



Article Growth of Populus × euramericana Plantlet under Different Light Durations

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Abstract: Using full-spectrum LED lights, six light treatments of 11 h, 12 h, 13 h, 14 h, 15 h, and CK (greenhouse natural light) were designed to examine the response of Populus euramericana plantlets to light duration in the greenhouse. Every 15 days during the 150-day experiment, plantlet height (H), ground diameter (GD), number of nodes (NN), number of leaves (NL), and the relative chlorophyll content(SPAD) were measured. The response of plantlets to different light durations was demonstrated by establishing and screening growth models, and rhythm and relative chlorophyll content were statistically analyzed. The light duration had a significant effect on the H and GD of Populus euramericana, and their growth was positively correlated with light duration. The short full-spectrum LED lighting duration will affect the rhythm and prematurely halt the growth of H, but the GD will continue to expand. The Gomperz model has the best fitting effect for the growth of Populus euramericana plantlets under LED lighting, with all R2s values greater than 0.89. Long light duration has a greater growth potential, and the rapid growth lasts longer. The delay in the cessation of the increase in the NN was a result of the increased illumination time. Compared with natural light, LED light lessens the NL. Poplar plantlets will have a lower SPAD value if the light duration exceeds 14 h. In the process of growing plantlets in the greenhouse, both light quality and light duration should be considered. In actual production, a combination of natural and artificial light can improve efficiency.

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Copyright: © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). Keywords: *Populus* × *euramericana*; light duration; plantlets; growth model; rhythm; SPAD

1. Introduction

The entire process of plant growth and development cannot be separated from the influence of environmental factors, among which light is the most important [1]. Light is not only an essential environmental signal for plant growth regulation, but also the only source of energy input and absorption, i.e., the energy source for photosynthesis [2]. Growing plants can create photoperiod signals that trigger a variety of physiological reactions in order to adapt to their environment, therefore altering their morphology [3–5]. Photoperiod is the light-time response that affects the seasonal growth, developmental changes, and reproductive behavior of plants [6]. Consequently, photoperiod is usually considered to be one of the most essential environmental elements for plant development and phenological seasonal variation [7].

Photoperiod is often equated with changes in light duration. Changes in light time can trigger blooming [8,9] and relieve dormancy [10]. Changing the light duration of plants in a suitable manner promotes the accumulation of photosynthetic products [11], which in turn impacts plant growth and development [12]. In terms of the morphological response to light duration, Oleksyn [13] discovered that the tree height growth and dry matter growth of *Pinus sylvestris* populations were higher during longer light periods. In recent

years, controlling plant development and productivity by lengthening or reducing the light duration has become a crucial aspect of greenhouse production. LED lighting can be used to overcome the problem of insufficient lighting time in greenhouses during the winter in northern China [14–16]. Previous research has demonstrated that LED supplementary lighting between plants improves the light environment of the middle and lower crop leaves, promotes plant photosynthesis, and increases tomato yield [17–19].

In addition, light duration affects the rhythm and photosynthetic ability of plantlets [20–22]. Although early studies demonstrated that light modulation can affect the growth and rhythmic variation of woody plants, research on efficient plantlet production has only just begun [23]. For the study of the growth law of plant plantlets, growth curves are often used [24], which fit time-series data into a mathematical growth process obtaining plantlet characteristics such as fast-growing interval and growth speed by calculating the relationship between parameters. Changes in the NN and NL best reflected the apparent influence of light duration on plantlet rhythm. The rapid growth of plantlets was accompanied by an increase in the NN and elongation; however, once the growth ceased, the NN did not increase again. The primary organ for photosynthesis is the leaf [25–27]. The NL can indicate the photosynthetic ability of plantlets to some degree [28], whereas the chlorophyll concentration of leaves reflects the photosynthetic status of leaves at that time [29]. When the light environment changes, the gradual decrease in chlorophyll content will affect the assimilation of carbon, which will in turn impair the growth and development of plantlets. In study, the relative chlorophyll content is frequently expressed by the SPAD(soil plant analysis development chlorophyll meter) value, which can be employed to comprehend the plantlets' desire for nitro-inorganic compounds and their reaction to light duration [30].

