

Simulation and Model Comparison of Photosynthetic Light Response Process in *Populus euphratica* under Drought Stress Postprint

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Abstract

Using two-year-old *Populus euphratica* seedlings from the Tarim arid desert region as experimental materials, pot culture simulations were conducted under five water gradients mimicking desert habitats. A Li-6400 portable photosynthesis system was employed to measure the light response processes of photosynthesis in *Populus euphratica* under drought stress, and four light response models were utilized for fitting and comparison, aiming to identify an optimal light response model suitable for arid desert environments and to elucidate the response patterns and adaptive mechanisms of *Populus euphratica* photosynthesis to drought stress. The results demonstrated that the net photosynthetic rate (P_n) of *Populus euphratica* exhibited a declining trend with intensifying drought stress, with the magnitude of P_n reduction increasing under identical photosynthetically active radiation (PAR). Under moderate drought stress and below (relative soil water content, $RSWC > 45\%$), *Populus euphratica* could maintain relatively high P_n under elevated PAR, with minimal photoinhibition; the rectangular hyperbola, non-rectangular hyperbola, and exponential models all satisfactorily simulated the P_n -PAR response process, yet the fitted values for maximum net photosynthetic rate (P_{nmax}) and light saturation point (LSP) differed extremely significantly from measured values ($P < 0.01$). Under moderate drought stress and above ($RSWC < 45\%$), P_n of *Populus euphratica* decreased significantly with increasing PAR, LSP and P_{nmax} declined extremely significantly, and photoinhibition became pronounced; only the modified rectangular hyperbola model yielded fitted light response processes and parameters consistent with actual conditions. The simulation efficacy ranking of the four models was: modified rectangular hyperbola model > exponential model > non-rectangular hyperbola model > rectangular hyperbola model. The four light response models exhibited differential adaptability to drought stress, with the modified rectangular hyperbola model being applicable across various water conditions, particularly in arid desert habitats, while the other three models were

suitable for habitats with more favorable water conditions. Light response characteristic parameters displayed distinct response thresholds to drought stress. With intensifying drought stress, the apparent quantum yield (AQY), P_n , LSP, and P_{nmax} of *Populus euphratica* continuously decreased, whereas dark respiration rate (R_d) and light compensation point (LCP) increased significantly under severe drought stress. At $RSWC > 45\%$, *Populus euphratica* maintained relatively high AQY, P_{nmax} , and LSP; at $RSWC < 45\%$, P_{nmax} and LSP decreased significantly. Drought stress substantially inhibited the photosynthetic process and light intensity tolerance range, reduced photosynthetic efficiency, and severe drought stress severely impacted the normal growth and photosynthetic activity of *Populus euphratica* seedlings. In arid desert environments, *Populus euphratica* adopts an ecological strategy of narrowing its light ecological amplitude, reducing light energy utilization efficiency, and decreasing respiratory consumption to actively combat desert drought adversity. Therefore, from the perspective of population conservation and vegetation restoration in extremely arid desert regions, soil moisture in *Populus euphratica* forests should be maintained at approximately 50% RSWC, aligning with management principles for plant growth and efficient water use in water-limited arid regions.

Full Text

Preamble

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Title: Simulated Photosynthetic Responses of *Populus euphratica* During Drought Stress Using Light-Response Models

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Abstract

Water is one of the major limiting factors for vegetation recovery and reconstruction in the extremely arid desert region of northwest China. We established five moisture gradients to simulate a desert habitat and measured the photosynthetic light responses of two-year-old *Populus euphratica* seedlings under drought stress using the Li-6400 portable photosynthesis system. The resulting data were fitted and analyzed using rectangular hyperbola, non-rectangular hyperbola, exponential, and modified rectangular hyperbola models. This study aimed to optimize these models, investigate the adaptability of light-response models to

different levels of drought stress, and understand the adaptation mechanisms of *P. euphratica* to arid desert conditions.

