Leaf Color Changes and Photosynthetic Characteristics of Five Superior Late-deciduous *Ginkgo biloba* Cultivars

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Abstract. *Ginkgo biloba*, a relict plant, has been popularized and planted in most areas of China for its leaves, timber, and fruits. In the present study, the dynamic changes in leaf color, leaf pigment content during the color change period, and photosynthetic characteristics in different growth periods were studied to explore the coloring mechanism and adaptability of five late-deciduous superior Beijing *G. biloba* cultivars (LD1–LD5). The results showed that the leaf color change of each superior cultivar was relatively stable, and the discoloration period of LD3 and LD5 was later than that of others. From September to November, the chlorophyll *a*, chlorophyll *b*, and total chlorophyll content in all superior cultivars showed a downward trend, except in LD3, in which the pigment content was slightly higher in October than in September. Except in LD3 and LD4, the ratio of carotene content to total chlorophyll content in other cultivars slightly decreased in October. In May, the photosynthetic capacity of LD5 was stronger than that of other cultivars. The photosynthetic capacity of LD3 was strong in July and October. Our results imply that LD3 and LD5 are suitable for mixed planting with common *G. biloba* to increase the overall leaf color viewing period. *Ginkgo biloba* leaves turn yellow in autumn because of both a decrease in the chlorophyll content after leaf senescence and an increase in the Car content during leaf senescence. Although LD5 presented rapid seedling emergence, LD3 grew faster during the vigorous and late growth stages and is thus suitable for agricultural production.

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Ginkgo biloba is a deciduous tree belonging to the family Ginkgoaceae. It is a well-known relict plant that originates from China and is considered a “living fossil” (Zhou and Zheng, 2003). It is an endangered species endemic to China, where it is listed as a national first-level key protected wild plant. Its root system is well developed, the main stem is straight, branches and leaves are lush, and leaf shape is unique and delicate. Moreover, the leaves turn golden in autumn, and hence, it is an important ornamental species in autumn (Chassagne et al., 2019; Guo et al., 2016). In addition to its high ornamental value, *G. biloba* has important practical values in various fields, such as medicine (Zhou et al., 2017), cosmetics (Zhang et al., 2016), and wood processing (Andersson et al., 2015). Moreover, the leaves of *G. biloba* tolerate contamination better than those of other forest tree species, and thus it is used in environmental protection (Shen and Ding, 1999).

The leaf color of plants is mainly related to the type, content, and distribution of pigments in the leaves (Chu et al., 2013; Hong et al., 2010). In most plants, the chlorophyll content is considerably higher than the carotenoid and anthocyanin content, and therefore, the leaves are generally green (Pan and Dong, 2001). In most red- or purple-leaf plants, the anthocyanin content and anthocyanin/chlorophyll content ratio are the most important factors determining leaf color (Feng et al., 2017; Gould, 2004; Hong et al., 2010). Conversely, the decrease in the chlorophyll content and chlorophyll/carotenoid content ratio, regardless of leaf anthocyanin content, determines the color of golden-leaf plants (Hu et al., 2007; Li et al., 2004).

Photosynthesis is considered the most important chemical reaction on Earth (Franck and de Zaccaro, 2012) and is the basis for material production in plants. This process is not only affected by environmental factors such as temperature, light, and water, but also related to plant genetic characteristics (Turnbull et al., 2002). Photosynthetic indexes and pigments can reflect the photosynthetic capacity of plants and are important as references for research on plant growth and development and the breeding of improved varieties. The ability of plants to adapt to the environment is considered to be directly or indirectly related to their photosynthetic capacity (Xia et al., 2011). Species with a stronger adaptability to environmental changes tend to have higher genetically determined photosynthetic adaptation potential, which can change plant photosynthetic characteristics according to the changes in the environmental factors (Major and Dunton, 2000). In recent years, the dynamic changes in the photosynthetic capacity of plants in different seasons or different growth periods have become a hot topic in ecological research.

