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Physiological Characteristics of *Zelkova serrata* Street Trees in Goyang and Paju, South Korea

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Abstract

Street trees have been incorporated into urban forests to regulate the microclimate and provide shade as well as provide aesthetic and environmental functions and to evaluate their physiological characteristics. *Zelkova serrata* is a major tree species that has been planted on various South Korean streets. We determined the physiological characteristics of *Z. serrata* in street trees of Goyang and Paju in Gyeonggi Province. According to survey sites, net CO_2 assimilation rates was 13.9-16.4 μmol CO_2 $m^{-2}s^{-1}$, chlorophyll fluorescence (Fv/Fm) was 0.80-0.82, and proline contents was showed 3.4-3.7 mg g^{-1} FW. The studied trees were assumed to be physiologically stressed, but it was found that *Z. serrata* was planted as street trees were not significantly stressed when compared to chlorophyll fluorescence responses and proline contents. In the future, the continuous monitoring system is needed to evaluate the physiological characteristics of urban trees.

Key Words: street trees, urban forests, photosynthesis, chlorophyll contents

Introduction

Urban forests have aesthetic benefits and absorb air pollutants in downtown areas where impervious buildings and roads dominate. The urban forests have conducted to screening trees, and climate control effects by forming a network of greenery (Sung 2003; Park and Kang 2010). Moreover, urban forests and street trees are important carbon sinks that sequester CO_2 (Yoon 2022). Recently, urban forests have been considered as a recreational resource by local governments, with street trees being increasingly promoted as part of local tourism campaigns.

Street trees have grown within confined spaces where the soil dries easily. They are also simultaneously exposed to intense light conditions and air pollutants sourced from transportation and fine dust (Bialecki et al. 2018; Petrova et al. 2022) Furthermore, some citizens also have a variety of complaints about particular species. For example, in South Korea, there were complaints from citizens that the fruit of *Ginkgo biloba* was induced the stench in autumn. The bark and fallen leaves of *Platanus occidentalis* are considered unappealing. For these reasons, trees such as *G. biloba* and

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P. occidentalis are not planted anymore. In some regions, replacement planting is being attempted with other popular tree species such as *Zelkova serrata*, *Prunus yedoensis* and *Chionanthus retusa*. Street trees are typically planted as a single species for easy management, but this also decrease species diversity, exposing trees to pests and diseases.

Zelkova serrata belongs to the Ulmaceae, which is found in South Korea, Japan, and China (Kim and Lee 2013). It has been planted as street trees even in severely dry urban areas due to drought resistance (Oh et al. 2020). *Z. serrata* not only provides shade in the streets, but it is also a valuable lumber source for the timber industry (Noh et al. 2020). The studies on the current status of tree planting were mainly conducted by region (Sung 2003; Na et al. 2019), the analysis of preference and satisfaction, the impact of street trees on the urban microclimate (Lee et al. 2021), and the carbon storage and uptake by street trees (Yoon et al. 2013; Jo et al. 2018). Additional studies were conducted on the effects of air pollutants (Lee et al. 1999), heavy metal pollution (Kim and Song 2015; Park et al. 2021), and calcium chloride treatment during the winter on street tree physiology. However, the research on roadside trees is still very limited, and most studies used seedlings that were between two and three years old.

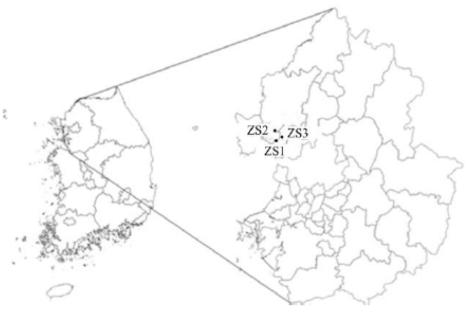
It was assumed that the street trees should be stressed by exposed to environments such as increasing temperature, air pollutant, and urban development. Therefore, this study was conducted to investigate the leaf physiological characteristics such as net CO_2 assimilation rate, chlorophyll, and proline content of *Z. serrata* among the street trees species, in Goyang and Paju in northern Gyeonggi Province, South Korea.

Materials and Methods

Study sites

This study was conducted on physiology of *Z. serrata*, a species mainly planted as street trees in urban green areas. The study sites were selected Goyang and Paju in northern Gyeonggi Province where the street trees planted the *Z. serrata*. The ZS1 (the road at Hallyu world, Ilsan New Town in Goyang) has been continuously developed since the first phase of the new town (1990s), and is one of the landmarks of Goyang where KINTEX and cultural facilities were located nearby. The ZS2 (the road at Mirae-ro, Unjeong New Town in Paju) is the center of Paju's Unjeong district as a residential area, which was developed as a second-phase new town (2000s). The ZS3 (the road of Goyangdaero, Ilsandong-gu in Goyang) has developed since 2010s for residential area and close to other sites (Fig. 1). Despite the lack of accurate planting record, the studied trees were assumed to be about 20 years old using past aerial photographs and tree size.

