Modelling the Effects of Post-Anthesis Heat Stress on Seed-Setting Rate in Rice

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Introduction

Seed-setting rate of rice significantly decreases under high temperature during the reproductive stage and the effects depend greatly on the timing and severity of heat stress. However, the stage sensitivity of seed-setting rate in response to heat stress is not yet well simulated by most of the present crop models.

This study was conducted (i) to quantify the heat stress by taking account into the interaction of high temperature levels and durations, and (ii) to develop a model that can quantify the variation of seed-setting rates of the whole plants under the heat events at different post-anthesis stages.

Materials & methods

Experimental design

Four-year phytotron heat stress experiments with different temperature levels and durations were conducted at 0, 6 or 12 days after anthesis with three japonica cultivars.

Table 1. Summary of heat stress treatments in the phytotrons.

Year	Site	Cultivar	The timing of treatment [a]	Temperature level [b] & Duration [c]
2011	Nanjing	Nanjing 41	12DAA	[T1, T3]×[D2]
		Wuxiangjing 14		[T2, T4]×[D1, D2, D3]
2012	Nanjing	Nanjing 41	12DAA	[T1,T2]×[D2]
		Wuxiangjing 14		[T3, T4]×[D1, D2, D3]
2014	Rugao	Nanjing41	0 DAA & 6 DAA	[T1]×[D2]
		Wuyunjing 24		[T2*, T3*, T4*]×[D1, D2, D3]
2015	Rugao	Nanjing41	0 DAA & 6 DAA	[T1]×[D2]
		Wuyunjing 24		[T2*, T3*, T4*]×[D1, D2, D3]

[a] 0 DAA, 6 DAA and 12 DAA: 0, 6 and 12 day after anthesis, respectively.
[b] T1, T2, T3,T4, T2*, T3*, T4* : the temperature levels (Tmax/Tmin) of 32/22 °C, 35/25 °C, 38/28 °C, 41/31 °C, 36/26, 40/30 °C and 44/34 °C, respectively.
[c] D1, D2 and D3: the durations of 2 days (d), 4 d and 6 d, respectively.

Fig. 1. Phytotron rooms in Rugao, Jiangsu, China ((32°16'N ,120°45'E)

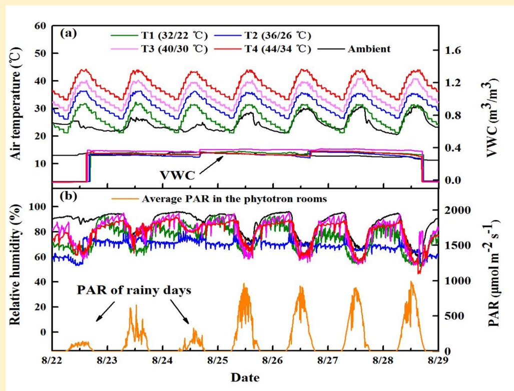

Fig. 2. Air temperature, soil VWC, RH and PAR in phytotron rooms

Data collection

At maturity, panicles were divided into three parts. Sterile grains and fertile grains were identified manually by pressing spikelets between thumb and index finger.

Model description

$$SR(HSI) = \frac{1}{1+\exp\{b(HSI-c)\}}$$

$$SR = SR_{max}\prod_{d_h}^{d_m} f(HSI_i)$$

$$f(HSI_i) = SR(HSI_i)/SR_{max}$$

SR : seed-setting rate (%)
HSI : heat stress index
b and c : fitting curve parameters
$f(HSI_i)$: heat factor of seed-setting rate of day i
d_h, d_m: dates of heading and maturity
$SR(HSI_i)$: seed-setting rate of day i
SR_{max}: potential seed-setting rate (%)

