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Stem Rust, Planting Date, Wheat Maturity and Genetic Resistance, Weather and Productivity

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ABSTRACT

This study attempted to predict the yield of wheat cultivars differing in maturity and planting date, and resistance to stem rust in four seasons. The highest yield ranking was associated with the earliest planting date (October) with a yield improvement of 184.55% compared to the latest date (January). Planting wheat cultivars at the optimum date (November) increased the yield ranking by 153.09% compared to very late plantings. Early onset of stem rust in wheat cultivars planted at different dates increased the maximum disease severity by 62%. Early onset of the disease improved the yield ranking by 27% compared to late-onset. The first principal factor was defined as the progress of stem rust related to weather. The second principal factor defined stem rust, planting date, and yield. The third principal factor defined stem rust resistance. The fourth factor contributed to the exponential parameters b and r. The results of the factor analysis simplified the selection of predictors for the model according to predictive values of the crop, stem rust, and weather descriptors tested at the field plot scale during four seasons. The model explained 96% of the variations in wheat yield. The higher yield was associated with earlier planting date and stem rust onset, fewer rainy days in the spring months, warmer spring, and higher wheat resistance index when interacting with a greater area under the stem rust progress curve.

Keywords: *Black rust, Cereals, Climate, Joint analyses, Puccinia graminis*

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INTRODUCTION

Stem (black) rust, caused by *Puccinia graminis* f. sp. *tritici*, attacks wheat-growing lands worldwide. The following agro-ecological factors have been effective in the development of stem rust in wheat: the disease onset, maturity duration, average monthly minimum temperature and rainy days in spring, autumn-winter-spring days with 5-20 °C minimum (min.) temperature, and maximum (max.) relative humidity (RH) above 60%, cultivar resistance and planting date (Naseri & Sabeti, 2021). In the next step, it was tried to evaluate the within and over-season progression of wheat stem rust by developing accurate, specific, and easy-to-use disease curve elements. Hence, a factor analysis indicated that AUSRPC, max. Disease incidence and exponential parameter *b* justified 67% of wheat stem rust variations across commercial cultivars planted at various dates (Naseri, 2022a). Furthermore, stem rust increased by 37% in late-sown cultivars, Pishgam and Sirwan, semi-resistant to the development of stem rust in wheat crops (Naseri, 2022a). Although these two recent findings highlighted the best and specific descriptors of wheat stem rust spread, associations of the above-mentioned agronomic, disease, and weather factors with yield are little understood. Soko *et al.* (2018) estimated yield losses to wheat stem rust using non-specific disease variables. In Iran, Naseri (2022b) modeled joint interactions of stripe, stem, and leaf rusts and powdery mildew with wheat yield at a plot scale research. Although this complex of these major diseases often reduces wheat yield under field conditions, every disease interacts with weather and wheat cultivars according to a different pattern (Naseri, 2022b). Therefore, advanced estimates of yield and breeding efforts based on such step-by-step selected indicators of wheat cropping system are still required not only for more accurate yield estimation but also for longer-lasting genetic resistance. The adaptability and stability of wheat lines evaluated in many breeding programs are determined according to the crop productivity and resistance to rust diseases across diverse environments. Therefore, the best stem rust predictor of wheat yield is greatly needed to describe the disease and yield fluctuations under highly different agronomic and climatic conditions impacting breeding outcomes.

As a result, an advanced understanding of how the development of wheat stem rust described based on the specific disease progress curve elements interact with different variables of agronomic, climatic, and yield is required. Therefore, the following aims were followed in the current investigation: (i) measure descriptive values of cultivar resistance, maturity duration, air temperature and RH, planting date, rainy days, and stem rust progress curve elements; (ii) detect linkages among the selected descriptors of agronomic, disease and weather; (iii) model wheat yield based on this influential array of agro-ecological and stem rust descriptors.

MATERIALS AND METHODS

Experiments

From the autumn of 2013 to the summer of 2017, the progression of wheat stem rust in eight cultivars was characterized across 282 field plots characterized in **Table 1**. Experiments were designed as a split plot with three replicates per treatment. Due to multiple variations in seasonal patterns of stem rust across the plots, various dates of planting and cultivars were studied. Based on the max. Stem rust severity rated from 2013 to 2017, the resistance levels of cultivars were grouped as follows: resistant for Baharan and Pishtaz; moderately resistant for Pishgam and Sirwan; susceptible for Bahar, Chamran II, Parsi, and Sivand (Naseri, 2022a).

Table 1. Plots, factors, and assessments at study station, Kermanshah, Iran.