The average temperature of the month (July 2021) was 26.8°C, the highest temperatures were 31.4°C, the lowest temperature was 22.0°C, and monthly total precipitation was 288.2 mm at the nearest meteorological observatory from the study site (Korea Meteorological Administration 2022). There has been no rainfall for several days before the field measurement, supporting that the moisture conditions were controlled between the field measurements. The air quality and particulate matter in study sites did not exceed the national air quality standard (Goyang: SO_2 at 0.003 ppm, NO_2 at 0.014 ppm, O_3 at 0.040 ppm, CO 0.4 ppm, PM_{10} at 31 μg m^{-3} and $PM_{2.5}$ at 17 μg m^{-3}; Paju: SO_2 at



Site code	ZS1	ZS2	ZS3
City	Goyang (Ilsan New Town)	Paju (Unjung New Town)	Goyang (Ilsan New Town)
Street	Hallyuworld-ro	Mirae-ro	Goyangdae-ro
GPS	37°39'47.0"N 126°45'12.1"E	37°42'36.8"N 126°44'46.8"E	37°40'46.7"N 126°47'27.2"E
Length	2.8 km	70 km	20.3 km
Width	35-40 m	18-30 m	35-40 m

Fig. 1. Study area of *Zelkova serrata* street trees in Goyang and Paju in Gyeonggi Province, South Korea.

0.002 ppm, NO_2 at 0.010 ppm, O_3 at 0.039 ppm, CO 0.4 ppm, PM_{10} at 26 $\mu g\ m^{-3}$ and $PM_{2.5}$ at 15 $\mu g\ m^{-3}$; Ministry of Environments 2021).

The trees without visible damage to the leaves were investigated at consistent daily times (8 am to 11 am) in July 2021 and each survey site was investigated for one day. It was measured by diameter at breast height (DBH). The soil moisture content and the tree vigor were investigated with three replicates per tree and no special problems were identified in the basic growth conditions of the studied trees. The soil moisture content was determined at 12 cm-depth using a portable time-domain reflectometry sensor (Spectrum® Field Scout, TDR 200, USA). The tree vigor was determined by the cambial electrical resistance (Junsmeter, PrumBio, South Korea) at three random orientations on the trunk at breast height (Kim and Yoo 2021). The value of tree vigor is presented with 0–100 scale; above 87 indicates healthy. The six trees per survey site were selected and measurements were done with three replicates.

Measurement of physiological characteristics

Measurements of photosynthesis were performed on ten replicate leaves from each tree that showed no visible damage and exposed to sunlight; from the third to fifth leaves of the leaf plastochron index (LPI) counting from the shoot tip. The light source, a PLU5 LED light (ADC BioScientific Ltd., UK), was attached to a photosynthetic measuring device. The photosynthetically active radiation value was fixed at 1,500 $\mu mol\ m^{-2}s^{-1}$ and measurements (logging every 10 s, each sample was measured for 5 minutes) were performed between 8 am and 11 am to minimize diurnal changes of tree physiological activities and environmental conditions. Measurements were performed using a portable infra-red gas analyzer (LCi-SD Ultra Compact Photosynthesis System; ADC BioScientific Ltd., UK). Before starting measurements at each survey sites, the gas analyzer was checked with the ambient CO_2 level and regularly calibrated. The measured parameters were leaf net CO_2 assimilation rate (A_{net}), transpiration rates (E), substomatal cavity CO_2 concentration in mesophyll cells (C_i), and water use efficiency (WUE; the net CO_2 assimilation rate/transpiration rate) (Ashraf 2002).

Chlorophyll fluorescence (Fo, Fm, Fv/Fm) was measured using the chlorophyll fluorometer (OS-30P, ADC Bioscientific Ltd., UK) for samples from LPI third to fifth, counting from the tip of the species. Chlorophyll fluorescence response was measured after applying a sample clip treatment to the leaves under the blocking light for 20 min, and adapting to darkness (Maxwell and Johnson 2000). The photochemical reaction efficiency (Fv/Fm=(Fm-Fo)/Fm) was compared by calculating the minimum chlorophyll fluorescence in dark-adapted tissue (Fo), the maximum chlorophyll fluorescence in dark-adapted tissue (Fm), and the variable chlorophyll fluorescence in dark-adapted tissue (Fv=Fm-Fo).

Chlorophyll content was measured with three replicates in six trees at each site, transported to the laboratory in an ice box, and then immediately analyzed. Chlorophyll content was measured for fully developed leaves (from the third to fifth leaves based on the LPI) with no visible damage. To extract chlorophyll, 0.1 g of leaf slices, without the main vein, were immersed in 8 mL of 80% acetone solution and stored in the dark for 1 week. The extracted solution was measured for absorbance at 470 nm, 645 nm, and 663 nm using a UV/VIS spectrophotometer (UV-2100, Shimadzu, Japan). Chlorophyll a, b, and total chlorophyll content were calculated using the following equations (Arnon 1949; Lichtenthaler 1987):

$$\text{Chlorophyll a} = 12.7 \cdot A663 - 2.69 \cdot A645$$
$$\text{Chlorophyll b} = 22.9 \cdot A645 - 4.68 \cdot A663$$
$$\text{Total chlorophyll (a+b)} = 20.2 \cdot A645 + 8.02 \cdot A663$$
$$\text{Carotenoid} = 1000 \cdot A470 - 1.82 \cdot \text{Chlorophyll a} - 85.02 \cdot \text{Chlorophyll b}/198$$