Different types of scions have different transport efficiencies of water and mineral nutrients after grafting, resulting in differences in the content of chlorophyll and nutrients in the scion leaves, thereby affected the photosynthesis ability of plants (Atkinson et al., 2000; Wu et al., 2020). Furthermore, different rootstocks have different effects on the chlorophyll content, photosynthesis, and growth potential of grafted seedlings (Zheng et al., 2010). They also substantially reduce nonphotochemical quenching and promote light energy absorption and utilization by grafted seedlings (Li et al., 2017; Sang et al., 2017). Several studies have shown that there is mutual exchange of genetic material between scion and rootstock (Stegemann et al., 2012). Therefore, different types of scions will affect the photosynthetic characteristics of grafted seedlings differently, owing to their own genetic characteristics and interaction with rootstocks (Wu et al., 2020).

Previous research on *G. biloba* has mainly focused on cultivation and reproduction (Cao et al., 2014; Yan et al., 2019), *G. biloba* extracts (Chen, 1996), and medicinal value (Ahlemeyer and Krieglstein, 2003; Liu and Yu, 1994). Studies on the photosynthetic characteristics of *G. biloba* have mainly

focused on a certain period in the growing season or the response of photosynthesis characteristics to specific environmental changes such as light, temperature, and moisture analyzed under short-term artificially controlled environmental conditions (Qian et al., 2018; Wei et al., 2012; Yang, 2013; Zhao et al., 2020). To the best of our knowledge, continuous observation of the dynamic changes in leaf photosynthesis in *G. biloba* throughout the growth period has not been reported.

For the present study, five late-deciduous superior *G. biloba* cultivars were selected by our research team over the past 20 years, based on a follow-up investigation of seedlings from major streets in Beijing. Its defoliation period is $\approx 10\text{--}20$ d later than that of common *G. biloba*, and thus the ornamental leaf color period of this *G. biloba* population can be prolonged via certain planting strategies, giving it important landscape application value. Therefore, in this study, 1-year-old grafted seedlings of the five late-deciduous superior *G. biloba* cultivars were used to study the dynamic changes in leaf color and the changes in pigment content and ratios in the leaves during the leaf color changing period. We also explored the reasons for leaf color change and late defoliation. Moreover, the photosynthetic characteristics of these *G. biloba* cultivars in different growth stages were studied to determine whether they are better than common *G. biloba* in terms of growth ability and adaptability. Our findings will provide guidance and suggestions for breeding new varieties of ornamental *G. biloba* and lay a theoretical foundation for the cultivation and production of ornamental *G. biloba*.

Materials and methods

Study materials

The experimental material was 1-year-old grafted seedlings of late-deciduous *G. biloba* from Beijing; the grafted rootstocks were from the same 4-year-old *G. biloba* seedlings from the Baima Base of the Nanjing Forestry University. The scions were of five late-deciduous superior *G. biloba* cultivars selected by our research team over the past 20 years, based on a follow-up investigation of seedlings from major streets in Beijing: LD1, LD2, LD3, LD4, and LD5 (Table 1). Each late deciduous cultivar was grafted with 75 plants, and the planting density was 1×1 m. One unit was set for every 25 plants, and three units were set for each cultivar. Three standard plants were set in each unit and were labeled. After grafting, unified cultivation management was carried out. Common *G. biloba* plants, which have been growing in the campus of Nanjing Forestry University under good growing conditions for 4 years, were used as a control.

Overview of the study site

The experimental site was the Baima Experimental Base in Nanjing Forestry University, located in Lishui County, south of Nanjing City ($119^{\circ}18'$ E, $36^{\circ}61'$ N). The site is characterized by a subtropical monsoon climate with

Table 1. Characteristics of the five superior *Gingko biloba* cultivars.

