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Prediction model of rice (*Oryza sativa*) yield under high temperature stress based on hyper-spectral remote sensing

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ABSTRACT

Canopy spectral reflectance on flowering, filling and ripening stages of two rice (*Oryza sativa* L.) cultivars during heading stage under different high temperature stress as well as yield and yield components after maturation were measured in 2007 and 2008. The results showed that relativities among theoretical yield, actual yield, yield components and hyper-spectral indices during flowering and filling stages were at the level of $P<0.05$ by contrast with ripening stage, which thus indicated these two stages could be used as key stages for forecasting rice yield. Further, difference vegetation index called as DVI[810, A(450, 560, 680)], perpendicular vegetation index called as PVI(810, 680), slope of red edge called as $Dë_{red}$ and Area 670-755 could be used for forecasting theoretical and actual yield of matured rice. Moreover, DVI(810, 450) and DVI(810, 560), PVI(810, 680) and $Dë_{red}$ could also be used for forecasting yield components of matured rice. The hyper-spectral indices with preferred fitting correlation were selected by regression analysis, and accordingly models for forecasting rice yield during different growth stages were established in the light of spectral index PVI (810,680). Finally, after testing these derived models with independently observed data, it was found that the model of flowering stage was more reliable to predict rice yield than those of filling and ripening stages.

Key words: Booting stage, Canopy hyper-spectral reflectance, High temperature stress, Rice, Yield, Yield components

Using remote sensing data to forecast crop yield mainly depends on quantitative relationships between crop spectral characteristics and their growth and yield (Shu *et al*, 2006). These will provide important evidences for rice (*Oryza sativa* L.) growth monitoring of nutrient stage and yield prediction by measuring hyper-spectral reflectance on primary stages, selecting appropriate hyper-spectral parameters, and establishing correlative models between hyper-spectral parameters and rice yield. In recent years, many researchers have studied the change tendency of crop canopy reflectance spectra and yield prediction (Ferrio *et al*. 2005, Xue *et al*. 2005, Zhuang *et al*. 2011), but few have reported quantitative inversion of rice yield under high temperature stress (Shen *et al*. 2007). With increasingly change of presently global climate, the extreme and sustained high temperature in summer occurs continually. As a result, the rice damage extent and frequency caused by high temperature in Yangtse River basin of China increase, which further leads to damage to rice yield. Therefore, study on monitoring high temperature damage and forecasting yield using hyper-spectral remote sensing should become one of the important techniques in the future (Lei *et al*. 2006, Cheng *et al*. 2008). Combining with rice growth parameters in the study, the canopy hyper-spectral reflectance of rice during primary growth stages were measured, and the relationships among canopy hyper-spectral parameters, theoretical yield, actual yield and yield components were further discussed. The objective in this paper is to supply important theoretic references for forecasting rice yield by selection of efficient hyper-spectral parameters, and promote application of hyper-spectral remote sensing technique on both rice heat injury and yield prediction.

MATERIALS AND METHODS

Experiment was carried out on the Jiangsu Academy of Agricultural Sciences in 2007 and 2008, and test samples were Yangdao 6 (conventional Indica rice, 138 days for total growth stage) and Nanjing 43 (conventional Japonica rice, 160 days for total growth stage). The two samples were treated as follows: cultivated on May 15, transplanted to plastic cases with specification of 30 cm×20 cm×10 cm on June 18, the cases were placed in a mesh room. The two rice cultivars started for heading on approx 20 August. By

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automatic control temperature system and far-infrared heating lamp with length of 1.5 m and rated power of 1000 W, cylindrical steel pipe was placed in testing rice field, and this lamp was kept far from ground by 1.5 m. Under adjustment of temperature control and ventilation system, the temperature change of heating area (0.8~1.2 m above ground) was controlled at approx ±0.2°C. At the beginning of heading stage for two cultivars, ten cases of rice were selected randomly to be treated with high temperature, another ten cases were used as control (CK), the heating device was switched on for preheating in early 30 min. to ensure that the temperature of rice surface was kept at 35°C, 38°C and 41°C respectively for three days and 5 hr/day (09:00-14:00).

Five cases of rice were randomly selected to be transplanted to the model RXZ microclimate-controlled culture case, treated with high-temperature of 35°C, 38°C and 41°C respectively for three days, and 5 hr/day (09:00-14:00). The natural condition was used as control (CK), and experiment data were used for testing the prediction models.

