

*Original Research*

# Response of Net Photosynthetic Rate to Environmental Factors under Water Level Regulation in Paddy Field

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## Abstract

Plant growth depends on soil and water environment of root and atmospheric environment of canopy. With the synergistic effect of environmental factors, it can affect the process of plant energy transportation, material interchange, and physiological accommodation. Aiming at two different micro-environments under flooding and drought condition in paddy field, this article conducted research on the net photosynthetic rate ( $P_n$ ) change law under water level regulation, and the relationship between  $P_n$  and soil and water environment and atmospheric environmental factors. Results showed that  $P_n$  descended in all growth stages under flooding or drought treatment. The descending range for lower leakage amount (2 mm/d) was slightly higher than that for higher leakage amount (4 mm/d), and it was slightly higher for heavy drought (-600 mm) with the comparison to light drought (-400 mm).  $P_n$  exhibited an impact of quadric relationship on photosynthetic active radiation (PAR) and  $CO_2$  concentration ( $C_i$ ) – both in the morning and in the afternoon, while it exhibited an impact of quadric relationship on air temperature ( $T_a$ ) in the morning, and a linear relationship in the afternoon. It showed no obvious relationship on relative humidity (RH) and vapor pressure deficit (VPD). With the comparison of two photosynthetic light response models under water-level regulation, it illustrated the flooding and drought conditions that resulted in  $P_n$  decreasing according to the light suppression effect, while it showed the physiological compensation effect after rewatering. Additionally, the new photosynthetic-light response model fit better on the photosynthetic-light response curve than the non-rectangular hyperbolic model.

**Keywords:** net photosynthetic rate, water level regulation, environmental factors, photosynthetic light response model

## Introduction

Rice irrigation area is an important carrier of regional ecological environment [1]. It involves regional economic development, social harmony and stability, improvement of ecological environment, and so on. However, there are still some problems in rice irrigation area, such as low efficiency of water and fertilizer utilization, and serious pollution of agricultural non-point sources, which restricts the sustainable development of the rice irrigation area [2, 3]. With the development of the theory of crop irrigation and drainage, water-saving irrigation and controlled drainage technology attracted great attention both within China and abroad [4, 5]. Agricultural water level is the depth of water layer after precipitation (or irrigation) and the depth of ground water level when there is no water layer. Water level regulation technique is crucial for water-saving irrigation drainage regulation, which is meaningful for water-saving pollution reduction and high rice yield in southern China [6-8].

As a major physiological process, photosynthesis provides energy and dry matter accumulation for plant growth. Also, the photosynthetic rate of rice leaves is related to final yield formation [9-11]. Water demand is different in different growth stages. On the one hand, the water deficit will make the leaf stomatal closure, photosynthetic product output slowed down; on the other hand, excessive soil moisture will make soil ventilation in poor conditions and produce secondary stress, resulting in decreased crop root vigor, indirectly affecting photosynthesis [12, 13]. Since the physiological indicators (leaf water potential, transpiration rate, stomatal conductance,  $P_n$ , chlorophyll fluorescence parameters, etc.) are sensitive to water, higher or lower water levels could result in changes to the physiological process [14, 15]. Li [16] found that water-logging stress in the late growth stage resulted in decreasing  $P_n$ , green leaves number of the main stem, and thousand-grain weight. Hirano [17] found that after water-logging, the transportation of carbon to the top internodes was promoted by adjusting the distribution of photosynthetic products to promote the growth of rice plant internodes. However, in reproductive growth stage, much more dry matter could be accumulated for light water-logging plants, thus the final plant production was promoted. Hu [18] found that under drought stress conditions,  $P_n$  was decreasing, and it decreased slowly with light water stress, while it decreased rapidly until water stress reached a certain level. However, Lv [19] found that moderate water deficit will not bring out the result of obvious photosynthetic rate descending. Ming [20] carried out the experiments with different concentrations of polyethylene glycol (PEG6000) to simulate drought. Results showed that with 10% PEG treatment,  $P_n$  decreased obviously, while stomatal conductance and leaf  $CO_2$  concentration increased; with 15% PEG treatment,  $P_n$  kept decreasing; also, it decreased with

stomatal conductance and leaf  $CO_2$  concentration decreasing.

The physiological response of rice with water-saving irrigation was based mostly on a single irrigation or drainage. Water depth was considered the irrigation upper limit, while the soil moisture in root zone irrigation was considered the lower limit. However, in the actual application, the soil moisture spatial variability is not easy to grasp [21, 22]. The problem of irrigation and drainage of rice is actually how to control the change of water level in farmland, that is the regulation of farmland water level [23]. At the field scale, the spatial variability of farmland water level is very small and easy to observe. So, taking water level regulation into consideration, this article carried out research on the response of  $P_n$  to environmental factors on the basis of the change of  $P_n$ . It was valuable for improving field water use efficiency and efficient agriculture.