Superior cultivars	Location of mother plant		Ht of mother tree (m)	Mother tree diam at breast ht (cm)
LD1	116°42310'E	39°90409'N	10.8	25.9
LD2	116°42322'E	39°90521'N	12.8	28.0
LD3	116°42282'E	39°90495'N	14.0	27.4
LD4	116°42042'E	39°90514'N	10.0	21.8
LD5	116°31918'E	39°94345'N	11.7	35.6

abundant rain and sufficient sunshine. The annual average temperature is 15.5°C , annual average sunshine duration is 2146 h, and annual average precipitation is 1037 mm. The four seasons are distinct; the rainy season is long and the annual average frost-free period is 230 d.

Methods

Determination of Chl content and observation of the dynamic changes in leaf color. From September to Nov. 2016, three healthy and mature leaves at the same level on each standard plant of each cultivar and unit were sampled at the same time in each month. The leaf samples were then cleaned and cut into pieces after removing the main vein. Subsequently, the leaf Chl content in each cultivar was determined using the acetone-ethanol mixture method (Zhang, 1986). The optical density (OD) of Chl at 663 nm (absorption peak of Chl *a*), 645 nm (absorption peak of Chl *b*), and 470 nm was determined by ultraviolet-visible spectrophotometry (Lambda25; PerkinElmer, Waltham, MA). Each treatment was repeated thrice, and the content of Chl and carotenoids ($\text{mg}\cdot\text{g}^{-1}$) was calculated according to the method described by Wang (2006). Furthermore, during the sprouting period of *G. biloba*, the Royal Colorimetric Card was used for leaf color comparison every 10 d. A SONYDSC-HXI digital camera (Tokyo, Japan) was used to capture colorimetric pictures at a close range (60 cm) and Adobe Photoshop CS4 11.0 (Adobe Systems Inc., San Jose, CA, USA) was used to draw the dynamic leaf color change map block.

Drawing the light response curve of photosynthetic parameters. In late May, late July, and late Oct. 2016, from 0800 to 1130 HR, net photosynthetic rate (P_n), transpiration rate

(T_r), stomatal conductance (g_s), and intercellular CO_2 concentration (C_i) of each cultivar were measured using a British PP-Systems Portable Photosynthesis Analyzer (Ciras-2, Shanghai, China). Three uniform mature leaves from the middle and upper branches facing the sun on each standard plant of different cultivars and units were selected for testing. Each leaf was tested thrice. The photosynthetically active radiation (PAR) value was set at $1000 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, and the light response curve was generated by controlling the PAR intensity with an light emitting diode (LED) light source. The gradient of PAR was set as 0, 50, 100, 200, 400, 600, 800, 1000, 1200, 1400, 1600, and $1800 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$. During the measurements, the relative humidity was controlled at 60% to 70%, the temperature of the leaf chamber was set to 25°C , and the adaptation time of each PAR gradient was at least 3 min. Three replicates were set for each group, and the average values were used for data analysis.

Analysis of characteristic parameters of net photosynthetic rate light response curve. A non-right-angle hyperbolic model (Marshall and Biscoe, 1980; Ye and Li, 2010) was used to fit the light response curve of the studied cultivars. The model expression was as follows:

Non-right-angle hyperbolic model:

$$P_n(I) = \left\{ \alpha I + P_{n\max} - \sqrt{(\alpha I + P_{n\max})^2 - 4k\alpha I P_{n\max}} \right\} / (2k) - R_d \quad [1]$$

where P_n is the initial value of the net photosynthetic rate, α is the initial optical quantum efficiency, I is the light quantum flux density, $P_{n\max}$ is the maximum net photosynthetic rate when light is saturated, R_d is the dark

Fig. 1. Dynamic changes in leaf color among the five late-deciduous superior *Gingko biloba* cultivars from Beijing (LD1–LD5).

respiration rate, and k is the curvature degree of the non-right-angle hyperbola ($0 < k \leq 1$). The initial values were set to $\alpha = 0.05$, $R_d = 1.0$, and $k = 0.5$.