Results & discussion

Comparison among heat stress indices

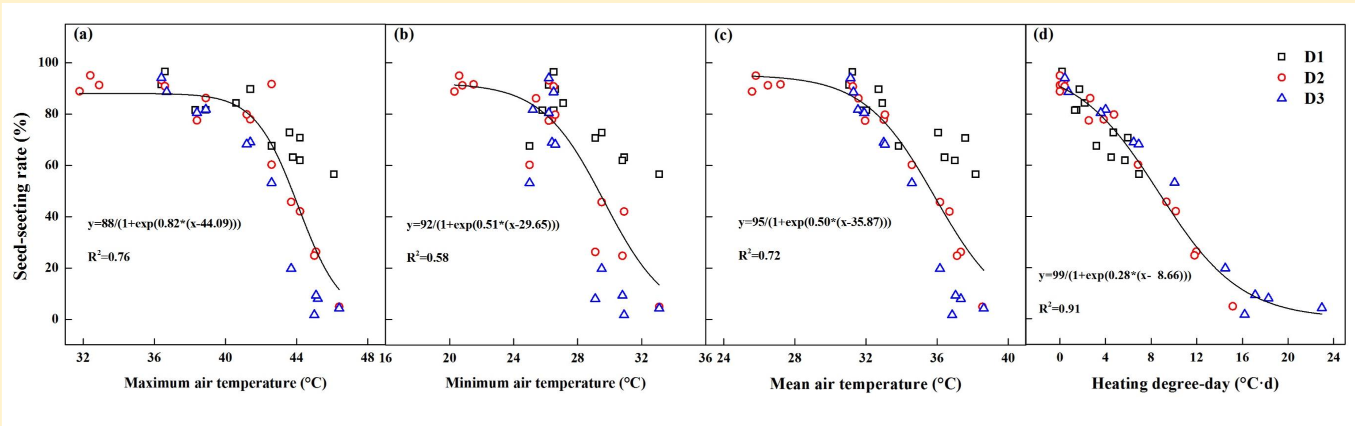

Fig. 3. Observed and fitting seed-setting rates in relation to maximum air temperature (a), minimum air temperature (b), mean air temperature (c) and heating degree-day (d, τ=35 °C) for the treatment at anthesis stage.

$$HDD = \sum_{d_h}^{d_m} HD_i$$

$$HD_i = \frac{1}{24}\sum_{j=1}^{24} \mathrm{Max}\,(T_j - \tau, 0)$$

d_h: date of heading
d_m: date of maturity
T_j: hourly air temperature
τ: temperature threshold