## Materials and Methods

### Experimental Site

This study was carried out at the saving water and agro-ecological experimental plot in 2011 and 2012, Key Laboratory of Efficient Irrigation-Drainage and Agricultural Soil-Water Environment in Southern China, Ministry of Education (latitude 31°55'N, longitude 118°46'E). The region has a subtropical humid monsoon climate zone, with an average annual evaporation of 900 mm, yearly average temperature of 15.4°C, and maximum and minimum air temperatures of 43.0°C and -14.0°C, respectively. Mean annual rainfall is 1,041 mm, of which more than 60% of precipitation happens in the rainy season (namely from May to September), and there are 220 frost-free days per year. The soil in the area is atypical permeable paddy soil formed on the loess deposits, with loamy clay. The area adopts a five-year rice-wheat rotation system. There are 32 fixed lysimeter plots (28 with closed bottom and 4 without) with specifications of 2.5 m length, 2 m width, and 2 m depth. The lysimeter layout is divided into two groups, with each group containing 16 plots. The underground corridors and underground equipment rooms are built between the two groups and the mobile canopy is equipped on the ground. The irrigation system is an automatic irrigation system controlled by the host-electromagnetic valve (Fig. 1). The topsoil (0-30 cm) with pH value of 6.97 in lysimeter contained 2.40% soil organic matter, 0.9048 g kg<sup>-1</sup> total nitrogen, 27.65 mg kg<sup>-1</sup> available nitrogen, 0.32 g kg<sup>-1</sup> total phosphorus, and 12.5 mg kg<sup>-1</sup> available phosphorus.

### Experimental Design

Paddy rice (*Oriza sativa* L. cv. Yang 4038) was grown under two leakage intensity (2 mm d<sup>-1</sup> and

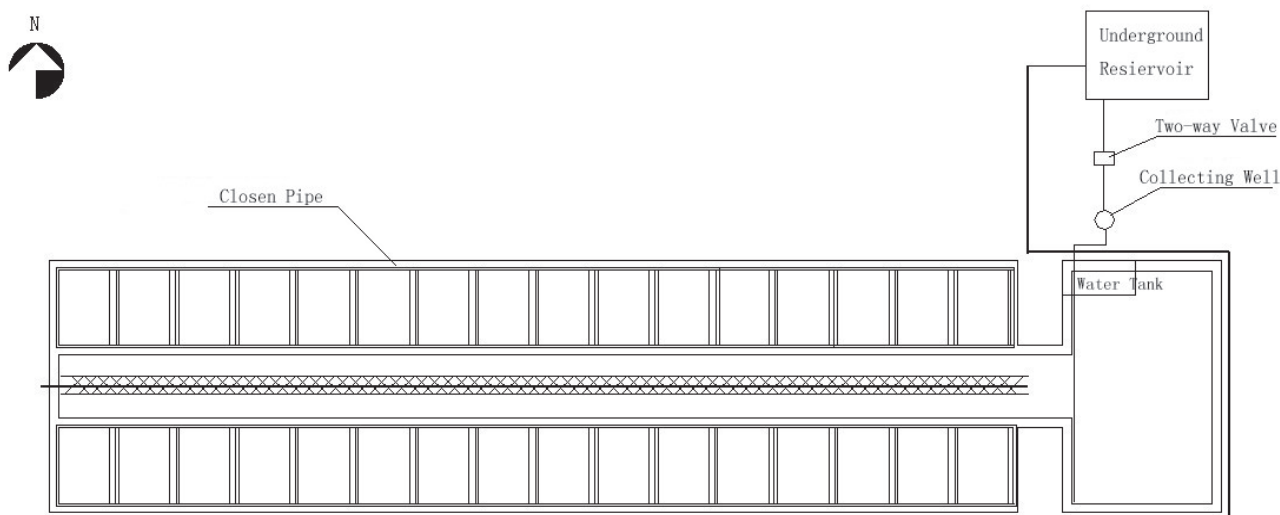


Fig. 1. Layout of the study area and experimental management.

Table 1. Water level regulation scheme and water control stages division in 2011.