The results showed that the net photosynthetic rate (P_n) declined under the same photosynthetically active radiation (PAR) as drought stress intensified. Relatively high photosynthesis rates and reduced photoinhibition were observed under conditions of low-to-moderate drought stress (relative soil water content (RSWC) > 45%). When models were used to express this relationship, the exponential, rectangular hyperbola, and non-rectangular hyperbola models fit the P_n -PAR response process well, but the maximum net photosynthetic rate ($P_{n\max}$) was significantly higher than measured values and the light saturation point (LSP) was significantly lower than measured values ($P < 0.01$).

When RSWC was lower than 45% (where seedlings experienced greater drought stress), obvious photoinhibition and significant decreases in P_n were observed under strong light, and LSP and $P_{n\max}$ were also significantly decreased. Under these circumstances, only the modified rectangular hyperbola model could fit the light response processes and parameters. Overall, the goodness-of-fit of the four light-response models to the observed data was as follows: modified rectangular hyperbola model > exponential model > non-rectangular hyperbola model > rectangular hyperbola model.

The adaptability of the four models to different drought stress levels was variable. The modified rectangular hyperbola model perfectly simulated the light response process and fitted photosynthetic parameters under all water conditions. It was especially suited to severe drought stress and extremely arid desert conditions, whereas the other three models were only suitable under high moisture conditions. The response threshold of light-response parameters differed with changing drought stress levels. The apparent quantum yield (AQY) of *P. euphratica* decreased gradually with increasing drought stress, but its dark respiration rate (R_d) and light compensation point (LCP) increased significantly under extremely severe drought stress.

Populus euphratica showed higher AQY, $P_{n\max}$, and LSP under RSWC > 45%, while its photosynthetic efficiency of $P_{n\max}$ and LSP decreased significantly when RSWC was less than 45%. Drought stress significantly inhibited the photosynthetic process and decreased the light tolerance range. Under severe drought stress, photoinhibition increased significantly while photosynthetic capacity and normal seedling growth were substantially inhibited. *P. euphratica* was sensitive to small changes in drought severity and decreased its light use efficiency and respiration to adapt to desert conditions.

We conclude that to enhance species conservation and restore vegetation in extremely arid desert regions, soil water content should be maintained at about 50% of field capacity, which would optimize desert plant growth and water management in the Tarim Desert area.

Keywords: *Populus euphratica*; drought stress; light-response model; photosynthetic parameter; simulation

Introduction

Photosynthesis is a complex biophysical and chemical process in which plants convert light energy into chemical energy usable for life processes and synthesize organic compounds. The quantitative relationship between plant net photosynthetic rate and photosynthetically active radiation forms the basis for revealing how photosynthetic physiological processes respond to environmental factors [?]. Measurement and simulation of light-response curves can yield key photosynthetic parameters such as maximum net photosynthetic rate ($P_{n\max}$), apparent quantum efficiency (AQY), light saturation point (LSP), light compensation point (LCP), and dark respiration rate (R_d), which help identify the operational status of photosynthetic machinery, photosynthetic capacity across different habitats, and adaptation patterns [?]. The development, parameter derivation, and application of light-response models have attracted widespread attention from scholars [?].

Researchers have constructed various light-response models with different derivation mechanisms, among which the non-rectangular hyperbola model, rectangular hyperbola model, and exponential model are most commonly applied. However, these traditional models have significant limitations: the fitted light-response parameters differ substantially from measured values, and they cannot accurately simulate the response process when photoinhibition occurs [?, ?, ?]. They are particularly suitable only for fitting plant light-response processes and parameters under normal water conditions [?] and cannot adapt to fitting different plants in various habitats. Consequently, there is a lack of deep understanding regarding the applicable conditions, scope, and fitted indices of different light-response models, leading to low credibility in model selection [?].

In recent years, Ye et al. [?] constructed a modified rectangular hyperbola model, pointing out that this model overcomes the limitations of traditional models and can more accurately fit the light-response processes and characteristic parameters of plants in various habitats [?, ?]. The modified rectangular hyperbola model has been applied to simulate photosynthesis in winter wheat and *Hippophae rhamnoides* under different soil moisture conditions [?], achieving good results. However, whether this model is equally feasible for simulating the response process of photosynthesis to drought stress and fitting characteristic parameters for plants in extremely arid desert regions, and whether the fitting effects of different light-response models under drought stress, as well as the quantitative relationship between *P. euphratica* photosynthesis and soil moisture, require further in-depth research.