- HDD fitted best with the seed-setting rate in all HSI

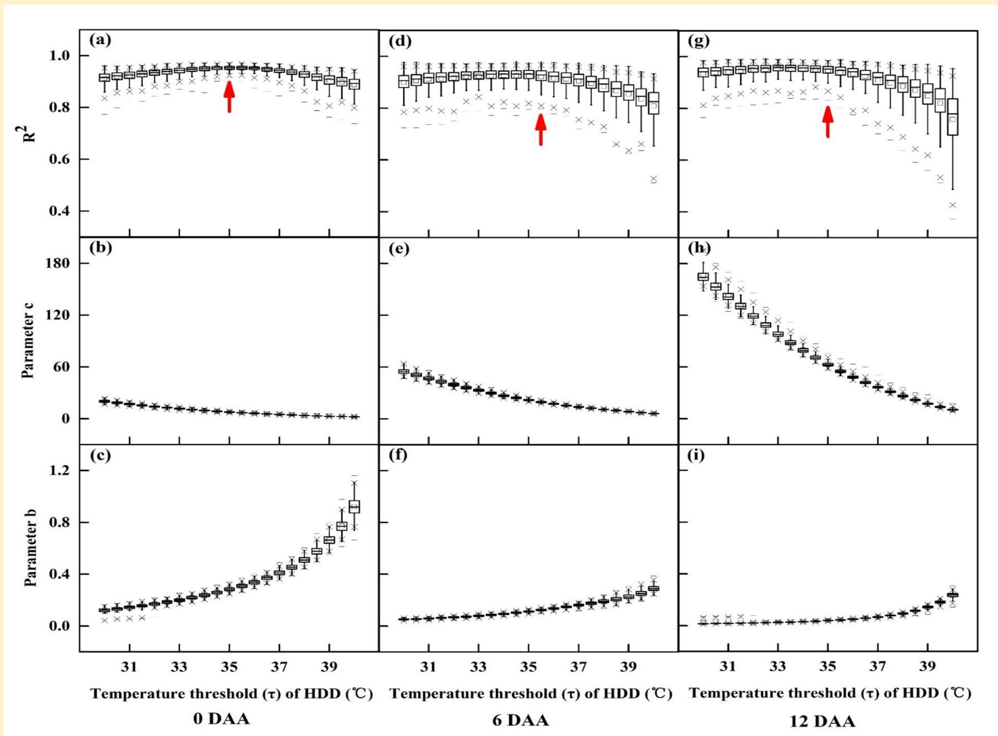

Figure 4. Variations of parameter b (c, f, i), parameter c (b, e, h) and determination coefficient (a, d, g) of logistic curves to fit seed-setting rates (%) with heating degree-day (HDD) above diverse thresholds of heat stress occurred separately at 0 (a, b, c), 6 (d, e, f) and 12 days (g, h, i) after anthesis. * The data used in the graph were randomly selected from training sets of 1000-group bootstrap samples. All the varieties were used in the graph.

- Threshold (τ) was similar among the treatments at 0 DAA, 6 DAA and 12 DAA (35°C, 35.5°C and 35°C)

Seed-setting rates at different positions of the panicles in response to HDD

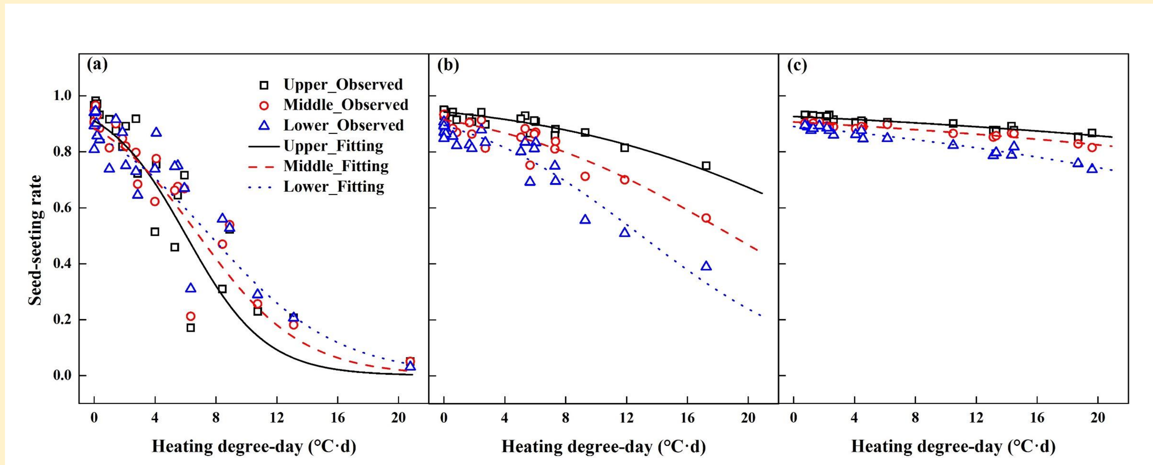

Figure 5. Observed and fitted seed-setting rates (%) of upper, middle and lower parts of the panicles in relation to heating degree-day (HDD) at treatment periods of 0 (a), 6 (b) and 12 (c) days after anthesis. * The data used in the graph were randomly selected from training sets of 1000-group bootstrap samples .

- The sensitivity of seed-setting rates in response to HDD varied with different positions on the panicle and the timing of treatments.

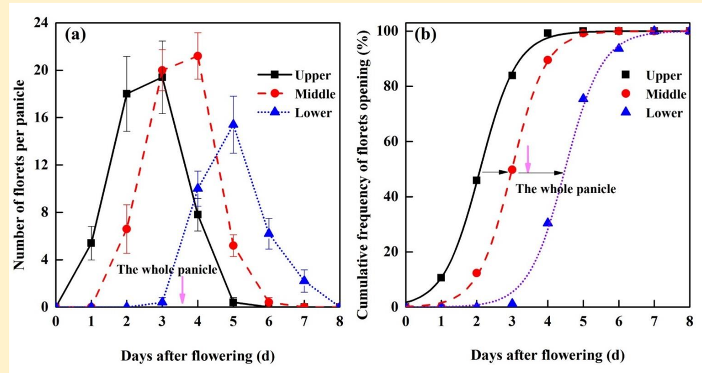

Fig 6. Frequency of timing of flowering on the upper, middle and lower panicles (a) and cumulative frequency of spikelets opening (b) in relation to days after anthesis.