Treatments		Tillering stage	Jointing-booting stage	Heading-flowering stage	Milky stage	Starting and ending time
		(07.05~08.05)	(08.06~08.26)	(08.27~09.09)	(09.10~10.10)	
Water flooding	L1	<b>120mm/2mm/d</b>	-300~30mm	-300~30mm	300~30mm	07.19~07.28
	L2	<b>120mm/4mm/d</b>	-300~30mm	-300~30mm	300~30mm	
	L3	-200~20mm	<b>250mm/2mm/d</b>	-300~30mm	300~30mm	08.14~08.23
	L4	-200~20mm	<b>250mm/4mm/d</b>	-300~30mm	300~30mm	
	L5	-200~20mm	-300~30mm	<b>250mm/2mm/d</b>	300~30mm	08.30~09.08
	L6	-200~20mm	-300~30mm	<b>250mm/4mm/d</b>	300~30mm	
	L7	-200~20mm	-300~30mm	-300~30mm	<b>250mm/2mm/d</b>	09.12~09.21
	L8	-200~20mm	-300~30mm	-300~30mm	<b>250mm/2mm/d</b>	
Water droughting	H1	<b>-300mm</b>	-300~30mm	-300~30mm	-300~30mm	07.19~
	H2	<b>-500mm</b>	-300~30mm	-300~30mm	-300~30mm	
	H3	-200~20mm	<b>-400mm</b>	-300~30mm	-300~30mm	08.14~
	H4	-200~20mm	<b>-600mm</b>	-300~30mm	-300~30mm	
	H5	-200~20mm	--300~30mm	<b>-400mm</b>	-300~30mm	08.30~
	H6	-200~20mm	-300~30mm	<b>-600mm</b>	-300~30mm	
	H7	-200~20mm	-300~30mm	-300~30mm	<b>-400mm</b>	09.12~
	H8	-200~20mm	--300~30mm	-300~30mm	<b>-600mm</b>	
Contrast treatment	CK	-300~30mm	-300~30mm	-300~30mm	-300~30mm	

Note:(1) During the water control period, water level and time was controlled according to table1.After that, water level was recovered to reasonable upper water level limit. (2) Water flooding test lasted 10 days, and it was controlled according to set leakage amount. At other stages, the leakage amount was set at 2 mm d<sup>-1</sup> when there was a water layer, while it was 0 when there was no water layer. During water control stage, there was no water supplement when water table decreasing. (3) Starting time for water flooding and water droughting in each growing stage was same. As for water droughting test, it was from no water layer decreasing to the set value. According to the water controlling days, once to twice drought was carried out in each growing stage.

4 mm d<sup>-1</sup>) and two groundwater tables during the growth stages (Table 1). The rice seed was soaked at 09:00 on 15 May and germinated at 10:00 on 17 May, then it was seedling on 19 May and transplanted on 29 June. It was at the 8-leaf stage when transplanted, and the planting density was 25×15 cm, with a total of 8×10<sup>5</sup> seedlings per hm<sup>2</sup>.

### Experimental Materials and Methods

The paddy field was irrigated and drained according to the experimental scheme in Table 1, and water amount of irrigation and drainage was recorded. For the measuring plot and soil column treatments, 4 seedlings and 3 seedlings were tagged respectively in each growth stage for measuring P<sub>n</sub>. The measuring time was 10:00 to 14:00, and the time interval was as follows: once before water control, once during water control, and 2-3 times after the water level returned to

normal. Photosynthetic parameters were measured by a portable photosynthesis system (Li-6400) and LED red/blue light source (LI-COR, USA). The environmental factors (light intensity, temperature, and humidity) were also recorded.

### Statistical Analysis

Simple data calculation and diagramming was completed by Excel 2010. Correlation analysis and regression analysis was carried out by IBM SPSS Statistics 19. Nonlinear model parameters solution and statistical analysis was conducted by MATLAB 7.0 and 1<sup>st</sup> Opt 1.5.

## Results and Discussion

### Dynamic Change of Net Photosynthetic Rate under Paddy Field Water Level Regulation

From Fig. 2 it was clear that P<sub>n</sub> was decreasing both under the flooding and drought treatments, and the decreasing degree was increasing with the water controlling time increasing. The P<sub>n</sub> descending degree at the leakage level of 2 mm/d was higher than that at the leakage level of 4 mm/d. The greater the degree of drought, the greater the P<sub>n</sub> decline. At the tillering stage, it showed a compensation effect after for about 7-8 days, while at the jointing-booting and heading-flowering stages it returned to the control level after rewatering for about 7-8 days, and at the milky stage it returned to the control level after rewatering for about 3-4 days. The descending order of accumulated P<sub>n</sub> value ( $\sum P_{n(10:00)}$ ) was: H1 > CK > H2 > L1 > L2 (tillering stage); CK > H3 > H4 > L4 > L3 (jointing-booting stage); CK > H5 > L5 > H6 > L6 (heading-flowering stage); and CK > H7 > L8 > H8 > L7 (milky stage). Zhu [24] found that there was an obvious interaction to photosynthetic productivity, dry matter accumulation on paddy field drainage degree, and canopy apparent photosynthetic rate at 15 days and 30 days was decreased, but returned after rewatering, which accorded with our study. Chaum [25] found that Glybet pre-treated plants maintained a high level of P<sub>n</sub> even under 25% soil water content, which illustrated that light drought had a slight effect on P<sub>n</sub> value, which was in accordance with our study results.

