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SHORT COMMUNICATION

Establishing a Forecast Mathematical Model of Sugarcane Yield and Brix Reduction Based on the Extent of Pokkah Boeng Disease

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Abstract To explore the effects of pokkah boeng disease (PBD) on sugarcane yield components and provide scientific evidence for the evaluation of production losses, in the present study, plant height, stem diameter, single-stem weight, millable stalks, Brix, yield, and disease index (DSI) of PBD-affected sugarcane during the July–October were investigated. The frequency distribution diagram showed reduction in plant height and stem diameter, i.e., ranging from 10 to 15 cm and 0.05 to 0.06 cm, respectively, and correlation analysis in plant height, stem diameter, single-stem weight, yield, and Brix were significantly negatively correlated with DSI. Furthermore, the yield loss equation ($y = 0.738 - 0.971 * x$) and Brix loss equation ($y = -3.464 - 1.067 * x$) were determined using forecast mathematical modeling. In this study, a new method to evaluate the effects of PBD on sugarcane has been reported.

Keywords Sugarcane · Pokkah boeng disease · Mathematical model · *Fusarium verticillioides*

Pokkah boeng disease (PBD) has gradually become a major fungal disease, after smut disease, in sugarcane areas of mainland China, since it was discovered in Java during the last century, in the 1950s (Siddique 2007). The cause of PBD and its prevention method has been studied in China and abroad (Liu et al. 1991; Lu 2007). Isolation and identification of PBD pathogens (Lin et al. 2014) and its pathogenic mechanism (Zhang et al. 2015; Lin et al. 2016) have also been reported. In case of PBD infection in sugarcane crop, high losses in yield and brix have been reported (Singh et al. 2006; Vishwakarma et al. 2013). Since 2013, inoculation of PBD pathogens and evaluation of resistance in sugarcane have been carried out, and a set of resistant materials were selected and evaluated under field conditions (Wang et al. 2017). Hence, fourteen different resistant materials were used as test subjects to explore the relationships among plant height, stem diameter, single-stem weight, millable stalks, Brix, and yield with disease index. Establishing the evaluation equation by mathematical modeling in order to discover the extent of disease impacts on yield and Brix, and futher to provide scientific evidence for accurate evaluation of PBD damage on sugarcane production.

The experiment was carried out in Dingdang sugarcane base of Guangxi Academy of Agricultural Sciences where the land is red soil. Sugarcane was planted on February 27, 2015, in a randomized arrangement with three replicates. Each plot had 5 rows (7 m × 1 m) with 88 buds sown per row. The method described by Wang et al. (2017) was used as reference for culturing the pathogen spore suspension,

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and the drop method was used for inoculation (May 10 and 25, 2015).

PBD caused by *Fusarium verticillioides* was provided by the Key Laboratory of Guangxi University. The tested plant materials are provided by the Sugarcane Institute of Guangxi Academy of Agricultural Sciences (Table 1).

According to the methods described by Chen (2003), agronomic characteristics and Brix analysis were studied in all tested varieties. Results were based on average of ten canes and mean of three locations from where the healthy and diseased canes of each variety were collected, i.e., plant height and stem diameter of various varieties (clones) were measured in centimeter from July to late October in 2015, millable stalks and Brix were investigated separately from October 2015 to late January 2016, and single-stem weight and yield were investigated.

The disease development was monitored by symptoms (Fig. 1), and the Wang Zeping method (Wang et al. 2016) was used as reference for disease index investigation when PBD occurrence peaked (July–October).

As shown in the frequency distribution chart (Fig. 2), sugarcane plants are significantly affected by the PBD disease in each month. The decrease in plant height and stem diameter ranged from 10 to 15 cm and 0.05 to 0.06 cm, respectively. Correlation analysis showed (Table 2) that DSI had a very significant negative correlation with plant height, single-stem weight, yield, and Brix, a significant negative correlation with stem diameter, and less negative but not significant correlation with millable stalks. Figure 3 shows that when sugarcane infected by PBD, the yield decreases by 3–18%, up to 21.5%, and the Brix declines by 4–20%, up to 27.8%.

