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Wheat Productivity as a Function of Cultivar, Planting Date, Powdery Mildew and Weather Interplay

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ABSTRACT

Background and Objective: Wheat productivity is influenced by an intricate interplay of cultivar selection, planting dates, disease pressures like powdery mildew, and weather conditions. Understanding these interactions is critical for optimizing yield and ensuring food security. This study aims to evaluate the combined impact of these factors on wheat growth and productivity to identify optimal management strategies. **Materials and Methods:** During 2013-2017, wheat yield was modeled using powdery mildew progress patterns, planting and maturity date, weather, and wheat resistance were examined in eight cultivars registered in Iran across 282 field plots. Studies were conducted using a split plot design having three replicated plots per experimental treatment. Datasets were analyzed by H-test, factor analysis, and linear regression. The significance level was determined at the 5% (p-value<0.05) probability level. **Results:** Early planting of wheat cultivars in October resulted in slower powdery mildew progress and higher yields, with a 12% greater yield compared to November, 70% more than December, and 185% more than January plantings. The highest yield was observed in the first study year (2013-2014). Factor analysis (81% variability) highlighted yield increases with later disease onset, faster disease progress, earlier planting and maturation, favorable weather conditions, and greater genetic resistance to powdery mildew. **Conclusion:** Such findings advance our knowledge for future attempts in estimating yield for breeding studies and sustainable production.

KEYWORDS

Mildew, cereals, climate, joint analysis, *Blumeria graminis*

INTRODUCTION

Powdery mildew caused by *Blumeria graminis* f. sp. *tritici*, threatens wheat cultivation across the world. The following agronomic and climatic characteristics have been driving the progression of powdery mildew in wheat crops: The disease onset date, maturation time, genetic resistance level of cultivar, planting date, mean monthly minimum temperature in Ordibehesht (second spring month in Iran, from 21 April to 21 May) and Khordad (third spring month in Iran, from 22 May to 21 June), wind speed in

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Khordad, and number of rainy days in Naseri, B. and Sheikholeslami[1]. In the next attempt, the patterns of wheat powdery mildew epidemics were characterized based on fitting accurate, specific, and easy-to-use disease progress curves. Therefore, later plantings were associated with a higher level of area under the disease progress curve (AUDPC), maximum disease severity and exponential parameters b and r in wheat cultivars semi-resistant and susceptible to powdery mildew[2]. Furthermore, powdery mildew AUDPC increased by 32 and 18% in late-sown semi-resistant and susceptible wheat cultivars, respectively. The onset of powdery mildew occurred also earlier by 13-15% in late sown resistant to susceptible wheat cultivars. Maximum powdery mildew severity was intensified by 39 and 13% in late-sown semi-resistant and susceptible wheat cultivars, respectively. The progress rate of powdery mildew, the exponential parameter r, increased by 14, 13, and 18% in late sown resistant, semi-resistant, and susceptible cultivars, respectively[2]. However, predictions of wheat yield according to these more accurate and specific powdery mildew progress descriptors, and the above-mentioned agronomic and weather conditions are still impossible. In Iran, the complex linkages of yellow, brown and black rusts and powdery mildew to wheat and sainfoin productivity were described at field scale[3,4]. Although such a joint predictive value of these four prevalent diseases has been determined previously[3], each disease reduces wheat yield based on a different trend influenced by weather and cultivars. Thus, it is highly desired to improve the accuracy of wheat yield adaptability and stability estimates according to such step-by-step chosen cropping system, powdery mildew, and weather predictors. To meet this requirement, the best powdery mildew predictor of wheat yield was explored under diverse farming and climatic conditions during four growing seasons. Therefore, associations of wheat yield with powdery mildew disease, planting and maturity date, weather, and wheat resistance indicators were examined using eight commercial cultivars at a field plot scale during four growing seasons.

MATERIALS AND METHODS

Field experiments: From the beginning of autumn in 2013 to the end of summer in 2017, the progress patterns of wheat powdery mildew in eight cultivars registered in Iran were monitored across 282 field plots[1,2]. Studies were conducted using a split plot design having three replicated plots per experimental treatment. To diversify seasonal patterns of wheat powdery mildew epidemics across the plots, different cultivars and planting dates were used as treatments. According to the maximum powdery mildew severity recorded from 2013 to 2017, the following levels of genetic resistance to powdery mildew in the cultivars were determined: resistant for Chamran II; moderately resistant for Baharan, Sirwan, and Sivand; susceptible for Bahar, Parsi, Pishgam, and Pishtaz[2].