Canopy spectra reflectance on flowering, filling and ripening stages were measured by using the hyper-spectral radiation device Fieldspec Pro FR2500. Ten sampling points in each test area were recorded, and the average value was used as hyper-spectral reflectance of this treatment. The calibration was performed with standard blank plate during measurement. After maturity, rice in test areas were dried and investigated for panicle number/µ (no./ha), spikelet/panicle (no.), kernel weight (g), panicle length (cm), panicle weight (g) and seed setting rate (%). Further, all rice were harvested for measuring actual yield (kg/ha).

Hyper-spectral parameter calculation methods in references were used and realized by programme from MATLAB 2007 (Jordan 1969, Richardson and Wiegand 1977, Gupta *et al*. 2003).

RESULTS AND DISCUSSION

Change of canopy spectra in rice cultivars under different high temperature stress

Canopy hyper-spectral reflectance characteristics of rice under different high temperature stress were almost similar with those of general green plant (Fig1). Liu *et al*.(2006) observes green peak of 550 nm and red light low valley of 680nm in visible light region of 400~700 nm as well as plateau area of 780~1,100 nm in near-infrared region. Further, there are mainly water-absorbing regions in 1 300~2 500nm, wherein there are strong absorbing regions in 1,450 nm and 1 930 nm (Cater *et al*.1996). But the hyper-spectral reflectance in different regions under high temperature stress was slightly different, which mainly presented the increased reflectance in visible light region with the elevation of temperature. This situation may be caused by reduced leaf area and chlorophyll content resulting from high temperature stress. And reflectance in near-infrared region was reversed and reduced with the elevation of temperature.

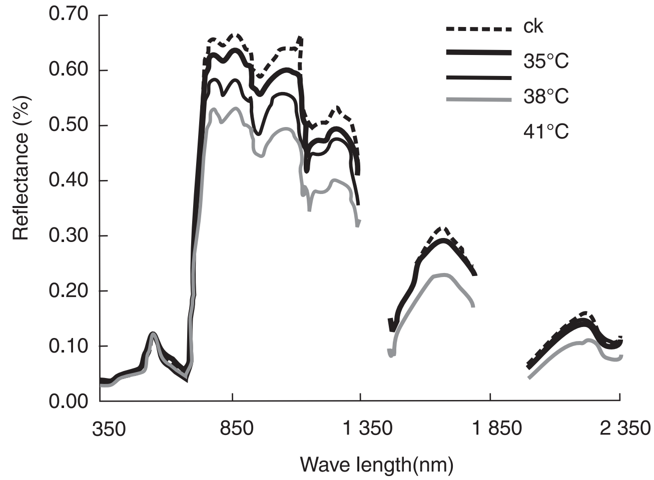

Fig 1 Change of hyper-spectra reflectance of Yangdao 6 during flowering stage under different high temperature

Relationship between hyper-spectral parameters and theoretical and actual yield in rice

For the two rice cultivars, the relationships among canopy hyper-spectral reflectance, spectral parameters and theoretical and actual yield were analyzed. It was shown that the relativities were significant at the level of $P<0.05$ or $P<0.01$, wherein yield prediction based on flowering and filling stages were preferred than that on ripening stage by much bigger correlation coefficient (Table 1).

In spectral parameters, difference vegetation index DVI[810, A(450, 560, 680)], perpendicular vegetation index PVI(810, 680), $Dë_{red}$ and Area 670–755 could be used for estimating theoretical and actual yield of matured rice, in which rice actual yield was positive relative to perpendicular vegetation index PVI(810, 680) on flowering and filling stages (Fig 2).

Liu *et al.* (2004) and Feng *et al*. (2007) found that correlations between characteristic spectral indices and wheat yield from tilling to maturing stage are close and yield models of different stages are established accordingly. Tang *et al*. (2004) have established compound yield models based on different growth stages to understand the formation process of rice yield thoroughly. Rice canopy spectra can objectively reflect leaf area and chlorophyll content, and also indirectly reflect capacity of rice photosynthesis and accumulation of photosynthetic assimilation products. Thus, the yield can be predicted by canopy hyper-spectra. It was found that theoretical and actual yield prediction based on flowering and filling stages was preferred than that on ripening stage. It was possible that formation of grain nutrient components mainly originated from transference of stems and leaf storage at the beginning of filling stage. Further, most of rice leaves and fringes on ripening stage turned yellow, and leaf area and chlorophyll content gradually reduced. Therefore, the contribution rate of whole canopy spectra from leaf chlorophyll which closely related to theoretical and actual

