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Photosynthetic model for citrus cultivar Huangguogan

Modelo fotossintético para cultivar cítrico Huangguogan

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Abstract

Grafting is an effective measure to improve the photosynthetic rate of citrus. The light responses of photosynthesis in leaves of two-year old grafted Huangguogan (citrus cultivar Huangguogan), Huanggougan / Trifoliate (HG/PT), Huanggougan / Tangerine (HG/CR), and Huanggougan / Ziyang Xiangcheng (HG/CJ) were studied using the LI-COR 6400 portable photosynthesis system. Light-response curves and photosynthetic parameters were analyzed and fitted using the rectangular hyperbola model (RHM), the exponential model (EM), the non rectangular hyperbola model (NRHM), and the modified rectangular hyperbola model (MRHM). The results showed that: (1) Grafting can change the photosynthetic characteristics of Huangguogan, and the value of photosynthesis rate of HG/CJ is the greatest; (2) The light-response curves of net photosynthetic rate (PN), the light compensation point (LCP), and the dark respiration rate (RD) were well fitted using the above four models. The modified rectangular hyperbola was the best model in fitting the data; the nonrectangular hyperbola model was the second, and the rectangular hyperbola model was the poorest one.
Key words: Citrus cultivar Huangguogan. Light-response curves. Photosynthetic parameters.

Resumo

O enxerto é uma medida eficaz para melhorar a taxa fotossintética de citros. As respostas leves da fotossíntese em folhas de Huangguogan (cultivar de citros Huangguogan), Huanggougan / Trifoliate (HG / PT), Huanggougan / Tangerine (HG / CR) e Huanggougan / Ziyang Xiangcheng (HG / CJ) foram estudadas usando o sistema de fotossíntese portátil LI-COR 6400.Curvas de resposta à luz e parâmetros fotossintéticos foram analisados e ajustados usando o modelo de hipérbole retangular (RHM), o modelo exponencial (EM), o modelo de hipérbole não retangular (NRHM) e o modelo de hipérbole retangular modificado (MRHM). Os resultados mostraram que: (1) O enxerto pode mudar as características fotossintéticas de Huangguogan, e o valor da taxa de fotossíntese de HG / CJ é o maior; (2) As curvas de resposta à luz da taxa fotossintética líquida (PN), do ponto de compensação de luz (LCP) e da taxa de respiração escura (RD) foram bem ajustadas usando os quatro modelos acima. A hipérbole retangular modificada foi o melhor modelo na adaptação dos dados; o modelo de hipérbole não-retangular foi o segundo, e o modelo de hipérbole retangular foi o mais pobre.
Palavras-chave: Cultivar cítrico Huangguogan. Curvas de resposta à luz. Parâmetros fotossintéticos.

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Introduction

Citrus is one of the most economically important fruits worldwide (Xie, Pan, Zhang, Ma, He, Zheng, & Ma, 2017). It is grown commercially in over 138 countries and ranks as the top fruit crop in world production. Huangguogan(*Citrus reticulata·Citrus sinensis*) is a new late maturing, high-yield, and seedless citrus hybrid produced by crossing orange and tangerine. It is mainly cultivated in dry-hot valley regions of southwest China (Liao, Cao, Rong, & Wang,2016).

Oxygenic photosynthesis is a process by which plants, algae, and cyanobacteria use energy from sunlight to produce sugar and to release oxygen (Blankenship, 2002; Govindjee & Krogmann, 2004). It is critical for support of life systems on the Earth and it is influenced by many factors, including temperature, carbon dioxide concentration, light intensity, rootstocks, and so on. Photosynthetic efficiency is a critical factor in plant productivity and crop yield (Peng, 2000). Rootstocks play central roles in the light reaction of the photosynthetic process of plants by influencing the leaf structure and leaf pigment content. Grafting superior, commercial cultivars onto rootstocks is a promising tool for improving the efficiency of photosynthesis in production and improving the fruit quality (Georgiou, 2002; Forner-Giner, Alcaide, Primo-Millo, & Fomer, 2003; Bassal, 2009; Castle, Baldwin, & Muraro, 2010). Morinaga and Ikeda (1990) suggested that the leaf photosynthetic rate and product distribution differ among rootstocks, and scion behavior is probably influenced by rootstock-induced effects on leaf gas exchange (González-Mas, Llosa, & Quijano, 2009; Rodríguez-Gami, Intrigliolo, Primo-Millo & Forner-Giner, 2010). Each plant species has its own optimal light intensity range, soil conditions, and other environmental needs for photosynthesis, Studies of the light response of plant photosynthesis under different rootstocks conditions can help to understand the photo-physiological characteristics of different grafted combination, reveal quantitative relationships between these characteristics and grafted combination, and give guidance in plant production processes, such as selection of good quality rootstocks and suitable cultivation conditions.