Populus × *euramericana*, a fast-growing, high-quality, high-yield, and adaptable tree species, is significant for plantation production worldwide [31,32]. It is simple to reproduce by clone cuttings [33–35] since it is a hybrid of *Populus deltoides* and *Populus nigra*. Poplar, like other species, grows in response to external environmental elements such as light, temperature, water, latitude, and more. The considerable photoperiod variation between middle and high latitudes has limited poplar species' popularity. In general, northern poplar species are adapted to long-day circumstances and stop growing in early summer in low latitudes, while southern species require short-day conditions and flourish until late fall [36–39]. However, poplar's light cycle response potential has been understudied, especially in early plantlet cultivation of poplars. Thus, this study will simulate different photoperiods by adjusting LED light durations to objectively analyze poplar plantlet and cultivation.

2. Materials and Methods

We hybridized 1000 genotypes of *Populus* \times *euramericana* in 2015, and screened 30 plantlets that grew well in the greenhouse with a 3% standard. They were bred in field conditions (39°73'35" N, 116°75'18" E) in the spring of 2016. In April 2017, 16 genotypes were randomly selected to make cuttings and cultivated in the greenhouse as an excellent *Populus* \times *euramericana* group. The plastic pots for cultivating plantlets have a diameter of 18 cm and a height of 25 cm; 150 pots per genotype. Substrate and plastic pots totaled 6.80 kg before watering, and the substrate volume ratio was loess: charcoal: coarse sand = 5:2:3. The pH value of the substrate is 6.58, the volume moisture content is about 45.40%, and the maximum moisture content is about 63.80%. The light experiment was started when the stems of the plantlets reached the semi-lignified stage (that is, the 45th day after cutting), and the light experiment was carried out for 105 days. The layout of the greenhouse is shown in Figure 1. To avoid the interference of natural light, the plastic greenhouse is divided into 6 rooms evenly by breathable black plastic sheets. Five of the rooms were completely darkened, the only light source in the room was a timed full-spectrum LED grow light (100 W), and the sixth room (CK) was untreated natural light. The five light durations are 11, 12, 13, 14 and 15 h, starting at 8:00 a.m. daily.



Figure 1. Cultivation and experimental procedures. The experimental group is the plantlets directly under the lamp, and the plantlets at the edge of the light are not relevant to this research.

The total duration of photosynthetically active radiation (PAR) that the plantlets can accept in the field on the summer solstice is 13 h, and the total sunshine duration of the day is 15 h. The experiment adopted a completely randomized block design with a total of 6 blocks. There are 5 plots in each block, 4 of which are used for repeated measurement of time-series data, and one plot is used for destructive sampling. Each plot has 16 genotypes and 5 clones per genotype. The experimental period is from June to November 2017, a total of 150 days.

From 0 to 150 days [34], the plantlet height (H) and ground diameter (GD) were measured every 15 days with a long steel ruler and a vernier caliper. From the 45th to the 120th day, the NN and NL were counted every 15 days. From day 30 to day 105, the SPAD values of the 4th, 5th and 6th functional leaves were measured from top to bottom with SPAD-502Plus every 15 days. The time-series growth data of H and GD were used to construct the growth curve, and the most suitable plantlet growth model for this experiment was selected by comparing the goodness of fit. The models to be tested are all commonly used plantlet growth curves, including four function types (Table 1). Among them, the fast-growing interval of the Gompertz [40,41] growth model is:

$$\begin{bmatrix} t_1, t_2 \end{bmatrix} = \begin{bmatrix} \frac{1}{c}Ln\frac{2b}{3+\sqrt{5}}, & \frac{1}{c}Ln\frac{2b}{3-\sqrt{5}} \end{bmatrix}$$
$$t_{max} = (t_1 + t_2)/2$$