In the process of model fitting, the initial value of P_m max was set to 8, and the apparent quantum yield was obtained by linear fitting when the PAR was $\leq 200 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, and the light compensation point and dark respiration rate were values of the linear functions $Y = 0$ and $X = 0$ when PAR was $\leq 200 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ (Lang et al., 2013; Ye, 2010).

Data processing. Excel 2010 software was used to analyze and process the data and draw charts. SPSS 19.0 software (IBM Corp, Armonk, NY) was used for variance analysis

and Duncan's multiple comparison test at the 5% probability level.

Results

Dynamic changes in leaf color

The dynamic changes in leaf color in the five late-deciduous, superior *G. biloba* cultivars are shown in Fig. 1. Because the leaf color in August was similar to that in July, only the leaf color in July is shown in the figure. The overall trend in leaf color change in the five superior cultivars was as follows: the young leaves first turned green-yellow or green, after which they gradually turned grass green and dark green, then light green, and finally dark

yellow or golden yellow in November. The rate of color change in each superior cultivar was relatively stable. LD3 and LD5 presented a later discoloration period than the other three superior cultivars.

Changes in the leaf photosynthetic pigment content

The changes in Chl *a* (Fig. 2A), Chl *b* (Fig. 2B), and total Chl (Fig. 2C) content in these cultivars were similar from September to November (Fig. 2), except in LD3, in which the content of Chl *a*, Chl *b*, and total Chl in October was slightly higher than that in September and November, whereas the other superior cultivars and control (CK) showed a

Fig. 2. Dynamic changes in the Chl *a* content (A), Chl *b* content (B), Chl content (C), carotene content (D), Chl *a*/Chl *b* content ratio (E), and Car/Chl content ratio (F) of five late-deciduous superior *Ginkgo biloba* cultivars from Beijing (LD1–LD5) and a control (CK) from September to November. Different letters indicate significant differences among the cultivars at $P < 0.05$.

monthly decrease in the Chl *a*, Chl *b*, and total Chl content. Among these cultivars, the Chl *a*, Chl *b*, and total Chl content decreased the most in LD2, with an overall decline of 75.27%, 57.71%, and 70.30%, respectively. The lowest decline in the Chl *a*, Chl *b*, and total Chl content was in LD3 × 18.97%, 10.11%, and 10.42%, respectively. The Chl *a*, Chl *b*, and total Chl content in LD3 was the highest in November, whereas that in LD2 was the lowest in November. The Chl *a*, Chl *b*, and total Chl content in LD5 rapidly decreased in October, and the decrease from October to November was the lowest in this cultivar.

The carotene content in each superior cultivar and CK decreased from September to November, which was consistent with the change in the Chl content (Fig. 2D). Among the cultivars, the highest decline was observed in LD2, at 52.56%, and the lowest was in LD3, which was only 9.56%. Except for the Chl *a*-to-Chl *b* ratio of LD3 and LD4, which increased slightly in October, the Chl *a*-to-Chl *b* ratio of other superior cultivars and CK decreased with time (Fig. 2E). Among the cultivars, the Chl *a*-to-Chl *b* ratio of LD3 and LD5 slightly changed between October and November, when the decline in LD3 was 9.88%, and that of LD5 was 16.72%. The carotene/total Chl content ratio of LD3 and LD4 slightly decreased in October, whereas this ratio of the other superior cultivars and CK increased monthly (Fig. 2F). In all cultivars

and the CK, the carotene-to-total Chl content ratio was the highest in November. Among them, the highest ratio was recorded for LD2 (0.836) and the lowest was for LD5 (0.547), followed by LD3 (0.582).

Analysis of basic photosynthetic characteristics

Changes in the net photosynthetic rate (P_n). The P_n of all cultivars initially increased and then decreased, and in all cultivars, the maximum P_n was observed in July (Fig. 3A). The P_n of LD5 and CK in October was significantly lower than that in May, whereas the changes in P_n in other superior cultivars were similar in May and October. In May, the P_n of each superior cultivar was lower than that of CK. In July, the P_n of all cultivars, except LD3, was lower than that of CK; whereas in October, the P_n of all superior cultivars was higher than that of CK. The P_n of LD3 was lower than that of LD5 in May, but in July and October, it was higher than that of all other superior cultivars.