Light-response models investigate the relationship between P_N and PAR, measuring P_N and fitting these data to a model is important to understand photosynthesis (Robert, Mark, & John, 1984). It allows to determine the main photosynthetic parameters, such as light saturation point (LSP), light-saturated net photosynthetic rate (P_{Nmax}), light compensation point (LCP), dark respiration rate (RD), and apparent quantum yield (AQY) can be estimated by drawing light response curves of photosynthesis (Webb, Newton, & Start, 1974; Ye, 2010; Lang, Wang, Zhang, & Zhao, 2013). Thus, the commonly used models include the rectangular hyperbola model (RHM) (Baly, 1935), the nonrectangular hyperbola model (NRHM) (Thornley, 1976), the exponential model (EM) (Bassman & Zwier, 1991), and the modified rectangular hyperbola model (MRHM) (Ye, 2007), all of which have certain advantages and disadvantages (Duan & Zhang, 2009; Lang et al., 2013). Researchers have applied these models for pamiricus bean (Wang, Yang, Du, Hu, Zhao, & Mao, 2009), tobacco (Zhong, Zhang, Hu, & Zhu, 2012), winter wheat (Ye & Yu, 2008), zizyphus jujube (Xia, Zhang, Wang, & Zhang, 2014), armeniaca sibirica (Wu, Zhang, Pei, Xu, & Fang, 2013) and other kinds of plant photosynthesis light response curve fitting, and achieved good results. But these models are not clear if their advantages still hold when applied to citrus plants under different rootstocks conditions. In this research, we used two-year-old potted seedlings of three combinations of grafted plants, Huanggougan/Trifoliate (HG/PT), Huanggougan/Tangerine (HG/CR), and Huanggougan/Ziyang Xiangcheng (HG/CJ) to examine the light responses of P_N. We analyzed the photosynthetic curves and main parameters and fitted them using the RHM, the EM, the NRHM, and the MRHM. Our objectives were to characterize the relationship between photosynthesis and rootstocks, to study the ability of these models to simulate the light response of photosynthesis under different citrus rootstocks conditions, and to gain further understanding of the photo-physiological characteristics of these grafted plants. Our results could also provide guidance for the cultivation of Huangguogan in dry-hot valley regions and for the selection of optimal light response models for cirtus trees under different rootstocks conditions.

Materials and Methods

Study area: Our experiment was carried out in 2017, the experimental site was located in Pomology and Olericulture Research Institute of Sichuan Agricultural University, Chengdu, Sichuan Province, China. The altitude is 508 m, the average annual precipitation is 966.1 mm, and the average relative humidity is 84%.

Experimental seedling selection: Two-year-old of grafted Huangguogan were selected for experiments. The rootstocks included trifoliate [*Poncirus trifoliata* (L.) Raf; HG/PT], tangerine (*Citrus reticulata* Blanco; HG/CR), and Ziyang Xiangcheng [*Citrus junos* (Sieb.) Tanaka; HG/CJ]. In April 2016, we selected 6 healthy seedlings with relatively uniform plant height and basal diameter for each grafted combination from the local nursery of the Huangguogan Demonstration Garden. Each seedling was planted in a in a pot (0.5m deep with a radius of 0.3 m). The trees were raised using standard cultural practices, including fertilization, watering, pest control, and so on. 3 best-growing plants of each grafted combination were selected for the experiments after 360 days.