Table 1 Correlation between canopy reflectance hyper-spectral parameters and theoretical and actual yield during different growth stages (n=40)

	Flowering stage		Filling stage		Ripening stage	
	Hyper-spectral parameter	Correlation coefficient	Hyper-spectral parameter	Correlation coefficient	Hyper-spectral parameter	Correlation coefficient
Theoretical yield (kg/ha)	DVI(810,A(450,560,680))	0.84**	DVI(810,A(450,560,680))	0.79**	DVI(810,A(450,560,680))	0.56**
	PVI(810,680)	0.89**	PVI(810,680)	0.82**	PVI(810,680)	0.35*
	RES	0.72**	RES	0.69**	RES	0.40**
	Area 670-755	0.84**	Area 670-755	0.82**	Area 670-755	0.47**
Actual yield (kg/ha)	DVI(810,A(450,560,680))	0.77**	DVI(810,A(450,560,680))	0.83**	DVI(810,A(450,560,680))	0.51**
	PVI(810,680)	0.86**	PVI(810,680)	0.82**	PVI(810,680)	0.36*
	RES	0.63**	RES	0.72**	RES	0.33*
	Area 670-755	0.77**	Area 670-755	0.83**	Area 670-755	0.41**
	BES	0.35*	Area 490-530	0.42**	P_Depth920	0.32*

*P=0.05, **P=0.01, r (0.05,40)=0.30, r(0.01,40)=0.39

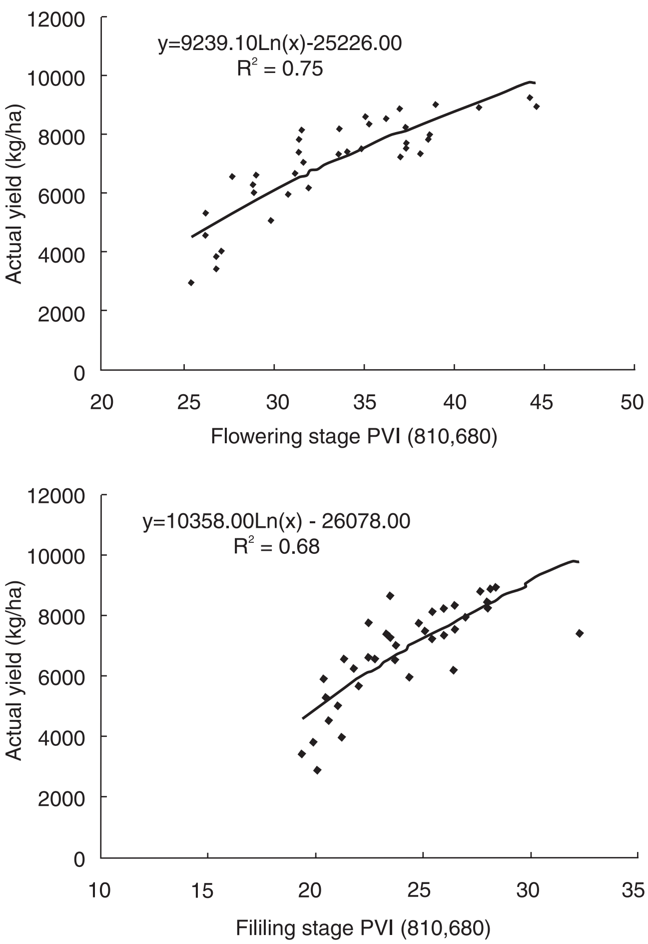

Fig 2 Quantitative relation between actual yield and PVI(810, 680) on different growth stages

yield would be reduced (Tang *et al.* 2007). In comparison, the prediction precision of rice yield using canopy hyper-spectra on ripening stage maybe reduced. These results were same as Yang *et al.* (2008).

