Effects of Artificially Layered Soil on Light-Response Parameters and Model Applicability of Elm in the Arid Region of the Qinghai-Tibet Plateau

2026-07-23

ChinaRxiv

Abstract

To reveal the effects of artificial layered soil (ArtificiallyLayeredSoil, ALS) on vegetation photosynthetic capacity in saline-alkali land of the arid region of the Qinghai-Tibet Plateau, and to evaluate the applicability of photosynthesis-light response models to typical vegetation in this region, Ulmus pumila, a typical vegetation species in the Huatugou area, was selected as the study object, with two treatments established: ALS and field undisturbed soil (Field Undisturbed Soil, FUS). During the growing seasons of 2024–2025 (July–September), under typical clear weather conditions, a GFS3000 photosynthesis system was used to measure the net photosynthetic rate (Net Photosynthetic Rate, Pn) of Ulmus pumila leaves under 14 photosynthetically active radiation (Photosynthetically Active Radiation, PAR) gradients, and Pn-PAR curves were constructed. The rectangular hyperbola model (Rectangular Hyperbola Model, RH), non-rectangular hyperbola model (Non-rectangular Hyperbola Model, NRH), modified rectangular hyperbola model (Modified Rectangular Hyperbola Model, MRH), and exponential model (Exponential Model, EM) were selected for fitting, and model performance was evaluated using the coefficient of determination (R2), root mean square error (RMSE), mean absolute error (MAE), and coefficient of variation of parameters (Cv). The results showed that Pn of Ulmus pumila under the ALS treatment was generally higher than that under FUS, with the maximum net photosynthetic rate increased by 45.85%~111.11% compared with FUS; stomatal conductance (Gs) was also generally higher and maintained high values for a longer duration, while the apparent quantum yield (ApparentQuantumYield, AQY) in the low-light range was generally higher. These findings indicate that the layered structure of ALS may synergistically enhance the high-light potential photosynthetic capacity, stomatal regulation ability, and low-light utilization efficiency of Ulmus pumila by regulating soil water-salt processes and improving the rhizosphere environment. In terms of model applicability, all four models could describe the overall trend of Pn-PAR, among which NRH and MRH showed smaller overall fitting errors and more reasonable parameters. Considering both goodness of fit and parameter stability, the applicability of the models was ranked as: NRH MRH>EM>RH. This study reveals the characteristics of vegetation photosynthetic responses and differences in model applicability under two soil structures in saline-alkali land of the arid region of the Qinghai-Tibet Plateau, providing data support and a theoretical basis for vegetation restoration, saline-alkali land improvement, and light response model selection in this region.

Full Text

DOI: 10.13866/j.azr.2026.07.12
CSTR: 32277.14.AZR.20260712

Effects of Artificially Layered Soil on Light-Response Parameters and Model Applicability of Elm in the Arid Region of the Qinghai-Tibet Plateau

Zhan Dongshan1, Chen Zhenxing2, Zhang Yongxing3, Hao Jia2, Wang Shangtao1, Gan Yongde1, Zhang Zhaolin1

(1. College of Civil Engineering and Water Conservancy, Qinghai University; Laboratory of Ecological Protection and High-Quality Development in the Upper Yellow River; Key Laboratory of Water Ecology Governance and Protection in the Jiangheyuan Region, Ministry of Water Resources, Xining, Qinghai 810016, China; 2. Qinghai Provincial Center for Land Consolidation and Ecological Restoration, Xining, Qinghai 810016, China; 3. Xining Natural Resources Comprehensive Survey Center, China Geological Survey, Xining, Qinghai 810000, China)

Abstract: To reveal the effects of artificially layered soil (ALS) in saline-alkali land of the arid region of the Qinghai-Tibet Plateau on plant photosynthetic capacity, and to evaluate the applicability of photosynthesis-light response models for typical vegetation in this region, this study took elm, a typical vegetation species in the Huahugou area, as the research object and established two treatments: ALS and field undisturbed soil (FUS). During the 2024-2025 growing seasons (July-September), under typical clear-weather conditions, a GFS-3000 photosynthesis system was used to measure the net photosynthetic rate of elm leaves under 14 gradients of photosynthetically active radiation (PAR), and P_n-PAR curves were constructed. The rectangular hyperbola model (RH), non-rectangular hyperbola model (NRH), modified rectangular hyperbola model (MRH), and exponential model (EM) were selected for fitting, and model performance was evaluated using the coefficient of determination (R^2), root mean square error (RMSE), mean absolute error (MAE), and coefficient of variation of parameters (C_v). The results showed that, under ALS treatment, elm P_n was overall higher than under FUS; the maximum net photosynthetic rate increased by 45.85%-111.11% compared with FUS; stomatal conductance (G_s) was generally higher, with a longer duration of high values; and apparent quantum yield (AQY) in the weak-light period was generally higher. This indicates that the layered structure of ALS may enhance the high-light potential photosynthetic capacity, stomatal regulation ability, and weak-light utilization efficiency of elm by regulating soil water-salt processes and improving the rhizosphere environment. In terms of model applicability, all four models could describe the overall trend of P_n-PAR; among them, NRH and MRH had smaller overall fitting errors and more reasonable parameters. The ranking of model applicability was NRH MRH>EM>RH. This study reveals the differences in vegetation light-response characteristics and model applicability under two soil structures in saline-alkali land of the arid region of the Qinghai-Tibet Plateau, and can provide data support and a theoretical basis for vegetation restoration, saline-alkali land improvement, and selection of light-response models in this region.

Keywords: arid region of the Qinghai–Tibet Plateau; artificially layered soil; elm; light-response model; light-response curve

Plant photosynthesis is highly sensitive to the light environment, and light-response curves can reflect the variation patterns and adaptability of plant photosynthetic capacity with changes in light intensity[1]. Among them, key parameters such as apparent quantum efficiency, maximum net photosynthetic rate, light saturation point, and light compensation point are important eco-physiological parameters of plant light-response characteristics, and are used to describe plant weak-light utilization capacity and high-light potential productivity[2]. Over the years, scholars in China and abroad have conducted in-depth studies on the light-response characteristics of various vegetation types in different regions. On this basis, multiple light-response models have been established, such as the rectangular hyperbola, non-rectangular hyperbola, exponential, and modified rectangular hyperbola models, which are used to study the light-response processes of different plants[3–6]. A comprehensive analysis indicates that these models may differ in their depiction of the slope in the weak-light segment, the curvature of the transition from low to moderate light, and the fitting of the high-light saturation plateau, thereby revealing the stability and reliability of estimated photosynthetic parameters[7]. However, related studies have mostly focused on vegetation in plains, farmland, and humid or semi-humid regions. For the arid region of the Qinghai–Tibet Plateau—a special habitat characterized by high elevation, strong radiation, large diurnal temperature differences, and water limitation—systematic experiments are still lacking on the cross-month stability of parameters in existing light-response models and the fitting reliability of these models across different light-intensity ranges. At the same time, studies on the light-response characteristics of typical vegetation and model applicability under different soil-structure conditions remain relatively weak.