The proline content was sampled from the third to fourth leaves around the growth point, and the average value was calculated. For proline content, three replicate leaf samples were collected from each tree, transported to the laboratory in an ice box, stored in a refrigerator at 4°C, and analyzed within 3 days. After crushing 0.5 g of leaves, 10 mL 3% sulfosalicylic acid was added, and the mixture was homogenized and centrifuged (3,400×g, 4°C, 20 min) to recover the supernatant. Then, 2 mL of the supernatant, 2 mL acid-ninhydrin (glacial acetic acid 30 mL, 6 M phosphoric acid 20 mL, 1.25 g ninhydrin), and 2 mL acetic acid were mixed and reacted at 100°C for 1 hour. After the reaction, the product was immediately transferred to ice and 4 mL of toluene was added. The chromophore-containing toluene layer was extracted by vortexing for 15-20 seconds and then separated from the resultant aqueous layer. The absorbance of the chromophore solution was measured at 520 nm using a UV spectrometer at room temperature (Jin et al. 2017).

Statistics

The data were presented as mean±standard deviation. A one-way ANOVA was performed to confirm the difference in measurements the survey site. Statistical significance was post-hoc tested by Duncan's multiple range test method ($p<0.05$). All statistical analyses were performed using SPSS (IBM Corp., USA, ver. 25.0).

Results

The DBH of studied trees ranged from 17.40 to 21.25 cm overall, while DBH was relatively smaller at ZS2 (17.40±2.17 cm) than the other sites. Soil moisture content was the highest at ZS2 (34%), while the other survey plots showed a soil moisture content of about 27% (Table 1). The tree vigor value at the survey site was over 90, confirming adequate tree vitality.

A_{net}, WUE, E, g_s and C_i were statistically different between the study sites (Table 2). The A_{net} was highest in leaves from ZS3 at 16.41±4.42 μmol CO_2 $m^{-2}s^{-1}$. The WUE was highest in leaves from ZS2 (7.13±1.60 μmol $mmol^{-1}$), followed by leaves from ZS3 (6.31±1.47 μmol $mmol^{-1}$), and ZS1 5.45±0.58 μmol $mmol^{-1}$. The E were highest in leaves from ZS1 (2.83±0.37, mmol H_2O $m^{-2}s^{-1}$), and lowest in leaves from ZS2 (2.00±0.25, mmol H_2O $m^{-2}s^{-1}$). The g_s was the highest in ZS2 (0.33±0.08 mmol H_2O $m^{-2}s^{-1}$), and the lowest in ZS3 (0.27±0.09 mmol H_2O $m^{-2}s^{-1}$). The C_i reflects the level of photosynthesis and plays an important role in evaluating the A_{net} of the trees. In the case of ZS2, C_i showed the highest absorption rate at 348.59±20.50 μmol CO_2 mol^{-1}, but the A_{net} (13.93±1.56 μmol CO_2 $m^{-2}s^{-1}$) was relatively low. Furthermore, the C_i was 346.71±9.56 (μmol CO_2 mol^{-1} in ZS1 and 307.24±23.53 μmol CO_2 mol^{-1} in ZS3 (Table 2).

The minimal chlorophyll fluorescence in dark-adapted tissue (Fo) was shown 153.74 to 167.94. Maximum chlor-

Table 1. DBH, soil moisture and vigor condition of *Zelkova serrata* street trees in Goyang and Paju, Gyeonggi Province, South Korea

Sites	DBH^{ns} (cm)	Soil moisture* (%)	Vigor condition*
ZS1	19.65±3.11	27.75±8.01^b	94.06±0.91^b
ZS2	17.40±2.17	34.38±4.05^a	96.46±1.53^a
ZS3	21.25±4.60	19.56±5.21^c	97.32±1.22^a

Data represent means±SD (n=15) in each column followed by the same letter did not differ significantly (*$p<0.05$; ns, not significant ($p>0.05$)) by one-way analysis of variance (ANOVA) and Duncan's multiple range test.
ZS1: Hallyu world-ro (Goyang), ZS2: Mirae-ro (Paju), Z3: Goyangdae-ro (Goyang).

Table 2. Changes in leaf net CO_2 assimilation rate (A_{net}), transpiration rate (E), water use efficiency (WUE), stomatal conductance (g_s), and substomatal cavity CO_2 concentration (Ci) of *Zelkova serrata* street trees in Goyang and Paju, Gyeonggi Province, South Korea

Sites	A_{net}*** (μmol CO_2 $m^{-2}s^{-1}$)	E*** (mmol H_2O $m^{-2}s^{-1}$)	WUE*** (μmol $mmol^{-1}$)	g_s*** (mmol H_2O $m^{-2}s^{-1}$)	C_i*** (μmol CO_2 mol^{-1})
ZS1	15.32±2.01^a	2.83±0.37^a	5.45±0.58^b	0.31±0.05^a	346.71±9.56^b
ZS2	13.93±1.56^b	2.00±0.25^c	7.13±1.60^a	0.33±0.08^a	378.59±20.50^a
ZS3	16.41±4.42^a	2.60±0.36^b	6.31±1.47^c	0.27±0.09^b	307.24±23.53^c