Function Type	Function Name	Equation	Ranges of C
Quasi-linear	Generalized Single Index	$y = a + b * \exp(-c * t)$	0–50
Quasi-power	Richards	$y = a * (1 - exp(-c * t))^{b}$	0–2
Quasi-hyperbolic	Logistic	y = a/(1 + b * exp(-c * t))	0.1–9
Quasi-power	Levakovic	$y = a * (t^2/(c + t^2))^b$	1-50
Quasi-exponential	Gompertz	$y = a * \exp(-b * \exp(-c * t))$	0–2
Quasi-linear	Log-Linear	$y = a + b * \log(t + c)$	0–50

Table 1. Models to be tested. Y is the value of triat, and t represents time. Parameter 'a' is the asymptotic (maximum) length, b and c are parameters to be estimated.

3. Results

3.1. Growth of Plantlets

The 11 h, 12 h, and 13 h plantlets' H stopped growing at 90–105 days; the rest continued until the end of the experiment. GD kept growing. CK had the largest H and GD, followed by 14 h and 15 h, 12 h and 13 h, and 11 h (Table 2).

Table 2. Descriptive statistics for H and GD. The data format is "mean \pm standard deviation".

Trait	Days	11 h	12 h	13 h	14 h	15 h	СК
Н	150	60.80 ± 10.07	61.66 ± 8.02	64.66 ± 15.87	101.51 ± 36.69	99.53 ± 31.33	102.19 ± 42.49
	135	60.80 ± 10.06	61.66 ± 8.02	64.66 ± 15.87	99.04 ± 35.93	95.92 ± 30.54	100.51 ± 42.73
	120	60.80 ± 10.05	61.66 ± 8.02	64.66 ± 15.87	96.07 ± 34.10	92.85 ± 27.70	100.10 ± 42.50
	105	60.80 ± 10.04	61.66 ± 8.02	64.66 ± 15.87	93.13 ± 31.57	88.80 ± 25.12	99.17 ± 41.36
	90	59.14 ± 10.22	60.18 ± 8.14	63.88 ± 15.27	89.27 ± 28.04	83.33 ± 20.97	95.51 ± 36.67
	75	58.32 ± 10.28	59.81 ± 8.27	62.31 ± 13.30	81.08 ± 19.71	75.63 ± 15.96	83.83 ± 28.18
	60	57.35 ± 10.23	59.08 ± 8.00	59.75 ± 10.22	72.48 ± 13.16	65.76 ± 10.09	68.69 ± 16.04
	45	54.83 ± 9.59	55.59 ± 6.84	55.53 ± 8.98	65.12 ± 11.32	58.58 ± 7.86	57.45 ± 11.58
	30	37.98 ± 5.11	37.32 ± 4.47	36.39 ± 4.84	41.25 ± 6.22	39.75 ± 5.38	39.37 ± 7.10
	0	23.67 ± 4.01	23.62 ± 3.90	23.69 ± 4.05	23.71 ± 4.10	23.71 ± 4.10	23.69 ± 4.08
GD	150	6.60 ± 0.88	6.46 ± 0.70	7.11 ± 1.30	7.76 ± 1.75	7.40 ± 1.62	9.49 ± 2.56
	135	6.29 ± 0.75	6.20 ± 0.68	6.57 ± 1.09	7.25 ± 1.48	6.92 ± 1.34	8.94 ± 2.41
	120	6.11 ± 0.70	6.04 ± 0.66	6.35 ± 1.00	6.86 ± 1.29	6.54 ± 1.12	8.58 ± 2.31
	105	5.98 ± 0.67	5.90 ± 0.63	6.07 ± 0.73	6.55 ± 0.99	6.22 ± 0.89	8.10 ± 1.96
	90	5.86 ± 0.66	5.75 ± 0.60	5.90 ± 0.66	6.34 ± 0.88	5.96 ± 0.78	7.65 ± 1.72
	75	5.67 ± 0.63	5.56 ± 0.59	5.64 ± 0.64	6.03 ± 0.70	5.67 ± 0.62	6.98 ± 1.41
	60	5.47 ± 0.63	5.34 ± 0.55	5.24 ± 0.52	5.70 ± 0.66	5.32 ± 0.50	5.89 ± 0.80
	45	5.25 ± 0.59	5.10 ± 0.53	4.96 ± 0.48	5.36 ± 0.59	5.08 ± 0.44	5.39 ± 0.64
	30	4.67 ± 0.56	4.40 ± 0.52	4.33 ± 0.49	4.58 ± 0.56	4.56 ± 0.45	4.59 ± 0.56
	0	3.66 ± 0.56	3.61 ± 0.55	3.62 ± 0.51	3.65 ± 0.56	3.65 ± 0.54	3.64 ± 0.56