The mathematical modeling summary of sugarcane PBD and yield or Brix (Table 3) indicates yield decline in all three regression models. The best fitting model was quadratic curve model ($R^2 = 0.987$), followed by linear model ($R^2 = 0.985$). However, judging from the F value, the linear model was the best fitting one because of its maximum F value. The probability of all three models was 0.000, indicating strong significance. Similarly, in the three regression models of Brix decline, the best fitting model was quadratic curve model ($R^2 = 0.944$) followed by linear model ($R^2 = 0.932$), although judging from the F value the linear model was the best fitting one. The three models also showed strong significant levels. Figure 4 shows the fitting curve and the scatter plot of observed values of three models. Judging from this figure, the relationship between DSI and ratio of yield reduction was $y = 0.738 - 0.971x$, that is, the yield will be reduced by 0.971% if DSI increases by 1 unit; the relationship between DSI and ratio of Brix decrease was $y = -3.464 - 1.067x$, that is, the Brix will be decreased by 1.067% if DSI increases by 1 unit.

As a fungal airborne disease, the PBD pathogen conidium has a long latent period and outbreaks rapidly under appropriate conditions. When the sugarcane is infected, young leaf bases often begin yellowing, narrowing, wrinkling, twisting, or shortening. When severely infected, it can cause cane shoot rot and drying, decreasing photosynthesis and blocking organic synthesis, which leads to the decrease in yield and Brix of sugarcane. Four stages, i.e., chlorotic phase I, chlorotic phase II, top rot phase, and knife cut phase, of PBD have been reported in India (Vishwakarma et al. 2013), but different findings about the disease symptom were observed

Table 1 Details of the materials used

Varieties (clones)	Parents	Disease index (DSI)	Grade of resistance
GT11	CP49-50 × CO419	12.56 ± 2.72c	MS
GT21	GZ76-65 × YC71-374	7.62 ± 0.16d	MR
GT28	CP80-1018 × CP89-1475	5.84 ± 0.22de	MR
GT29	YC94-46 × ROC22	0.28 ± 0.02g	HR
GT36	ROC23 × CP84-1198	1.25 ± 0.24g	R
GT37	ZZ92-126 × CP72-2086	20.44 ± 1.92a	HS
GT42	ROC22 × GT92-66	4.63 ± 0.35f	R
GT50	GT92-66 × ROC10	13.82 ± 1.27bc	MS
GT03-2287	ROC25 × ROC22	0.74 ± 0.23g	HR
GT03-2112	ROC22 × YT85-177	21.65 ± 2.63a	HS
GT05-3846	CP93-1634 × CP90-1424	0.02 ± 0.00g	HR
GT12-502	ZZ74-141 × CP84-1198	15.37 ± 3.01b	S
GT12-508	ZZ74-141 × CP84-1198	16.44 ± 2.26b	S
ROC22	ROC5 × 69-463	1.89 ± 0.53g	R

Lowercase letters indicate significant differences at $P < 0.05$

Fig. 1 Pokkah boeng disease development was monitored by symptoms (*grade 1–grade 5*). *Grade 1* Chlorotic or generate slight etiolation symptom at the base of young leaves; slight shrinkage; very few irregular reddish specks or stripes. *Grade 2* Narrower or shorter; distinct distortion (wrinkling and twisting); the reddish areas develop into lens-shaped holes or form ladder-like lesions often with dark edges. *Grade 3* The infection in the spindle continues downward into the stalk, and dark reddish streaks may be found extending through several internodes; or the infection may form long lesions with cross depressions that give them a ladder-like appearance. *Grade 4* In the stem, the fungus causes a dark-brown discoloration of the infected tissues. The ladder-like lesions are due to rupturing of the diseased cells which cannot keep up with the growth of the healthy tissue. *Grade 5* The entire top (growing point) of the plant dies (referred to as "top rot")