The arid region of the Qinghai–Tibet Plateau has a dry climate, scarce precipitation, and intense evaporation, accompanied by the coexistence of frequent windblown sand and strong sunshine. In combination with adverse soil conditions such as saline–alkali soils, these factors impose significant constraints on the stable growth of vegetation[8–10]. In

Received: 2025-12-29; **Revised:** 2026-03-17
Funding: Ministry of Natural Resources ministry–province cooperation project (2024ZRBHZ116); comprehensive ecological survey of salt lakes in the Qaidam Basin (DD20220958); Qinghai University research capacity enhancement project (2025KTST07)
Author biography: Zhan Dongshan (2001–), male, master' s student, mainly engaged in research on ecohydrological processes in arid regions. E-mail:

17630925010@163.com
Corresponding author: Wang Shangtao. E-mail: 2019990024@qhu.edu.cn

Against this background, road greening and ecological restoration often rely on salt-tolerant tree species to enhance windbreak, sand-fixation, and landscape-service functions. As one of the common local tree species, elm is of considerable ecological and engineering significance in studies of environmental adaptability. Meanwhile, to improve the soil environment and promote vegetation growth in the arid saline-alkaline areas of the plateau, our previous work proposed an artificial sand-interlayered topsoil structural reconstruction technique—artificial layered soil configuration [11–12]. Based on principles of soil physics, this technique reconstructs the layering and particle composition of surface soil through engineering measures, with the aim of improving infiltration capacity, reducing ineffective evaporation, improving the vegetation growth environment, and optimizing ecohydrological characteristics such as photosynthesis and transpiration. Therefore, this study takes elm, a species with strong adaptability and wide distribution in the arid regions of the Qinghai–Tibet Plateau, as the research object [13], analyzes the light-response parameters of its leaves under different soil treatments, and compares the applicability of four models in the arid region of the Qinghai–Tibet Plateau. On the basis of regional environmental characteristics and previous research, the following hypotheses are proposed: compared with undisturbed field soil, artificial layered soil configuration can improve the photosynthetic capacity of elm by improving the soil water–salt environment; compared with the rectangular hyperbola model and the exponential model, the non-rectangular hyperbola model and the modified rectangular hyperbola model have better fitting performance and higher parameter stability in the arid region of the Qinghai–Tibet Plateau; and the applicability of different models may differ between the low-light transition stage and the high-light saturation stage. This paper aims to clarify the light-response characteristics and model applicability of vegetation under different soil-structure conditions in the arid region of the Qinghai–Tibet Plateau, thereby providing data support for research on vegetation photosynthetic characteristics and model application.

1 Data and Methods

1.1 Overview of the Study Area

The experimental field is located in Huatugou Town, Mangya City, Haixi Prefecture, Qinghai Province ($38°18'N, 90°51'E$), at an average elevation of 2940 m, as shown in Fig. 1. Huatugou Town is situated in the northwestern part of the Qaidam Basin and is the main crude-oil production base of the Qinghai Oilfield. Huatugou Town has a continental desert climate, with a mean annual temperature of 3.8 °C. The hottest month is July, with a mean temperature of 18.5 °C; the coldest month is January, with a mean temperature of −12.4 °C. Mean annual precipitation is 44 mm. There are more than 125 days of strong winds annually, mostly northwesterly winds above Force 8; the mean annual wind speed is 3.1 $m \cdot s^{-1}$, and the maximum wind speed is 22.3 $m \cdot s^{-1}$. Annual sunshine duration is 3173.2 h, with a sunshine percentage of 72%. The regional soil type is mainly saline sandy soil, with high salt content, representing a typical saline–alkaline land. The principal greening tree species is elm.

1.2 Experimental Design

The study area has scarce precipitation, high evaporation, and relatively high soil salinity; the soil is severely desertified and subject to serious wind erosion. To reduce ineffective soil evaporation, control salt return to the soil surface, and enhance the soil' s resistance to wind erosion, the structure of the regional soil profile was reconstructed. The engineering treatment consisted of directly covering the original soil layer with a soil–gravel mixed medium; the fine soil was sandy soil, the mass ratio of gravel to sandy soil was 2:3, the gravel particle size was 1–3 cm, and the covering thickness was 10 cm (Fig. 2).

Fig. 1 Map of study area.

Labels in Fig. 2: 10 cm; protective layer; water-separating layer; water-storage layer.

Fig. 2 Schematic diagram of artificially layered soil

This study included only a field undisturbed-soil control treatment, FUS (Field Undisturbed Soil, FUS), and a 10 cm-thick artificially layered soil treatment, ALS (Artificially Layered Soil, ALS). The choice of a 10 cm thickness was mainly based on the fact that, in engineering practice, it can better meet the basic requirements of blocking capillary water rise, suppressing salt return, and improving the root-zone environment, while also taking into account material cost and construction feasibility[^12]. Therefore, this paper aims to compare the differences between the representative ALS treatment and the FUS control, rather than to optimize and screen different layer thicknesses. The soil particle gradation of FUS is shown in Table 1. The irrigation method was surface flooding.

The experiment established two treatment plots, ALS and FUS. The area of each plot was approximately 333 m^2. Within each plot, elm trees were planted at a spacing of 1 m, with a row spacing of 1.2 m, to ensure sufficient growing space; planting was carried out in May 2024. The experimental group (ALS) and the control group (FUS) were both planted with elm seedlings of the same seedling age; the initial plant height and diameter at breast height were 1.9 m and 3.34 cm, respectively. When photosynthetic indices were measured, the elms under the ALS treatment had plant heights of 2.58–4.2 m and diameters at breast height of 3.67–5.41 cm; the sample plants under the FUS treatment had plant heights of 2.14–3.37 m and diameters at breast height of 3.46–4.55 cm.

Table 1. FUS soil particle gradation

Soil-layer depth / cm	Elevation / m	Clay (<2 μm) / %	Silt (2–50 μm) / %	Sand (>50 μm) / %
0–25	2910.48	5.78	93.19	1.02
25–50	2910.48	5.88	92.77	1.35
50–75	2910.48	3.24	79.04	17.72
75–100	2908.39	2.85	92.37	4.78

1.3 Measurement Methods

A portable photosynthesis-fluorescence measurement system (model GFS-3000, WALZ) was used to measure the light-response characteristics of elm leaves under the two soil treatments, obtaining net photosynthetic rate-photosynthetically active radiation (P_n-PAR) curves. In this experiment, healthy leaves free of diseases and insect pests were measured under constant leaf-chamber temperature and CO_2 concentration (25 °C, 400 ppm) at 14 photosynthetically active radiation (PAR) gradients, namely 1800, 1600, 1400, 1200, 1000, 900, 800, 700, 600, 500, 400, 300, 200, and 100 $\mu\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, to determine net photosynthetic rate (P_n). In this study, the lowest PAR gradient was set to 100 $\mu\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, and the low-light intervals of PAR = 0 and 0–100 $\mu\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ were not covered. Therefore, the light compensation point (LCP) and dark respiration rate (R_d) could not be obtained by strict direct measurement, and instead mainly relied on model fitting for estimation. Although apparent quantum yield (AQY) can be obtained by fitting the low-light segment, because the initial interval closer to the light compensation point was not covered, the estimated results may have certain deviations. Based on this, the analysis of LCP and R_d in this paper mainly focuses on comparing differences among models, and no further coefficient of variation (C_v) analysis was conducted for the two parameters. During the growing seasons of 2024 and 2025 (July–September), measurements were carried out each month on selected typical clear, cloudless, and dust-free days. For each measurement, one elm tree was fixed as the observation object, and data from different individuals were not mixed throughout the observation period. To reduce the influence of differences in leaf position, mature leaves with relatively consistent leaf positions and normal growth were selected each time from the sun-facing side of the middle and upper crown of that plant. One complete light-response curve measurement was completed each month. Under the preset PAR gradients, net photosynthetic rate was recorded after the leaves had acclimated for 180 s; each light-intensity gradient was measured continuously three times, and the mean value was taken as the observed value at that light-intensity level.

