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Effects of light radiation intensity on photosynthetic characteristics and water use efficiency of *Platycladus orientalis* and *Pinus tabulaeformis* seedlings

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Abstract In order to offer a scientific basis for cultivation and management of forests, effects of light radiation intensity on photosynthetic characteristics and water use efficiency of *Platycladus orientalis* and *Pinus tabulaeformis* were studied under different soil moisture contents. By adopting artificial control methods to soil moisture, and under simulated photosynthetic radiation (*SPR*), the net photosynthetic rate (P_N), transpiration rate (T_r), water use efficiency (*WUE*) and intercellular CO_2 concentration (C_i) of *Platycladus orientalis* and *Pinus tabulaeformis* in the semi-arid region of the Loess Plateau, were studied. Results are as follows: within the photon range of 0–2,200 $\mu\text{mol}/(\text{m}^2 \cdot \text{s})$, P_N , T_r and *WUE* were enhanced with an increase in *SPR* in both species. P_N and *WUE* of *Platycladus orientalis* and *Pinus tabulaeformis*, however, declined with continued increase in *SPR*. P_N , T_r , *WUE* and light saturation point (*LSP*) of *Platycladus orientalis* were higher than those of *Pinus tabulaeformis*, while light compensation point (*LCP*) of *Platycladus orientalis* was lower than that of *Pinus tabulaeformis* at the same soil moisture content. The efficiency of light energy utilization of *Platycladus orientalis* was higher than that of *Pinus tabulaeformis*; P_N , T_r and C_i of *Platycladus orientalis* and *Pinus tabulaeformis* were enhanced by increasing soil moisture content, whereas *WUE* declined. At soil moistures

of 7.90%, 13.00% and 19.99%, *LSP* of *Platycladus orientalis* was 1,275, 1,450 and 1,675 $\mu\text{mol}/(\text{m}^2 \cdot \text{s})$ respectively, and *LCP* was 42, 25 and 13 $\mu\text{mol}/(\text{m}^2 \cdot \text{s})$ respectively, with corresponding maximal net CO_2 photosynthetic rates (P_{max}) of 3.04, 4.06 and 5.53 $\mu\text{mol}/(\text{m}^2 \cdot \text{s})$. At soil moistures of 7.83%, 13.04% and 20.15%, the *LSP* of *Pinus tabulaeformis* was 1,100, 1,325 and 1,500 $\mu\text{mol}/(\text{m}^2 \cdot \text{s})$ respectively, and *LCP* was 60, 30 and 23 $\mu\text{mol}/(\text{m}^2 \cdot \text{s})$, with P_{max} of 1.08, 3.35 and 4.36 $\mu\text{mol}/(\text{m}^2 \cdot \text{s})$ respectively.

Keywords *Platycladus orientalis*, *Pinus tabulaeformis*, seedlings, simulated photosynthetic radiation, soil moisture content, photosynthetic characteristics, water use efficiency

1 Introduction

Photosynthesis is a very complicated physiological process, restricted by both the physiological status of trees and their responses to changes in the external environment (Xiao et al., 2002). Many studies have reported on the relationships among photosynthetic characteristics, water use efficiency and the environment in the light of gas exchange characteristics of plants (Kumar et al., 1999; Yordanov et al., 2000; Bunce et al., 2001; Colom et al., 2001; Johnson et al., 2002; Xiao et al., 2002; Li et al., 2003; Xu et al., 2003; Tian et al., 2004; Yu et al., 2004; Zhang et al., 2004). However, only a small quantity of studies have focused on the response of light radiation intensity to photosynthetic characteristics and water use efficiency (Jiang et al., 1999; Su et al., 2003a, 2003b; Sun et al., 2003; Zackary et al., 2003). In this paper, we studied the photosynthetic characteristics of transpiration and water use efficiency of *Platycladus orientalis* and *Pinus tabulaeformis* in response to increasing light radiation intensity, by pot experiment under different soil moisture contents. Comparing *Platycladus orientalis* and *Pinus tabulaeformis* could theoretically improve the survival ratio of anti-drought afforestation in the semi-arid region of the Loess Plateau.