Disease and yield data collection: The powdery mildew severity declared weekly records of the percentage aerial part of wheat plants covered by grayish hyphal growth of *B. graminis* f. sp. *tritici* for at least 9 arbitrarily assessed plants per plot[1,2]. The disease severity was recorded across 282 plots at 4-6 measurement times during the four growing seasons. Such a powdery mildew recording method provided a comprehensive dataset involving 11664, 6804, 8505, and 9072 disease records over four years. For yield data, the weight of wheat seeds produced by each plot was recorded and expressed as kg/ha[3].

Data analysis: To determine the progress patterns of wheat powdery mildew epidemics across the field plots, the disease severity datasets over the four growing seasons were fitted to standard curves[2]. The seasonal patterns of wheat powdery mildew progress were examined based on the following indicators: (1) Duration of disease onset in days, (2) AUDPC of the seasonal disease severity, (3) Maximum disease severity over the four seasons and (4) Exponential curve parameters[2]. In the exponential model, a showed the initial powdery mildew severity, b showed the factor of disease progress, r showed the rate of disease progress, and x showed the time intervals between the disease measurements (Table 1).

Table 1: Indicators of powdery mildew development studied in wheat cultivars varying in planting and maturity date, and genetic resistance

Indicators	Indicator classes							
Weather	Mean minimum temperature in Ordibehesht (second spring month from 21 April to 21 May)							
	Mean minimum temperature in Khordad (third spring month from 22 May to 21 June)							
	Number of rainy days in Ordibehesht and Khordad							
	Six monthly minimum temperature from October to March (autumn-winter)							
	Wind speed in Khordad							
Mean maturity date	Bahar	Baharan	Chamran II	Parsi	Pishgam	Pishtaz	Sirwan	Sivand
Days from planting	261	259	260	258	257	259	260	261
Planting date	Early		Optimum		Late			Very late
	October		November		December			Early January
Powdery mildew	Area under the disease progress curve							
	Disease onset date[2]					Early and Late		
	$Y = a+br^x$					Exponential parameters b&r		
	Maximum disease during four growing seasons					Disease severity		
Resistance index	Bahar	Baharan	Chamran II	Parsi	Pishgam	Pishtaz	Sirwan	Sivand
	80	50	100	20	30	40	80	85

Mean powdery mildew severity and wheat yield for diverse classes of cultivar, planting date, measurement time, and season were provided by earlier publications[2,3]. A Kruskal-Wallis one-way ANOVA (H-test) was used to rank the date of powdery mildew onset, planting date, resistance index, and season factors affecting maximum disease severity, exponential parameter b and r, and yield. The significance level was determined at the 5% ($p<0.05$) probability level. A factor analysis (FA) provided predictive values of disease, weather and wheat indicators for the yield model. The GENSTAT was used to analyze all the datasets obtained in this four-year research.

RESULTS

Powdery mildew exponential parameters: The H-test results indicated the non-significant effects of two factors of planting date and genetic resistance on the exponential parameter b of powdery mildew occurred in the eight wheat cultivars studied in this four-season research (Table 2). However, the disease onset date (Chi $p<0.001$; adjusted H = 10.30) and the growing season (Chi p = 0.016; adjusted H = 10.30) significantly affected the exponential parameter b. Late onset of wheat powdery mildew in commercial cultivars planted at diverse dates was ranked higher for the exponential parameter b compared with early onset. The third growing season, 2015-2016, was ranked lower for the exponential parameter b than the other three seasons (Table 2).