Measurement of photosynthesis: P_N were measured in 5 fully developed, mature leaves from the center of each plant in response to light. The same leaf was measured 3 times. This was performed using a portable photosynthesis system (LI-COR 6400, LI-COR Inc., Lincoln, NE, USA) between 9:00-11:30h on the same days. During each measurement, CO_2 concentration was maintained at 395±5.0 ppm, air temperature at 26-29 ºC, and relative humidity at 67±3.0%. For every observation, PAR was controlled at 2,300; 2,000; 1,800; 1,600; 1,400; 1,200; 1,000; 800, 600,400, 200, 150, 100, 75,50, and 0 $\mu mol \cdot m^{-2} \cdot s^{-1}$, with an interval of 120s by LI-COR LED (LI-COR Inc., Lincoln, NE, USA) irradiation source.

Data processing: We analyzed the photosynthetic parameters data under different rootstocks conditions. By drawing the photosynthetic light response curves (P_N -PAR curves) for three grafted combinations using Microsoft Excel 2013, LSP, P_{Nmax} (J. Chen, Zhang, Zhang & Wang, 2008; Xia, Zhang, Zhang, & Li, 2009), LCP (PAR when $P_N = 0$), and RD (P_N when PAR = 0) were obtained. At the same time, the AQY was calculated using the linear regression method of the P_N-PAR curve under PAR ≤ $200 \mu mol \cdot m^{-2} \cdot s^{-1}$ (Xia et al., 2009; Xu, 2002). These photosynthetic parameters were considered the measured values and they were used to compare with the fitted values obtained using the following models.

Nonlinear fitting of light-response models: Using the SPSS 18.0 for Windows (SPSS, Chicago, USA), light-response curves and photosynthetic parameters were analyzed statistically and fitted nonlinearly using four models: the RHM, the NRHM, the EM, and the MRHM. The initial values used in the models were (1) α = 0.06, RD = 1.0 for both RHM and EM; (2) α = 0.06, RD = 0.5,k = 0.5 for the NRHM; (3) α = 0.06, β= 0.002, γ = 0.01, RD = 1.0 for the MRHM (Ye, 2010; Ye & Yu, 2008; Ye & Gao, 2008; Ye & Wang, 2009). For all models, the initial value of P_{Nmax} was set to be the integral part of the measured light-saturated net photosynthetic rate.

Rectangular hyperbola model

The rectangular hyperbola model (Baly, 1935) was expressed as follows:

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

where P_n was the net photosynthetic rate, I was the photosynthetic active radiation intensity; α was the initial quantum yield. and P_{nmax} was the maximum net photosynthetic rate.

Nonrectangular hyperbola model

The Nonrectangular hyperbola model (Thornley, 1976) was expressed as follows:

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

where P_n is the total photosynthetic rate; θ (0 <θ≤ 1) is the curvilinear angle of the nonrectangular hyperbola; and α; I, and P_{nmax} are as described above.

Exponential model

The Exponential model (Bassman & Zwier, 1991) was expressed as follows:

$$P_n = P_{nmax}\left(1 - e^{-\alpha I / P_{nmax}}\right) - R_d \quad (3)$$

where α; I; P_{nmax} ; P_n, and Rd were as described above.

The modified rectangular hyperbola model

The modified rectangular hyperbola model (Ye, 2007) was expressed by:

$$P_n = \alpha_p \frac{1 - \beta_p I}{1 + \gamma_p I} I - R_d, \quad (4)$$

where α, β, and γ were coefficients that were independent of I (Ye, 2007). All the other parameters were as described above. If β = 0, γ=α/P_{nmax}, the formula (4) equals formula (1).

Results

Light response of P_N: The light response of P_N to PAR could be divided into three stages (Figure 1), the three stages showed similar patterns of the response regardless of rootstocks for all three grafted combinations, and for different combination, the change scope of the response amplitude is different. In the first stage, where PAR ≤ 200μmol·m^{-2}·s^{-1}, P_N increased linearly as PAR increased, indicating that PAR was the key factor influencing photosynthesis in this PAR range; In the second stage, where 400μmol·m^{-2}·s^{-1}≤ PAR ≤ 1400μmol·m^{-2}·s^{-1}, the increase of P_N slowed down because of possible influence by several other factors, such as temperature, CO_2 concentration, and leaf characteristics. With the further increase of PAR, the response entered the third stage and the increase of P_N slowed basically maintain invariable or modest decline.