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2 Study area

Study area was the experimental station on runoff forestry of the Beijing Forestry University, located in the semi-arid region of Loess Plateau (37°36'58"N, 110°02'55"E), Yukou town, Fangshan County, Shanxi province, China. This area is a typically hilly and gully loess region with an altitude of 1,200 m, and is dominated by a warm temperate continental monsoon with the typical characteristics of severe spring drought in North China. The annual mean temperature is 7.3°C, and the accumulative temperature above 10°C is up to 2,223.5°C; dryness coefficient is 1.3; annual precipitation is 416 mm; the amount of precipitation from June to September is over 70%; annual free water surface evaporation is 1,857.7 mm, and evaporation maximally occurs from April to June. At this time, soil texture is an even loess soil, and average soil bulk density is 1.20 g/cm³.

3 Materials and methods

3.1 Materials

Two cultivars of *Platycladus orientalis* and *Pinus tabulaeformis* were selected for the study. Three-year-old seedlings were selected on March 25, 2004 from Fangshan Garden. They were 79 cm and 62 cm high, respectively, with corresponding diameters at breast height being 3.55 cm and 5.12 cm. They were put into pots (35 cm diameter and 50 cm height, respectively) containing loess soil. According to the actual soil water content, the optimum soil water content and maximum field moisture capacity (He et al., 2003), three soil water content levels of 8% ± 1% (A), 13% ± 1% (B) and 20% ± 1% (C) were designed with three replications. The plots were placed outdoors in the sun, under canopy shelter to protect from rain. The soil water content was controlled by weighing, and transpiration was regulated by adding water and covering with a plastic membrane. In order to stabilize soil water infiltration, net photosynthetic rate (P_N), transpiration rate (T_r), intercellular CO₂ concentration (C_i), etc. were recorded after 24–36 h.

3.2 Methods

Net photosynthetic rate (P_N), transpiration rate (T_r), and intercellular CO₂ concentration (C_i), etc. of *Platycladus orientalis* and *Pinus tabulaeformis* were measured from 9:00 to 11:00 on July 19 in 2004 with the Li-6400 portable photosynthetic system (US). Simulated light radiation intensity was set using the artificial red-blue light of the Li-6400, with values of 0, 50, 100, 200, 400, 600, 800, 1,000, 1,200, 1,500, 1,800, 2,000, 2,200 μmol/(m²·s). Four healthy leaves in the middle-upper part of each seedling were then chosen as experimental samples, and three sets of data from each leaf were measured continuously using the Li-6400. These data were then analyzed statistically by SPSS. Air temperature was between

29.5 and 32.9°C and relative air humidity was between 40.6% and 44.8% during the course of the measurements.

The leaf area of *Platycladus orientalis* was measured by the Li-3000 analytic apparatus. The leaf of *Pinus tabulaeformis* was calculated with the widely used formula for drainage, as follows:

$$A = 2L \left(\frac{\pi}{n} \right) \sqrt{V_n / L\pi}$$

where A is the whole leaf area of the pine needle bundle in cm²; n is the number of each pine needle bundle; V_n is the total cubage of the pine needle in cm³; and L is the total length of the pine needle in cm.

Soil moisture content was measured by the oven dry method. Instantaneous water use efficiency was obtained as the ratio of the net photosynthetic rate to the transpiration rate.

4 Results and analysis

4.1 Photosynthetic rate and transpiration rate

The light response curve of plant photosynthesis is the curve of the response of plant photosynthesis to light radiation intensity. The curve is used to determine the ability of a plant to photosynthesize, and LSP , LCP and a maximum P_N of a plant can be calculated based on this curve. The light response curve of plant photosynthesis is thus very important in the field of plant physiological ecology. As seen in Figs. 1 and 2, under different soil moisture contents, in both *Platycladus orientalis* and *Pinus tabulaeformis*, net P_N and T_r were enhanced to different degrees with increasing SPR ; P_N was less enhanced, and an increase in unit quantity of SPR contributed less to an increase in P_N . There was a markedly descending trend in P_N with a continuous increase in SPR . T_r was observed to increase at corresponding increments with an increase in SPR under (13 ± 1)% and (20 ± 1)% soil moisture contents. However, T_r of *Pinus tabulaeformis* showed a descending trend, while T_r of *Platycladus orientalis* showed a slow increasing trend at (8 ± 1)% soil moisture content.