1.4 Research Methods

To evaluate the typical vegetation light-response characteristics and model applicability of different photosynthesis–light response models under different soil-structure conditions, four commonly used models were selected to fit and assess the light-response curves. The main forms of the models are summarized as follows:

Rectangular hyperbola model (RH)[^13]:

$$P_n = \frac{\alpha I P_{n\max}}{\alpha I + P_{n\max}} - R_d \tag{1}$$

where P_n is the net photosynthetic rate (μmol · m^{-2} · s^{-1}); α is the initial quantum efficiency (μmol · m^{-2} · s^{-1}); $P_{n\max}$ is the maximum net photosynthetic rate (μmol · m^{-2} · s^{-1}); R_d is the dark respiration rate (μmol · m^{-2} · s^{-1}); and I is photosynthetically active radiation (μmol · m^{-2} · s^{-1}), expressed as PAR.

The formula for calculating the light compensation point I_c is[^14]:

$$I_c = P_{n\max} R_d / [\alpha (P_{n\max} - R_d)] \tag{2}$$

Non-rectangular hyperbola model (NRH)[^5]:

$$P_n = \frac{\alpha I + P_{n\max} - \sqrt{(\alpha I + P_{n\max})^2 - 4\theta \alpha I P_{n\max}}}{2\theta} - R_d \tag{3}$$

where θ is the curvature of the non-rectangular hyperbola[^15], and the meanings of the other parameters are the same as in Eq. (1).

The LCP expression is:

$$I_c = (R_d P_{n\max} - \theta R_d^2) / [\alpha (P_{n\max} - R_d)] \tag{4}$$

Modified rectangular hyperbola model (MRH)[^16]:

$$P_n = \alpha \frac{1 - \beta I}{1 + \gamma I} I - R_d \tag{5}$$

$$P_{n\max} = \alpha \left(\frac{\sqrt{(\beta + \gamma)/\beta} - 1}{\gamma} \right) - R_d \tag{6}$$

where α, β, and γ are coefficients independent of I; the meanings of the other parameters are the same as in Eq. (1).

Exponential model (EM)[6]:

$$P_n = P_{n\max} \left(1 - e^{-\alpha I / P_{n\max}}\right) - R_d \tag{7}$$

The expression for LCP is:

$$I_c = (P_{n\max}/-\alpha)\ln\left[(P_{n\max} - R_d)/P_{n\max}\right] \tag{8}$$

Model accuracy was validated using the root mean square error[17] (RMSE), mean absolute error[17] (MAE), and coefficient of determination (R^2) to test the goodness of fit of the four models. In addition, the coefficient of variation of parameters[18] (C_v) was used to evaluate the cross-month stability of model parameters. The calculation formulas are as follows:

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(O_i - S_i)^2} \tag{9}$$

$$\mathrm{MAE} = \frac{1}{n}\sum_{i=1}^{n}|O_i - S_i| \tag{10}$$

$$C_v = \frac{\sigma}{\mu} \times 100\% \tag{11}$$

where O_i is the measured value; S_i is the simulated value; n is the sample size; C_v is the coefficient of variation of the parameters; σ is the standard deviation; and μ is the mean.

The parameters of each model were fitted using the nonlinear least-squares method. Initial values were obtained from empirical estimates based on the observed data: the initial value of α was taken as the slope of the linear regression of P_n-PAR in the low-light range ($100 \sim 400\ \mu\mathrm{mol} \cdot \mathrm{m}^{-2} \cdot \mathrm{s}^{-1}$), and the initial value of $P_{n\max}$ was taken as the maximum P_n value in the high-light plateau range. To ensure parameter rationality and improve convergence stability, parameter boundaries were set as $P_{n\max} > 0$, $R_d \geq 0$, $\alpha > 0$, and $\theta \in (0, 1]$; the fitting results were verified by repeating the fits with different initial values. To more accurately reflect the light conditions of the arid region of the Qinghai–Tibet Plateau and the actual photosynthetic behavior of plants, this study separately discussed the applicability of the models in the high-light range ($\mathrm{PAR} \geq 1200\ \mu\mathrm{mol} \cdot \mathrm{m}^{-2} \cdot \mathrm{s}^{-1}$) and in the medium- and low-light range ($\mathrm{PAR} < 1200\ \mu\mathrm{mol} \cdot \mathrm{m}^{-2} \cdot \mathrm{s}^{-1}$).

1.5 Data processing and analysis

Microsoft Excel 2019 was used for statistical processing and preliminary calculation of the data. Origin 2019b was used for data fitting and graphing. Analysis of variance, regression analysis, and other statistical analyses were completed using SPSS statistical analysis software (SPSS 26.0 for Windows, USA).

2 Results and analysis

2.1 Characteristics of photosynthetic light-response curves of elm trees under two soil treatment methods

The light-response curves of elm trees under the two treatment methods are shown in Fig. 3. Across the entire PAR gradient, the net photosynthetic rate of elm trees under ALS treatment was significantly higher than that under FUS. During the two growing seasons, from July to September, the maximum net photosynthetic rate under ALS treatment increased by 45.85%–111.11% compared with FUS. From the monthly

Legend: ALS; FUS. Panels: (a) July 2024; (b) August 2024; (c) September 2024; (d) July 2025; (e) August 2025; (f) September 2025.

Figure 3 Light response of elm trees under two soil treatment methods

Fig. 3 Light response curves of *Ulmus pumila* trees under two soil treatment methods

Fig. 4 Diurnal variations of stomatal conductance of *Ulmus pumila* under two treatment methods

Subpanels: (a) July 2024; (b) August 2024; (c) September 2024; (d) July 2025; (e) August 2025; (f) September 2025. Treatments: ALS and FUS. Vertical axis: G_s ($\mathrm{mmol \cdot m^{-2} \cdot s^{-1}}$). Horizontal axis: time.

Judging from the characteristics of intermonthly variation, the maximum P_n of *Ulmus pumila* under ALS treatment showed a seasonal trend of first increasing and then decreasing, reaching the highest value during the observation period in July and declining slightly in August–September. In contrast, the maximum P_n under FUS treatment was generally at a lower level, with smaller fluctuations from July to September and relatively gentle seasonal variation. The P_n of *U. pumila* under ALS treatment reached a relatively high level when PAR was around $1200 \sim 1600\ \ \mathrm{mol \cdot m^{-2} \cdot s^{-1}}$, and the maximum values in both years occurred in July, at $17.999\ \ \mathrm{mol \cdot m^{-2} \cdot s^{-1}}$ and $19.75\ \ \mathrm{mol \cdot m^{-2} \cdot s^{-1}}$, respectively. The light-response curve under FUS treatment increased slowly; its maximum net photosynthetic rate over the two years, $11.27\ \ \mathrm{mol \cdot m^{-2} \cdot s^{-1}}$, was significantly lower than the P_n of *U. pumila* under ALS treatment. Moreover, the two-year average net photosynthetic rate under ALS treatment, $10.49\ \ \mathrm{mol \cdot m^{-2} \cdot s^{-1}}$, was 78.1% higher than that under FUS ($5.89\ \ \mathrm{mol \cdot m^{-2} \cdot s^{-1}}$).