- 1 and 3-day delay of anthesis stage for the spikelets on the middle and lower panicles
- The change of sensitivity can be partly attributed to the flowering pattern among the rice population.

Parameters in response to the timing of the treatments

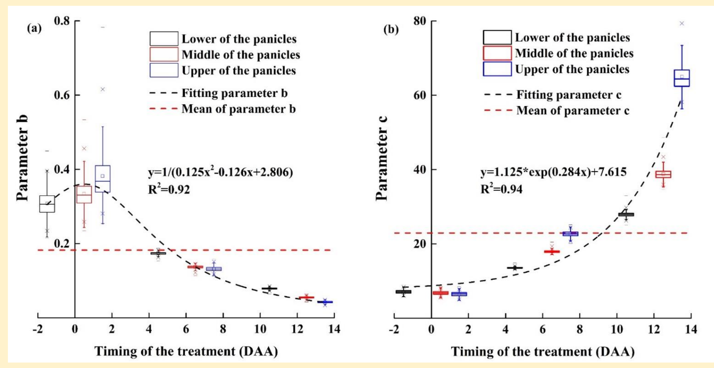

Fig 7. Parameter b (a) and c (b) of logistic curves in response to the timing of heat stress treatments. * The data were training sets of 1000-group bootstrap samples.

b: Gaussian curve
c: Exponential curve

- Parameter b and c changed with the timing of treatments

Model evaluation

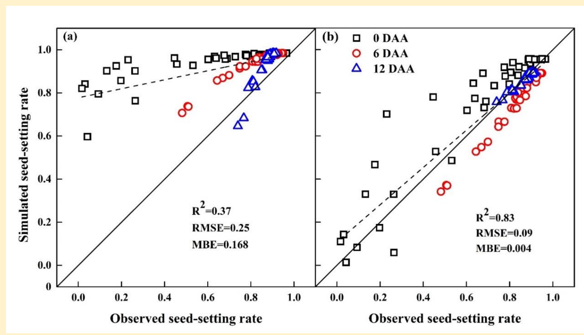

Fig 8. Comparison between observed and simulated seed-setting rates (%) by Model 1 with constant parameters across different growth stages (a) and Model 2 with stage-dependent parameters (b). * The data were randomly selected from testing sets of 1000-group bootstrap samples .

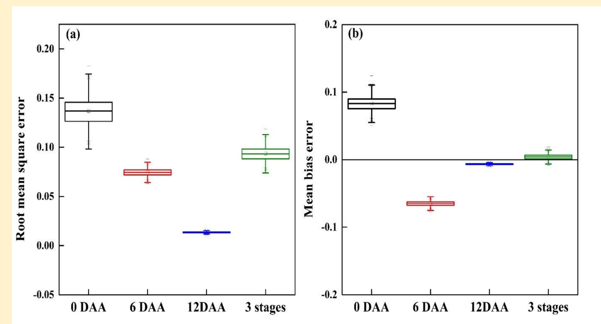

Fig 9. RMSE (a) and MBE (b) between observed and simulated seed-setting rates (%) by Model 2 under the heat stress occurred at different stages, and the average performance across all 3 stages. * The data were randomly selected from testing sets of 1000-group bootstrap samples .

- The performance of Model 2 was much improved compared to Model 1, with significantly reduced RMSE and virtually no bias if three stages combined.

Conclusion

This study proposed a model that accounts for the effects of heat events with different durations and intensities by using of heating degree-day (HDD) and stage-dependent parameters of the impact function of HDD. The model can be a robust basis for quantifying grain yield losses under increasing temperature conditions.

Acknowledgements

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