### Response of P<sub>n</sub> to Environmental Factors under Paddy Field Water Level Regulations

As shown in Fig. 3, the net P<sub>n</sub> value in the morning was higher than that in the afternoon under the same PAR. Compared to flooding treatment, the P<sub>n</sub> value decreased obviously in the morning for drought treatment, reaching the peak value at the PAR of around 900 μmol·m<sup>-2</sup>·mol<sup>-1</sup>. At noon, the PAR value concentrated in the range of 900-1800 μmol·m<sup>-2</sup>·mol<sup>-1</sup> for both flooding

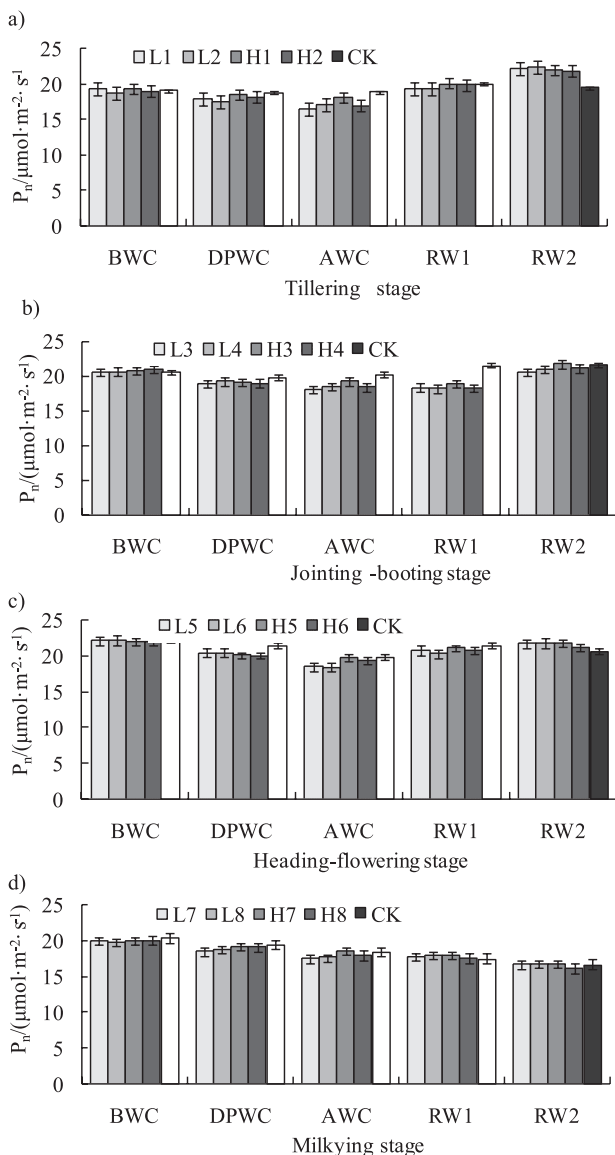


Fig. 2. Dynamic change of net photosynthetic rate.

and drought treatments. Also, the change of  $P_n$  value for flooding treatment ( $10\text{--}25 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{mol}^{-1}$ ) was greater than that for drought treatment ( $15\text{--}25 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{mol}^{-1}$ ).  $T_a$  is a major factor for photosynthesis process, and the physical exchange of  $\text{CO}_2$  and water vapor between leaves and air. It could also affect the  $P_n$  level according to the effect on enzyme activity. The  $P_n$  value reached

the peak at temperatures of  $37^\circ\text{C}$  and  $35^\circ\text{C}$ , respectively, for flooding and drought treatments in the morning. The  $T_a$  at noon ranged from  $35^\circ\text{C}$  to  $42^\circ\text{C}$ , and the  $P_n$  ranged from  $15 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{mol}^{-1}$  to  $35 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{mol}^{-1}$ . The  $P_n$  in the afternoon was lower than that in the morning under the same  $T_a$ .  $\text{CO}_2$  is the raw material for photosynthesis. The concentration change of  $\text{CO}_2$  in the air could affect the  $\text{CO}_2$  concentration ( $C_i$ ) among leaf cells. The  $P_n$  values for flooding and drought treatments reached the peak in the morning, when the  $C_i$  levels were  $380 \mu\text{mol}\cdot\text{mol}^{-1}$  and  $350 \mu\text{mol}\cdot\text{mol}^{-1}$ , respectively. When the  $C_i$  ranged from  $330 \mu\text{mol}\cdot\text{mol}^{-1}$  to  $360 \mu\text{mol}\cdot\text{mol}^{-1}$  at noon, the  $P_n$  value ranged from  $15 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{mol}^{-1}$  to  $35 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{mol}^{-1}$ . At the same leaf  $C_i$ , the  $P_n$  value in the afternoon was lower than that in the morning, which showed the hysteresis of photosynthetic rate on  $\text{CO}_2$  concentration. RH and VPD could affect the photosynthetic rate according to the effect on stomatal conductance and transpiration rate. As shown in Fig. 2, the  $P_n$  change trend was not clear at the three periods, however, the distribution area of scatter points is obviously divided in each time interval. Xia [26] found that PAR was the most important ecological factor affecting  $P_n$ , followed by air  $\text{CO}_2$  concentration, and with the intensification of water stress the  $T_a$  evidently restrained  $P_n$  by using path analysis. The relative water content (RWC) regimes were different than our study.