3.2. Construction of Growth Curves

The results of fitting the growth curve to the 105-day H and GD time series are shown in Table 3. Gompertz better explained the growth of poplar plantlets based on the model's R^2 fit coefficient, which were all greater than 0.89. Figure 2 depicts the Gompertz growth curve, and Table 4 lists the model's parameters.

The expected fast-growing days of H increased with increasing light duration, with the greatest increase occurring at CK (207 days); with the exception of 13 h, the expected fast-growing days of GD were consistent with those of H, and the expected fast-growing days of GD at 13 h were 210 days.

P !	Ranges of R ²				
rigure —	Н	GD			
Generalized Single Index	0.7756-0.9802	0.8583-0.9751			
Richards	0.5535-0.7746	0.4132-0.6666			
Logistic	0.5516-0.7732	0.7640-0.9566			
levakovic	0.5524-0.7738	0.4121-0.6655			
Gompertz	0.8947-0.9871	0.9104-0.9793			
Log-Linear	0.7676-0.9755	0.8321-0.9694			

Table 3. Goodness of fit comparison.



Figure 2. Gomperz growth curve comparison.

Table 4. Gomperz equation parameters and fast growth interval.

Trait	Treatment	a	b	с	t ₁	t _{max}	t ₂	Expected Duration	<i>R</i> ²
Н	11 h	62.736	0.992	0.033	12	46	80	68	0.9484
	12 h	63.913	1.017	0.032	12	48	83	71	0.9547
	13 h	68.032	1.083	0.029	14	56	98	84	0.9153
	14 h	110.867	1.572	0.021	29	114	199	170	0.9386
	15 h	112.989	1.587	0.018	34	135	235	201	0.9871
	CK	119.668	1.667	0.018	35	139	242	207	0.8947
GD	11 h	6.650	0.594	0.018	12	49	85	73	0.9664
	12 h	6.706	0.623	0.016	15	59	103	88	0.9758
	13 h	8.607	0.869	0.009	36	141	246	210	0.9634
	14 h	8.997	0.900	0.011	32	125	219	187	0.9793
	15 h	9.527	0.946	0.008	45	175	305	261	0.9663
	CK	15.030	1.443	0.008	71	279	488	417	0.9104

'a' represents the final value: the growth potential (110-120 cm) of H at 14 h, 15 h, and CK is nearly double that of 11 h, 12 h, and 13 h (62-68 cm). GD has the greatest growth potential in CK (15 mm), followed by 13-15 h (8-9 mm), and 11 h and 12 h have the least (6.7 mm).

3.3. Number of Nodes and Leaves and SPAD Value

GD's growth rate varies, but its growth never stops. However, the growth of H stopped at 11 h, 12 h and 13 h. The NN increase in natural light almost stopped at day 75,

and the elongation of nodes did not stop (Figure 3). The increase in NN at 11 h and 12 h stopped 15 days later than that of CK, and the elongation of nodes lasted until the 105th day. NN increased at 13 h, and nodal elongation stopped at 105th day. The increase in NN at 14 h and 15 h stopped at day 120, but the elongation of nodes did not stop.