Data represent means±SD (n=59) in each column followed by the same letter did not differ significantly (***$p<0.001$) by one-way analysis of variance (ANOVA) and Duncan's multiple range test.
A_{net}, Leaf net CO_2 assimilation rate; E, Transpiration rate; C_i, substomatal cavity CO_2 concentration in mesophyll cells; g_s, Stomatal conductance; WUE, Water use efficiency.
ZS1: Hallyu world-ro (Goyang), ZS2: Mirae-ro (Paju), Z3: Goyangdae-ro (Goyang).

ophyll fluorescence in dark-adapted tissue (Fm) was shown 767.13 to 931.44 Fo and Fm, were highest at ZS1, on the other hands, lowest at ZS2. The photochemical efficiency of photosystem II in dark-adapted tissue (Fv/Fm) was about 0.80 to 0.82, similar value among the study sites (Table 3).

The chlorophyll a, chlorophyll b, total chlorophyll (a+b), and carotenoid contents were significantly different (Table 4). It was showed the highest chlorophyll content at 16.97±4.25 mg g^{-1} FW in ZS3 and the lowest at 10.29±3.85 mg g^{-1} FW in ZS1. The carotenoid content was the highest in ZS3 at 1.86±0.66 mg g^{-1} FW, and a significant difference was confirmed ZS2 (1.32±0.23 mg g^{-1} FW), indicating a site-specific dependence. The proline content was highest in ZS2 (3.66±0.25 mg g^{-1} FW), followed by

Table 3. Chlorophyll fluorescence of *Zelkova serrata* street trees in Goyang and Paju, Gyeonggi Province, South Korea

Site	Chlorophyll fluorescence		
	Fo[ns]	Fm*	Fv/Fm**
ZS1	167.94±20.38	931.44±69.69[a]	0.82±0.03[a]
ZS2	153.74±40.45	767.13±201.00[b]	0.80±0.01[b]
ZS3	157.93±16.15	781.20±125.39[b]	0.81±0.02[ab]

Data represent means±SD (n=15) in each column followed by the same letter did not differ significantly (*$p < 0.05$, **$p < 0.01$; ns, not significant ($p > 0.05$)) by one-way analysis of variance (ANOVA) and Duncan's multiple range test.
Fo, Minimum chlorophyll fluorescence in dark-adapted tissue; Fm, Maximum chlorophyll fluorescence in dark-adapted tissue; Fv, Variable chlorophyll fluorescence in dark-adapted tissue; Fv/Fm, Photochemical efficiency of photosystem II in dark-adapted tissue.
ZS1: Hallyu world-ro (Goyang), ZS2: Mirae-ro (Paju), Z3: Goyangdae-ro (Goyang).

Table 4. Chlorophyll contents of *Zelkova serrata* street trees in Goyang and Paju in Gyeonggi Province, South Korea (mg g^{-1} FW)

Sites	Chlorophyll[a]***	Chlorophyll[b]***	Total Chlorophyll***	Carotenoid**	Proline[ns]
ZS1	7.38±2.93[c]	2.91±0.93[c]	10.29±3.85[c]	1.62±0.33[ab]	3.39±0.99
ZS2	8.43±2.32[bc]	3.27±0.64[b]	11.70±2.95[bc]	1.32±0.23[b]	3.66±0.25
ZS3	12.09±3.00[a]	4.88±1.30[a]	16.97±4.25[a]	1.86±0.66[a]	3.49±1.47

Data represent means±SD (n=18) in each column followed by the same letter did not differ significantly (**$p < 0.01$, ***$p < 0.001$; ns, not significant) by one-way analysis of variance (ANOVA) and Duncan's multiple range test.
ZS1: Hallyu world-ro (Goyang), ZS2: Mirae-ro (Paju), Z3: Goyangdae-ro (Goyang).

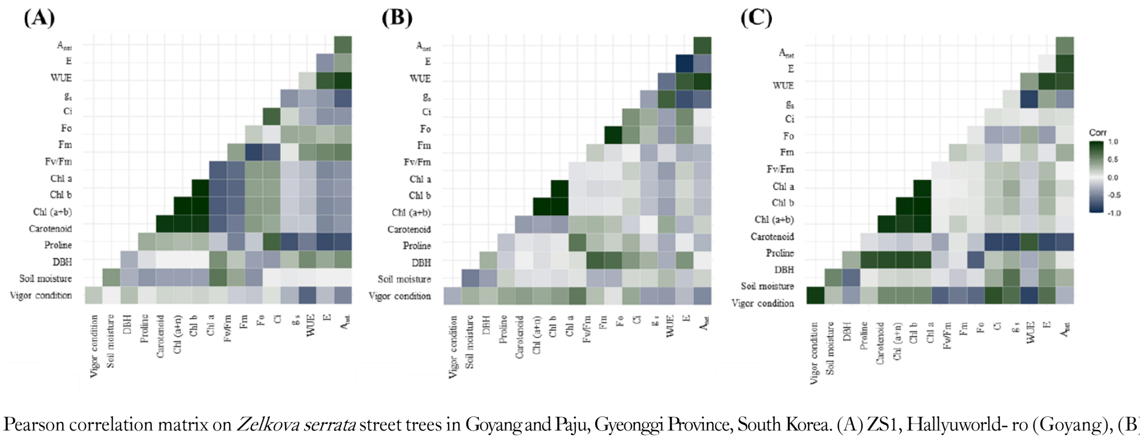


Fig. 2. Pearson correlation matrix on *Zelkova serrata* street trees in Goyang and Paju, Gyeonggi Province, South Korea. (A) ZS1, Hallyuworld- ro (Goyang), (B) ZS2, Mirae-ro (Paju) and (C) ZS3, Goyangdae-ro (Goyang).