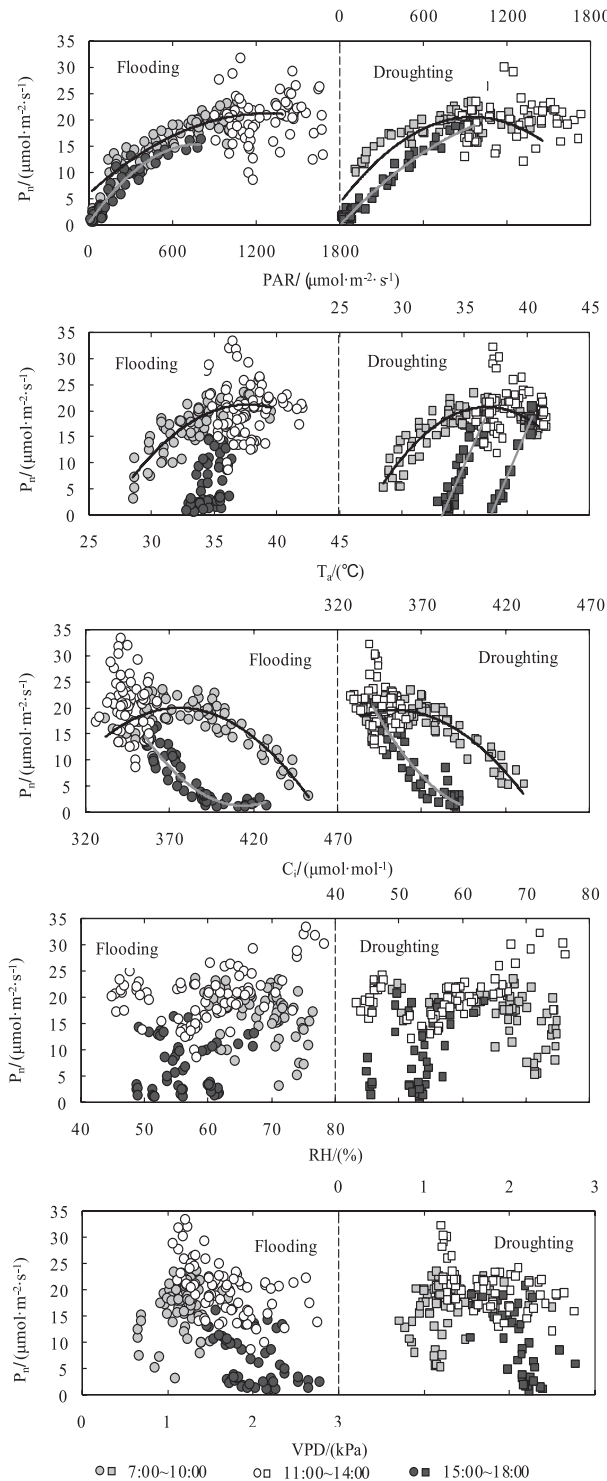


Fig. 3. Response of  $P_n$  to environmental factors under paddy field water level regulation.

### Correlation Analysis on $P_n$ and Environmental Factors under Water Level Regulation

From Table 2, for both flooding and drought treatments, at the time period of 07:00-10:00 and 15:00-18:00,  $P_n$  exhibited an impact of quadric relationship on PAR. At the time period of 07:00-10:00, 11:00-14:00, and 15:00-18:00,  $P_n$  exhibited an impact of quadric relationship on  $T_a$  in the morning, while it showed a linear relationship in the afternoon. Moreover,  $P_n$  exhibit an impact of quadric relationship on  $C_i$  both in the morning and in the afternoon.

### Modeling on Photosynthetic-Light Response under Different Paddy Field Water Level Regulation

Traditional photosynthetic-light response model is a non-rectangular hyperbolic model proposed by Herrick [27] and based on the kinetic principle of enzymatic reaction, as follows:

$$\theta \cdot P^2 - P(\alpha \cdot PPFD + P_{max}) + \alpha \cdot PPFD \cdot P_{max} = 0 \quad (1)$$

...where  $P$  is total photosynthetic rate,  $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ ;  $\theta$  is convexity of non-rectangular hyperbola; and  $PPFD$  is photosynthetically effective quantum flux density,  $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ . When  $\theta = 0$ , the non-rectangular hyperbola convert to rectangular hyperbola. When  $\theta \neq 0$ , since  $P_n = P - R_d$ , the above formula (1) could convert to the following formula (2):



Table 2. Relationship between  $P_n$  and environmental factors in different time periods.