from 2013 to 2016 in sugarcane areas of China. Keeping in view the seriousness of the problem, the present review summarizes the grading standard through the statistics of typical symptoms. As we know, sugarcane yield is determined by its height, single-stem weight, stem diameter, and millable stalks (Chen 2003), and correlation analysis of the test results showed that DSI had a strong significant negative correlation with plant height, single-stem weight, yield, and Brix, which suggests that the disease has an important effect on the healthy growth of sugarcane and that production losses caused by the disease cannot be ignored. Singh et al. (2006) reported maximum reduction in weight length, internodes, total juice, girth, pol percent, and total sugars was recorded in the varieties, i.e., CoS 8436 and CoS 88230. Vishwakarma et al. (2013) reported increasing trend of disease incidence, and most of the commercial cultivars affected by the disease ranged from 1 to 90% based on the survey during 2007–2013. As such, we propose to not only avoid using highly susceptible and susceptible materials while developing new sugarcane varieties but to also to firmly commit to the one-vote veto system to the susceptible clones during the "five-nursery system" breeding process, and continue to strengthen the importance of resistance to pokkah boeng in the process of variety popularization to avoid massive economic losses due to outbreak of the disease.

Previous studies used growth model forecasting method (Wang et al. 1987), survival analysis (Wu 1998), power index model (Li et al. 2005), and other models to study the incidence of plant disease, which provide the theoretical and scientific basis for establishing the forecast mathematical model of PBD causing sugarcane yield and Brix reduction. The yield traits of sugarcane keep changing during the growth period, so it is necessary to introduce disease index over the reproductive stages if there is a demand to know the relevance between PBD and sugarcane production at a time. This study used yield-related