ZS3 (3.49±1.47 mg g^{-1} FW) and ZS1 (3.39±0.99 mg g^{-1} FW). However, differences in proline content were statistically insignificant between survey sites (Table 4).

According to the correlation analysis using the measured variables in each study sites, A_{net}, E and g_s values showed a significant positive correlation (Fig. 2). In particular, the g_s value in all three sites was showed a strong positive correlation between the A_{net} and E values. On the other hand, negative correlations between A_{net}, C_i and proline were observed. In ZS1 and ZS2, E and WUE showed a negative correlation (Fig. 2A, B). In addition, the correlation of soil moisture and photosynthesis was not significant in ZS1 and ZS2. In ZS3, soil moisture and g_s value showed a positive correlation, and soil moisture and tree vigor were showed strong positive correlations (Fig. 2C).

Discussion

Tree vigor can be measured through the electrical resistance of the cambium of a tree, which is a non-destructive and non-invasive way to check the vitality of a living plant (Tattar and Blanchard 1976; Hwang and Kim 2016). Hwang and Kim (2016) reported that each species has a unique electrical resistance and that the resistance value changes with the growth stage. As measured in March with a shigometer, Hwang and Kim (2016) reported a decrease of 4.3 kΩ from 11.0 kΩ in *Z. serrata* and confirmed that the vigor of the tree increased during growth in the summer. In this study, the overall growth of *Z. serrata* was healthy at the entire survey sites, with the tree vitality of both species being 94.1-97.3 (Table 1). The management of street trees by local government, it could be involved irrigation during dry periods, along with nutrient injection in cases of poor growth or pest infection, which could have contributed to the relative vitality of the street trees in this study

According to Oh et al. (2020), the CO_2 absorption rate of *Z. serrata* in spring was 4.86 μmol CO_2 $m^{-2}s^{-1}$ and 3.27 μmol CO_2 $m^{-2}s^{-1}$ in summer. In addition, Park (2006) analyzed the tissue moisture characteristics of *Z. serrata* leaves and reported that drought resistance was high and that it can adapt to stress-prone environments due to poor soil moisture. Lee et al. (2013) reported in *Bupleurum latissimum* that with low photosynthetic efficiency, even when C_i is low, CO_2 cannot be used efficiently to increase the amount of photosynthesis. In this study, the C_i in ZS2 was the highest at 378.59±20.50 μmol CO_2 mol^{-1}, but A_{net} was the lowest at 13.93±1.56 μmol CO_2 $m^{-2}s^{-1}$(Table 2). The C_i is determined by the CO_2 diffusion resistance of mesophyll cells according to atmospheric CO_2 concentrations. Diffusion resistance is controlled by microclimatic conditions and the stomatal conductance of trees (Franck and Vaast 2009). Lee (2018) reported that the initial C_i was very low in a drought stress test *Dendropanax* species. Although drought stress was addressed after 1 week, the water imbalance in the leaves became very severe.

These results suggest that while C_i was high in some of the sites, the net CO_2 assimilation rate was also low, indicating that CO_2 could not be efficiently used for photosynthesis. The A_{net} was related to environmental factors such as photosynthetic active radiation, temperature, relative humidity, and CO_2 concentration, as well as stomatal conductance, E and C_i (de Santana et al. 2015).

In ZS3, the g_s and C_i concentration value was the lowest. However, photosynthesis was the highest compared to the other sites. In ZS3, the soil water content was low, it could act as a low level of water stress. Je and Kim (2016) determined that the decrease in stomatal conductivity was to prevent water loss in the leaves and to increase the water potential of the leaves. Wünsche et al. (2005) reported that a decrease in stomatal conductance could inhibit photosynthesis by reducing the C_i. The stomata did not open efficiently; instead photosynthesis was maintained by consuming C_i stored in the plant. CO_2 in mesophyll cells may have been used to increase A_{net}. More analysis on the interactions between g_s, CO_2, and photosynthesis need to be investigated in the future.

WUE is the photosynthetic assimilation rate for water loss, and as the C_i decreases, the E decreases while water use efficiency rises (Hamerlynck and Knapp 1996; Peñuelas et al. 1998). A momentary decrease in stomatal conductivity may result in a temporary rise in water use efficiency (Heschel et al. 2002; Lim et al. 2006; Lee et al. 2013). Sonti et al. (2021) reported that warmer temperatures in urban area (i.e., heat island effect) may increase not only photosynthesis but also respiration and soil evaporation under the increased CO_2, nitrogen, and temperature which can lower A_{net} carbon capture and potentially limit growth.