Relationship between hyper-spectral parameters and yield components in rice

Panicle no./mu, spikelet/panicle, kernel weight, panicle length, panicle weight and seed setting rate are yield components of rice. The relationships among canopy hyper-spectral reflectance, spectral parameters and the above-mentioned yield components are shown in Table 2. In similar with results from theoretical and actual yield, yield components prediction based on flowering and filling stages were preferred than that on ripening stage with correlation coefficient over 0.51. Compared with correlation coefficients of the same spectral parameters such as DVI(810, 450), DVI(810, 680) and $Dë_{red}$, the relativities between hyper-spectral parameter on three stages and panicle number/mu were higher than those of spikelet/panicle and kernel weight. The prediction model of panicle number/mu was thus mainly used for forecasting rice yield.

Correlation coefficient among spectral parameters on three stages and panicle length and panicle weight were higher than that of seed setting rate. By contrast with flowering and filling stages, spectral parameters and correlation coefficient of panicle length, panicle weight and seed setting rate on ripening stage were lower. Consequently, the best stage for forecasting panicle length, panicle weight and seed setting rate was before filling stage.

As shown in Figs 3 and 4, panicle number/mu and kernel weight were significantly positive relative to PVI(810, 680) on flowering and filling stages, and quantitative equations on two stages passed the significant level test of 0.01. Thus, PVI(810, 680) could be used for predicting rice yield

Panicle no./mu, spikelet/panicle and kernel weight which usually contribute to the final yield are main yield components of gramineous crops. Yang *et al.* (2008) find that stages from tilling to pre-filling are important to forecast rice yield components by analyzing canopy multispectral and hyper-

Table 2 Relationships between canopy reflectance hyper-spectral parameters and yield components during different growth stages (n=40)

	Flowering stage		Filling stage		Ripening stage	
	Hyper-spectral parameter	Correlation coefficient	Hyper-spectral parameter	Correlation coefficient	Hyper-spectral parameter	Correlation coefficient
Panicle number/mu (no./ha)	DVI(810,450)	0.90**	DVI(810,450)	0.84**	DVI(810,450)	0.68**
	DVI(810,680)	0.86**	DVI(810,680)	0.78**	DVI(810,680)	0.51**
	PVI(810,680)	0.91**	PVI(810,680)	0.84**	PVI(810,680)	0.36*
	RES	0.73**	RES	0.66**	RES	0.43**
	Area 670-755	0.85**	Area 490-530	0.51**	Area 670-755	0.49**
Spikelet/panicle (no.)	DVI(810,450)	0.81**	DVI(810,450)	0.80**	DVI(810,450)	0.57**
	DVI(810,680)	0.77**	DVI(810,680)	0.75**	DVI(810,680)	0.41**
	PVI(810,680)	0.81**	PVI(810,680)	0.76**	PVI(810,680)	0.34*
	RES	0.66**	RES	0.61**	RES	0.31*
	Area 670-755	0.77**	Area 670-755	0.75**	Area 670-755	0.38*
Kernel weight (g)	DVI(810,560)	0.75**	DVI(810,560)	0.70**	DVI(810,560)	0.53**
	DVI(810,680)	0.81**	DVI(810,680)	0.81**	DVI(810,680)	0.47**
	PVI(810,680)	0.91**	PVI(810,680)	0.86**	PVI(810,680)	0.40**
	RES	0.67**	RES	0.70**	RES	0.37*
	Area 670-755	0.81**	Area 670-755	0.82**	Area 670-755	0.44**
Panicle length (cm)	DVI(810,560)	0.73**	DVI(810,450)	0.89**	DVI(810,450)	0.66**
	DVI(810,680)	0.80**	DVI(810,680)	0.83**	DVI(810,560)	0.54**
	PVI(810,680)	0.91**	PVI(810,680)	0.87**		
	RES	0.63**	RES	0.75**		
Panicle weight (g)	DVI(810,450)	0.90**	DVI(810,450)	0.82**	DVI(810,450)	0.63**
	DVI(810,560)	0.83**	DVI(810,560)	0.65**	DVI(810,560)	0.51**
	DVI(810,680)	0.86**	DVI(810,680)	0.77**		
	PVI(810,680)	0.90**	PVI(810,680)	0.82**		
	RES	0.73**	RES	0.66**		
Seed setting rate (%)	DVI(810,450)	0.50**	DVI(810,450)	0.40**	DVI(810,450)	0.34*
	PVI(810,680)	0.49**	DVI(810,560)	0.32*		
	RES	0.47**	DVI(810,680)	0.38*		
	Area 670-755	0.47**	Area 670-755	0.39**		

*P=0.05, **P=0.01, r (0.05,40)=0.30, r(0.01,40)=0.39

spectral data. The results are similar as forecasting stages of rice yield components in this study. Hou *et al.* (2008) also point out that stages from full-flowering to boll-opening are key stages for cotton yield components. Consequently, it is considered that the important stages for forecasting yield components of crops are from vegetative growth to pre-reproductive growth stage.