As shown in Table 1, the average net P_N and T_r , and the maximum net P_N of *Platycladus orientalis* were higher than those of *Pinus tabulaeformis* under the same soil moisture content. The respective average net P_N , average T_r , and maximum net P_N of *Platycladus orientalis* were 3.10, 2.00, 2.40 times more than those of *Pinus tabulaeformis* under (8 ± 1)% soil moisture content. Finally, the difference between *Platycladus orientalis* and *Pinus tabulaeformis* shows a descending trend with increasing soil moisture content.

As shown in Table 2, *Platycladus orientalis* LSP photons were 1,275, 1,450 and 1,675 μmol/(m²·s), respectively, and LCP photons were 42, 25 and 13 μmol/(m²·s), respectively, with corresponding P_{max} values at 3.04, 4.06 and 5.53 μmol/(m²·s) under soil moisture content values of 7.90%, 13.00% and 19.99%. For *Pinus tabulaeformis*, the LSP photons were

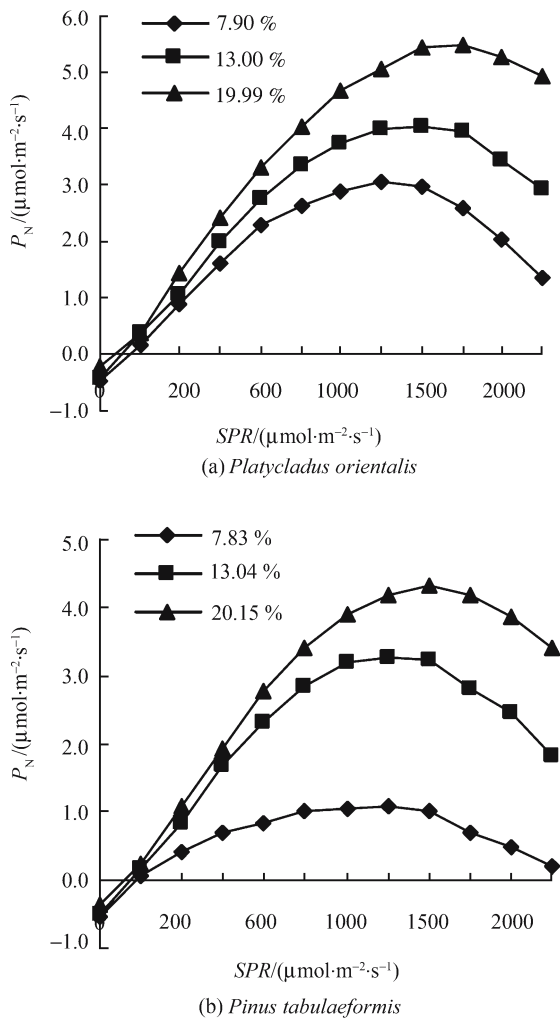


Fig. 1 Effects of enhancing simulated photosynthetic radiation (SPR) intensity on net photosynthetic rate (P_N) of *Platycladus orientalis* and *Pinus tabulaeformis*

1,100, 1,325 and 1,500 $\mu\text{mol}/(\text{m}^2 \cdot \text{s})$, the LCP photons were 60, 30 and 23 $\mu\text{mol}/(\text{m}^2 \cdot \text{s})$, and the corresponding P_{max} values were 1.08, 3.35 and 4.36 $\mu\text{mol}/(\text{m}^2 \cdot \text{s})$, under the respective soil moisture content values of 7.83%, 13.04% and 20.15%.