The light response in the second stage was quite diverse under different rootstocks. With increasing PAR, P_N of HG/CR has the largest range of rise (Figure 1C), followed by HG/CJ (Figure 1B), and HG/PT (Figure 1A) has the minimum. This shows that although the three stages showed similar patterns of the response, but the response amplitude of the light intensity is HG/CR > HG/CJ > HG/PT.

Light-response model of photosynthetic rate: The light-response curves of Huangguogan leaves under different rootstocks conditions were fitted to 4 models (Figure 1), such as the RHM, the NRHM, the EM, and the MRHM. All 4 models fitted the light-response curves of all three grafted combinations well, the 4 fitting curves showed similar patterns of the measured curves of the photo response, although there were some differences. For HG/CR (Figure 1C), the deviation between the 4 fitting curves and the measured ones shows that: the MRHM < the NRHM < the RHM < the EM; For HG/CJ (Figure 1B), the deviation between the 4 fitting curves and the measured ones shows that: the MRHM < the EM < the NRHM < the RHM; For HG/PT (Figure 1A), the deviation between the 4 fitting curves and the measured ones shows that: the MRHM < the NRHM < the EM < the RHM. Results showed that for three combinations the MRHM shows the best fitting degree with the measured values.

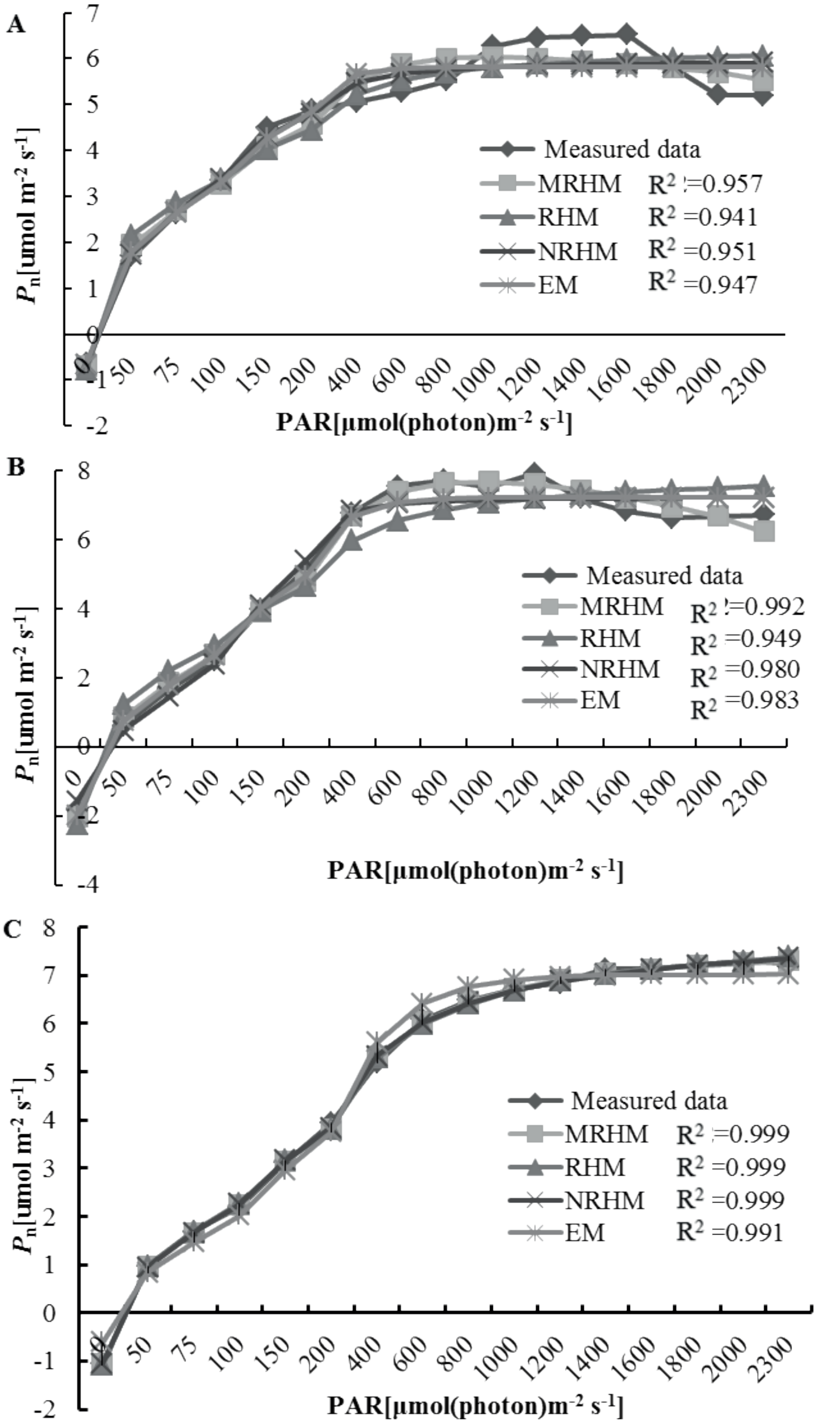

Figure 1. Light response of photosynthetic rate (P_N) under different rootstocks conditions in Huangguogan. And simulation of P_N/PAR curves of the three tree species by the rectangular hyperbola model; the nonrectangular hyperbola model; the exponential model; and the modified rectangular hyperbola model. P_N – net photosynthetic rate; PAR – photosynthetically active radiation; A – HG/PT; B – HG/CJ; C – HG/CR.