Although the resistance index factor did not affect the exponential parameter r, the planting date (Chi p = 0.097; adjusted H = 6.32), growing season (Chi $p<0.001$; adjusted H = 10.30) and the onset of powdery mildew (Chi $p<0.001$; adjusted H = 10.30) occurred in the cultivars tested in this study (Table 3). Early planting of wheat cultivars provided the lowest ranking of the exponential parameter r which increased at later plantings. This demonstrated a slower powdery mildew progress in early plantings of experimental plots. The disease onset date of wheat powdery mildew was ranked with a higher exponential parameter r in the early onset than the late one. This suggested that the early occurrence of powdery mildew in wheat cultivars corresponded with a faster disease increase. The third growing season, 2015-2016, was ranked with the highest exponential parameter r than the other three seasons, suggesting the fastest disease progress in the 2015-2016 season (Table 3). The findings indicate that planting date significantly impacts powdery mildew onset, as shown by an adjusted H value of 6.32 and a chi-square p-value of 0.097, suggesting a trend but not a significant result. Resistance index comparisons among different wheat cultivars, with an adjusted H value of 3.52 and a p-value of 0.741, did not show a significant difference in resistance levels. However, the timing of mildew onset (early or late) and the growing season had substantial effects, with an adjusted H value of 91.09 and a highly significant p-value (<0.001), highlighting the influence of these factors on disease incidence across the study years.

Table 2: Rankings of powdery mildew exponential parameter b for disease onset and planting date, wheat resistance, and year

Factors	Factor levels							
Planting date	Early		Optimum			Late		Very late
Adjusted H = 0.98	50.50		47.02			47.35		45.35
Chi p-value = 0.806								
Resistance index	Bahar/80	Baharan/50	Chamran II/100	Parsi/20	Pishgam/30	Pishtaz/40	Sirwan/80	Sivand/85
Adjusted H = 7.37	46.07	38.07	50.50	46.75	45.85	56.50	46.07	44.29
Chi p-value = 0.288								
Powdery mildew onset	Early					Late		
Adjusted H = 10.30	37.07					50.50		
Chi p-value<0.001								
Growing season	2013-2014		2014-2015			2015-2016		2016-2017
Adjusted H = 10.30	50.50		50.50			37.07		50.50
Chi p-value = 0.016								

Table 3: Rankings of powdery mildew exponential parameter *r* for disease onset and planting date, wheat resistance, and year

Factors	Factor levels							
Planting date	Early		Optimum			Late		Very late
Adjusted H = 6.32	37.00		49.44			49.37		52.85
Chi p-value = 0.097								
Resistance index	Bahar/80	Baharan/50	Chamran II/100	Parsi/20	Pishgam/30	Pishtaz/40	Sirwan/80	Sivand/85
Adjusted H = 3.52	43.86	58.21	45.21	46.89	52.00	48.43	43.86	46.36
Chi p-value = 0.741								
Powdery mildew onset	Early					Late		
Adjusted H = 91.09	84.00					37.00		
Chi p-value<0.001								
Growing season	2013-2014		2014-2015			2015-2016		2016-2017
Adjusted H = 91.09	37.00		37.00			84.00		37.00
Chi p-value<0.001								

Table 4: Rankings of maximum powdery mildew severity for disease onset and planting date, wheat resistance, and year

Factors	Factor levels							
Planting date	Early		Optimum			Late		Very late
Adjusted H = 6.32	40.45		45.41			49.63		54.50
Chi p-value = 0.097								
Resistance index	Bahar/80	Baharan/50	Chamran II/100	Parsi/20	Pishgam/30	Pishtaz/40	Sirwan/80	Sivand/85
Adjusted H = 5.37	42.93	52.36	41.29	52.04	53.85	49.32	42.93	47.25
Chi p-value = 0.497								
Powdery mildew onset	Early					Late		
Adjusted H = 50.63	73.12					40.13		
Chi p-value<0.001								
Growing season	2013-2014		2014-2015			2015-2016		2016-2017
Adjusted H = 51.76	43.46		38.50			73.12		38.50
Chi p-value<0.001								

Maximum powdery mildew severity: The H-test results indicated that only the resistance index had no significant effect on the maximum disease severity, and the other three factors of planting date (Chi p = 0.097, adjusted H = 6.32), the disease onset date (Chi p<0.001; adjusted H = 50.63) and the growing season (Chi p<0.001; adjusted H = 51.76) were significantly effective on the maximum severity of powdery mildew occurred in the cultivars over the four seasons (Table 4). The ranking of maximum disease severity increased with postponing planting wheat plots for the optimum, late and very late dates tested in this study. Early onset of powdery mildew in wheat cultivars planted at diverse dates was associated with 82% greater ranking of the maximum disease severity. The highest ranking of the maximum disease severity was determined for the third year of this study, 2015-2016 (Table 4).