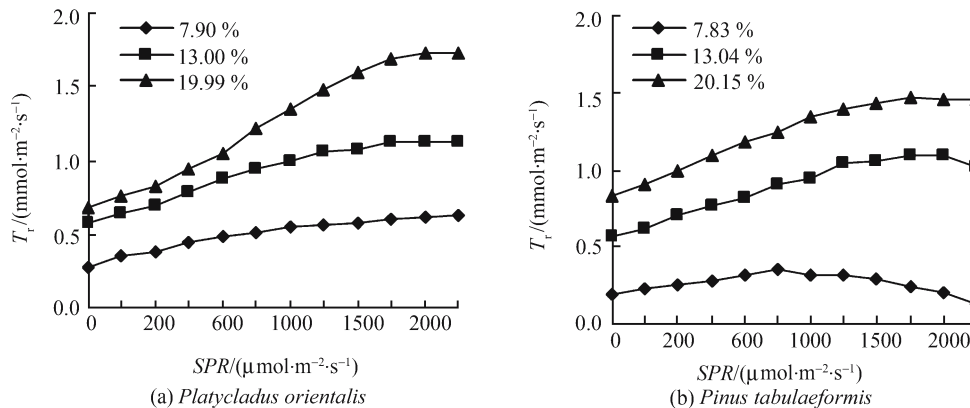


Fig. 2 Effects of enhancing simulated photosynthetic radiation (SPR) intensity on transpiration rate (T_r) of *Platycladus orientalis* and *Pinus tabulaeformis*

LSP and efficiency of light energy utilization under the same soil moisture content were both higher, while LCP was lower in *Platycladus orientalis* than in *Pinus tabulaeformis*. In both *Platycladus orientalis* and *Pinus tabulaeformis*, LSP was enhanced by increasing the soil moisture content, although a similar trend for LCP was not noted.

Referring to Tables 3 and 4, net P_N was significantly different for soil moisture content values of $(8 \pm 1)\%$ and $(20 \pm 1)\%$ for *Platycladus orientalis*. For *Pinus tabulaeformis*, significant differences were found at $(8 \pm 1)\%$ and $(13 \pm 1)\%$, or $(8 \pm 1)\%$ and $(20 \pm 1)\%$ soil moisture contents. T_r values of *Platycladus orientalis* and *Pinus tabulaeformis* were significantly different at $(8 \pm 1)\%$, $(13 \pm 1)\%$, and $(20 \pm 1)\%$ soil moisture contents. The results suggest that the effect of soil moisture content on T_r was greater than on P_N .

4.2 Water use efficiency

Water use efficiency is a comprehensive reflection of plant photosynthesis and transpiration. As seen in Fig. 3, from the initial stage to the gradual increasing of SPR , the corresponding incremental increases in net P_N became higher than that of T_r , so, recalling the formula for WUE as the ratio of net P_N to T_r , WUE showed increasing values under different soil moisture contents. However, WUE gradually declined due to the narrower effective range for net P_N than that for T_r . The observation of the WUE value going from an instantaneous increase and reaching maximal value, then declining with continued increase of the SPR , was seen in both *Platycladus orientalis* and *Pinus tabulaeformis*. Therefore, soil drought resulted in the descent of stomata conductance and net P_N and T_r , while conversely, water use efficiency increased (Damesin et al., 1997). Table 1 shows WUE values of *Platycladus orientalis* and *Pinus tabulaeformis* reaching peaks of 3.66 and 2.32 $\mu\text{mol} \cdot \text{mmol}^{-1}$ respectively at $(8 \pm 1)\%$ soil moisture content; median values of 2.83 and 2.28 $\mu\text{mol} \cdot \text{mmol}^{-1}$ respectively, were seen at $(13 \pm 1)\%$ soil moisture content; finally, minimum values were 2.82 and 2.22 $\mu\text{mol} \cdot \text{mmol}^{-1}$, respectively, at $(20 \pm 1)\%$ soil moisture content. These results show that for both *Platycladus orientalis* and *Pinus*