2.2 Diurnal variation characteristics of stomatal conductance of *Ulmus pumila* under two soil treatment methods

As shown in Fig. 4, during two consecutive growing seasons, the stomatal conductance (G_s) of *U. pumila* under ALS treatment was generally higher than that under FUS treatment, and the period during which high values persisted was longer. In terms of seasonal variation, G_s of *U. pumila* during the two growing seasons generally showed the characteristic of being higher in the early growing season and decreasing in the later period: it was generally at a relatively high level in July, followed by August, and was lowest in September. The intermonthly decline was more pronounced in the second growing season. In July 2024, the diurnal variation of G_s under ALS treatment showed a bimodal pattern, with peaks of 95.50 $\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ and 60.93 $\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, respectively, which were 50.37% and 58.46% higher than those under FUS treatment. In August and September 2024, the daily mean G_s under ALS treatment was 9.31% $\sim$ 31.94% higher than that under FUS. From July to September 2025, G_s fluctuated markedly under both treatments; in August and September 2025, the mean G_s under ALS treatment was 11.80% $\sim$ 22.84% higher than that under FUS.

2.3 Comparison of photosynthesis-light response curve models for *Ulmus pumila* under two soil treatment methods

It can be seen from Table 2 and Figs. 5-8 that all four models could fit well the relationship between leaf P_n and PAR of *U. pumila* under the two treatment methods ($R^2 \geq 0.95$ in most months), with only individual months showing lower values (for example, RH fitting the ALS treatment in August 2024, $R^2 = 0.908$). Among them, for the light-response curve models under FUS treatment, the differences in R^2, RMSE, and MAE were all not significant ($P > 0.05$); NRH had the largest R^2, RH the smallest, MRH had the smallest RMSE and MAE, and RH the largest. In contrast, under ALS treatment, the differences among models were more pronounced: RH and EM differed significantly from NRH and MRH ($P < 0.05$); MRH had the largest R^2, and NRH had the smallest RMSE and MAE. As shown in Fig. 5, for $P_{n\,\max}$, the C_v values of the various models under ALS and FUS treatments were relatively low, ranging from 8% $\sim$ 31%. Among them, the C_v of $P_{n\,\max}$ for MRH was the lowest, while that for RH was the highest. For AQY, the C_v values fluctuated greatly; under FUS treatment, the AQY C_v fitted by NRH and MRH was markedly higher than that of the other models, whereas under ALS treatment, the AQY C_v was relatively low, varying within 10% $\sim$ 22%.

The photosynthesis-light response curve reflects the dynamic response process of the net photosynthetic rate P_n to photosynthetically active radiation (PAR) [19–23]. The light-energy utilization efficiency of leaves under ALS treatment fluctuated little overall in the low-light range; under FUS treatment,

Tab. 2 Photosynthesis of *Ulmus pumila* trees under two soil treatment conditions and comparison of photosynthetic parameters fitted by four photosynthetic-light response models with the measured values

Treatment method	Time/year-month	Model	AQY / (μmol·mol^{-1})	P_{max} / (μmol·m^{-2}·s^{-1})	LCP / (μmol·m^{-2}·s^{-1})	R_d / (μmol·m^{-2}·s^{-1})	R^2	RMSE	MAE
ALS		Measured value	–	13.00–20.00	–	–	–	–	–
ALS	2024-07	RH	0.0235	41.18	59.39	1.350	0.961	1.245	0.971
ALS	2024-07	NRH	0.0146	17.87	6.71	0.098	0.990	0.332	0.469
ALS	2024-07	MRH	0.0164	18.71	63.05	0.465	0.982	0.583	0.675
ALS	2024-07	EM	0.0213	24.99	3.24	0.069	0.965	1.136	0.939
ALS	2024-08	RH	0.0232	24.52	62.04	1.367	0.908	1.586	1.079
ALS	2024-08	NRH	0.0121	13.01	12.98	0.157	0.977	0.395	0.533
ALS	2024-08	MRH	0.0141	13.03	70.73	0.459	0.959	0.698	0.725
ALS	2024-08	EM	0.0219	15.29	63.04	1.320	0.978	1.414	1.024
ALS	2024-09	RH	0.0326	19.74	28.09	0.875	0.966	0.431	0.546
ALS	2024-09	NRH	0.0100	11.08	49.70	0.497	0.971	0.358	0.456
ALS	2024-09	MRH	0.0137	14.90	3.17	0.580	0.981	0.241	0.406
ALS	2024-09	EM	0.0231	14.56	38.33	0.859	0.969	0.39	0.55
ALS	2025-07	RH	0.0255	42.40	84.69	2.055	0.962	1.16	1.005
ALS	2025-07	NRH	0.0154	19.04	38.83	0.598	0.988	0.42	0.512
ALS	2025-07	MRH	0.0172	21.12	5.24	0.970	0.985	0.548	0.62
ALS	2025-07	EM	0.0223	25.35	39.93	0.875	0.966	1.22	0.977
ALS	2025-08	RH	0.0256	39.14	59.83	1.474	0.981	0.641	0.602
ALS	2025-08	NRH	0.0146	18.03	14.26	0.211	0.993	0.211	0.366
ALS	2025-08	MRH	0.0172	18.96	51.02	0.342	0.992	0.27	0.432

Treatment method	Time/year-month	Model	AQY / (μmol·mol^{-1})	$P_{\max}$ / (μmol·m^{-2}·s^{-1})	LCP / (μmol·m^{-2}·s^{-1})	R_d / (μmol·m^{-2}·s^{-1})	R^2	RMSE	MAE
ALS	2025-08	EM	0.0234	25.72	6.40	1.330	0.983	0.555	0.564
ALS	2025-09	RH	0.0211	47.42	7.80	0.164	0.983	0.574	0.606
ALS	2025-09	NRH	0.0137	18.34	17.88	0.245	0.997	0.101	0.259
ALS	2025-09	MRH	0.0149	19.07	89.47	0.374	0.995	0.161	0.354
ALS	2025-09	EM	0.0201	29.34	0.65	0.013	0.984	0.527	0.591
FUS		Measured value	–	9.00-11.50	–	–	–	–	–
FUS	2024-07	RH	0.0171	20.19	17.63	0.297	0.981	0.960	0.358
FUS	2024-07	NRH	0.0082	10.14	32.68	0.268	0.988	0.12	0.258
FUS	2024-07	MRH	0.0100	11.34	7.65	0.336	0.991	0.095	0.239
FUS	2024-07	EM	0.0147	13.88	4.71	0.069	0.983	0.175	0.336
FUS	2024-08	RH	0.0106	15.89	7.87	0.083	0.994	0.032	0.159
FUS	2024-08	NRH	0.0290	12.89	45.45	1.318	0.956	0.233	0.418
FUS	2024-08	MRH	0.0220	8.59	9.36	0.321	0.987	0.024	0.124
FUS	2024-08	EM	0.0095	11.01	17.50	0.165	0.993	0.037	0.169
FUS	2024-09	RH	0.0118	18.25	33.51	0.387	0.982	0.126	0.298
FUS	2024-09	NRH	0.0067	8.51	32.84	0.220	0.988	0.081	0.246
FUS	2024-09	MRH	0.0078	9.09	16.60	0.098	0.991	0.061	0.198
FUS	2024-09	EM	0.0110	12.02	27.53	0.299	0.983	0.112	0.281
FUS	2025-07	RH	0.0102	21.50	29.42	0.296	0.991	0.058	0.221
FUS	2025-07	NRH	0.0059	8.82	40.51	0.239	0.985	0.110	0.274