Changes in the intercellular CO_2 concentration (C_i). The C_i initially increased and then decreased, with the highest C_i in July (Fig. 3B). The C_i in LD5 in May and that in LD1 and LD2 in July were slightly higher than C_i in CK in the respective months, and the C_i in the remaining cultivars was lower than that in CK. In October, the C_i in all superior cultivars decreased compared with

that in July; the C_i in LD1, LD2, and LD5 decreased to a similar level as that in CK, but they were all higher than their C_i values in May. In October, the C_i in LD3 and LD4 was lower than that in CK, and the C_i in LD4 in October was lower than that in May.

Changes in the transpiration rate (T_r). Two trends in T_r were observed (Fig. 3C). First, the T_r of LD2, LD4, and CK decreased over time; the maximum T_r was observed in May and the minimum T_r was observed in October. Second, the T_r of LD1, LD3, and LD5 initially increased and then decreased over time; the maximum T_r was observed in July, and the minimum T_r was observed in October, except in LD5, in which the minimum T_r was observed in May.

Changes in g_s . The g_s of the superior *G. biloba* cultivars initially increased and then decreased (Fig. 3D). In most cultivars, the g_s was the highest in July, whereas the g_s of LD3 and LD5 was only slightly lower in July than in May. In October, the g_s of all superior cultivars decreased compared with that in July, and LD4 had the lowest g_s value of only 18 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$.

Comparison of the differences in photosynthetic capacity

After assessing the model fit of the measured values, we found that the non-right angle hyperbolic model best fit the photosynthetic response of the superior *G. biloba* cultivars,

Fig. 3. Net photosynthetic rate (P_n) (A) intercellular CO_2 concentration (C_i) (B), transpiration rate (T_r) (C), and stomatal conductance (G_s) (D) variation in five late-deciduous superior *Ginkgo biloba* cultivars from Beijing (LD1–LD5) and a control (CK) in May, July, and October.

Table 2. Light response curve characteristic parameter values in five late-deciduous, superior *Gingko biloba* cultivars from Beijing (LD1–LD5) and a control (CK) in May, July, and October. P_n max, maximum net photosynthetic rate; AQY, apparent quantum yield; LCP, light compensation point; R_d , dark respiration rate; CD, coefficient of determination. The data are shown as mean $\pm$ sd ($n = 3$). Different letters indicate significant differences among the cultivars at $P < 0.05$.