Figure 3. The number of nodes and leaves and the change of SPAD value. The shaded area is the 95% confidence interval.

NL hardly increased at 11 h, 12 h and 13 h on the 45–60th day, and then decreased. At 14 h, the NL first decreased and then increased, and at 15 h, the NL continued to increase. CK NL first increased and then decreased.

The range of CK's SPAD values is 35 to 40. The plantlets were given a light treatment when they reached day 45 of growth. The SPAD values of CK began to decline 15 days after the light treatment began. The influence of light accelerated the rate at which each treatment's SPAD declined, and all treatments' SPAD values reached their lowest points on the 60th day. The SPAD value of CK was consistently higher than those under light treatments. Then, the SPAD values of plantlets exposed to the 11 h and 15 h treatments started to rise, and then it started to fall again after approximately 95 days and 80 days, respectively. By contrast, the SPAD exposed to the 12 h, 13 h, 14 h, and CK treatments generally continued to rise until the experiment's conclusion. After 105 days of light treatments, SPAD values at 12 h and 13 h were noticeably larger than CK, SPAD values at 11 h were comparable to CK, and SPAD at 14 h and 15 h was noticeably smaller than CK.

4. Discussion

Light is one of the most influential factors on plantlet development, rhythm, and photosynthetic capacity [5]. In this study, the H and GD of plantlets grown under the 11 h, 12 h, and 13 h treatments were significantly smaller than those grown under the 14 h, 15 h, and CK treatments, as were their growth potentials, a finding consistent with previous research [42]. This is due to the fact that short light duration decreases the ability of plants to absorb and assimilate CO_2 during growth [43,44], whereas prolonged photosynthesis under long light duration promotes the production of carbohydrates necessary for plant growth [45,46]. However, our results may not be absolutely flawless or as crystal-clear as

we had hoped. For instance, the actual light duration of CK is short and varies seasonally, but it is obvious that natural light is more efficient than full-spectrum LED lights, which indirectly indicates that light intensity or light quality is another determinant of plantlet development [47]. In addition, the use of 100 W LED lights in the experiment has dissipated a great deal of heat, so the greenhouse must be ventilated; otherwise, the constant high temperature and high humidity will be detrimental to the plantlets' growth. If the light intensity of natural light is simulated, higher power plant growth lights and a more advanced temperature and humidity control environment are required, which is obviously difficult and costly.

In addition, the variation of H among different light treatments was much larger than that of GD. The growth rhythm of plantlets played an important role in this process, and the effect of light duration was consistent with previous research results [20,21,23]. These phenomena can also be explained from the comparison between CK and 13 h, that is, 13 h is the longest daylight duration (summer solstice) in the local area. With seasonal changes, the daily duration of photosynthetically active radiation received by CK treatment gradually decreases. On the 75th day, the growth of the NN in the CK treatment stagnated, indicating that the length of natural light at this time had limited the increase in the NN of the plantlets. After autumn, the temperature decreased, and the NN of plantlets under the treatment of short light duration gradually stopped increasing, and then the elongation of nodes began to be limited, which was the end of its growth and cold tolerance [36]. The difference is that the increase and elongation in the NN of the plantlets under long-term light continued, which indicated that the length of light played a leading role in the increase in the NN, and had little relationship with light quality and intensity. *Picea pungens* plantlets need at least 16 h of light to continue to grow [3], while *Populus euramericana* only need more than 14 h, which may be caused by the difference in leaf type and genetic difference between coniferous and broad-leaved trees.