For three combinations, all 4 models fitted the light-response curves well, as shown by the determination coefficients (R^2 ≥94.1%), although there were some differences (Table 1). For HG/CR, the average R^2 value from all 4 models were greater than 99.9%; For HG/CJ, the average R^2 value from the MRHM (99.2%) was greater than that for the NRHM (98.0%), these values were followed by those of the EM (97.8%) and the RHM (94.9%); For HG/PT, the average R^2 value from the MRHM (95.7%) was also greater than other models.

Table 1
Fitting four models to the net photosynthetic rate (P_N)-light response curves and parameters in cv.Huangguogan. Each value of P_N is the mean of 15 replicates. R^2 – determination coefficient; RD – respiration rate; AQY – apparent quantumyield; LCP – light compensation point; P_{Nmax} – maximum net photosynthetic rate; LSP – light saturation point. RHM – rectangular hyperbola model; NRHM –nonrectangular hyperbola model; EM – exponential model; MRHM – modified rectangular hyperbola model

Rootstock	Light-response model	AQY	R^2[%]	RD	P_{Nmax}	LSP	LCP
HG/PT	MRHM	0.078	0.957	0.697	6.032	993	9.667
	RHM	0.101	0.941	0.791	7.058	310	8.818
	NRHM	0.053	0.951	0.673	6.66	257	12.817
	EM	0.055	0.947	1.114	5.815	591	22.315
HG/CJ	MRHM	0.074	0.992	2.018	7.680	946	32.479
	RHM	0.105	0.949	2.247	10.207	387	27.379
	NRHM	0.041	0.980	1.569	8.828	298	38.540
	EM	0.050	0.978	1.276	7.210	786	27.787
HG/CR	MRHM	0.051	0.999	1.049	7.381	3470	23.103
	RHM	0.053	0.999	1.081	9.094	431	23.077