Treatment method	Time/year-month	Model	AQY / (μmol·mol^{-1})	P_{max} / (μmol·m^{-2}·s^{-1})	LCP / (μmol·m^{-2}·s^{-1})	R_d / (μmol·m^{-2}·s^{-1})	R^2	RMSE	MAE
FUS	2025-07	MRH	0.0185	10.25	7.93	0.286	0.993	0.053	0.190
FUS	2025-07	EM	0.0094	13.88	28.90	0.269	0.992	0.060	0.228

Table 2 (continued)

Treatment method	Time / year-month	Model	AQY / (μmol·mol^{-1})	P_{nmax} / (μmol·m^{-2}·s^{-1})	LCP / (μmol·m^{-2}·s^{-1})	R_d / (μmol·m^{-2}·s^{-1})	R^2	RMSE	MAE
FUS		Measured value	–	9.00–11.50	–	–	–	–	–
FUS	2025-08	RH	0.0108	22.55	19.25	0.206	0.982	0.142	0.336
FUS	2025-08	NRH	0.0075	10.87	51.47	0.386	0.984	0.127	0.304
FUS	2025-08	MRH	0.0079	10.62	8.18	0.390	0.985	0.123	0.29
FUS	2025-08	EM	0.0103	14.72	11.11	0.114	0.983	0.138	0.333
FUS	2025-09	RH	0.0136	16.37	39.88	0.525	0.959	0.276	0.422
FUS	2025-09	NRH	0.0069	8.14	32.75	0.226	0.988	0.078	0.226
FUS	2025-09	MRH	0.0082	8.72	31.41	0.148	0.987	0.085	0.243
FUS	2025-09	EM	0.0123	11.10	37.94	0.457	0.965	0.238	0.388

Note: RH denotes the rectangular hyperbola model; NRH denotes the non-rectangular hyperbola model; MRH denotes the modified rectangular hyperbola model; EM denotes the exponential model; AQY denotes apparent quantum efficiency; P_{nmax} denotes the maximum net photosynthetic rate; R_d denotes the dark respiration rate.

Note: RH denotes the rectangular hyperbola model; NRH denotes the non-rectangular hyperbola model; MRH denotes the modified rectangular hyperbola

model; EM denotes the exponential model. The same applies below.

Fig. 5 Comparison of the coefficient of variation of each model parameter under the two treatments

The AQY fluctuated markedly: under ALS, AQY was 0.01-0.0326, whereas under FUS it was 0.0058-0.029. When estimating P_n in the high-light region, the EM fitted curve was clearly lower; its estimates of AQY were relatively concentrated under ALS treatment (0.0201-0.0231), but fluctuated more markedly under FUS (0.0094-0.0147). Moreover, under both treatments, the EM-fitted values for the maximum P_n were higher than the measured values, with mean differences of 5.092 (ALS) and 3.12 (FUS). The peak P_n simulated by the RH model ranged from 19 to 42 μmol$\cdot$m$^{-2}\cdot$s^{-1} under ALS and from 15 to 23 μmol$\cdot$m$^{-2}\cdot$s^{-1} under FUS, both differing substantially from the actual values; its AQY was higher and more variable under ALS (0.0211-0.0326), and was 0.0102-0.0171 under FUS. The RH-fitted maximum P_n under the two soil treatments differed significantly from the measured values ($P < 0.05$) (Fig. 8), with mean differences as high as 18.505 (ALS) and 9.477 (FUS), indicating the poorest fitting performance. By comparison, the AQY fitted by MRH was relatively stable under ALS treatment (0.0137-0.0172). When PAR $\geq$ 1200 μmol$\cdot$m$^{-2}\cdot$s^{-1}, the MRH estimates of the maximum P_n were closer to the measured values in most months ($P = 0.919$), and the mean differences in maximum P_n under the two treatments were only 0.359 (ALS) and 0.815 (FUS). Across different months of the two-year growing season and under the two soil treatments, the maximum P_n estimated by NRH was generally comparable to that estimated by MRH; the mean difference was 0.948 under ALS (higher than MRH) and 0.247 under FUS (lower than MRH). Its AQY under ALS treatment was 0.0100-0.0154.

3 Discussion

In this study, the soil structure was reconstructed using an artificial layered soil configuration technique, thereby altering the soil environment for elm root growth. Compared with FUS treatment, ALS treatment significantly increased the measured maximum net photosynthetic rate (P_{nmax}) and stomatal conductance (G_s) of elm leaves, and the apparent quantum efficiency (AQY) fitted by the models was also generally at a higher level. This indicates that ALS treatment can simultaneously enhance the photosynthetic potential of elm leaves under high-light conditions and their stomatal regulatory capacity, while also improving their light-energy utilization efficiency during low-light periods. This conclusion is broadly consistent with the findings of Zhang Yongxing et al. [12] that ALS treatment can improve the photosynthetic capacity of alfalfa. Considering the ecological context of the arid Qinghai-Tibet Plateau, where high evaporation, strong radiation, and saline-alkaline stress coexist, it can be inferred that ALS, by reconstructing the surface soil structure, to some extent suppressed ineffective evaporation and salt return, improved the water-salt environment and soil physical conditions in the root zone [24-27], thereby enhancing root water uptake capacity, reducing the degree of stomatal closure in leaves, and ultimately producing synchronous increases in P_n, G_s, and AQY. Therefore, the promoting effect of ALS on the photosynthetic characteristics of elm is not a change in a single parameter, but more likely reflects a coupled process of "improvement of the root-zone environment—enhancement of stomatal regulation—increase in light-energy utilization effi-

Figure 6. Simulation of photosynthetic light-response curves of *Ulmus pumila* under FUS and ALS treatments using four models

- **FUS treatment**: (a) July 2024; (b) August 2024; (c) September 2024; (d) July 2025; (e) August 2025; (f) September 2025.
- **ALS treatment**: (g) July 2024; (h) August 2024; (i) September 2024; (j) July 2025; (k) August 2025; (l) September 2025.
- Legend: observed value; RH; NRH; MRH; EM.
- Axes: $P_n/(\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1})$ and $PAR/(\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1})$.

⋯a synergistic response of "increased rate."

Many scholars in China and abroad have proposed and fitted different light-response models. Because their derivation mechanisms and approaches differ, each model has certain advantages and disadvantages [28–29]. In this study, four models were used to fit the photosynthetic light-response process of a typical vegetation species in the arid region of the Qinghai–Tibet Plateau under two soil-treatment methods. RMSE, MAE, and R^2 were used to measure fitting accuracy, while C_v was used to evaluate the stability of model parameters across months. The fitting performance and parameter stability of the four models for the P_n-PAR response process of elm differed markedly. MRH and NRH had lower RMSE and MAE and higher R^2, indicating that their overall fitting accuracy for the measured curves was relatively high.