Test for prediction models of yield and yield components in rice

For testing reliability and applicability of prediction model of yield and yield components based on PVI(810, 680), hyper-spectral estimation equations of rice actual yield and panicle number/mu were tested by independently observed data. The results showed that predicted values of model on flowering stage were in preferred conformity with actual observed values (Fig 5), and RMSE values were 11.17 and 9.61 respectively, which indicated that established models could be reliable to predict rice actual yield and panicle number/mu. In comparison with flowering stage, there was worse prediction result for rice actual yield and panicle number/mu with model of filling stage. It was possible that rice leaves turned yellow during filling stage, resulting in elevated reflectance on visible light waveband, and thus the shape of reflectance spectral curves changed significantly.

Thus, the best hyper-spectral parameter for forecasting rice yield and yield components under high temperature stress was PVI(810, 680).In comparison with general forecasting methods, such as statistical, agronomical and meteorological methods, the remote sensing method with instantaneous and universal properties is given more attention by worldwide agriculturalists. However, since there are various changes of climate conditions during prediction, such as temperature, light illumination, nitrogen level and moisture in soil, the yield predicted by remote sensing may have a great deviation. Crop growth model with continuity

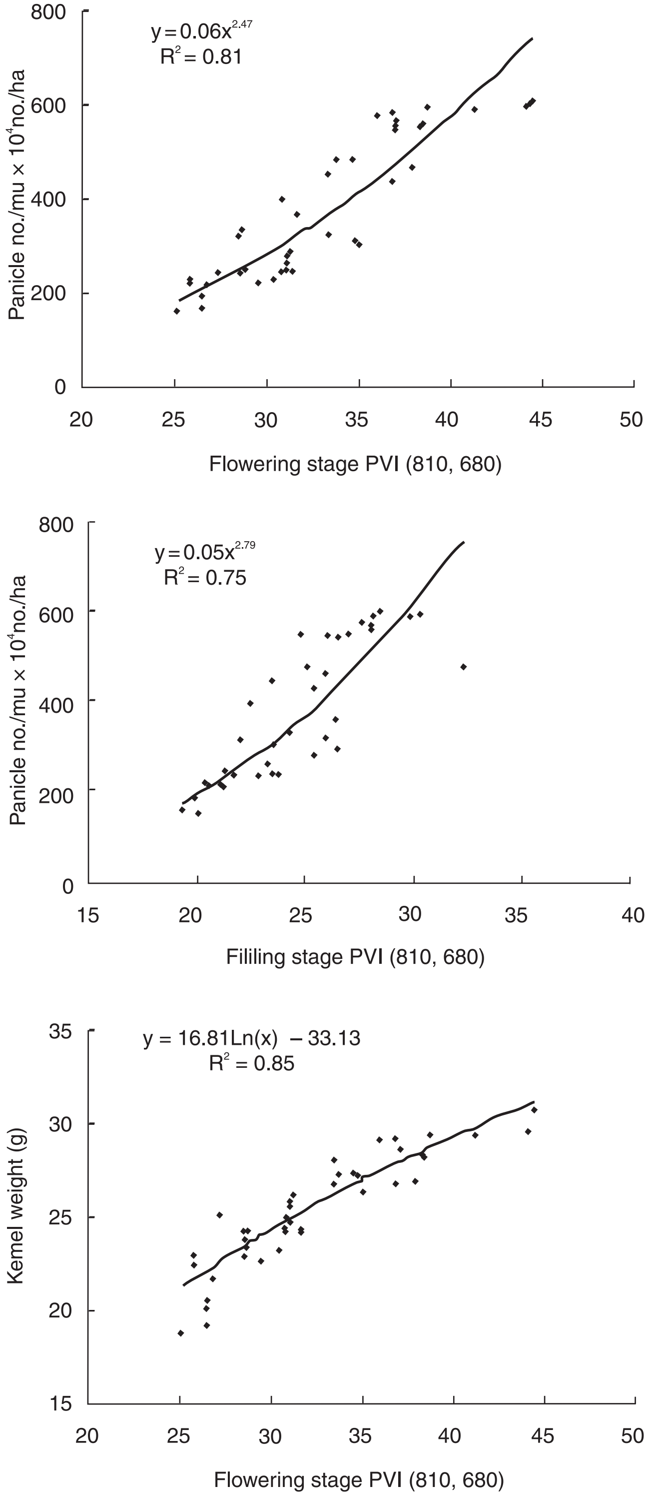

Fig 3 Quantitative relation between panicle no./mu and PVI(810, 680) on different growth stages