To evaluate the accuracy of the 4 models, the residual sum of squares (RSS) was calculated according to the formula: RSS = $\sum(yt - \hat{y}t)^2$ (Table 2), where ŷt is the measured data and yt is the fitted data; neither of these values can be 0. The greater the RSS, the greater the deviation of the measured value from the fitted value. The smaller the RSS, the better is the fit of the model to the data. The photosynthetic fitting curve of Huangguogan can be divided into three stages. When the PAR was 0-200μmol•m^{-2}•s^{-1}, the rate of photosynthesis increases rapidly, all models could pass through the measured points well, except the RHM model has some points not fall on the fitted curve of HG/CJ; while the PAR was 400-1400μmol•m^{-2}•s^{-1}, part of the measured points of the EM, the NRHM, the MRHM models did not fall on the fitted curve of HG/PT, part of the measured points of the EM, the NRHM, the RHM models did not fall on the fitted curve of HG/CJ, but 4 models all can be well through the measured point well of HG/CR. The rate of photosynthesis were flat or falling when the PAR was 1600-2300μmol•m^{-2}•s^{-1}, for HG/PT and HG/CJ, only the MRHM model can be well through the measured point well, but 4 models all can be well through the measured point well of HG/CR.

The AQY is the quantum efficiency calculated according to the number of incident photons, which reflects the power of the plant's light utilization (Table 1). The maximum initial quantum efficiency of the plant is between 0.08- 0.125 in theory and the light response curve tends to be smooth with the increased of light. For good growing crops, the average response is between 0.04-0.07 (Long, Humphries, & Falkowski, 1994; Lu, Yu, Luo, & Liu, 2001). Yet AQY of some plants is lower than 0.03 even under optimal conditions (Zhang, Wan, Liu, Zhang, & Wang, 2009; Chen, Zhang, Zhang, & Wang, 2008; Xia, Zhang, Liu, Han, Chen, & Liu, 2007). The 4 model fitted the AQY of HG/PT is between 0.053-0.101, the AQY of HG/CJ is between 0.041-0.105, and the AQY of HG/CR is between 0.030-0.053 (Table 2). The AQY of Huangguogan is between 0-0.125, that is to say the four models can be used to fit the different rootstock of Huangguogan leaves photosynthetic light response curve, the AQY of HG/CR (0.030-0.053) is at the lower limit range (0.03-0.05) of known plants (Li, 2002). indicating that the HG/CR has low ability to use weak light. For three kinds of the rootstocks, the HG/CJ, the HG/CR has the strongest and weakest ability to use weak light, respectively.

Table 2
Residual sum of squares of light-response curves fitted by four models. RHM – rectangular hyperbola model; NRHM –nonrectangular hyperbola model; EM – exponential model; MRHM – modified rectangular hyperbola model

Rootstock	Light-response model	PAR [μmol m^{-2} s^{-1}]		
		0-200	400-1400	1600-2300
HG/PT	MRHM	0.354	1.385	0.769
	RHM	0.689	0.987	1.769
	NRHM	0.043	1.384	1.423
	EM	0.065	1.811	1.261
HG/CJ	MRHM	0.266	0.233	0.523
	RHM	1.286	3.070	2.371
	NRHM	0.234	1.315	1.036
	EM	0.108	1.101	1.059
HG/CR	MRHM	0.017	0.037	0.005
	RHM	0.019	0.040	0.018
	NRHM	0.015	0.043	0.012
	EM	0.362	0.464	0.176

The importance of dark respiration (RD) in plant life is using photosynthetic products to provide energy for metabolism and physiological activities and to provide materials for the synthesis of various biological macromolecules (Xiong, Zeng, Xiao, Zeng, Tu, Jiang, Qiu, Wu, & Jiang, 2012). The 4 models of RD fitting rate range for HG/PT, HG/CJ and HG/CR is 0.673-1.114, 1.276-2.247 and 1.049-1.088, respectively (Table 1). The results show clearly that the HG/CJ, and the HG/PT has the strongest and weakest ability to use consumption of photosynthetic products, respectively. The maximum net photosynthetic rate (P_{Nmax}) is an important parameter of plant growth rate, describing the maximum net light plant potential, and reflecting the maximum potential of plants can be turn the CO_2 from the atmosphere into organic matter in the unit area (Xiong et al., 2012). The 4 models fitting P_{Nmax} results shows that the the RHM, the MRHM, the NRHM, and the EM model deviation of the fitted values and the measured values of HG/PT is 7.1%, 7.5%, 9.4%, 10.9%, respectively; The 4 models fitting P_{Nmax} results shows that the MRHM ,the RHM ,the NRHM, and the EM model deviation of the fitted values and the measured values of HG/CJ is 3.0%, 4.6%, 8.8%, 8.9%, respectively; and the 4 models fitting P_{Nmax} results shows that the MRHM ,the RHM ,the NRHM, and the EM model deviation of the fitted values and the measured values of HG/CR is 3.0%, 4.6%, 8.8%, 8.9%, respectively. Thus, the results shows that the best fitted theoretical model for the P_{Nmax} is the MRHM model.