At the same time, both models had generally low C_v values for $P_{\max}$, indicating relatively stable estimates of high-light parameters; therefore, their overall performance was the best. Among them, MRH fitted more accurately in the high-light saturation stage ($PAR \geq 1200\ \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$), whereas NRH had greater advantages in the transition from low to medium light ($100\ \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1} \leq PAR < 1200\ \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$). The RMSE and MAE of the EM model were generally lower than those of RH, and its R^2 was also relatively high, indicating acceptable overall fitting ability. Moreover, its C_v for AQY was relatively low, suggesting good parameter stability; however, it slightly underestimated P_n in the high-light range, so its overall accuracy was still slightly inferior to that of MRH and NRH. By contrast, the RH model not only had higher RMSE and MAE, but its R^2 was relatively biased⋯

Figure 7 text within panels: (a) FUS-R^2; (b) FUS-RMSE; (c) FUS-MAE; (d) ALS-R^2; (e) ALS-RMSE; (f) ALS-MAE. Model labels: RH, NRH, MRH, EM. Axis labels include R^2, RMSE, and MAE.

Note: $n = 6$; one light-response curve was selected for each month from July to September in two growing seasons. Different lowercase letters indicate significant differences ($P < 0.05$). The same applies below.

Fig. 7 Goodness of fit of four light-response models under two treatments

Figure 8 text within panels: (a) FUS; (b) ALS. The y-axis is P_{nmax}. Model/value labels: RH, NRH, MRH, EM, measured value.

Fig. 8 Comparison of measured and fitted values of maximum net photosynthetic rate of *Ulmus pumila* under two treatments with four light-response models ($n = 6$)

low, and the C_v values of both P_{nmax} and AQY were also relatively large; thus, its overall applicability was the poorest. It is worth noting that under the FUS treatment, the coefficients of variation of AQY for NRH and MRH were relatively high, which was mainly related to abnormal fitted values in individual months. Therefore, this should be understood more as a sensitivity of low-light parameters to local fitting deviations, rather than as a significant decline in the overall stability of the models. Considering both fitting accuracy and parameter stability, the applicability of the four models to the photosynthesis-light-response process of a typical vegetation species (*Ulmus pumila*) in the arid region of the Qinghai–Tibet Plateau can be ranked as:

NRH MRH>EM>RH.

Both EM and RH are essentially asymptotic curves without an extremum, and their ability to characterize saturation plateaus and local fluctuations under high-light conditions is limited[^30]. Because they have fewer adjustable parameters, their capacity to modify the degree of curve curvature is relatively weak. Consequently, their fitting deviations in the high-light region are relatively large, which further affects the stable estimation of parameters such as AQY, R_d, and LCP. Although NRH is also a model without an extremum, it regulates the transition of the curve from a linear increase under low light to saturation under high light through the curvature parameter θ[^5]. Therefore, it can better approximate the actual feature of the P_n-PAR curve of *Ulmus pumila* leaves, namely "rapid increase followed by gradual saturation." This is consistent with the findings of Song et al.[^31] and He[^32]. Overall, both NRH and MRH showed good applicability, but their advantages differed in emphasis: NRH is more suitable for describing the continuous transition from low to moderate light and the overall curve shape, whereas MRH imposes a stronger constraint on P_{nmax} in the high-light saturation stage and is more suitable for describing potential photosynthetic capacity under high-light conditions.

The results of this study indicate that ALS treatment has good application potential for vegetation restoration and ecological rehabilitation of saline–alkali land in the arid region of the Qinghai–Tibet Plateau. On the one hand, this measure can improve the photosynthetic capacity, stomatal regulation capacity, and low-light utilization efficiency of elm leaves; on the other hand, the artificial layered soil-allocation method is characterized by site-specific adaptation, use of local materials, and strong engineering implementability, and thus has certain value for wider application. This study only set up a 10 cm-thick ALS treatment and a FUS control; therefore, the results mainly reflect the differences between the 10 cm layered treatment and the original soil, and cannot be extrapolated to the optimization effects under different layered-thickness conditions. In terms of the models, AQY, LCP, and R_d are all parameters sensitive to the low-light region. Among them, AQY mainly reflects the initial slope of the curve in the low-light segment; LCP corresponds to the light intensity at which the net photosynthetic rate is zero; and R_d is related to the intercept characteristics of the curve in the low-light region. In this study, PAR did not cover the extremely low-light range of 0–100 $\mu\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$; therefore, all three parameters depend on low-light data to constrain the initial shape of the curve. In the absence of measured points under extremely low light, the initial slope of the curve, the x-axis intersection, and the intercept rely more heavily on model estimation, and differences in the functional forms of different models are more easily amplified. This leads to stronger model dependence in the estimated results of AQY, LCP, and R_d, and reduces the stability of these parameters when compared among models. However, these limitations mainly affect the accuracy of low-light parameters. The discussion in this study regarding LCP, R_d, and some AQY results is mainly limited to comparisons of relative differences among models, and does not change the main conclusions that ALS treatment enhances the photosynthetic capacity of elm, and that NRH and MRH are generally superior to EM and RH. Future studies may combine different layered-thickness settings, dynamic monitoring of water and salt in the root zone, and more complete observations along low-light gradients to further deepen the interpretation of the ecophysiological mechanisms and the evaluation of engineering applicability.

4 Conclusions

(1) ALS treatment increased the net photosynthetic rate and apparent quantum yield (AQY) of elm leaves, and prolonged the duration of high stomatal conductance. During two consecutive growing seasons (July–September), the maximum net photosynthetic rate of elm leaves under ALS treatment increased by 45.85%–111.11% compared with the FUS treatment, indicating that ALS can enhance the photosynthetic potential, stomatal regulation capacity, and low-light utilization efficiency of elm leaves.

(2) For typical vegetation in the arid region of the Qinghai–Tibet Plateau—elm—the fitting performance of light-response curves showed clear segmental differences. In the low- to medium-light region (PAR $< 1200\ \mu\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$), NRH had the best fitting effect; whereas in the high-light region (PAR $\geq 1200\ \mu\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$), MRH showed better applicability.

(3) ALS treatment has good engineering and ecological application prospects in the arid region of the Qinghai–Tibet Plateau. By reconstructing the soil profile structure through measures adapted to local conditions and using

local materials, it helps improve the growth environment of the vegetation root zone, enhance plant photosynthetic capacity, stomatal regulation capacity, and weak-light utilization efficiency, and has positive significance for vegetation restoration, saline–alkali land improvement, and ecological rehabilitation in plateau arid regions.

References (References):

[1] Zhang Zhenwen, Zhang Baoyu, Tong Haifeng, et al. Study on the photosynthetic light compensation point and light saturation point of grapevines during flowering [J]. Journal of Northwest Forestry College, 2010, 25(1): 24–29. [Zhang Zhenwen, Zhang Baoyu, Tong Haifeng, et al. Photosynthetic LCP and LSP of different grapevine cultivars[J]. Journal of Northwest Forestry College, 2010, 25(1): 24–29.]