Urban environments can directly or indirectly affect plant growth through the urban heat island phenomenon, sensitivity to climate change, and damage to the photosynthetic apparatus such as the photosystem II (Takahashi and Murata 2008). Chlorophyll fluorescence analysis can be used to investigate the reaction of photosystem II, and it provides a variety of information on the photosynthetic machinery and the physiological response to stress (Strasser and Strasser 1995). Generally, in previous studies, the Fv/Fm of healthy leaves is around 0.83 (Johnson et al. 1993; Maxwell and Johnson 2000). The level of Fv/Fm is known to decrease during stress (Kycko et al. 2018). Hwang and Kim (2016) reported that the Fv/Fm values of *Z. serrata* were between 0.7 and 0.9 and that the values of healthy plants fell between 0.74 and 0.84. In this study, a relatively low Fv/Fm value of 0.80 was confirmed in ZS2, but due to subtle deviation, the value seemed to indicate low-stress exposure.

Chlorophyll is the most important pigment for photosynthesis. In this study, the chlorophyll content of *Z. serrata* was found to be relatively high at 10.29 to 16.97 mg g^{-1} (Table 4). In the treatment through ozone treatment, which is one of the stress factors of urban, Cho et al. (2020) studied the effect of ozone on the chlorophyll content in two-year-old seedlings of major street tree species. The chlorophyll content in *Z. serrata* was reported to be 7.5 mg g^{-1} FW in untreated samples, but was reduced by 53% under ozone treatment stress. Studies have corroborated the observation that chlorophyll content decreases under stress conditions (Lee et al. 2015; Kwak et al. 2019; Cho et al. 2020). However, Lee et al. (2022) reported an increased chlorophyll content in leaves that lack moisture. Some studies have been reported that plants have high concentrations of chlorophyll due to resistance to pollutants (Missanjo et al. 2015; Chaudhary and Rathore 2019). Especially, Missanjo et al. (2015) was reported that *Prunus persica* had a chlorophyll content of 14.21 to 31. mg g^{-1} FW depending on the exposed areas to air pollutions. The reason of increased chlorophyll content was due to high resistance to related pollutants due to air pollutants in the surrounding area. In this study, the study sites were located close to a four-lane road, and the high chlorophyll content of street trees was suspected to be a result of the plants resistance to pollutants and dust generated by the vehicles. Therefore, future analysis of the relationship between chlorophyll content and stress tolerance will be necessary to identify and continuously monitor possible stressors in urban forests.

The amino acid proline plays a role in osmotic pressure regulation, cell membrane protection, and the removal of active oxygen (Jin et al. 2017). Proline accumulation in plants is a general adaptation against stress factors including various conditions such as high salinity, drought, biotic stress, and presence of heavy metals with in the environment (Purcarea et al. 2022; Manghwar et al. 2021). Proline is also an indicator of stress since it controls the absorption and movement of potassium ions (K^+) in plants. The increase in proline content has been interpreted as a defense mechanism against water stress, as experienced in dry or adverse growth environments. Also, it was reported that plants with high drought resistance had a relative small increase in proline content compared to plants without drought resistance (Liu and Zhu 1997; Jin et al. 2017). However, no standard values for proline content have been established, so future research should be conducted to research proline content in street trees to establish reference values, in the future.

According to the correlation analysis of this study, A_{net} and E showed a positive relationship, and the WUE showed a negative relationship with photosynthetic in ZS2 unlike the other two sites. It can be assumed to the trees of ZS2 are subjected to drying stress (Fig. 2). Jin et al. (2022) was reported that in order to respond to drying stress, they showed a response to reduce water loss by reducing the photosynthetic rate and transpiration and increasing the water utilization efficiency, and when the soil moisture content was lowered to 10% or less, the overall photosynthetic activity showed a difference. In case of E and g_s, the negative correlation was shown the proline and photosynthetic assimilation. E and WUE showed negative correlation in ZS1 and ZS2. It could be assumed that when the trees were subjected to drought, it closes the stomata to prevent internal water loss, thereby lowering the transpiration rate and increasing the water use efficiency, which is the water loss rate for photosynthetic assimilation products (Je et al. 2006).

Conclusion

This study investigated the physiological characteristics of *Z. serrata*, street trees planted in Goyang and Paju. Urban forests are generally exposed to intense light, urban heat island effects and air pollutants, which could limit plant growth. Contrary to such an assumption on physiological stresses of street trees, the analysis of physiological characteristics such as A_{net}, proline content, and chlorophyll fluorescence made rejecting the assumption. This study has limitations in that only some areas of planted street trees were investigated. Moreover, soil moisture was measured, but water potential such as effective moisture was not measured and analyzed. To solve these challenges, further researches which determine and diagnose the stress levels in planted trees are suggested. Nevertheless, this study was the first report conducted on planted street trees, and has the potential to be used as a reference level in relation to the stress physiology of *Z. serrata*. It is necessary to study the physiological characteristics and establish a continuous monitoring system of urban forests and street trees for development of healthy urban forests.

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References

Arnon DI. 1949. Copper Enzymes in Isolated Chloroplasts. Polyphenoloxidase in *Beta vulgaris*. Plant Physiol 24: 1-15.

Ashraf M. 2002. Salt Tolerance of Cotton: Some New Advances. Crit Rev Plant Sci 21: 1-30.

Bialecki MB, Fahey RT, Scharenbroch B. 2018. Variation in Urban Forest Productivity and Response to Extreme Drought Across a Large Metropolitan Region. Urban Ecosyst 21: 157-169.