Month	Superior cultivars	P_n max	AQY	LCP	R_d	CD
May	LD1	5.951 $\pm$ 0.252 a	>0.01 $\pm$ 0.001 b	>56.061 $\pm$ 2.432 a	>0.609 $\pm$ 0.030 b	>0.993
	LD2	>3.845 $\pm$ 0.461 a	>0.005 $\pm$ 0.002 a	>96.612 $\pm$ 15.549 b	>0.421 $\pm$ 0.106 ab	>0.994
	LD3	>5.63 $\pm$ 0.186 a	>0.005 $\pm$ 0.002 a	>99.288 $\pm$ 16.492 b	>0.453 $\pm$ 0.082 ab	>0.993
	LD4	>4.984 $\pm$ 0.306 a	>0.006 $\pm$ 0.002 ab	>77.787 $\pm$ 15.351 ab	>0.448 $\pm$ 0.052 ab	>0.993
	LD5	>9.706 $\pm$ 2.725 b	>0.011 $\pm$ 0.002 b	>50.136 $\pm$ 1.504 a	>0.499 $\pm$ 0.064 ab	>0.994
	CK	>6.367 $\pm$ 1.042 a	>0.006 $\pm$ 0.001 ab	>60.932 $\pm$ 9.479 ab	>0.359 $\pm$ 0.051 a	>0.996
July	LD1	>10.933 $\pm$ 0.574 a	>0.008 $\pm$ 0.0003 ab	>35.482 $\pm$ 3.142 ab	>0.269 $\pm$ 0.0336 a	>0.996
	LD2	>12.327 $\pm$ 2.673 a	>0.006 $\pm$ 0.0003 a	>33.673 $\pm$ 6.908 ab	>0.215 $\pm$ 0.044 a	>0.997
	LD3	>13.766 $\pm$ 1.234 a	>0.01 $\pm$ 0.0009 c	>19.108 $\pm$ 3.417 a	>0.186 $\pm$ 0.015 a	>0.999
	LD4	>12.913 $\pm$ 1.079 a	>0.01 $\pm$ 0.0005 c	>34.354 $\pm$ 7.516 ab	>0.326 $\pm$ 0.061 a	>0.997
	LD5	>10.996 $\pm$ 1.456 a	>0.01 $\pm$ 0.001 c	>46.09 $\pm$ 3.315 b	>0.462 $\pm$ 0.0196 b	>0.998
	CK	>12.006 $\pm$ 2.460 a	>0.007 $\pm$ 0.0005 a	>36.283 $\pm$ 7.628 ab	>0.255 $\pm$ 0.063 a	>0.996
October	LD1	>4.504 $\pm$ 0.417 a	>0.007 $\pm$ 0.002 ab	>66.966 $\pm$ 21.761 ab	>0.405 $\pm$ 0.048 ab	>0.996
	LD2	>3.377 $\pm$ 0.587 a	>0.004 $\pm$ 0.001 a	>109.073 $\pm$ 31.511 b	>0.319 $\pm$ 0.025 a	>0.993
	LD3	>4.565 $\pm$ 0.637 a	>0.009 $\pm$ 0.001 b	>39.843 $\pm$ 6.188 a	>0.339 $\pm$ 0.026 a	>0.993
	LD4	>3.885 $\pm$ 0.493 a	>0.009 $\pm$ 0.001 b	>63.777 $\pm$ 8.135 ab	>0.555 $\pm$ 0.03 b	>0.995
	LD5	>3.813 $\pm$ 0.340 a	>0.005 $\pm$ 0.001 ab	>97.185 $\pm$ 24.889 ab	>0.452 $\pm$ 0.044 ab	>0.993
	CK	>3.947 $\pm$ 0.709 a	>0.008 $\pm$ 0.001 ab	>55.807 $\pm$ 3.889 ab	>0.435 $\pm$ 0.115 ab	>0.994

with a coefficient of determination (CD) of $R^2 > 0.99$. Therefore, in the present study, the non-right-angle hyperbolic model was used to calculate the photosynthetic parameters.

There were significant differences in the characteristic parameters of the light response curve among the five *G. biloba* cultivars ($P < 0.05$) (Table 2). In May, the maximum net photosynthetic rate (P_n max) of LD5 was the highest, and it was significantly higher than that of CK and other superior cultivars. The apparent quantum yield (AQY) of LD5 was the highest and was significantly higher than that of LD2 and LD3. The light compensation point (LCP) of LD3 was the highest and that of LD5 was the lowest. The dark respiration rate (R_d) of LD1 was the highest and that of CK was the lowest. The R_d of LD1 was not significantly different from that of the other cultivars, except that of CK. In July and October, there was no significant difference in the P_n max between CK and the superior cultivars. Among them, the P_n max of LD3 was the highest; the LCP and R_d of LD3 were the lowest. In July, the AQY of LD5, LD4, and LD3 was the highest, which was significantly higher than that of CK and other superior cultivars. In October, the AQY of LD4 and LD3 was the highest.