[2] Wang Haizhen, Han Lu, Xu Yali, et al. Responses of photosynthesis in heteromorphic leaves of *Populus euphratica* to light intensity and CO_2 concentration [J]. Chinese Journal of Plant Ecology, 2014, 38(10): 1099–1109. [Wang Haizhen, Han Lu, Xu Yali, et al. Photosynthetic responses of the heteromorphic leaves in *Populus euphratica* to light intensity and CO_2 concentration[J]. Journal of Plant Ecology, 2014, 38(10): 1099–1109.]

[3] Lewis J D, Olszyk D, Tingey D T. Seasonal patterns of photosynthetic light response in Douglas-fir seedlings subjected to elevated atmospheric CO_2 and temperature[J]. Tree Physiology, 1999, 19(4/5): 243–252.

[4] Ye Zipiao, Yu Qiang. Comparison of a new model of photosynthetic light response with traditional models [J]. Journal of Shenyang Agricultural University, 2007, 38(6): 771–775. [Ye Zipiao, Yu Qiang. Comparison of a new model of light response of photosynthesis with traditional models[J]. Journal of Shenyang Agricultural University, 2007, 38(6): 771–775.]

[5] Thornley J H M. Mathematical Models in Plant Physiology[M]. London: Academic Press, 1976: 86–110.

[6] Bassman J H, Zwier J C. Gas exchange characteristics of *Populus trichocarpa*, *Populus deltoides* and *Populus trichocarpa* × *P. deltoides* clones[J]. Tree Physiology, 1991, 8(2): 145–159.

[7] Huang Hongying, Dou Xinyong, Sun Beiyu, et al. Comparison of summer photosynthetic characteristics in two different ecotypes of *Jatropha curcas* [J]. Acta Ecologica Sinica, 2009, 29(6): 2861–2867. [Huang Hongying, Dou Xinyong, Sun Beiyu, et al. Comparison of photosynthetic characteristics in two ecotypes of *Jatropha curcas* in summer[J]. Acta Ecologica Sinica, 2009, 29(6): 2861–2867.]

[8] Yang Zhaoming, Li Hongmei. The Second Climate Change Assessment Report of Qinghai Province[M]. Beijing: Meteorological Press, 2021: 1–10. [Yang Zhaoming, Li Hongmei. The Second Climate Change Assessment Report of Qinghai Province[M]. Beijing: Meteorological Press, 2021: 1–10.]

[9] Zheng Jingwen, Wang Haiou, Maigepiretiguli Dawuti, et al. Physiological responses of seedlings of two typical desert plants to stress under salt stress mediated by arbuscular mycorrhizal networks [J]. Arid Zone Research, 2026, 43(4): 781–791. [Zheng Jingwen, Wang Haiou, Maigepiretiguli Dawuti, et al. Physiological responses of two typical desert plants seedlings under salt stress mediated by arbuscular mycorrhizal networks[J]. Arid Zone Research, 2026, 43(4): 781–791.]

[10] Qiang Xinxin, Gao Wenwen, Wang Bo, et al. Remote-sensing-based risk assessment of soil salinization and its evolution patterns [J]. Arid Zone Research, 2025, 42(3): 431–444. [Qiang Xin-

huan, Gao Wenwen, Wang Bo, et al. Remote sensing-based risk assessment of soil salinization and its change over time[J]. Arid Zone Research, 2025, 42(3): 431–444.]

[11] Zheng Liping, Gan Yongde, Jia Yangwen, et al. Experimental study on water and soil regulation methods based on layered soil[J]. South-to-North Water Transfers and Water Science & Technology (Chinese and English), 2023, 21(4): 708–730. [Zheng Liping, Gan Yongde, Jia Yangwen, et al. Experimental study on water and soil regulation method based on layered soil[J]. South-to-North Water Transfers and Water Science & Technology, 2023, 21(4): 708–730.]

[12] Zhang Yongxing, Yuan Riping, Gan Yongde, et al. Effect of stratified soil mixed with sand on the photosynthesis and transpiration characteristics of alfalfa[J]. Journal of Irrigation and Drainage, 2025, 44(4): 47–56. [Zhang Yongxing, Yuan Riping, Gan Yongde, et al. Effect of stratified soil mixed with sand on photosynthesis and transpiration of alfalfa[J]. Journal of Irrigation and Drainage, 2025, 44(4): 47–56.]

[13] Du Jiujun, Zuo Lihui, Liang Haiyong, et al. Comparison of photosynthetic characteristics of five *Ulmus* species[J]. Molecular Plant Breeding, 2018, 16(7): 2348–2357. [Du Jiujun, Zuo Lihui, Liang Haiyong, et al. Comparison of photosynthetic characteristics of 5 *Ulmus*[J]. Molecular Plant Breeding, 2018, 16(7): 2348–2357.]

[14] Lang Y, Wang M, Zhang G C, et al. Experimental and simulated light responses of photosynthesis in leaves of three tree species under different soil water conditions[J]. Photosynthetica, 2013, 51(3): 370–378.

[15] Wu Qin, Zhang Guangcan, Pei Bin, et al. CO_2 response process and its simulation of *Prunus sibirica* photosynthesis under different soil moisture conditions[J]. Chinese Journal of Applied Ecology, 2013, 24(6): 1517–1524. [Wu Qin, Zhang Guangcan, Pei Bin, et al. CO_2 response process and its simulation of *Prunus sibirica* photosynthesis under different soil moisture conditions[J]. Chinese Journal of Applied Ecology, 2013, 24(6): 1517–1524.]

[16] Ye Zipiao, Yu Qiang. Comparison of photosynthetic light-response models[J]. Chinese Journal of Plant Ecology, 2008, 32(6): 1356–1361. [Ye Zipiao, Yu Qiang. Comparison of new and several classical models of photosynthesis in

response to irradiance[J]. Chinese Journal of Plant Ecology, 2008, 32(6): 1356–1361.]

[17] Zhang Dandan, Wang Yuqing, Ying Yaolin, et al. Applicability analysis of several photosynthetic light-response models to *Populus pruinosa*[J]. Ecological Science, 2025, 44(2): 179–185. [Zhang Dandan, Wang Yuqing, Ying Yaolin, et al. Applicability analysis of several photoresponse models of photosynthesis to *Populus pruinosa*[J]. Ecological Science, 2025, 44(2): 179–185.]

[18] Botta-Dukát Zoltán. Quartile coefficient of variation is more robust than C_v for traits calculated as a ratio[J]. Scientific Reports, 2023, 13(1): 4671.

[19] Bu Jianchao, Zhou Tonghui, Liu Fengshan, et al. Adaptability of different photosynthesis–light response curve models for *Cenchrus* sp. under regulated deficit irrigation conditions[J]. Northern Horticulture, 2023, 21(12): 122–128. [Bu Jianchao, Zhou Tonghui, Liu Fengshan, et al. Adaptability of *Cenchrus* sp. regulated deficit irrigation of different photosynthesis-light response curve model[J]. Northern Horticulture, 2023, 21(12): 122–128.]

[20] Han Tuo. Mechanisms of carbon–water coupling in typical vegetation of arid green oases[D]. Lanzhou: Lanzhou University, 2020. [Han Tuo. Mechanisms of Typical Vegetation in an Arid Oasis Ecosystem[D]. Lanzhou: Lanzhou University, 2020.]

[21] Hovenden M J. Photosynthesis of coppicing poplar clones in a free-air CO_2 enrichment (FACE) experiment in a short-rotation forest[J]. Functional Plant Biology, 2003, 30(4): 391–400.