Populus euphratica, a species of the genus *Populus* (Salicaceae), is among the first batch of rare and endangered species designated in China [?]. It has become a valuable desert tree species, a natural barrier preventing land desertification, maintaining ecological security of oasis in southern Xinjiang, and ensuring

sustainable agricultural and pastoral production. Influenced by global climate change and driven by rapid regional population growth, large areas of land have been reclaimed, leading to frequent changes in the Tarim River channel and continuous decline in groundwater levels, even causing long-term flow interruption in downstream areas. This has triggered a sharp decline in species diversity of desert riparian forests that rely solely on groundwater for survival and ecosystem degradation [?]. Domestic and foreign scholars have conducted extensive research on gas exchange parameters, chlorophyll fluorescence parameters, and reasonable ecological water levels of *P. euphratica* [?], but simulation and comparative studies on the photosynthetic light-response process of *P. euphratica* under drought stress are rarely reported, and the quantitative relationship between its photosynthetic physiological parameters and soil moisture remains unclear.

Using two-year-old *P. euphratica* seedlings from the Tarim Basin as research material, this study simulated desert habitat water conditions through pot experiments, measured photosynthetic light-response curves under drought stress, and simulated and compared the light-response processes using four widely-used models. The objectives were to clarify the adaptation patterns of *P. euphratica* light-response processes and characteristic parameters to drought stress and their quantitative relationship with soil moisture, evaluate the applicability of different light-response models in fitting the light-response processes and characteristic parameters of *P. euphratica* under drought stress, and select the optimal light-response model for leaf photosynthesis of *P. euphratica*, thereby providing theoretical support for water-saving irrigation of oasis shelter forests and natural vegetation restoration in the Tarim Basin.

1. Experimental Design

The experiment was conducted from May to September 2014 in a self-built artificial rain shelter at the Horticulture Experimental Station of Tarim University. The experimental material consisted of two-year-old *P. euphratica* seedlings, a dominant desert tree species in the Tarim Basin. Plastic pots with a diameter of 28 cm and height of 30 cm were used, each containing equal amounts of sieved brown calcic soil (soil organic matter 1.33 g/cm³, pH 8.35, soil bulk density 1.43 g/cm³, field capacity 24.43%). Based on soil water content, soil bulk density, and field capacity, different drought stress treatments were calculated.

In late March, seedlings with similar ground diameter were selected and planted in plastic buckets. To simulate desert habitats, five different soil water treatments were established: (A1) RSWC 75%-80% (soil water content 18.32%-19.54%); (A2) RSWC 60%-65% (14.66%-15.88%); (A3) RSWC 45%-50% (10.99%-12.21%); (A4) RSWC 30%-35% (7.33%-8.55%); and (A5) RSWC 20%-25% (4.89%-6.11%). A randomized block design was adopted with three replicates for each water treatment.

After planting, all seedlings were placed under identical environmental conditions and watered to ensure normal germination and growth. In early May, water treatments were implemented according to the experimental design. Pot weight was measured using an electronic scale. On rainy days, rain shelters were used to block precipitation. When soil moisture naturally declined to the set standard, water was supplemented using fixed containers to control soil moisture within the set range. The daily weight gain of each seedling was calculated from the weight difference between the previous evening and the current evening. To improve experimental precision, each seedling was weighed separately by roots, stems, and leaves for fresh weight, then oven-dried at 105°C for 30 minutes and 75°C to constant weight to obtain dry weight. The actual daily water supplement was calculated by subtracting the seedling weight gain from the calculated water supplement.