Table 5: Rankings of wheat yield for powdery mildew onset, planting date, genetic resistance, and year

Factors	Factor levels							
Planting date	Early		Optimum		Late		Very late	
Adjusted H = 32.93	66.67		59.30		39.33		23.43	
Chi p-value<0.001								
Resistance index	Bahar/80	Baharan/50	Chamran II/100	Parsi/20	Pishgam/30	Pishtaz/40	Sirwan/80	Sivand/85
Adjusted H = 7.95	55.76	35.57	49.21	54.43	31.30	47.21	55.76	44.29
Chi p-value = 0.242								
Powdery mildew onset	Early				Late			
Adjusted H = 1.50	41.07				49.35			
Chi p-value = 0.220								
Growing season	2013-2014		2014-2015		2015-2016		2016-2017	
Adjusted H = 36.25	67.71		59.74		41.07		25.82	
Chi p-value<0.001								

Wheat yield: The H-test verified the significant effects of planting date (Chi p<0.001, adjusted H = 32.93) and growing season (Chi p<0.001; adjusted H = 36.25) on wheat yield (Table 5). The greatest yield ranking in the four-season study of eight wheat cultivars was detected for the early plantings, followed by optimum, late and very late plantings. The early planting of different wheat cultivars at plot scale was ranked with a 12% greater yield than the optimum date of planting. The ranking of wheat yield in the late plantings improved by 70% compared to early plantings in October tested during the four growing seasons. Planting the eight cultivars at early date in October improved the ranking of wheat yield by 185% when compared with the very late planting in January. For the growing season factor affecting wheat yield, the greatest yield ranking was detected for the first year of study, 2013-2014, followed by the second, third and fourth years (Table 5).

Factor analysis prior to modeling: From the FA results, the four principal factors accounted for 81% of the variability in the maturation and planting date, genetic resistance to powdery mildew, weather, disease progress, and wheat yield datasets (Table 6). The first principal factor which explained 44% of the total dataset's variability indicated the significant loading values for the disease onset date (0.37), exponential r (-0.36), and number of rainy days in Ordibehesht and Khordad (-0.37) contributions in the first principal factor. This factor was considered as the interaction of powdery mildew onset and progression rate in interaction with the spring rainy day predictor. The maturation (0.40) and planting date (0.37), six-monthly mean temperature (-0.43), and yield (-0.49) predictors contributed significantly to the second principal factor accounting for 17% of dataset variability. This factor was considered as the interaction of wheat maturation, planting date, air temperature over autumn-winter, and productivity (Table 6).

The third principal factor which accounted for 10% of the total dataset variability, provided a major negative loading value, -0.61, for the index of genetic resistance to powdery mildew (Table 6). This factor was considered as the remarkable impact of wheat resistance on the disease-weather-wheat interaction. The fourth principal factor provided great and moderate contributions of the planting date (0.52) and mean minimum temperature in Khordad (0.46). Thus, this factor was considered as the significant interaction of planting date and air temperature in the third month of spring. The current FA outcomes provided predictive values of disease-weather-wheat indicators to be involved in the regression model of yield production at field plot scale over the four seasons (Table 6).

Wheat yield model: This multivariate model accounted for a total of 96% variability in wheat yield (F probably<0.001; R^2 = 0.96) obtained from the eight cultivars planted at different dates across 282 plots over the four study years (Table 7). The powdery mildew onset, exponential parameter r, maturation, and planting date, mean minimum the temperature in Khordad, the number of rainy days in Ordibehesht and Khordad, six monthly minimum temperature over autumn-winter and genetic resistance were considered as the most predictive indicators to model wheat yield. The two-way interaction of planting date with the minimum the temperature in Khordad significantly corresponded with the dependent variable, yield. This two-way interaction and maturation date were negatively associated with wheat yield.

