious surfaces can cut-off the soil-atmosphere gas exchange (Scalenghe and Marsan, 2009). Oxygen gas cannot recharge into
the soil, and greenhouses gases, such as CO₂ and CH₄, cannot release into the atmosphere. Impervious surfaces also impact urban plant growth (Zhao et al., 2010; Viswanathan et al., 2011). Scalenghe and Marsan (2009) reported the large impervious surfaces in urban regions leads to a loss in biodiversity. Several studies reported that because of urban heat island, plants flourished earlier in urban relative to rural areas (Roetzer et al., 2000; Neil and Wu, 2006). However, little research regarding eco-physiological responses of urban plants to impervious surfaces has been performed.

The objectives of this study were to measure the effects of impervious surfaces on photosynthesis and fluorescence of G. biloba, and to determine the main driving environmental factors affecting the eco-physiological characteristics of G. biloba in impervious surfaces. We hypothesized impervious surfaces would decrease photosynthetic production and chlorophyll fluorescence.

Materials and methods

Plant material and experimental design

The research site was located at Huaiqing, in Haidian District, Beijing, China (39°54′20″N, 116°23′29″E). The experimental design is shown in Fig. 1. Twenty G. biloba trees were measured-TIS (four trees), PIS (eight trees), and GL (eight trees). G. biloba planted on the three treatments were pre-existing mature trees aged 15–17 years with an average height of 7.5 m (±1.3), average diameter at breast height of 14.5 cm (±1.5), and average crown of 4.0 m (±0.6). The totally impervious surface (TIS) was a marble square, approximately 240 m². The partly impervious surface (PIS) was a brick surface square, approximately 625 m², and the grass land (GL) was an urban grass area, approximately 340 m². The distance between TIS and PIS is 15 m, and the distance between GL and PIS is 45 m. On the TIS and PIS, G. biloba were planted in a 0.8 m² pit, and the pit is closed to outside soil and the bottom is impervious, so the trees cannot access soil outside for water and nutrients. On the GL, the trees were planted in the ground directly. All trees were planted 5.0 to 5.5 m apart.

According to Kong et al. (1998) and Song et al. (2014), the water permeability (WP) of concrete, asphalt and marble surface was nearly 0%, and the water permeability of brick surface was about 33%, and grass was 88%. During the experimental period, we watered all trees by watering can on the soil surrounding the tree. The trees were irrigated twice a month with 401 applied to the soil around each tree. The soil was not fertilized during the experimental period.

Eco-physiological characteristics measurements

The Li-6400 portable Photosynthetic System (Li-6400, Li-Cor, Lincoln, NE, USA) was used to measure photosynthetic gas exchange parameters of G. biloba during June to October, 2012. Measurements were conducted once a month. For each Tree 3–5 healthy leaves were selected in facing sun directions at a height of 2.0–2.5 m for testing. Net photosynthetic rate (Pn, μmol CO₂ m⁻² s⁻¹), transpiration rate (Tr, mmol H₂O m⁻² s⁻¹), stomatal conductance (Gs, g mol H₂O m⁻² s⁻¹), intercellular CO₂ concentration (Ci, μmol mol⁻¹) and leaf vapor pressure deficit (VPDLP, kPa) were measured from 9:00 to 11:00 AM on sunny, windless days. After the leaf was tested, we collected the leaf and brought it to the laboratory to calculate fresh and dry weight to test the leaf water content (LWC).

Water use efficiency (WUE), CO₂ use efficiency (CUE), and light use efficiency (LUE) were calculated using the following formulas (Long et al., 1993; Nijs et al., 1997; He and Ma, 2000; Yan et al., 2010):

\[
\text{WUE} = \frac{P_n}{T_r}
\]

\[
\text{CUE} = \frac{P_n}{C_i}
\]

\[
\text{LUE} = \frac{P_n}{\text{PAR}}
\]

where \(P_n\) is the net photosynthetic rate, \(T_r\) is the transpiration rate, \(C_i\) is the intercellular CO₂ concentration, PAR is the photosynthetically active radiation.