Relationship	Treatment	Time Period	Fitting Equation	R <sup>2</sup>	F	p
$P_n$ and PAR	Flooding	am	$y = -9E-06x^2 + 0.0240x + 5.9349$	0.8053	142.733	<0.001
		pm	$y = -3E-05x^2 + 0.0426x + 0.0023$	0.9101	280.226	<0.001
	Drought	am	$y = -2E-05x^2 + 0.0346x + 4.0830$	0.8302	149.140	<0.001
		pm	$y = -9E-06x^2 + 0.0287x - 0.1358$	0.9684	643.306	<0.001
$P_n$ and $T_a$	Flooding	am	$y = -0.1648x^2 + 12.414x - 212.73$	0.7026	81.496	<0.001
		pm	$y = 2.4912x - 80.012$	0.3081	22.260	<0.001
	Drought	am	$y = -0.2178x^2 + 16.019x - 273.79$	0.8019	123.476	<0.001
		pm	$y = 5.2912x - 175.71$	0.8410	163.999	<0.001
$P_n$ and $C_i$	Flooding	am	$y = -0.0029x^2 + 2.1674x - 387.24$	0.7322	94.308	<0.001
		pm	$y = 0.0039x^2 - 3.2062x + 665.26$	0.8504	139.257	<0.001
	Drought	am	$y = -0.0028x^2 + 1.9558x - 326.94$	0.8036	124.807	<0.001
		pm	$y = 0.004x^2 - 3.3269x + 683.67$	0.8392	109.567	<0.001

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

When the light response curve is expressed by the non-rectangular hyperbolic model, it is an asymptote line. In the actual application process, the saturation light intensity may be much lower than the actual measured value, and maximum photosynthetic rate may be much greater than the measured value; also, the data under the condition of light suppression cannot be dealt with. Ye [28] improved a new model against the above issue, as shown in the following formula (3),

$$P_n = \alpha \frac{1 - \gamma \cdot I}{1 + \gamma \cdot I} \cdot I - R_d \tag{3}$$

...where  $P_n$  is net photosynthetic rate,  $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ ;  $I$  is photosynthetic active radiation,  $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ ;  $R_d$  is dark respiration rate,  $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ ;  $\alpha$  is initial slope of light

response curve ( $I = 0$ );  $\beta$  is the correction coefficient; and  $\gamma$  is the ration of initial slope to the maximum photosynthetic rate of light response curve ( $\gamma = \alpha/P_{max}$ ).

In this study, two models were adopted to simulate the photosynthetic light response curve for flooding and control treatments at joint-booting stage, and the results are shown in Fig. 4, Table 3, and Table 4. This illustrated that the  $P_n$  value was increasing then decreasing with the increasing light intensity under the flooding treatment, which showed obvious light suppression phenomenon, while there was no obvious light suppression under control treatment. When  $\text{PAR} < 800 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ , the change trends for two treatments were consistent; when  $\text{PAR} = 1000 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ , the  $P_n$  reached the saturation under flooding treatment;  $P_n$  decreased rapidly when  $\text{PAR} > 1000 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ , which illustrated that the light suppression of rice leaves was aggravated under the waterlogging stress, resulting in  $P_n$  decreasing under strong light conditions. As for the non-rectangular hyperbolic model, it fit better for the light response curve with no light suppression, while it fit worse for

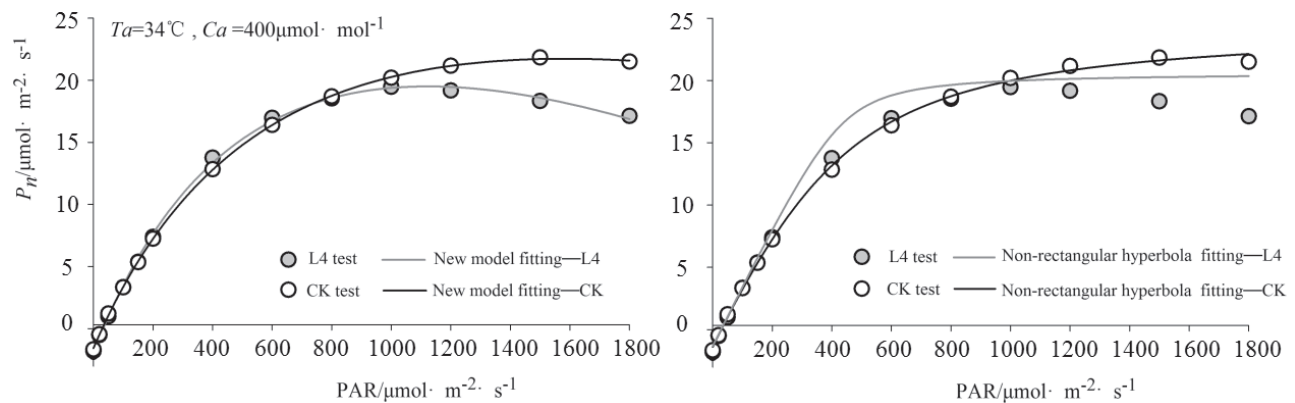


Fig. 4. Simulation results of photosynthetic-light response curve for flooding and control treatment at jointing-booting stage.