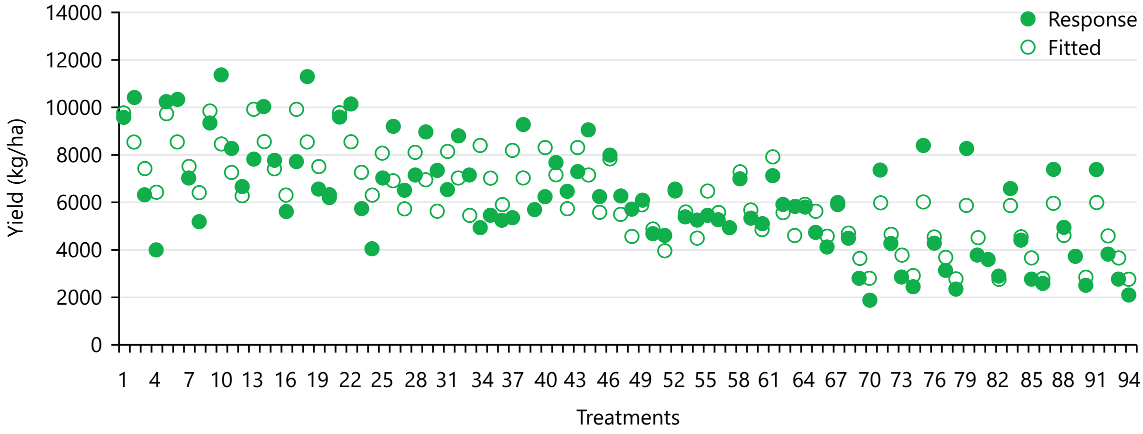

Fig. 1: Simple univariate regression of fitted yield values

Simple univariate regression of fitted yield values associated with observed values in eight wheat cultivars varying in maturity and planting date, powdery mildew progress, genetic resistance, and weather conditions; x-axis: Means of three replicate plots per treatment and y-axis: Fitted/observed values for yield

Table 6: Factor analysis of powdery mildew progress in wheat cultivars varying in maturity and planting date, and genetic resistance

	Principal components			
Variables	1	2	3	4
Maturation date	-0.21	0.40	-0.27	0.32
Planting date	-0.18	0.37	-0.14	0.52
Genetic resistance	0.05	0.07	-0.61	-0.08
Powdery mildew				
Area under the stem rust progress curve	-0.28	-0.18	0.32	0.26
Disease onset	0.37	0.17	0.05	0.03
Exponential parameter b	0.15	0.06	0.13	-0.03
Exponential parameter r	-0.36	-0.19	-0.03	-0.03
Maximum disease severity	-0.30	-0.20	0.30	0.22
Weather				
Minimum temperature in Ordibehesht	-0.32	0.05	-0.27	-0.25
Minimum temperature in Khordad	0.26	-0.33	-0.08	0.46
Number of rainy days in Ordibehesht and Khordad	-0.37	-0.01	-0.17	-0.22
Six monthly minimum temperature	-0.21	-0.43	-0.29	0.28
Wind speed in Khordad	-0.31	0.13	0.25	-0.27
Yield (kg/ha)	0.11	-0.49	-0.26	-0.16
Latent roots	6.19	2.38	1.41	1.29
Variation (%)	44.23	17.00	10.07	9.23
Sum of variation (%)	44.23	61.23	71.30	80.53

Bold numbers indicate significant loadings ≥0.35[1]. Negative sign indicates the reverse association of the variable with the principal component

Table 7: Multivariate model of wheat yield (kg/ha) according to powdery mildew progress in wheat cultivars varying in maturity and planting date, genetic resistance, and weather indicators

Indicators	Parameter estimates	Standard errors	t-probability
Disease onset	10151.00	1934.00	<0.001
Exponential parameter r	3473.00	1783.00	0.055
No. rainy days in Ordibehesht and Khordad	425.00	115.00	<0.001
Maturation date	-45.80	17.00	0.008
Planting date×Minimum temperature in Khordad	-87.00	15.70	<0.001
Six monthly minimum temperature	543.50	46.90	<0.001
Genetic resistance	2.13	4.99	0.671

R^2 = 96% and p<0.001

The significant association of response and fitted datasets for wheat yield has been illustrated in Fig. 1. Such a significant association (simple linear univariate regression) between the response or observed values and the fitted or estimated values by the current regression model (Table 7) verified the goodness of variables selected according to the FA (Table 6). This model demonstrated that greater yield levels corresponded with a later powdery mildew onset, a faster disease progress rate, an earlier maturation and planting date, further rainy days in mid-late spring, warmer autumn, winter and spring, and a greater genetic resistance to the disease (Table 7). The findings indicate significant relationships between key environmental and genetic factors and the studied outcomes. Disease onset, number of rainy days in Ordibehesht and Khordad, maturation date, planting date concerning minimum temperature in Khordad, and six-month minimum temperatures all show highly significant associations ($p<0.01$). Although genetic resistance, did not exhibit a significant association ($p = 0.671$), its involvement in the multivariate regression improved the predictability of the yield model. Notably, the exponential parameter provided a trend similar to the genetic resistance variable. These two variables were still involved in the model to increase the accuracy of yield estimations.