Table 1 The characteristic values of photosynthetic light response curves of *Platykladus orientalis* and *Pinus tabulaeformis* under different soil moisture contents

Species	Soil moisture content /%	Maximum P_n /($\mu\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$)	Average P_n /($\mu\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$)	Average T_r /($\mu\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$)	Average WUE / $\mu\text{mol} \cdot \text{mmol}^{-1}$
<i>Platykladus orientalis</i>	7.90	3.04	1.83	0.50	3.66
	13.00	4.06	2.60	0.92	2.83
	19.99	5.53	3.52	1.25	2.82
<i>Pinus tabulaeformis</i>	7.83	1.08	0.58	0.25	2.32
	13.04	3.35	2.01	0.88	2.28
	20.15	4.36	2.75	1.24	2.22

Table 2 Light saturation point and light compensation point of *Platykladus orientalis* and *Pinus tabulaeformis* under different soil moisture contents

Species	Soil moisture /%	Regressive equation	Correlation coefficient	Significance level	Light saturation point /($\mu\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$)	Light compensation point /($\mu\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$)
<i>Platykladus orientalis</i>	7.90	$Y = -0.209,8 + 0.005,1X - 0.000,002X^2$	0.904	0.000	1,275	42
	13.00	$Y = -0.141,3 + 0.005,8X - 0.000,002X^2$	0.927	0.000	1,450	25
	19.99	$Y = -0.082,6 + 0.006,7X - 0.000,002X^2$	0.935	0.000	1,675	13
<i>Pinus tabulaeformis</i>	7.83	$Y = -0.129,5 + 0.002,2X - 0.000,001X^2$	0.747	0.002	1,100	60
	13.04	$Y = -0.157,5 + 0.005,3X - 0.000,002X^2$	0.914	0.000	1,325	30
	20.15	$Y = -0.135,9 + 0.006X - 0.0000,02X^2$	0.921	0.000	1,500	23

Y: net photosynthetic rate, X: light radiation intensity.

Table 3 Multiple comparisons of net photosynthetic rates of *Platykladus orientalis* and *Pinus tabulaeformis* under different soil moisture contents

Soil moisture	<i>Platykladus orientalis</i>			<i>Pinus tabulaeformis</i>			
	Standard error of mean	Standard error	Significance level	Standard error of mean	Standard error	Significance level	
A	B	-0.773	0.663	0.252	-1.442*	0.499	0.007
	C	-1.691*	0.663	0.016	-2.175*	0.499	0.000
B	A	0.773	0.663	0.252	1.442*	0.499	0.007
	C	-0.918	0.663	0.175	-0.733	0.499	0.151
C	A	1.691*	0.663	0.016	2.175*	0.499	0.000
	B	0.918	0.663	0.175	0.733	0.499	0.151

* was significant difference ($\alpha = 0.05$).

Table 4 Multiple comparisons of transpiration rate of *Platykladus orientalis* and *Pinus tabulaeformis* under different soil moisture contents

Soil moisture	<i>Platykladus orientalis</i>			<i>Pinus tabulaeformis</i>			
	Standard error of mean	Standard error	Significance level	Standard error of mean	Standard error	Significance level	
A	B	-0.420*	0.108	0.000	-0.633*	0.071,7	0.000
	C	-0.753*	0.108	0.000	-0.983*	0.071,7	0.000
B	A	0.420*	0.108	0.000	0.633*	0.071,7	0.000
	C	-0.333*	0.108	0.004	-0.351*	0.071,7	0.000
C	A	0.753*	0.108	0.000	0.983*	0.071,7	0.000
	B	0.333*	0.108	0.004	0.351*	0.071,7	0.000

* was significant difference ($\alpha = 0.05$).

tabulaeformis, instantaneous WUE values decline with increasing soil moisture content. Instantaneous WUE of *Platykladus orientalis* was higher than that of *Pinus tabulaeformis* at the same soil moisture content.