Chlorophyll fluorescence parameters were measured with a Li-6400–40 leaf chamber fluorometer (Li-COR, Inc. USA). We have selected 4 trees for each treatment. And we took 3–5 leaves and averaged to get a single value per tree. The leaves were selected in facing sun directions at a height of 2.0–2.5 m for testing within the middle of the crown. Before testing minimum (F₀) and maximum fluorescence (Fₘₚₚ) (Gorbe and Calatayud, 2012), leaves were shaded at least 30 min. F₀ was determined under particularly low light, and did not induce variable fluorescence (Yu et al., 2013). Fₘₚ was determined with a 0.8 s saturation pulse. Minimum (F₀) and maximum (Fₘₚ) light fluorescence were determined on light-adapted leaves, we selected leaves in facing sun directions at a height of 2.0–2.5 m for testing, within the middle of the crown, but without shaded. And then we measured F₀ and Fₘₚ. The measurements were similar to F₀ and Fₘₚ. Steady state yield of PSII fluorescence in the light (F₁) was determined under 600 μmol PAR (photons m⁻² s⁻¹). The following fluorescence parameters were calculated based on the above measurement:

\[
\text{ΦPSII} = \frac{(F_m - F_0)}{F_m - F_0} \times 100\%
\]

Environmental factor measurements

Environmental factors were tested at the same time, when the eco-physiological characteristics measurement. Photosynthetically active radiation (PAR, μmol m⁻² s⁻¹), air temperature (Tᵣ, °C), and relative humidity (RH, %) were tested by Li-6400 (Li-COR, Inc. USA). Soil temperature (Tₛ, °C), soil electric conductivity (EC, dS m⁻¹), and soil volumetric moisture content (SMC, %) were conducted by ECH2O sensor EC-5 (Decagon Inc., USA). The probe was inserted into the soil to a depth of 10 cm, 50 cm away from the tree.
stem. For the PIS and TIS testing we measured these parameters in the pit.

Statistical analyses

Results were analyzed using SPSS software version 18.0 for Windows (Chicago, IL, USA). A Generalized Linear Model was used to analyze of variance among different treatments, and significant differences between different treatments were determined using an LSD multiple range test. Differences were considered statistically significant when \( p < 0.05 \).

Canonical Correlation Analysis (CCA) was conducted on eco-physiological characteristics and environmental factors using Canoco 4.5 software (Lepš and Šmilauer, 2003). Detrended Correspondence Analysis (DCA) showed G. biloba physiological and ecological responses were linear to environmental factors, so the Canonical Redundancy Analysis (RDA) was a applied (Zhang et al., 2011) to test relationships between environmental factors (WP, RH, VPDL, Ta, TR, PAR, EC, and SMC) and physiological and ecological traits (\( Pn \), \( T_s \), \( G_s \), \( F_v/F_m \), \( OPSL \), NPQ, WUE, LUE, and CUE). A manual forward selection process was chosen to detect significant factors at \( p < 0.05 \) (Braak and Smilauer, 2002).

We generated \( t \)-value biplots with CanoDraw software (Lepš and Šmilauer, 2003). \( t \)-Value biplots was initially used in biology to reveal statistically significant relationships between species and environmental factors. The reason why we used the biplot was that the biplot shows the relationships between dependent variables (arrows) and independent variables (circles). The circle diameter corresponds to the multiple regression coefficient of the dependent and independent variables. The direction and length of the arrow represents the canonical correlation relationship between variables.

Results

Effects of impervious surfaces on G. biloba’s habitat

Among the six environmental factors, \( T_s \), \( T_r \), RH, and SMC were the four most impacted (Table 1). \( T_s \) above TIS and PIS was, respectively, 3.22 and 2.07 °C higher than GL and there were significant differences between these 3 different treatment (\( n = 4 \), \( p = 0.007 \), 0.014, 0.009, and 0.01 in June, July, August, and September). \( T_r \) under TIS and PIS was, respectively, 2.2 and 1.46 °C higher than GL. The \( T_s \) of impervious surface (TIS and PIS) was significant higher than \( T_s \) under GL (\( n = 4 \), \( p = 0.047 \), 0.036, 0.27, and <0.0001 in June, July, August, and September). Air RH of impervious surface (TIS and PIS) was significant lower than GL (\( n = 4 \), \( p = 0.016 \), 0.031, 0.0015, 0.04, and, 0.029 in June, July, August, September, and October); RH above TIS and PIS was, respectively, 6 and 5 (%) lower than GL. Soil moisture content under impervious surface (TIS and PIS) was significant lower than that under GL (\( n = 4 \), \( p = 0.01 \) and 0.02 in June and September), and soil moisture content under TIS and PIS was, respectively, 3% and 4% lower than GL.