DISCUSSION

Wheat plants showed higher susceptibility to powdery mildew disease and ten times higher sporulation at 14 than 7°C as reported by Last[5]. Elsewhere, the optimal temperature and relative humidity were determined as 10-22°C and 95-100%, respectively, for the germination of *B. graminis* f. sp. *Tritici*[6]. These previous findings are in agreement with our findings in the current research, as the third growing season showed the greatest ranking of powdery mildew severity and progress rate due to a moister and warmer late spring[3,4]. Furthermore, this research added to our knowledge the remarkable linkages of wheat yield with the air temperature during autumn-winter-spring period and rainfall in mid-late spring. Therefore, this novel finding on the significant association of such weather conditions with powdery mildew progress and wheat yield is beneficial in future yield estimations in breeding studies for durable and influential disease resistance.

Although there are a number of documents on significant associations of agronomic and climatic factors with the development of powdery mildew on wheat crops[1,7], the interaction of this disease and the agro-ecosystem with the productivity in wheat needed further consideration. Hence, the current research focused on exploring the linkages of wheat yield with a manageable number of agro-ecological indicators at field plot scale. This multivariate linear regression model indicated greater levels of wheat yield following a later powdery mildew onset, a faster disease progress rate, an earlier maturation and planting, further rainy days in mid-late spring, warmer autumn, winter and spring, and a greater genetic resistance to the disease. The remarkable part of variability in the disease, weather and wheat datasets, 96%, was justified by the present model that is obtained via a wisely FA selected predictors to model yield.

Moreover, earlier documents did not study the duration and timing of appropriate climatic conditions required for powdery mildew epidemics and wheat yield[5,6]. Ge *et al.*[8] and Gu *et al.*[9] reported interactions among the climate, powdery mildew and genetic resistance in wheat cultivation systems. However, they ignored the noticeable effect of planting date on this pathosystem. To meet this requirement, the current findings addressed gaps in the literature to efficiently predict powdery mildew progress and subsequent yield losses under highly diverse agro-ecological characteristics. Such a potential methodology allowed an accurate evaluation of the complex interaction of powdery mildew onset and progress, genetic resistance of cultivar, wheat maturation, air temperature, rainy days and planting date with the yield at field scale. In addition, the current findings demonstrated the value of early planting of wheat to restrict losses to not only severe powdery mildew epidemics but also very cold winters which occurred in 2015-2016 and 2016-2017 seasons, respectively[3]. Such novel findings encourage wheat breeders to seek genetic resistance sources in wheat genotypes for more durable resistance to powdery mildew, improve tolerance to cold winter by early planting, and identify early-maturing and high yielded genotypes in the future worldwide.

CONCLUSION

In this research, attempts were made to estimate wheat yield in cultivars differing in maturation and planting date, powdery mildew intensity, and genetic resistance to the disease at plot scale during four growing seasons. Early disease onset intensified powdery mildew by 82% when compared to the late onset. Factor analysis assisted with selecting highly associated predictors with wheat yield for model development purposes. Greater yield levels corresponded with a later powdery mildew onset, a faster disease progress rate, an earlier maturation and planting date, further rainy days in mid-late spring, warmer autumn, winter and spring, and a greater genetic resistance to the disease.

SIGNIFICANCE STATEMENT

Detection of best predictors of wheat yield received little consideration under diverse powdery mildew levels, farming, and climatic conditions. Early planting of different wheat cultivars in October at plot scale was ranked with a 12% greater yield than the optimum date of planting in November, 70% than late plantings in December, and 185% than very late planting in January. A greater yield was obtained following a later powdery mildew onset, a faster disease progress rate, an earlier maturation and planting date, further rainy days in mid-late spring, warmer autumn, winter, and spring, and a greater genetic resistance to the disease. Such findings advance our knowledge for future attempts in estimating yield for breeding studies and sustainable production.

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