4.3 Intercellular CO_2 concentration

As seen in Fig. 4, C_i reached a very high value (approximately $400 \mu\text{mol/mol}$) under faint SPR . Because respiration results

in energy consumption and CO_2 release, the initial increase in SPR can be explained in that there was probably mass consumption of intercellular CO_2 with small stomata conductance. The amount of CO_2 supplied by the external environment was far less than that produced by photosynthesis, so C_i rapidly declined. C_i was enhanced with an increase in soil moisture content under a different SPR , however, because of the size of stomata conductance and the capacity for carboxylase assimilation of CO_2 , C_i of *Platykladus orientalis*

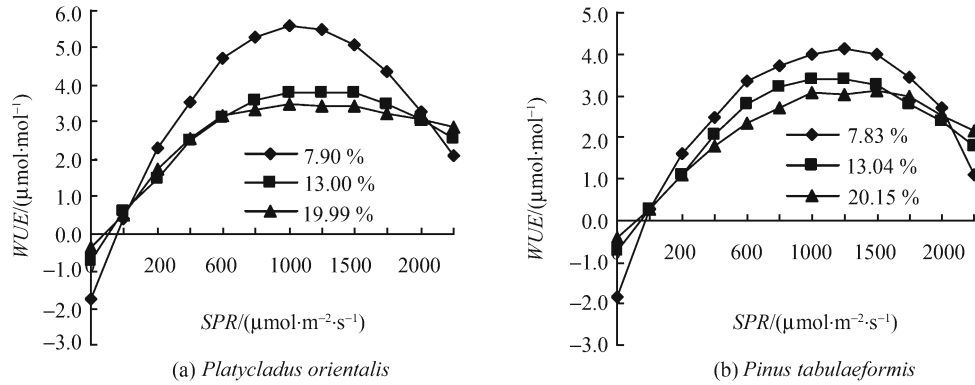


Fig. 3 Effects of enhancing simulated photosynthetic radiation (SPR) intensity on instantaneous water use efficiency of *Platycladus orientalis* and *Pinus tabulaeformis*

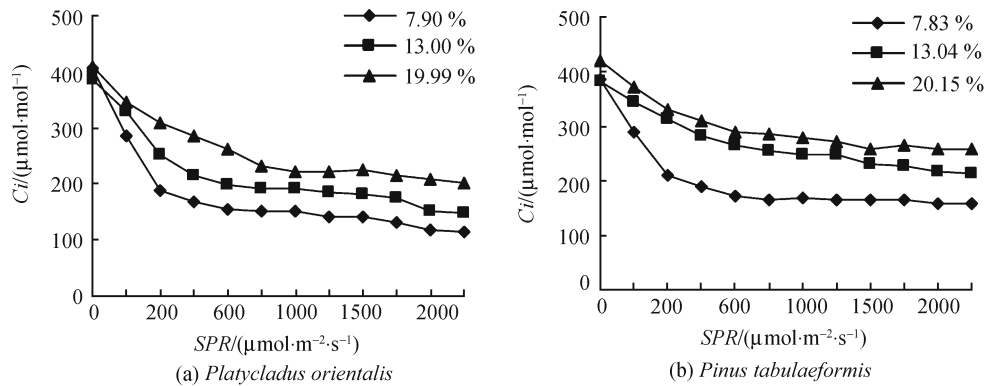


Fig. 4 Effects of enhancing simulated photosynthetic radiation intensity on intercellular CO_2 concentration of *Platycladus orientalis* and *Pinus tabulaeformis*

and *Pinus tabulaeformis* showed different descending trends. Although the amount of CO_2 supplied by external environment was less than that of photosynthesis wastage, high stomata conductance resulted in a gentler decrease at $(13 \pm 1)\%$ and $(20 \pm 1)\%$ soil moisture contents; however, at $(8 \pm 1)\%$ soil moisture content, low stomata conductance led to a fall in CO_2 . Because the physiological activity of *Platycladus orientalis* is higher than that of *Pinus tabulaeformis*, C_i of *Platycladus orientalis* was less than that of *Pinus tabulaeformis* under the same soil moisture content.