Discussion

Color rendering is a complex process in colored-leaf plants, and it is related to the type, content, proportion, and distribution of pigment in the leaves (Sun et al., 2019). Chlorophyll and carotenoids are two important types of photosynthetic pigments in plant leaves, and they are found in the thylakoid membrane of the chloroplasts in the form of pigment protein complexes (Bartley and Scolnik, 1995). When the leaves enter the senescence period, chloroplasts gradually disintegrate, resulting in a decrease in the Chl content. Carotenoids play an important role in photoprotection (Cardinif and Bonzi, 2005; Giuliano et al., 2000);

therefore, the changes in the Chl and carotenoid content are not completely synchronized. In addition, the Chl content is related to the degree of plant leaf senescence; the older the leaves, the lower the Chl content (Chen et al., 1991). In the current study, the Chl content in *G. biloba* leaves continued to decrease from September to November, especially in October, which showed that the accelerated senescence of *G. biloba* leaves occurred in October, that is, ≈ 1 month before the leaves dropped. At this time, the rapid decline in the Chl content may have been caused by the disintegration of a large number of chloroplasts (Wei et al., 2008). During this period, the carotene/Chl content ratio did not decrease but increased, indicating that there was an increase in carotenoid production during the leaf senescence period in *G. biloba*. The increased production of carotenoids is conducive to their photoprotective activity, which occurs via quenching the reactive oxygen species produced during senescent leaf cell metabolism, thus retarding the process of leaf senescence (Niyogi, 2003). Previous studies have mostly concluded that the leaves turn yellow in autumn because the Chl content in the leaves decreases, which makes carotenoids visible and the leaves appear yellow (Hörtensteiner, 2006). However, there have been a few studies on whether the content of carotenoids changes in the leaves during autumn. We demonstrated that *G. biloba* leaves turn yellow in autumn because of both a decrease in the Chl content after leaf senescence and an increase in the carotenoid content in the leaves during leaf senescence. The Chl content in LD3 did not decrease but increased in October, and its Chl content in November was higher than that in other cultivars in October and November, which partially explains why the leaves of this cultivar remained green for longer and dropped later than the leaves of other cultivars.

Photosynthetic capacity is an important index for estimating whether plants are adapted to a certain habitat (Cai et al., 2013). The

indicators reflecting the strength of photosynthesis include apparent quantum yield, maximum net photosynthetic rate, light saturation point, light compensation point, and other light response curve parameters. Among them, P_n max reflects the photosynthetic potential of plants—

the greater the P_n max value, the higher the photosynthetic potential of plant leaves, and the more the photosynthetic products synthesized under effective light (Liu et al., 2020; Zhang et al., 2019). AQR and LCP reflect the ability of plants to use weak light (Richardson and Berlyn, 2002). The higher the AQY and the lower the LCP, the stronger the plant's ability to use weak light. Here, according to the parameters of the light response curves of the five late-deciduous superior *G. biloba* cultivars, the LCP of LD5 in May was the lowest among the five cultivars, which indicated that this cultivar had the strongest ability to use weak light and had the highest P_n max, highest AQY, and lowest R_d compared with the other cultivars. Therefore, LD5 has a strong photosynthetic capacity and photochemical conversion efficiency in the early stages of plant growth. Moreover, it has a lower respiratory consumption rate than the other cultivars. Thus, under the same environmental conditions, LD5 may synthesize more photosynthetic products than common or other late-deciduous *G. biloba* cultivars. Moreover, LD5 grew faster, and therefore, it can be cultivated as a fast-emerging plant. In July and October, after the vigorous growth stage and in the plant maturity stage, the LCP of LD3 was the highest, and LD3 had a higher P_n max and a higher AQY but a lower R_d than the other cultivars, indicating that its photosynthetic capacity was the strongest. Under the same environmental conditions, the synthesis of photosynthetic products during the growth period of LD3 was greater than that of common *G. biloba* and other late-deciduous superior cultivars. LD5 grew faster and presented excellent characteristics, and hence, it is suitable as

an ornamental plant. In July and October, LD5 had lower LCP, lower P_n max, lower AQY, and higher R_d than other cultivars, which indicated that the strong photosynthetic capacity of LD5 decreased after May and was weaker in July and October.