2. Light-Response Curve Measurement

From late June to early July, three *P. euphratica* seedlings were randomly selected from each water treatment. For each seedling, three mature leaves from the middle-upper portion with similar positions were chosen. On clear, cloudless days between 9:30-11:30, the light-response process was measured using a Li-6400 portable photosynthesis system (Li-Cor, Inc, USA) after natural light induction. An open air path was adopted, leaf chamber temperature was controlled at $(25 \pm 1)^\circ\text{C}$ by a temperature controller, gas flow rate was controlled at $500 \mu\text{mol/s}$, and CO_2 concentration was maintained at $(370 \pm 5) \mu\text{mol/mol}$. Different photosynthetic active radiation gradients were provided by a blue light source (Li-6400-02 BLEED) with settings of 0, 20, 50, 100, 200, 500, 1000, 1500, 2000, 2500, 2800, and 3000 $\mu\text{mol photons m}^{-2} \text{s}^{-1}$. Each light intensity was maintained for 120-150 seconds with three repeated readings, and the Li-6400 automatically recorded P_n .

Based on the measurement data, light-response curves of *P. euphratica* photosynthesis under different drought stresses were plotted (P_n -PAR). According to the trend of measured data points, parameters such as maximum net photosynthetic rate ($P_{n\text{max}}$), LSP, LCP, and dark respiration rate (R_d) were estimated [?]. Simultaneously, the traditional weak light linear regression method ($\text{PAR} \leq 200 \text{ mol m}^{-2} \text{ s}^{-1}$) was used to calculate the apparent quantum efficiency (AQY). The estimated light-response characteristic parameters were used as measured values for comparison with fitted values from the four models.

Models

1. Rectangular Hyperbola Model

The rectangular hyperbola model is expressed as [?]:

$$P_n = \frac{\alpha I P_{n \max}}{\alpha I + P_{n \max}} - R_d$$

where P_n is the net photosynthetic rate, $P_{n \max}$ is the maximum net photosynthetic rate, R_d is the dark respiration rate, I is photosynthetically active radiation, and α is the initial quantum efficiency.

The mathematical expression for the light compensation point is [?]:

$$\Phi_c = P'|_{I=I_c} = \frac{\alpha P_{n \max}^2}{(\alpha I_c + P_{n \max})^2} = \frac{\alpha R_d^2}{P_{n \max}^2}$$

If the model fits well, the light compensation point can be calculated using the intersection with the linear equation under weak light [?].

2. Non-rectangular Hyperbola Model

The non-rectangular hyperbola model is expressed as [?]:

$$P_n = \frac{\alpha I + P_{n \max} - \sqrt{(\alpha I + P_{n \max})^2 - 4\theta\alpha I P_{n \max}}}{2\theta} - R_d$$

where θ is the curvature angle of the non-rectangular hyperbola with a value range of [0,1], and other parameters have the same meaning as in equation (1).

The mathematical expressions for $P_{n \max}$ and LSP are [?]:

$$P_{n \max} = \frac{P_{n \max} - R_d}{\theta}$$

The LSP is the light intensity corresponding to the intersection of the P_n - I curve with the line $P_n = P_{n \max}$ [?].

3. Exponential Model

The exponential model is expressed as [?]:

$$P_n = P_{n \max}(1 - e^{-\alpha I/P_{n \max}}) - R_d$$

where the parameters have the same meaning as in equation (1). The mathematical expressions for $P_{n \max}$ and LSP are [?]:

$$P_{n \max} = P_{n \max} - R_d$$

$$LSP = \frac{P_{n \max}}{\alpha} \ln \left(\frac{\alpha}{R_d} \right)$$

4. Modified Rectangular Hyperbola Model

The modified rectangular hyperbola model is expressed as [?, ?, ?]:

$$P_n = \frac{\alpha I}{1 - \beta I} - \gamma I^2 - R_d$$

where β and γ are coefficients independent of I , and other parameters have the same meaning as in equation (1). The light intensity corresponding to $P_{n \max}$ is the saturation light intensity (LSP) [?, ?].

The mathematical expressions are [?]:

$$P_{n \max} = \frac{\alpha}{2\sqrt{\beta\gamma}} - R_d$$

$$LSP = \frac{1}{\sqrt{\beta\gamma}}$$

$$LCP = \frac{R_d}{\alpha}$$

1. Photosynthetic Light-Response Process of *P. euphratica* Under Drought Stress

The photosynthetic light-response curve reflects the potential photosynthetic capacity of plants under certain light intensities and their adaptability to the growth environment. Under drought stress, the P_n of *P. euphratica* showed different response patterns. Under different drought stresses, P_n increased curvilinearly with increasing PAR up to the light saturation point where maximum net photosynthetic rate ($P_{n \max}$) appeared, after which the light-response process showed obvious differences depending on drought stress severity.