Effects of impervious surfaces on gas exchange characteristics of G. biloba

During June to October 2012, \( P_n \) of G. biloba on different surface types showed the following: \( P_n \) (GL) \( > \) \( P_n \) (PIS) \( > \) \( P_n \) (TIS). \( P_n \) of G. biloba on TIS were significantly lower than those on GL (\( n = 4 \), \( p = 0.001 \), 0.013, 0.002, 0.041, and 0.019 in June, July, August, September, and October), but there were no significant difference between TIS and PIS and there were also no significant difference between PIS and GL. \( P_n \) of G. biloba on TIS and PIS were, respectively 39% and 22% lower than those on GL (Fig. 2A). \( T_r \) of G. biloba on TIS and PIS were, respectively, 30% and 11% lower than those on GL.
GL (Fig. 2B), but the differences among three treatments were not significant \( (n = 4, p < 0.05) \). \( G_s \) of G. biloba on TIS were significantly lower than those on PIS and GL \( (n = 4, p = 0.009, 0.003, 0.031, 0.001, \) and 0.029 in June, July, August, September, and October) \( \text{(Fig. 2C)} \). The VPD of G. biloba on TIS were significantly higher than those on GL \( (n = 4, p = 0.029, 0.005, 0.041, 0.001, \) and 0.039 in June, July, August, September, and October) \( \text{(Fig. 2D)} \). From June to October the leaf water content (LWC) of G. biloba on GL was about 80%, however those on TIS and PIS the LWC gradually decreased from 73% and 79% to 57% and 64%, respectively. But only in October there were significant difference among three treatment \( (n = 4, p = 0.005) \) \( \text{(Fig. 2E)} \).

Fig. 2. Gas exchange characteristics of Ginkgo biloba in different types of surface (mean ± SD). \( n = 4, P_n \): net photosynthetic rate, \( T_r \): transpiration rate, \( G_s \): stomatal conductance, VPD: leaf vapor pressure deficit; LWC: leaf water content; TIS: Totally impervious surface; PIS: Partially impervious surface; GL: Grass land.

Effects of impervious surfaces on chlorophyll fluorescence characteristics of G. biloba

\( F_v/F_m \) for G. biloba on grass exceeded 0.8 in all months, with the exception of October, but \( F_v/F_m \) on impervious surfaces (TIS and PIS) was below 0.8 from June to October \( \text{(Fig. 3A)} \). In June, August and October there were significant difference among three treatment \( (n = 4, p = 0.009, 0.031, 0.001) \). \( \Phi PSII \) of the three surface types were \( \Phi PSII \) (GL) > \( \Phi PSII \) (PIS) > \( \Phi PSII \) (TIS) \( \text{(Fig. 3B)} \). On GL \( \Phi PSII \) was 33% and 19% higher than TIS and PIS, respectively. In June and July, the NPQ on impervious surfaces was higher than GL, however inverse results were detected from August to October \( \text{(Fig. 3C)} \).

The WUE, LUE, and CUE of G. biloba

WUE of G. biloba on TIS and PIS was, respectively 22% and 20% lower than those on GL \( \text{(Table 2)} \). In August, WUE of G. biloba reached a peak of 4.4, 3.46, and 3.5 mmol mol\(^{-1}\) on GL, PIS, and TIS, respectively. During June to August, the WUE of G. biloba on GL were significantly higher than those on TIS \( (n = 4, p = 0.006, 0.025, \) and 0.002). LUE of G. biloba on GL was 46% and 21% higher than that on TIS and PIS \( \text{(Table 2)} \). LUE of G. biloba on TIS were significantly higher than those on TIS \( (n = 4, p = 0.042, 0.001, 0.004, 0.023, \) and 0.001 in June, July, August, September, and October). CUE of G. biloba on GL was 46% and 25% higher, than those on TIS and PIS, respectively \( \text{(Table 2)} \). And in August, the differences of CUE among three treatments were significantly \( (n = 4, p = 0.02) \).

Canonical correlation analysis of environmental factors

WP, PAR, \( T_m \), RH, VPD, \( T_s \), SMC, and EC were the environmental factors applied as independent variables, and \( P_n, T_r, G_s, F_v/F_m, \Phi PSII, \) NPQ, WUE, LUE, and CUE were the eco-physiological attributes used as dependent variables. RDA results \( \text{(Table 3)} \) showed the
Fig. 3. Chlorophyll fluorescence of *Ginkgo biloba* on different types of surface (mean ± SD, n = 4). $F_v/F_m = (F_m - F_s)/F_m$. $\Phi_{PSII} = (F_m - F_s)/F_m$. NPQ (Non Photochemical Quenching) = $(F_m - F_s)/F_m$. TIS: Totally impervious surface; PIS: Partially impervious surface; GL: Grass land.