Chaudhary IJ, Rathore D. 2019. Dust pollution: Its Removal and Effect on Foliage Physiology of Urban Trees. Sustain Cities Soc 51: 101696.

Cho SB, Lee HS, Lee JK, Park SH, Kim HD, Kwak MJ, Lee KA, Lim YJ, Woo SY. 2020. Air Pollution Tolerance Index (APTI) of Main Street Trees Following Ozone Exposure. J Korean Soc For Sci 109: 50-61.

de Santana TA, Oliveira PS, Silva LD, Laviola BG, F. de Almeida AA, Gomes FP. 2015. Water Use Efficiency and Consumption in Different Brazilian Genotypes of *Jatropha curcas* L. Subjected to Soil Water Deficit. Biomass Bioenergy 75: 119-125.

Franck N, Vaast P. 2009 Limitation of Coffee Leaf Photosynthesis by Stomatal Conductance and Light Availability Under Different Shade Levels. Trees 23: 761-769.

Hamerlynck E, Knapp AK. 1996. Photosynthetic and Stomatal Responses to High Temperature and Light in Two Oaks at the Western Limit of Their Range. Tree Physiol 16: 557-565.

Heschel MS, Donohue K, Hausmann N, Schmitt J. 2002. Population Differentiation and Natural Selection for Water-Use Efficiency in *Impatiens capensis* (Balsaminaceae). Int J Plant Sci 163: 907-912.

Hwang DK, Kim DY. 2016. Assessment of Landscape Tree Vigor Using Cambial Electrical Resistance. Ecol Resil Infrastruct 3: 302-306.

Je SM, Kim SH. 2016. Effects of $CaCl_2$ on Gas Exchange and Stomatal Responses in the Leaves of Prunus serrulata. J Korean For Soc 105: 303-308.

Jin EJ, Cho MG, Bae EJ, Park J, Lee KS, Choi MS. 2017. Physiological Responses to Drought Stress of Seven Evergreen Hardwood Species. J Korean For Soc 106: 397-407.

Jo HK, Kim JY, Park HM. 2018. Carbon Storage and Uptake by Street Trees in Seoul. J For Environ Sci 34: 162-164.

Kim HE, Song U. 2015. Eco-physiological Responses of Roadside Tree Species to Contamination of Soil with Lead. Ecol Resil Infrastruct 2: 237-246.

Kim IS, Lee JH. 2013. Geographic Variation of Seed Characteristics and 1-year-old Seedling Growth of *Zelkova serrata*. Korean J Agric For Meteorol 15: 234-244.

Kim YJ, Yoo G. 2021. Suggested Key Variables for Assessment of Soil Quality in Urban Roadside Tree Systems. J Soils Sediments 21: 2130-2140.

Korea Meteorological Administration. 2022. Weather Resources Database. https://www.weather.go.kr/. Accessed 4 Jan 2023.

Kwak MJ, Lee J, Kim H, Park S, Lim Y, Kim JE, Baek SG, Seo SM, Kim KN, Woo SY. 2019. The Removal Efficiencies of Several Temperate Tree Species at Adsorbing Airborne Particulate Matter in Urban Forests and Roadsides. Forests 10: 960.

Kycko M, Zagajewski B, Lavender S, Romanowska E, Zwijacz-Kozica M. 2018. The Impact of Tourist Traffic on the Condition and Cell Structures of Alpine Swards. Remote Sens 10: 220.

Lee HJ, Choi KY, Chiang MH, Choi EY. 2022. Photosynthesis, Growth and Yield Characteristics of *Peucedanum japonicum* T.

Grown under Aquaponics in a Plant Factory. J Bio-Environ Control 31: 67-76.

Lee KC, Wang MH, Song JM. 2013. Physiological Responses of *Bupleurum latissimum* Nakai, Endangered Plants to Changes in Light Environment. Prot Hortic Plant Fact 22: 154-161.

Lee KC. 2018. Changes in Photosynthetic Performance and Water Relation Parameters in the Seedlings of Korean *Dendropanax* Subjected to Drought Stress. Korean J Med Crop Sci 26: 181-187.

Lee KJ, Han SH, Kim GB, Kim TK. 1999. A Study on the Correlation between Ambient Ozone Concentration and Tree Health of *Zelkova serrata* Makino Street Trees in Seoul. Bull Seoul Natl Univ Arbor 19: 54-65.

Lee SB, Choe HY, Jo HK, Yun YJ, Kil SH. 2021. The Effects of Street Tree's Vertical Structures on Thermal Comfort. J Korean Environ Res Technol 24: 15-29.

Lee SH, Woo SY, Je SM. 2015. Effects of Elevated CO_2 and Water Stress on Physiological Responses of *Perilla frutescens* var. *japonica* HARA. Plant Growth Regul 75: 427-434.

Lichtenthaler HK. 1987. Chlorophyll Fluorescence Signatures of Leaves during the Autumnal Chlorophyll Breakdown. J Plant Physiol 131: 101-110.

Lim JH, Woo SY, Kwon MJ, Chun JH, Shin JH. 2006. Photosynthetic Capacity and Water Use Efficiency under Different Temperature Regimes on Healthy and Declining Korean Fir in Mt. Halla. J Korean For Soc 95: 705-710.