Under low-to-moderate drought stress (RSWC > 45%), P_n reached saturation at approximately 2000 mol m⁻² s⁻¹, then decreased slowly and maintained relatively high levels with weak photoinhibition. Under moderate-to-severe drought stress (RSWC < 45%), P_n saturated at low light intensity, and when PAR > 1000 mol m⁻² s⁻¹, photoinhibition was obvious, indicating that insufficient soil moisture exacerbated photoinhibition of *P. euphratica* photosynthesis under strong light. As drought stress intensified, P_n decreased with significantly greater reduction amplitude.

[Figure 1: see original paper] The light-response curves of *P. euphratica* photosynthesis under different drought stresses

Compared with the control (A1), the P_n of *P. euphratica* under treatments A2, A3, A4, and A5 at PAR = 1500 mol m⁻² s⁻¹ decreased by 13.84%, 22.92%,

50.99%, and 71.54%, respectively; $P_{n\max}$ decreased by 13.41%, 25.29%, 51.72%, and 67.78%, respectively. Under low-to-moderate drought stress, *P. euphratica* could maintain relatively high P_n and $P_{n\max}$. From the perspective of population conservation and vegetation restoration, soil moisture in *P. euphratica* forests should be controlled at RSWC = 50%, which conforms to the management principles of plant growth and efficient water use in arid water-deficient areas.

2. Simulation of Photosynthetic Light-Response Process Under Drought Stress

The fitting effects of the four light-response models on the P_n -PAR response process of *P. euphratica* under drought stress showed obvious differences. Except for the modified rectangular hyperbola model, the other three models could not fit the decreasing process of P_n after reaching saturation light intensity. The rectangular hyperbola and non-rectangular hyperbola models produced asymptotic lines without extreme values, with the rectangular hyperbola model showing the greatest deviation from measured curves. The fitted points of these three models all showed large differences from measured points, especially under A4 and A5 treatments where the simulation effects were poorest.

The modified rectangular hyperbola model could better fit the P_n -PAR response under different drought stresses, with the highest consistency with measured curves, overcoming the shortcomings of other models that cannot simulate the decreasing trend of P_n with increasing PAR. The fitting effect was optimal, particularly under severe drought stress.

[Figure 2: see original paper] Simulation of photosynthesis-light response curves of *P. euphratica* by four models under different drought stresses

The fitted characteristic parameter values of the four photosynthetic models for *P. euphratica* P_n -PAR response under different drought stresses showed certain differences from measured values. When RSWC = 45%-80% (A3, A2, A1), all four models could fit the P_n -PAR response of *P. euphratica* well ($R^2 > 0.98$), but the fitting accuracy of light-response parameters varied among models. The rectangular hyperbola, non-rectangular hyperbola, and exponential models all fitted $P_{n\max}$ and LSP that were significantly higher than measured values and significantly lower than measured values ($P < 0.01$). The fitted $P_{n\max}$ values were 36.62%, 69.31%, and 72.14% lower than measured values, respectively; LSP values were 1.64%, 19.64%, and 8.16% lower than measured values, respectively.

When RSWC < 45%, the rectangular hyperbola and non-rectangular hyperbola models showed poor fitting effects ($R^2 < 0.936$), with large deviations between fitted and measured light-response characteristic parameter values, reaching extremely significant differences ($P < 0.01$). Only the modified rectangular hyperbola model could fit the P_n -PAR response and its characteristic parameters

well ($R^2 > 0.993$), especially under severe drought stress. This indicates that the model is suitable for fitting the P_n -PAR response process and characteristic parameters of *P. euphratica* in extremely arid desert regions.