Photosynthesis is the basis for plant material production and is not only affected by environmental factors but is also closely related to the growth, development, and physiological and ecological characteristics of plants (Turnbull et al., 2002). With continuous changes in environmental temperature and humidity during the growth and development of plants due to the change in seasons, the photosynthetic characteristics of plants will inevitably change with the changing seasons and growth periods (Cheng et al., 2018; Li et al., 2019; Wang et al., 2017). In the present study, the photosynthetic capacity of the late-deciduous superior cultivars changed with the season, indicating that environmental factors influenced their photosynthetic capacity. Furthermore, the photosynthetic capacity differed among different superior cultivars, which indicated that the photosynthetic capacity may also be related to the inherent genotypes of the studied plants. Therefore, for future promotion and application of *G. biloba*, reasonable planting should be carried out according to the physiological photosynthetic characteristics of different superior cultivars and different production needs.

The scions of the grafted seedlings used in this study were of five late-deciduous superior *G. biloba* cultivars planted in Beijing for many years. However, the latitude of Nanjing is lower than that of Beijing, with hot summer and high humidity. Thus, there is a considerable difference in climate between Nanjing and Beijing. This study showed that the T_r of LD2, LD4, and CK decreased with month (May, July and October), whereas the T_r of LD1, LD3, and LD5 initially increased and then decreased with time. This could be because LD2, LD4, and CK showed photoinhibition at high temperatures in Nanjing during July, which resulted in stomatal closure and T_r decrease. However, the higher T_r of LD1, LD3, and LD5 in July can be attributed to the plant damage caused by the self-defense mechanisms induced by high light intensity and high temperature. This study also showed that, in October, the P_n values of all cultivars except LD5 and CK were almost similar with that in May, which can be attributed to the relatively similar climatic factors such as temperature and light intensity in Nanjing in May and October. In July, the P_n of all cultivars, except LD3, was lower than that of CK, which may be because the other superior cultivars failed to adapt to the climate of Nanjing after grafting there. Therefore, climatic conditions are also important factors affecting plant photosynthetic characteristics. In the future, the changes in leaf color and photosynthetic characteristics of the five late-deciduous superior *G. biloba* cultivars in different regions should be further studied.

Although the rootstocks of the superior cultivars of *G. biloba* in the present study were the same, the factors affecting the photosynthetic characteristics of the grafted seedlings

included scion characteristics, interaction effects between rootstock and scion, and environmental factors. In this study, we failed to verify factors that played the main role. Therefore, in future research, the experimental design should include the scion genetic characteristics, interactions of related genetic materials between rootstock and scion, and environmental factors to explore the specific factors affecting the photosynthetic characteristics of late-deciduous *G. biloba* grafted seedlings.

Conclusions

This study showed that the leaf color change in five late-deciduous superior *G. biloba* cultivars was relatively stable and the discoloration period of LD3 and LD5 was later than that of the other cultivars. The leaves of *G. biloba* turn yellow in autumn because of both a decrease in the Chl content after leaf senescence and an increase in the Car content during leaf senescence. The photosynthetic capacity of the five superior cultivars with different types of scions differed. Furthermore, changes in environmental factors such as temperature, light, and humidity caused by seasonal changes also affect the photosynthetic capacity of the cultivars. Among the cultivars, the photosynthetic capacity of LD5 was stronger in May, whereas that of LD3 was stronger in July and October. Therefore, although LD5 showed rapid seedling emergence, LD3 grew faster during the vigorous and late growth stages and is thus suitable for agricultural production. This study can aid in understanding the leaf color changes in the five late-deciduous superior *G. biloba* cultivars studied and further explore the causes of late defoliation in these cultivars. Additionally, it provides useful information for agricultural production and garden ornamental application of these cultivars.

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