Earlier studies suggested that maximizing the growing season may benefit trees [48]. In this study, the expected fast-growing time of Gompertz at 14 h, 15 h and CK was more than twice that of the short light duration, and had obvious growth potential. It shows that the LED light duration of at least 14 h has a positive effect on the growth of poplar plantlets. In addition, prolonging the light duration of plants to a certain extent can promote the accumulation of assimilates [11,15,30]; this was verified in this study and previous studies [49]. Of course, if trees cannot induce proper dormancy periods, there may be an increased risk of late spring/early autumn frost damage and a lack of adequate cold resistance during winter [50,51]. Therefore, it is also crucial to confirm the appropriate light time for the growth, dormancy induction, and cold resistance development of *Populus euramericana* plantlets.

Leaves are the most important vegetative organ of plantlets, and NL can represent the ability of plantlets to accumulate nutrients. Natural light and 15 h light duration can continuously increase NL, and LED light duration below 15 h can continuously reduce NL, indicating that long-term light promotes the vegetative growth of plantlets. However, under short light, the photosynthetic time of plantlets is shortened, the material accumulation ability is reduced, and the limited energy preferentially ensures apical dominance, which limits the formation of leaves and branches, which is similar to the results of other studies [52]. In addition, chlorophyll is a key factor for plants to complete the absorption and conversion of light energy, and its content changes affect the photosynthetic capacity and nutritional level of plants [49].

The SPAD value is significantly positively correlated with leaf greenness and nitrogen content, and is an important predictor of plant photosynthetic yield [53]. Although full-spectrum LED plant growth lights were used in this study, compared with natural light, there is still a shortage. Continuous weak light will weaken photosynthetic capacity and lead to continuous degradation of chlorophyll [54]. Therefore, under 14 h and 15 h light, the SPAD value of *Populus euramericana* plantlets was always lower than that of CK. However, the decline in SPAD may also be due to the continuous high growth and increased NL that

consumes a large amount of soil nutrients, resulting in lower leaf nitrogen content [55,56]. With the prolongation of the growth days, the SPAD value of the plantlets under the 11–13 h light treatment is generally greater than that of CK. It may be that the plantlets under shorter light conditions are adapted to survive, and energy and nutrients are given priority to the leaves to increase the chlorophyll content to ensure the smooth progress of photosynthesis. It may also be that with the arrival of autumn, the ambient temperature decreases, and the heat emitted by LED lights increases the temperature in the greenhouse, and the relative increase in temperature promotes the synthesis of chlorophyll [57]. Interestingly, the SPAD value under the 13 h treatment was higher than that of CK, which further explained that the difference between the full-spectrum LED light and natural light is not the factor that affects the decrease in chlorophyll content of *Populus euramericana* plantlets and the weakening of photosynthesis, but the length of light. As for whether the lack of soil nutrients or temperature affects the relative chlorophyll content, follow-up supplementary experiments are needed.

In essence, the light duration should last at least an hour longer than the maximum daylight period in the area, and mixed light sources are preferable to pure LEDs. Growth is best in natural light, but with seasonal variations in temperature and light intensity acting as restrictions. Continuous plant growth is possible with long-term LED full-spectrum light, but the results are not as good as with sunlight. The best course of action is to combine the two during the period of rapid growth. Since LED light is unevenly irradiated, it is necessary to study the growth of the near and far light source areas in the future.

5. Conclusions

The duration of light had a substantial impact on the development of *P. euramericana* plantlets. In the absence of an increase in light duration, the growth of plantlets, the NN, and fast-growing duration can be inhibited. The Gomperz growth curve best approximates the plantlet growth's curve, with R2 greater than 0.89. In this experiment, the light duration has the greatest impact on the SPAD value, with light durations exceeding 14 h inhibiting the relative chlorophyll content and durations below 13 h promoting its increase. The NL is influenced by the quality and intensity of light. Under natural light, the NL is greatest, and the longer the duration of light, the greater the NL. When growing *P. euramericana* poplar plantlets in a greenhouse, the total daily light duration should be greater than 14 h and should include both natural and supplemental light.

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