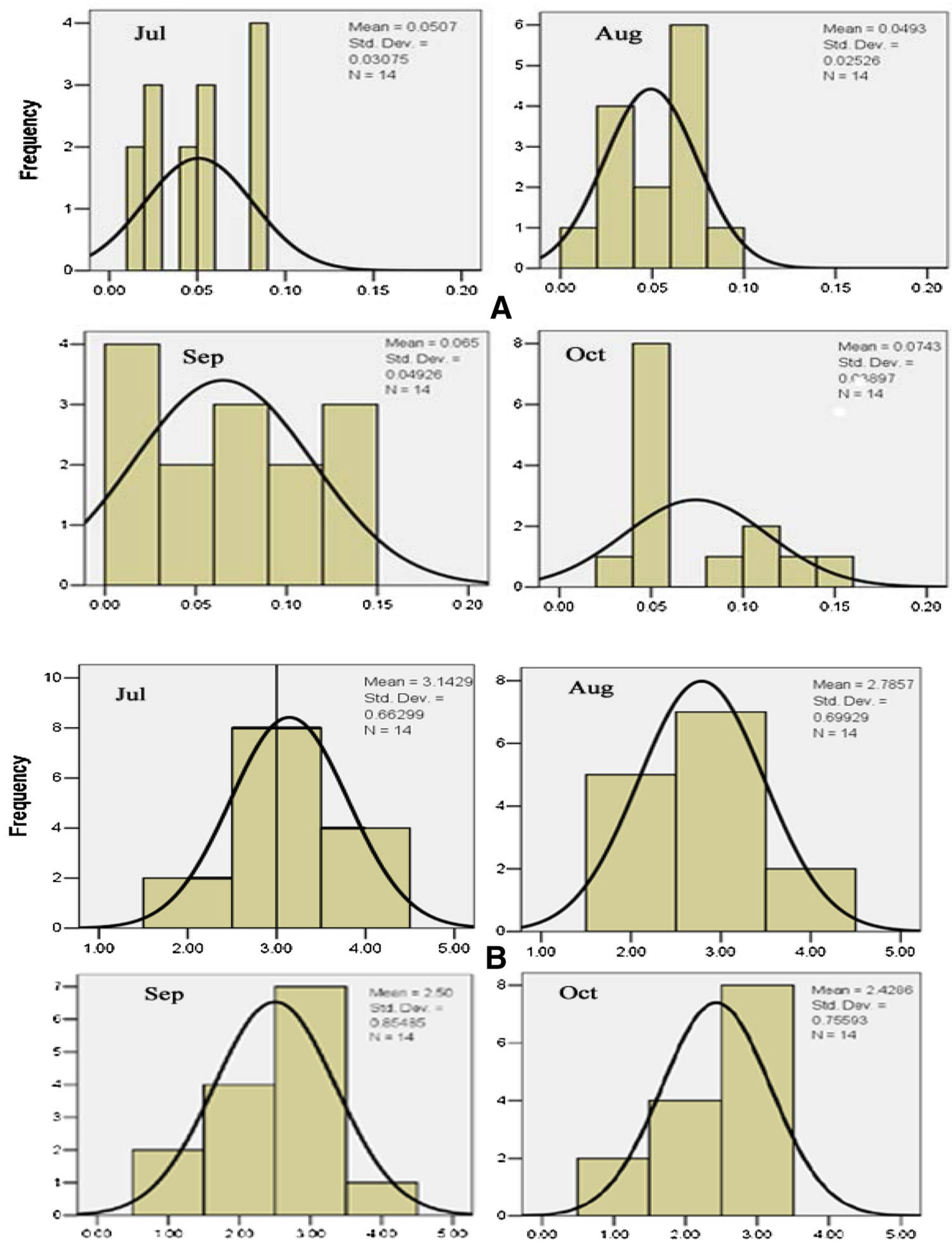

Fig. 2 Effect of PBD on sugarcane plant height and stem diameter (July–October). **a** *x* axis showed the decreasing range of plant height, and the numbers 1.00, 2.00, 3.00, 4.00, and 5.00 correspond to the values <5, 5–10, 10–15, 15–20, and >20 cm, respectively, and *y* axis shows the amount of sugarcane; **b** *x* axis shows the decreasing amount of stem diameter, *y* axis shows the amount of sugarcane

Table 2 Correlation analysis between DSI and yield traits

	Plant height	Stem diameter	Millable stalks	Single-stem weight	Yield	Brix	DSI
Plant height	1						
Stem diameter	−0.426	1					
Millable stalks	−0.454	−0.628*	1				
Single-stem weight	0.806**	0.785**	−0.397	1			
Yield	0.535*	0.547*	0.866**	0.528*	1		
Brix	−0.102	−0.214	−0.521*	−0.062	−0.165	1	
DSI	−0.868**	−0.536*	−0.083	−0.872**	−0.865**	−0.978**	1

**, * Significant at 0.01, 0.05 levels, respectively

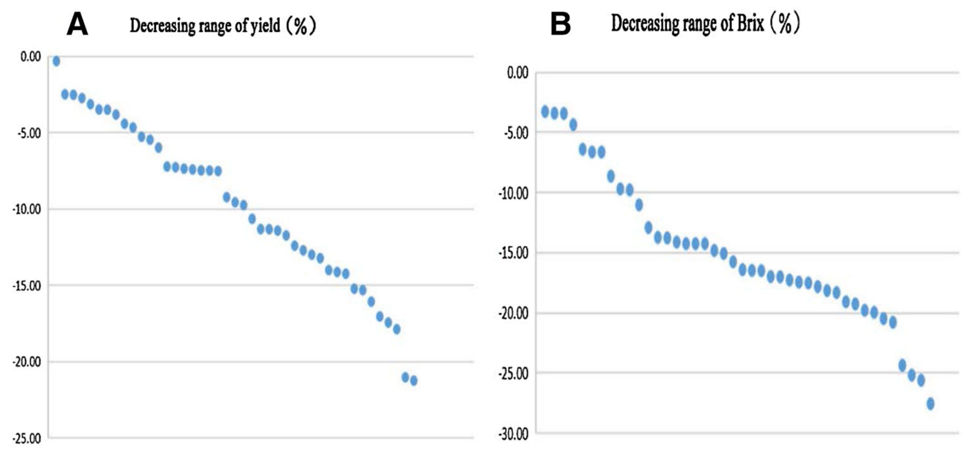

Fig. 3 Effect of PBD on sugarcane yield and Brix. **a** Yield; **b** Brix

Table 3 Mathematical modeling of sugarcane PBD DSI and yield or Brix

Equation	Model summary					Parameter estimates		
	R^2	*F*	*df1*	*df2*	Significance	Constant	*b1*	*b2*
Decreasing range of yield								
Linear	0.985	2551.967	1	40	0.000	0.738	−0.971	
Logarithmic	0.818	180.367	1	40	0.000	6.083	−7.185	
Quadratic	0.987	1451.096	2	39	0.000	−0.050	−0.788	−0.008
Decreasing range of Brix								
Linear	0.932	543.990	1	40	0.000	−3.464	−1.067	
Logarithmic	0.891	328.114	1	40	0.001	3.680	−8.475	
Quadratic	0.944	326.143	3	39	0.000	−1.364	−1.555	0.022