Comparison with measured values of light-response parameters of *P. euphratica* and the fitted values by four models

3. Fitting Analysis of Light-Response Characteristic Parameters of *P. euphratica* Photosynthesis Under Drought Stress

Based on the above comparative analysis, the modified rectangular hyperbola model showed the highest fitting accuracy for light-response characteristic parameters [?]. Using this model to analyze the response patterns of *P. euphratica* photosynthesis to drought stress revealed that AQY reflects photosynthetic capacity under weak light conditions [?]. The AQY of *P. euphratica* under drought stress showed values between 0.036-0.055, decreasing gradually with intensifying drought stress but with small declines under moderate drought stress and obvious increases under moderate-to-severe drought stress, indicating that moderate drought stress is the turning point for significant changes in *P. euphratica* photosynthesis.

$P_{n\max}$, LSP, and LCP showed regular changes with drought stress intensification. $P_{n\max}$ and LSP decreased continuously with drought stress, with reductions of 14.23%, 25.83%, 50.16%, and 67.32% for $P_{n\max}$, and 6.52%, 20.50%, 51.76%, and 67.03% for LSP under A2, A3, A4, and A5 compared with A1 (control), respectively. This indicates that as drought stress intensified, the ability of *P. euphratica* to utilize strong light weakened and its effective photosynthetic range narrowed. LCP decreased continuously with drought stress when RSWC $> 30\%$, but increased significantly under severe drought stress (RSWC $< 25\%$), indicating that *P. euphratica* could enhance weak light utilization and conversion while reducing respiratory consumption to accumulate organic matter and resist drought stress. However, under extremely low soil moisture, the light inhibition term β and light saturation term γ [?, ?] increased substantially, indicating that under severe drought stress, the ability to utilize weak light decreased, light saturation and photoinhibition were easily reached, photosynthetic machinery was damaged, organic matter production capacity declined while respiratory consumption increased, leading to material supply-demand imbalance and susceptibility to starvation and death.

3. Discussion

Plant photosynthesis models have been widely applied to simulate photosynthetic processes and determine light-response characteristic parameters [?, ?, ?],

servicing as important tools for elucidating photosynthetic response mechanisms and evaluating photosynthetic efficiency. Many scholars have proposed different light-response models [?], each with certain advantages and disadvantages due to different derivation mechanisms [?, ?]. This study compared the simulation effects of four light-response models under different drought stresses. The rectangular hyperbola and non-rectangular hyperbola models could simulate the P_n -PAR response of *P. euphratica* under drought stress with better effects at higher water contents, consistent with results from Lang [?] and Wu [?]. However, they could not fit the photoinhibition stage under low water conditions, with extremely large deviations between fitted and measured points, the rectangular hyperbola model showing the poorest fitting effect.

Because the rectangular hyperbola model does not consider the curvature degree of light-response curves, to make curves better fit measured point distributions, the initial slope must be increased [?], resulting in poor fitting effects. These three models are asymptotic lines without extreme values, making it impossible to directly solve $P_{n\max}$ and LSP. Instead, nonlinear least squares methods must be used for estimation or the light intensity corresponding to 0.75, 0.9, or 0.99 of $P_{n\max}$ is used as saturation light intensity [?, ?, ?], causing fitted values to be significantly lower than measured values. These models are only suitable for habitats with good water conditions and are not suitable for studying light-response characteristics of desert plants under drought stress.

The modified rectangular hyperbola model can better fit the P_n -PAR response process under different drought stresses. Even under severe and extreme drought stress, it can well simulate the photoinhibition stage, making it suitable for simulating plant P_n -PAR response processes under various water conditions. Its simulation effect is superior to other models, consistent with reports that the modified rectangular hyperbola model shows better simulation effects than other models for plants such as apricot, *Artemisia ordosica*, and *Periploca sepium* under different water conditions [?, ?, ?], especially for fitting the photoinhibition stage under severe drought [?, ?, ?]. These results indicate that this model is not sensitive to drought stress responses and has strong applicability.