Table 3. Fitting parameters of new photosynthetic-light response model at jointing-booting stage.

Treatment	Model Parameter			Characteristic Parameter				Statistical Parameter	
	$\alpha$	$\beta$	$\gamma$	$R_d$	$P_{max}$	$L_{sp}$	$L_{cp}$	$R^2$	SSE
L4	0.061725	0.0002758	0.001099	1.908649	19.5	1121.53	32.31	0.999136	0.714888
CK	0.055873	0.0001671	0.001132	1.567677	21.72	1579.02	29.12	0.99992	0.07615

Table 4. Fitting parameters of non-rectangular hyperbolic model at jointing-booting stage.

Treatment	Model Parameter		Characteristic Parameter		Statistical Parameter	
	$\alpha$	$\theta$	$R_d$	$P_{max}$	$R^2$	SSE
L4	0.048	0.961	1.33	21.96	0.994	5.23
CK	0.049	0.732	1.387	25.809	0.999	0.924

the light response curve with light suppression. As for the new model, it fit well for both situations above. The characteristic parameter in the non-rectangular hyperbolic model was higher than that in the new model, and the simulation results for the new model were much closer to the measured value. Galmés [29] and Contin [30] found that with the high light intensity at sunny noon, it was prone to have light suppression. With the combination of high light intensity and environmental stress (high temperature or drought), the sensitivity

to light suppression could increase, resulting in light suppression under the condition of not too strong light, which was consistent with the results obtained by the new model.

The fitting curve of photosynthetic-light response at heading-flowering and milky stages under water level regulation was shown in Fig. 5, and the parameters were in Table 5. Under the same light intensity,  $P_n$  value decreased at the end of water level control both for flooding and drought treatments at the

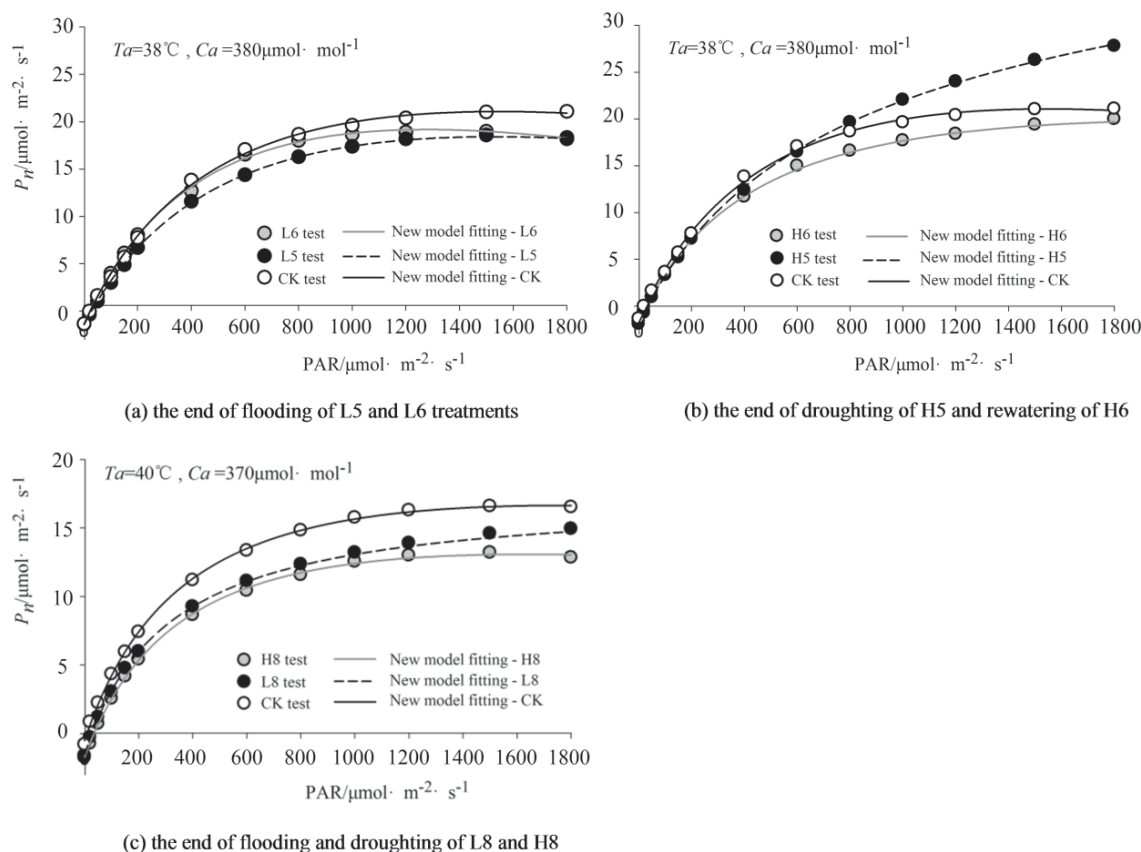


Fig. 5. Fitting curve of photosynthetic light response.