The LSP and the LCP reflect the requirement of plants for light conditions. Generally, plants with lower LSP and LCP belong to shade tolerant plants, and conversely, they belong to positive plants. (Xiong et al., 2012). There is no theoretical maximum of the RHM model, NRHM model and EM, fitting the light response data of the linear relationship between P_N and PAR under weak light conditions (PAR≤200 umol·m^{-2}·s^{-1}), and combined with the RHM model and NRHM model LSP can be calculated (Liu, Li, & Xie, 2016). The LSP of the EM is calculated at the maximum of 99% when the photosynthetic rate is reached (Huang, Dou, Sun, Deng, Wu, G. & Peng, 2009). 4 models fitted Saturated light intensity (I_{SAT}) values of 3 kinds of rootstocks are as follows: the MRHM model is closest to the measured value, the EM is the second best, the RHM and the NRHM is far less than the measured value. The LCP of heliophyte is 9-18 umol•m^{-2}•s^{-1} (Pan, 2001), the LCP of Huangguogan is 8.818-39.834 (Table 1), and from the 4 models, the LCP fitting values of MRHM are most close to the measured values. the LCP of HG/PT is the lowest, which shows that the HG/PT has strong shade resistance.

Plants with lower LCP and higher LSP have stronger adaptability to light environment (Xiong et al., 2012). Comparison the LSP and LCP of 3 kinds of rootstocks shows that HG/CR has the strongest adaptability to light environment. The results of Tables 1 and 2 show that the NRHM fitted the RD the best. Therefore, the NRHM also provided the best fit for the AQY and the LCP, and the MRHM provided the best fit for the P_{Nmax} and the LSP.

Discussion

Photosynthesis is critical for support of life systems on the Earth. Each plant species has its own optimal light intensity range, soil conditions, and other environmental needs for photosynthesis. Under natural conditions, the photosynthetic rate of citrus is not only lower than C_3 crops such as wheat, rice and C_4 crops such as corn , but also lower than the pecans, peaches, apples, pears, grapes, blackberry, figs and other fruit (Andersen, 1991; Papadakis, Dimassi, Bosabalidis, Therios, Patakas, & Giannakoula, 2004), grafting is an effective measure to improve the photosynthetic rate of citrus. Many rootstock types are used for citrus cultivation in China, each having particular advantages and limitations when matched to different geographical regions. Huangguogan has been cultivated for over 300 years in the local, trifoliate [*Poncirus trifoliata* (L.) Raf], tangerine (*Citrus reticulata* Blanco), and Ziyang Xiangcheng [Citrus junos (Sieb.) Tanaka] are used frequently in Huangguogan grafting (Liao et al., 2016). A good rootstock should be compatible with the scion cultivar, resistant and/or tolerant to pests and diseases, and adaptable to a wide range of soil types and climatic conditions (Hernández, Pinochet, Moreno, Martínez, & Legua, 2010). Trifoliate orange is a good germplasm resources, resistance to Citrus tristeza virus (Gmitter, Xiao, Huang, Hu, Garnsey, & Deng, 1996) and *Tylenchulus semipenetrans* Cobb (Casde, Tucker & Krezdom,1993). Another important citrus rootstock in China is tangerine, in Sichuan and Fujian province, tangerine is shown as developed root system, resistance to drought, desert, salt, and root rot. Ziyang Xiangcheng is a good rootstock in alkaline soil, it had strong resistance and tolerance to environmental factors and it is good in fruit quality, adaptability is wide. In this study, the photosynthetic capacity of different kinds of rootstocks is notably different, that is to say grafting can change the photosynthetic characteristics of Huangguogan. The results in this study suggested that with the climate conditions in Chengdu, SiChuan province, the value of photosynthesis rate of HG/CJ is the greatest, with Ziyang Xiangcheng grafting has heavy development potentiality.