Decreasing range of yield and decreasing range of Brix are dependent variables; the DSI is the independent variable

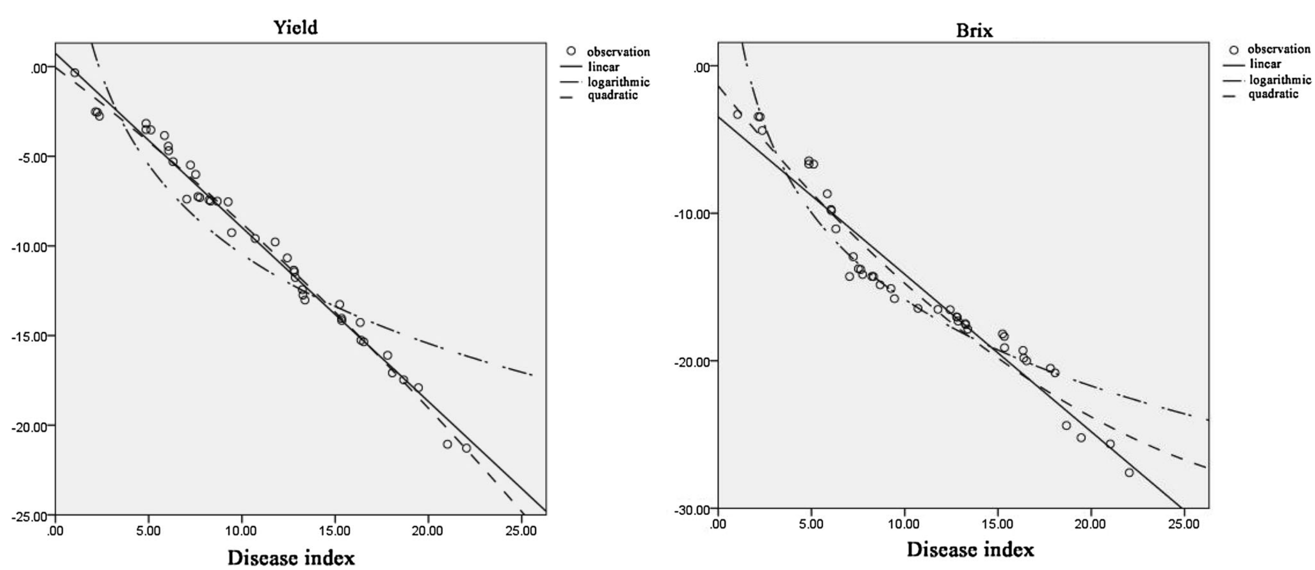

Fig. 4 Fitting curve and the scatter plot of observed values of three models

traits and DSI of 14 different resistance materials from July to October. Using correlation analysis, the equations of three kinds of curve models to fit were determined, thus introducing the independent variable of sugarcane growing period. In the decline model of fitting curve that related to production in this study, the fitting curve of quadratic model was the best fitting with the original value and observed value, followed by linear model, but several observation points did not fit well in the logarithmic model. Due to the limited number of samples, according to the principle that fewer parameters model should be chosen when curve fitting is almost the same, a linear equation $y = 0.738 - 0.971 * x$ was obtained. However, in relation to the fitting curve of Brix decrease model, the fitting curve of linear model was the best fitting with the overall original value and observed value. The logarithmic model only represented the fitting highlight in the concentrated area of decreasing range (3–20%). Therefore, the relationship between DSI and Brix reduction ratio can be given as $y = -3.464 - 1.067 * x$.

In this study, linear, quadratic, and logarithmic curves were utilized to simulate the losses of sugarcane yield and Brix, caused by PBD thus opening up a new way to evaluate the loss of sugarcane yield traits caused by the disease. This method can also be applied to other crop plants as reference.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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