5 Conclusions

Plant photosynthesis is affected not only by its physiologic characteristics but also by many environmental factors, such as light radiation intensity, air temperature, air humidity and so on. Based on this rationale, our experiments comparing *Platycladus orientalis* and *Pinus tabulaeformis* were conducted with air temperature and air humidity kept relatively stable, and light radiation intensity and soil moisture content determined under the same conditions during the course of measurement.

Although the net P_N and T_r were enhanced with an increase in SPR in *Platycladus orientalis* and *Pinus tabulaeformis*, the trends by which they increased were different. Owing to soil water stress, low stomata conductance can create a protective mechanism for preventing more water consumption and gas exchange of leaves (Flexas et al., 2002). There was an obvious declining trend in the P_N of *Platycladus orientalis* and *Pinus tabulaeformis* corresponding to increases in SPR . The T_r values of *Platycladus orientalis* and *Pinus tabulaeformis* continuously showed corresponding increasing increments with increases in SPR at $(13 \pm 1)\%$ and $(20 \pm 1)\%$ soil moisture contents. However, the T_r of *Pinus tabulaeformis* started to decline, while that of *Platycladus orientalis* showed a slowed increasing trend at $(8 \pm 1)\%$ soil moisture content. The average values of net P_N , T_r and P_{max} of *Platycladus orientalis* were higher than those of *Pinus tabulaeformis* under the same soil moisture content.

LSP of *Platycladus orientalis* was higher than that of *Pinus tabulaeformis*, while conversely, LCP of *Pinus tabulaeformis* was higher than that of *Platycladus orientalis*. Thus, efficiency of light energy utilization of *Platycladus orientalis* was higher than that of *Pinus tabulaeformis* under the same soil moisture content. Generally, the LSP 's of *Platycladus*

orientalis and *Pinus tabulaeformis* were enhanced by increasing soil moisture content, while their *LCP* values declined by decreasing soil moisture content.

WUE values of *Platyclusus orientalis* and *Pinus tabulaeformis* became maximal (3.66 and $2.32 \mu\text{mol} \cdot \text{mmol}^{-1}$) at $(8 \pm 1)\%$ soil moisture content, while median values (2.83 and $2.28 \mu\text{mol} \cdot \text{mmol}^{-1}$) were recorded at $(13 \pm 1)\%$ soil moisture content, and minimum values (2.82 and $2.22 \mu\text{mol} \cdot \text{mmol}^{-1}$) were seen at $(20 \pm 1)\%$ soil moisture content. These results show that for both *Platyclusus orientalis* and *Pinus tabulaeformis*, instantaneous *WUE* values decline with increasing soil moisture content. Instantaneous *WUE* of *Platyclusus orientalis* was higher than that of *Pinus tabulaeformis* under the same soil moisture content.

C_i of *Platyclusus orientalis* and *Pinus tabulaeformis* showed different descending trends. Although the amount of CO_2 supplied by external environment was less than that of photosynthesis wastage, high stomata conductance resulted in a gentle decrease at $(13 \pm 1)\%$ and $(20 \pm 1)\%$ soil moisture contents; however, at $(8 \pm 1)\%$ soil moisture content, low stomata conductance led to a fall in CO_2 . Because physiological activity inherent in *Platyclusus orientalis* was higher than that in *Pinus tabulaeformis*, C_i of *Platyclusus orientalis* was less than that of *Pinus tabulaeformis* under the same soil moisture content.

There are many factors limiting plant growth in the semi-arid region of the Loess Plateaus, such as water stress, strong light and high temperature. We found that the metabolic capability of the *Platyclusus orientalis* seedling was higher than that of the *Pinus tabulaeformis* seedling, and the adaptive capacity to strong light was also better. This implies that the *Pinus tabulaeformis* seedling is especially affected by strong light leading to the restraining of growth of *Pinus tabulaeformis* at low soil moisture content.

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