Soil moisture is an important factor affecting plant photosynthetic physiological processes [?], directly regulating important physiological activities such as plant photosynthesis, water physiology, and metabolism. The results show that when $\text{PAR} > 200 \text{ mol m}^{-2} \text{ s}^{-1}$, there is a threshold response relationship between P_n changes and soil moisture content. The lower the soil moisture, the more significant the photoinhibition. When $\text{PAR} \leq 200 \text{ mol m}^{-2} \text{ s}^{-1}$, photoinhibition was not obvious under low-to-moderate drought stress ($\text{RSWC} > 45\%$), but became obvious under moderate-to-severe drought stress ($\text{RSWC} < 45\%$). Apparent quantum efficiency (AQY) is an important indicator reflecting plant light use efficiency, generally determined as the slope of the regression equation fitting light-response data under weak light ($\text{PAR} \leq 200 \text{ mol m}^{-2} \text{ s}^{-1}$) [?, ?]. Under suitable growth conditions, AQY of most plants ranges between 0.03-0.05 [?]. Under different soil moisture conditions, AQY of *Ziziphus jujuba* var. *spinosa*,

Artemisia ordosica, and *Periploca sepium* ranges between 0.023-0.067, 0.042-0.066, and 0.015-0.047, respectively, decreasing with intensifying drought stress [?, ?, ?]. The AQY of *P. euphratica* under drought stress ranges between 0.036-0.055, indicating relatively high light use efficiency in desert habitats, though drought stress significantly reduced its light use efficiency (AQY, $P < 0.01$), consistent with results from Lu et al. [?, ?, ?].

However, some scholars believe that the light response under drought stress is nonlinear and suggest using the curve slope at $\text{PAR} \leq 200 \text{ mol m}^{-2} \text{ s}^{-1}$ as a measure of plant light use efficiency under weak light [?]. From the changing trends and patterns of *P. euphratica* light-response characteristic parameters under drought stress, $P_{n \max}$, LSP, and LCP showed regular changes with intensifying drought stress, gradually decreasing but with different response thresholds among parameters. Moderate drought stress (RSWC = 50%) was the turning point for significant changes in *P. euphratica* photosynthesis. When RSWC > 30%, LCP decreased continuously with drought stress, but increased significantly under severe drought stress (RSWC < 25%), indicating that as drought stress intensified, the light ecological amplitude of *P. euphratica* gradually narrowed, its adaptability to strong light environments gradually weakened, and its photosynthetic capacity decreased. However, *P. euphratica* could enhance weak light utilization and reduce respiratory consumption of photosynthetic products to accumulate organic matter and resist drought stress, adapting to desert arid environments. Nevertheless, under severe drought stress, both $P_{n \max}$ and LSP decreased significantly while respiration consumption increased [?], leading to organic nutrient imbalance. In the experiment, *P. euphratica* under severe drought stress showed obvious poor growth, yellowing and subsequent leaf shedding, eventually leading to premature senescence and death.

4. Conclusion

Light-response models show different adaptability to drought stress. The rectangular hyperbola, exponential, and non-rectangular hyperbola models are only suitable for habitats with good water conditions, whereas the modified rectangular hyperbola model is applicable to various environmental water conditions with more accurate estimation of light-response characteristic parameters, showing better applicability in extremely arid desert regions. In applying light-response models, the most appropriate fitting model should be selected based on actual habitat conditions to maximally ensure the correctness of fitted light-response characteristic parameters.

Low-water-variable desert arid habitats significantly inhibit the photosynthetic process and reduce photosynthetic efficiency of *P. euphratica*, narrowing its light ecological amplitude. When RSWC > 45%, *P. euphratica* can maintain relatively high $P_{n \max}$ and LSP, but when RSWC < 45%, drought stress causes irreversible damage to photosynthetic machinery, severely affecting normal seedling

growth and photosynthesis. In desert arid adversity, *P. euphratica* adopts ecological adaptation strategies of narrowing light ecological amplitude, reducing light energy use efficiency, and decreasing respiratory consumption of photosynthetic products to resist drought stress damage. From the perspective of population conservation and vegetation restoration in extremely arid desert regions, soil moisture in *P. euphratica* forests should be maintained at 50% RSWC, which conforms to the management principles of plant growth and efficient water use in water-deficient areas.

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