**eco-physiological indicators for *G. biloba* were significantly correlated with environmental factors.** The correlation coefficient ($r$) was 0.99 ($p = 0.009$). The canonical variation included $Ta$, VPDL, RH, $Ts$, WP, PAR, and EC, which explained 66.5% of the total variation of *G. biloba* eco-physiological indicators. Axis I was correlated with temperature ($Ta$ and $Ts$), and explained 58.3% of the total variation in eco-physiological characteristics (Fig. 4); axis II was correlated with RH and VPDL, and accounted for 6.2% of the total variation; and axis III and IV, respectively accounted for 1.7% and 0.2% of the total variation, which was correlated with WP, SMC, and EC. Axis III was positively correlated with $Pn$ (A), $G_{s}$ (C), $\Phi_{PSII}$ (E), WUE (G), LUE (H), and CUE (I), which were positively correlated with WP, but negatively correlated with $Ta$ and $Ts$. While NPQ exhibited a positive correlation with $Ta$, $Ts$, and PAR, indicating that high environmental temperature resulted in increased fluorescence and heat dissipation, however energy used for photochemical reactions decreased. $T_s$ (B) and $F_v/F_m$ (D) were positively correlated with SMC.

**The driving factors of impervious surface on eco-physiological changes**

Canoco 4.5 manual selection forward process was used to determine the contribution of every driving factor contributing to eco-physiological changes (Table 4). Results showed, with the exception of SMC, all environmental factors significantly contributed to the eco-physiological variation of *G. biloba* ($p < 0.05$). $Ta$ explained 36% of the total variation ($p = 0.001$), and VPDL explained 15% of the total variation ($p = 0.001$). RH was 5%, and $Ta$, WP, and PAR were each 3%.

**Relationship of the environment and eco-physiological characteristics of *G. biloba***

A significant negative correlation was detected between $Ta$ and $Pn$, $T_s$, LUE, CUE ($n = 4, p = 0.001$). NPQ showed a positive correlation with $Ta$ (Fig. 5a). WUE and LUE exhibited a positive correlation with VPDL, while $Pn$, $T_s$, $F_v/F_m$, and CUE were negatively correlated with VPDL (Fig. 5b). $Pn$, $T_s$, $F_v/F_m$, and CUE were all positively correlated with RH, while a negative correlation was detected between WUE, LUE, and RH (Fig. 5c). A significant negative correlation between $T_s$ and $Pn$, WUE, LUE, CUE was identified ($n = 4, p = 0.005$) (Fig. 5d). All characteristics with the exception of NPQ were positively correlated with WP (Fig. 5e). PAR was negatively correlated with WUE and LUE, which might also have an indirect effect on $Ta$ (Fig. 5f).

**Discussion and conclusion**

**Impervious surfaces caused stress in urban plants**

Impervious substrates in the urban environment increased air and surface temperatures, reduced air humidity, and soil moisture content during the summer months in Beijing. These changes have previously been report to threatened plant physiological and ecological processes (Zhao et al., 2012). Chlorophyll fluorescence ($F_v/F_m$) reflects the potential quantum efficiency of PSII and is used as a sensitive indicator of plant photosynthetic performance. According to Sarjieva et al. (2007) and Feng et al. (2012) the $F_v/F_m$
and GL. So the impervious surface has caused a serious impact on \textit{G. biloba}'s carbon uptake and probably leads to lower growth in these plants. There is some previous research about the impact impervious pavement on plant aboveground growth (Morgenroth and Visser, 2011) and root growth (Viswanathan et al., 2011), where results showed that the impervious pavement had a negative effect on plant growth. But there also some conclusion that the impervious surface had increased the root abundance and caused shallow root distribution (Morgenroth, 2011). So the effects of impervious surface on tree growth still needs more experimental studies.

In contrast to unpaved surfaces, the impervious surface increased the soil temperature. Some researchers have drawn similar conclusion, Scalenghe and Marsan (2009) found that impervious surfaces can increase the soil temperature, then temperature of the air close to the surface would be increased. A potential outcome is that the local climate will be modified, leading to urban heat island effect (Takebayashii and Moriyama, 2009; Schueler, 1994; Zhao et al., 2011). Xiao and Weng (2007) revealed that a change in land use toward urban impervious surfaces brought about an increase of air temperature in the Guizhou province.

Impervious surfaces decreased the soil moisture relative to the unpaved surface. This is in contrast to previous research, Morgenroth and Buchan (2009) found that the soil moisture differences are insignificant between pervious and impervious paving.
while other studies have reported that soil moisture is generally greater in soil beneath paved rather than unpaved soil (Morgenroth et al., 2013; Qian et al., 2010). Some other researches have shown that soil moisture is not necessarily lower beneath impervious pavements (Eigenbrod and Kennepolh, 1996; Oh et al., 2010; Hedayati et al., 2014; Grabosky et al., 2009). Clearly more research is needed in this research field.

The main factors affecting G. biloba on impervious surfaces

The eco-physiological change for G. biloba on impervious surfaces was the result of a series of environmental factor changes. Air temperature is an important factor for photosynthesis; under higher Ta, net photosynthetic rate was higher, but decreased when Ta was higher than 25 °C. VPD is the water vapor pressure...