[22] Yuan Riping. Study on water use efficiency and photosynthetic characteristics of typical vegetation in artificially layered soil in an alpine region[D]. Xining: Qinghai University, 2024. [Yuan Riping. Study on Water Use Efficiency and Photosynthetic Characteristics of Typical Vegetation in Artificially Layered Soil in Alpine Region[D]. Xining: Qinghai University, 2024.]

[23] Dos Santos Junior, Ulysses Moreira, José Francisco. Measuring the impact of flooding on Amazonian trees: Photosynthetic response models for ten species flooded by hydroelectric dams[J]. Trees, 2013, 27(1): 193–210.

[24] Wang Huanli, Cao Fuliang, Liu Xinliang. Fitting of light response curves of different leaf-color ginkgo grafting seedlings under high-temperature stress[J]. Journal of Nanjing Forestry University (Natural Science Edition), 2015, 39(2): 14–20. [Wang Huanli, Cao Fuliang, Liu Xinliang. Fitting of light response curves of different leaf color ginkgo grafting seedlings under high temperature stress[J]. Journal of Nanjing Forestry University (Natural Science Edition), 2015, 39(2): 14–20.]

[25] Deng Nan, Liu Xinliang, Zhu Liwei, et al. A review of characteristics of plant stomatal regulation behavior and its carbon–water traits in response to the environment[J]. Journal of Tropical and Subtropical Botany, 2026, 34(2): 235–244. [Deng Nan, Liu Xinliang, Zhu Liwei, et al. A review of characteristics

of plant stomatal regulation behavior and its carbon-water traits in response to environment[J]. Journal of Tropical and Subtropical Botany, 2026, 34(2): 235-244.]

[26] Zheng Liping. Mechanism and numerical simulation of water and heat transport in artificial layered soil engineering[D]. Xining: Qinghai University, 2024. [Zheng Liping. Mechanism and Numerical Simulation of Water and Heat Transport in Artificial Layered Soil Engineering[D]. Xining: Qinghai University, 2024.]

[27] Zhang Zhaolin, Wang Hao, Zheng Liping, et al. Analysis of soil water and heat balance under the condition of sandy layered soil preparation[J/OL]. China Rural Water and Hydropower, 2026, 1-19. [Zhang Zhaolin, Wang Hao, Zheng Liping, et al. Analysis of soil water and heat balance under the condition of sandy layered soil preparation[J/OL]. Chinese Rural Water and Hydropower, 2026, 1-19.]

[28] Qian Yifan, Liao Yongmei, Quan Qiumei, et al. Practicability of four light-response curve models for three *Mahonia* species[J]. Plant Research, 2014, 34(5): 716-720. [Qian Yifan, Liao Yongmei, Quan Qiumei, et al. Practicability of four models of light-response curves of photosynthesis to three mahonia species[J]. Plant Research, 2014, 34(5): 716-720.]

[29] Wang Haizhen, Han Lu, Xu Yali, et al. Simulation of photosynthetic response processes of *Populus euphratica* during drought stress and comparison of models[J]. Acta Ecologica Sinica, 2017, 37(7): 2315-2324. [Wang Haizhen, Han Lu, Xu Yali, et al. Simulated photosynthetic responses of *Populus euphratica* during drought stress using light-response models[J]. Acta Ecologica Sinica, 2017, 37(7): 2315-2324.]

[30] Zheng Wei, He Qinfeng, Peng Yuhua, et al. Comparison of photosynthetic light-response curve models for *Leucaena glauca* plantations in karst rocky desertification areas[J]. Journal of Southwest Forestry University (Natural Sciences), 2018, 38(2): 23-29. [Zheng Wei, He Qinfeng, Peng Yuhua, et al. Comparison of photosynthesis light response curve models for *Leucaena glauca* plantation in karst area[J]. Journal of Southwest Forestry University (Natural Sciences), 2018, 38(2): 23-29.]

[31] Song Dianxing, Li Ma, Wang Quanju, et al. Photosynthetic light response models for spring wheat mulching treatments in a northwestern China desert oasis[J]. Crop Science, 2021, 61(3): 2036-2047.

[32] He Ke. Comparison of four light-response models using relative curvature measures of nonlinearity[J]. Scientific Reports, 2024, 14(1): 24058.

Effects of layered soil matching on light response parameters and model applicability of *Ulmus pumila* in arid regions of the Qinghai-Xizang Plateau

ZHAN Dongshan1, CHEN Zhenxing2, ZHANG Yongxing3, HAO Jia2, WANG Shangtao1, GAN Yongde1, ZHANG Zhaolin1

(1. School of Civil Engineering and Water Resources, Qinghai University, Laboratory of Ecological Protection and High Quality Development in the Upper Yellow River, Key Laboratory of Water Ecology Remediation and Protection at Headwater Regions of Big Rivers, Xining 810016, Qinghai, China; 2. Qinghai Provincial Center for Land Consolidation and Ecological Restoration, Xining 810016, Qinghai, China; 3. Xining Integrated Natural Resources Survey Center, China Geological Survey, Xining 810000, Qinghai, China)

Abstract: In this study, we investigated the effect of artificially layered soil (ALS) on the photosynthetic capacity of vegetation in saline-alkali land of the arid region of the Qinghai-Xizang Plateau, and we evaluated the applicability of photosynthetic light response models for typical vegetation in this region. This study took the typical *Ulmus pumila* in the Huatugou area as the research object. Two treatments were established: ALS and field undisturbed soil (FUS). During the growing seasons (July to September) of 2024–2025, under typical clear weather conditions, the net photosynthetic rate (P_n) of *Ulmus* leaves was measured using a GFS-3000 photosynthesis system across 14 gradients of photosynthetically active radiation (PAR), and P_n-PAR curves were then constructed. Four models—the rectangular hyperbola model (RH), non-rectangular hyperbola model (NRH), modified rectangular hyperbola model (MRH), and exponential model (EM)—were applied for curve fitting. Model performance was evaluated using the coefficient of determination (R^2), root mean square error (RMSE), mean absolute error (MAE), and coefficient of variation of parameters. The results show that P_n under ALS was generally higher than that under FUS, with the maximum net photosynthetic rate increasing by 45.85%–111.11%. Stomatal conductance (G_s) was also generally higher and remained elevated for a longer duration under ALS, whereas the apparent quantum yield under low light was greater overall. These findings suggest that the layered structure of ALS may synergistically enhance the high-light photosynthetic capacity, stomatal regulation, and low-light utilization efficiency of *Ulmus* by modulating soil water-salt processes and improving the rhizosphere environment. Regarding model applicability, all four models effectively described the overall P_n-PAR trends, with the NRH and MRH showing smaller fitting errors and more reasonable parameters. Based on the combined evaluation of goodness-of-fit and parameter stability, model ranking in terms of applicability is as follows: NRH MRH>EM>RH. This study elucidates the photosynthetic response characteristics and differences in model applicability of vegetation under two soil configurations in saline-alkali land of the arid Qinghai-Xizang Plateau, providing data support and theoretical reference for vegetation restoration, saline-alkali land improvement, and light response model selection in this region.

Keywords: Qinghai-Xizang Plateau arid region; layered soil; *Ulmus pumila*; light response model; light response curve

Note: Figure translations are in progress. See original paper for figures.