and dynamic properties just remedy this drawback (Yan *et al.*2006, Li *et al.*2008). If yield prediction model is performed for coupling computation with remote sensing inversion in practice, the accuracy could be improved greatly.

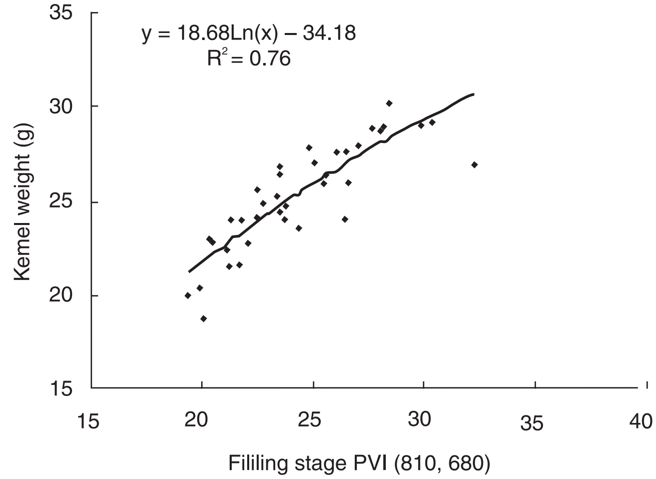

Fig 4 Quantitative relation between kernel weight and PVI(810, 680) on different growth stages

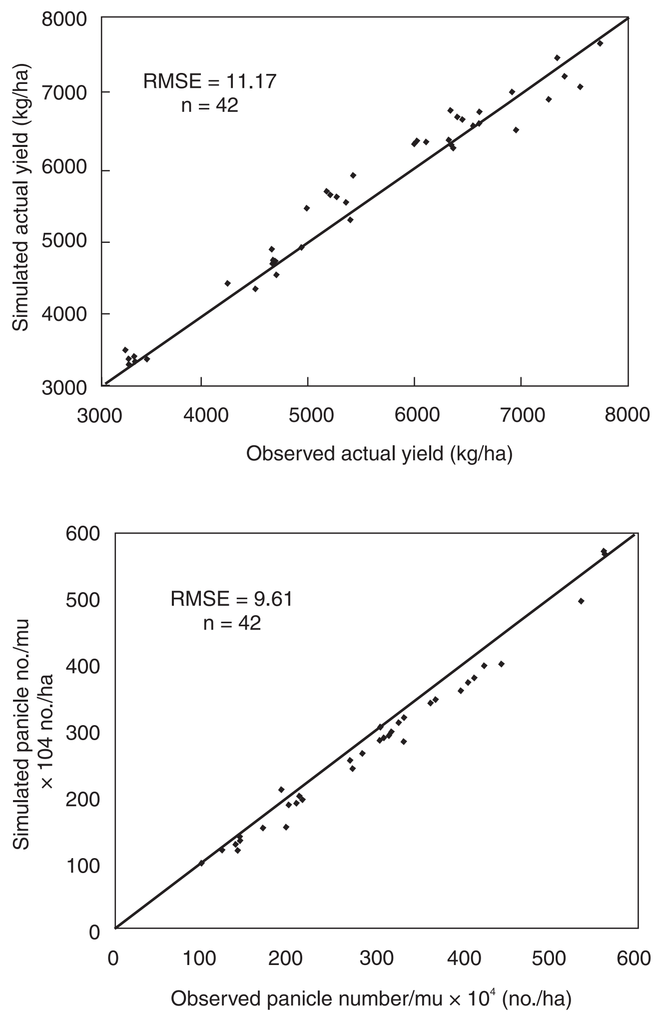

Fig 5 Comparison of observed actual yield and panicle number/mu in rice with simulated ones based on hyper-spectral model

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