Light response models are essential for studying responses of photosynthesis. Photosynthesis of plant leaves under low light is helpful to determine whether photosynthetic apparatus is functioning normally, and the range of light saturation points in photosynthesis can be measured to understand the photosynthetic capacity of plants under saturated light (Zeng, Yuan, & Shen, 2002). Many static plant response models (Webb et a1., 1974; Jassby & Platt, 1976; Marshall & Biscoe, 1980; Bassman & Zwier, 1991) and dynamic light response models (Farquhar, Caemmerers & Berry, 1980; Falkowski & Wirick, 1981; Fasham & Platt, 1983; Megard, Tonkyn & Senti, 1984; Eilers & Peeters, 1988; Hand, Warren, & Acock,1993; Zonneveld, 1998; Rubio, Camacho, Sevilla, Chisti, & Grima, 2003) are now available. The RHM, the NRHM, and the EM are the most widely used. These models are usually evaluated qualitatively (Duan & Zhang, 2009; Lang et al., 2013), which restricts their accuracy in determining how well the data fit the models. In the practical application, it is found that the maximum net photosynthetic rate is much higher than the measured value when fitting the photo response data with these models (Steel, 1962; Evans, Jakonbsen & Ogren, 1993; Ye, 2007; Posada, Lechowicz & Kitajima, 2009), and the light saturation point is much smaller than the measured value (Ye & Wang 2009; Chen, Peng, Yang, Chen, & Ou-Yang 2011), and it can't fit the response data of photosynthesis rate decrease with the increase of light intensity after light saturation point (Evans et al., 1993; Yu, Zhang, Liu & Shi, 2004). There is evidence that the MRHM may overcome disadvantages of the three former models and fit light-response curves and main parameters of photosynthesis more accurately (Ye & Yu, 2008). The MRHM has been applied mainly to crops and herbaceous plants under different temperatures or different carbon dioxide concentrations (Ye & Wang, 2009). The AQY is an important indicator of light utilization efficiency by plants. Our study shows that rootstocks is an important factor affecting plant AQY, However, the exact quantitative relationship between rootstocks and AQY is not clear. Recently, a number of models have been quantitatively evaluated by calculating the mean absolute error, the mean square error, or the root mean square error (Chen et al., 2011; Li, Yang, & Zhang, 2011). However, these evaluation indices have limitations in evaluating the fit of different parameters. In this study, the RRS was used to address this difficulty. The result showed that the MRHM fitted best the P_N light-response curves and parameters and the NRHM provided the next best fit. It was followed by the EM and the RHM. The order of the models from best to worst fit was consistent with the results of studies on *Ziziphus jujuba* var. *spinosus* (Xia et al., 2014) and winter wheat (Li et al., 2011). The MRHM fitted the P_{Nmax} and the LSP well, and the NRHM fitted the RD, the AQY, and the LCP. These data indicated that the MRHM is suitable for light-response parameters at high light intensities and the NRHM is suitable for response parameters at low light intensities (Xia et al., 2014).

Therefore, the MRHM its advantages still hold when applied to citrus plants under different rootstocks conditions.

Conclusion

Our experiment conducted to study the light response of photosynthesis in Huangguogan under different citrus rootstocks conditions revealed that the thresholds required to reach the light-saturated net photosynthetic rate varied among these three graft combinations. Our results showed that the photosynthetic rate of different rootstocks were different, and the value of photosynthesis rate of HG/CJ is the greatest. Although the MRHM did not generate the best fit for LCP and RD, it did provide the best fit for LSP and P_{Nmax}, when compared with the other three models (the RHM, the EM, and the NRHM). Moreover, among four models discussed, only the MRHM could successfully fit the light-response curves of photosynthesis and all parameters (LCP, LSP, RD, P_{Nmax}).

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