Table 5. Parameters of photosynthetic-light response model.

Growth Stage	Treatment	New Model Parameter			Characteristic Parameter				Statistical Parameter	
		$\alpha$	$\beta$	$\gamma$	$R_d$	$P_{max}$	$L_{sp}$	$L_{cp}$	$R^2$	SSE
Heading-flowering	H6	0.061898	0.000070	0.001951	1.718386	20.05	2239.59	29.41	0.999640	0.282875
	H5	0.057465	-0.000044	0.001529	1.776384			32.21	0.999738	0.362194
	L6	0.063148	0.000198	0.001515	1.347480	19.17	1279.76	22.15	0.999360	0.491342
	L5	0.053202	0.000159	0.001374	1.428143	18.41	1528.77	28	0.999736	0.189045
	CK	0.062544	0.000151	0.001488	1.401615	21.07	1543.53	23.27	0.998895	1.016175
Milky	L8	0.052873	0.000104	0.002360	1.686762	13.08	1638.59	34.63	0.999442	0.212245
	H8	0.061408	-0.000005	0.003191	1.510599			26.69	0.999892	0.045579
	CK	0.059164	0.000092	0.002326	0.499873	16.65	1779.65	8.62	0.999536	0.235432

heading-flowering stage. Referring to drought treatment, the  $P_n$  increased obviously with light intensity increasing after rewatering. For two flooding treatments,  $P_n$  for L6 decreased slightly more slowly than that for L5. Furthermore,  $P_n$  for L6 was lower than CK only when  $PAR > 800 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{mol}^{-1}$ , while  $P_n$  for L5 was lower than CK at a lower light intensity ( $PAR = 200 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{mol}^{-1}$ ). This illustrated that under flooding conditions, keeping higher leakage intensity (4 mm/d) was favorable for alleviating the decline of  $P_n$  caused by flooding, while lower leakage intensity (2 mm/d) might result in waterlogging. At the milky stage, both flooding and drought could result in  $P_n$  decreasing under the same light intensity, with a higher reducing range for drought treatment. Milky stage was the key period for grain formation, which needed a certain amount of water supply. However, long-time flooding could result in root hypoxia and lower root system activity, affecting leaf photosynthesis.

### Conclusions

With the comparison of flooding and drought condition, this article conducted research on the difference of the responses of net photosynthetic rate on environmental factors. The following conclusions could be drawn from the above discussion:

- 1) The  $P_n$  with a lower leakage amount (2 mm/d) decreased slightly more than that with a higher leakage amount (4 mm/d), and  $P_n$  under heavy drought treatment (-600 mm) decreased slightly more than that under light drought treatment (-400 mm). After rewatering at the tillering stage,  $P_n$  recovered rapidly and showed compensation effect, while it recovered slowly at the jointing-booting stage and was even difficult to recover at the heading-flowering stage. At the milky stage, it was easy to recover.
- 2)  $P_n$  exhibited an impact of quadric relationship on PAR and  $C_i$  both in the morning and in the afternoon.  $P_n$  exhibit an impact of quadric

relationship on  $T_a$  in the morning, while it showed a linear relationship in the afternoon.  $P_n$  reached peak when PAR was  $900 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{mol}^{-1}$  in the morning for drought treatment, while it decreased not obviously for flooding treatment.  $P_n$  reached its peak at 37°C and 35°C for flooding and drought treatment, respectively, while it reached peak when the leaf  $\text{CO}_2$  concentration was  $380 \mu\text{mol}\cdot\text{mol}^{-1}$  and  $350 \mu\text{mol}\cdot\text{mol}^{-1}$ , respectively. Under the same PAR,  $C_i$ , or  $T_a$ ,  $P_n$  value in the afternoon was lower than that in the morning, performing the characteristic of hysteresis.

- 3) Both flooding and drought condition could result in  $P_n$  decreasing, aggravating the effect of light suppression of the rice leaves. The photosynthetic-light response curve after rewatering at heading-flowering stage showed that  $P_n$  increased rapidly with light intensity increasing after rewatering, showing physiological compensation. Keeping a higher leakage intensity (4mm/d) was favorable for alleviating the decline of  $P_n$  caused by flooding. With the comparison of two model simulation results, the new model fit better on the photosynthetic-light response curve than the non-rectangular hyperbolic model, and simulation results were much more close to measured value.

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### Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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