Liu J, Zhu JK. 1997. Proline Accumulation and Salt-Stress-Induced Gene Expression in a Salt-Hypersensitive Mutant of *Arabidopsis*. Plant Physiol 114: 591-596.

Manghwar H, Hussain A, Ali Q, Saleem MH, Abualreesh MH, Alatawi A, Ali S, Munis MFH. 2021. Disease Severity, Resistance Analysis, and Expression Profiling of Pathogenesis-elated Protein Genes after the Inoculation of *Fusarium equiseti* in Wheat. Agronomy 11: 2124.

Maxwell K, Johnson GN. 2000. Chlorophyll fluorescence--a practical guide. J Exp Bot 51: 659-668.

Ministry of Environment. 2021. Monthly Report of Air Quality, July, 2021. Ministry of Environment, Sejong.

Missanjo E, Ndalama E, Sikelo D, Kamanga-Thole G. 2015. Quarry Dust Emission Effects on Tree Species Diversity in Chongoni Forest Reserve and Vegetation Characteristics in Adjacent Villages, Dedza, Malawi. Int J Inf Res Rev 2: 511-515.

Na SS, Sung JW, Che SH, Kang SK. 2019. Satisfaction Analysis According to Planting Status of Roadside Trees in Gumi. J Korean Inst For Recreat 23: 53-62.

Noh NJ, Kwon B, Yang AR, Cho MS. 2020. Effect of Planting Density on Early Growth Performances of *Zelkova serrata* Trees. J Korean Soc For Sci 109: 281-290.

Oh S, Kim HC, Kang HS, Shin CH, Koh SC. 2020. Seasonal Change in the CO_2 Fixation Rate and Water-Use Efficiency of Broad-leaved Tree Species on Jeju Island. J Environ Sci Int 29: 123-132.

Park BJ, Lee CG, Jeong SS, Lim JE, Kim KR, Kim SC, Yang JE, Kim HS. 2021. Assessment of Heavy metal(loid)s Pollution in Urban Soil at Street Tree Planting Sites in Chuncheon. Korean J Soil Sci Fert 54: 78-86.

Park EJ, Kang KY. 2010. Estimation of C Storage and Annual CO_2 Uptake by Street Trees in Gyeonggi-do. Korean J Environ Ecol 24: 591-600.

Park YM. 2006. Comparison of Tissue Water Relation Parameters in Three Gardening Tree Species. J Ecol Environ 29: 581-584.

Peñuelas J, Filella I, Llusià J, Siscart D, Piñol J. 1998. Comparative Field Study of Spring and Summer Leaf Gas Exchange and Photobiology of the Mediterranean Trees *Quercus ilex* and *Phillyrea latifolia*. J Exp Bot 49: 229-238.

Petrova S, Velcheva I, Nikolov B, Vasileva T, Bivolarski V. 2022. Antioxidant Responses and Adaptation Mechanisms of *Tilia tomentosa* Moench, *Fraxinus excelsior* L. and *Pinus nigra* J. F. Arnold towards Urban Air Pollution. Forests 13: 1689.

Purcarea C, Laslo V, Memete AR, Agud E, Miere F, Vicas SI. 2022. Antigenotoxic and Antimutagenic Potentials of Proline in *Allium cepa* Exposed to the Toxicity of Cadmium. Agriculture 12: 1568.

Sonti NF, Hallett RA, Griffin KL, Trammell TLE, Sullivan JH. 2021. Chlorophyll Fluorescence Parameters, Leaf Traits and Foliar Chemistry of White Oak and Red Maple Trees in Urban Forest Patches. Tree Physiol 41: 269-279.

Strasser BJ, Strasser RJ. 1995. Measuring Fast Fluorescence Transients to Address Environmental Questions: The JIP-Test. In: Photosynthesis: From Light to Biosphere (Mathis P, ed). Kluwer Academic Publishers, Dordrecht, pp 977-980.

Sung H. 2003. A Study on the Present Status of Urban Roadside Trees by Major Road types: Focusing on 7 Cities in Kyonggi Province. J Korea Plan Assoc 38: 245-257.

Takahashi S, Murata N. 2008. How do Environmental Stresses Accelerate Photoinhibition? Trends Plant Sci 13: 178-182.

Tattar TA, Blanchard RO. 1976. Electrophysiological Research in Plant Pathology. Annu Rev Phytopathol 14: 309-325.

Wünsche JN, Greer DH, Laing WA, Palmer JW. 2005. Physiological and Biochemical Leaf and Tree Responses to Crop Load in Apple. Tree Physiol 25: 1253-1263.

Yoon TK. 2022. Urban Soil Carbon: Processes and Patterns. In: Soils in Urban Ecosystem (Rakshit A, Ghosh S, Vasenev V, Pathak H, Rajput VD, eds). Springer, Singapore, pp 65-100.

Yoon TK, Park CW, Lee SJ, Ko S, Kim KN, Son Y, Lee KH, Oh S, Lee WK, Son Y. 2013. Allometric Equations for Estimating the Aboveground Volume of Five Common Urban Street Tree Species in Daegu, Korea. Urban For Urban Green 12: 344-349.