Assessments	Year	Plot no.	Experimental factors			
			Planting date(Main plot)	**Cultivar(Subplot)**	**Pedigree**	**Released**
Stem rust	2013-14	72	Oct. 10, Nov. 7, Dec. 3 & 31	Bahar	ICW84–0008-013AP-300 L-3AP-300 L-0AP	2007
Yield (kg/ha)	2014-15	63	Oct. 12, Nov. 14, Dec. 19	Baharan	KAUZ/PASTOR//PBW343	2014
	2015-16	63	Oct. 27, Dec. 13 & 30	Chamran II	Attila50Y//Attila/Bacanora	2013
	2016-17	84	Oct. 11, Nov. 15, Dec. 11, Jan. 5	Parsi	Dove^s^/Buc^s^//2*Darab	2009
				Pishgam	Bkt/90-Zhong87	2008
				Pishtaz	Adlan/Ias58//Alvand	2002
				Sirwan	PRL/2*PASTOR	2011
				Sivand	KAUZ^s^/Azadi	2009

Plot properties:
- Cool temperate climate: annual mean temperature 13.7°C& rainfall of 479.8 mm
- Fertilized with 225 kg/ha urea & 50 kg/ha superphosphate
- Latitude 34°7´ north, longitude 46°28´ east
- No fungicide use
- Pesticide used at 180 kg/ha Decis
- Sprinkler irrigated every 7–10 days
- Weather data obtained from the station

Datasets

The stem rust severity represented weekly detection of percentage leaf area pustulating for the three newest leaves for 3-5 plants per plot (Naseri, 2022a). The severity of stem rust was rated across 282 plots at 4-6 assessment times depending on the length of epidemics developed each season. This resulted in 11664, 6804, 8505, and 9072 disease measurements during the 2014, 2015, 2016 and 2017 seasons.

Analysis

To characterize the progression of wheat stem rust, the disease severity dataset was subjected to modeling (Naseri, 2022; Diakité *et al.,* 2024). The seasonal progress of stem rust was characterized using the following criteria: (1) the disease onset; (2) the AUSRPC calculated for the disease severity over the season; (3) max. Disease severity; (4) exponential curve parameters (Naseri, 2022; Cissé *et al.,* 2024). The GENSTAT (Payne *et al*., 2009) was applied to all the datasets assessed. The exponential model indicated the best fitness to the stem rust progress (Luo, 2008; Naseri, 2022a). In this model, *a* described the initial disease severity rating, *b* described the increase factor, *r* described the disease increase rate, and *x* described the time intervals **(Table 2)**.

Table 2. Descriptors examined in wheat cultivars differing in planting date, maturity duration, and resistance index under stem rust epidemics.

Descriptors	Descriptor definition/levels							
Weather	Number of days with min. Temperature within 5-20°C& max. relative humidity ≥ 60%							
	Number of rainy days in spring							
	Mean min. Temperature for the second month of spring							
Maturity time	Bahar	Baharan	Chamran II	Parsi	Pishgam	Pishtaz	Sirwan	Sivand
(Days from planting)	255-267	251-267	251-268	247-268	247-266	250-268	251-269	252-270
Planting date	Early		Optimum		Late		Very late	
	October		November		December		Early January	
Resistance index	Bahar	Baharan	Chamran II	Parsi	Pishgam	Pishtaz	Sirwan	Sivand
	20	50	10	30	40	80	60	5
Stem rust	The area under the stem rust progress curve				AUSRPC			

	Disease onset	Early & Late
	$Y = a + br^x$	Exponential parameters b&r
	Max. disease over four seasons	Severity

Mean values for the disease and yield provided for different levels of cultivar, planting date, assessment time, and season were used here according to the previous reports (Naseri & Sabeti, 2021; Naseri, 2022; Suchy, 2024). In the present research, a non-parametric analysis ranked factors (disease onset, maturity, planting date, resistance index, and season) levels affecting wheat yield according to Kruscal-Wallis one-way ANOVA plus *H*-test. By a factor analysis (FA), interrelationships among agronomic, weather, yield, and stem rust progress descriptors were assessed. Those principal factors receiving eigenvalues (data variance proportion) ≥ 1.0 were considered for regression modeling (Kranz, 2003; Naseri & Sabeti, 2021). The adjusted coefficient of determination (R^2) and Mallows Cpwere used for stepwise descriptor selections (Brusco & Stahl, 2005; Naseri & Sabeti, 2021).

RESULTS AND DISCUSSION

H-test results demonstrated that planting date and resistance index did not affect the maximum severity of stem rust developed in the eight commercial wheat cultivars tested during the four growing seasons. However, the timing of wheat stem rust onset affected the maximum disease severity rating (*Chi* $P < 0.001$; mean $H = 68.24$). Early onset of stem rust in wheat cultivars planted at different dates corresponded with a 62% increase in the maximum disease severity **(Table 3)**.

Table 3. Ranking max. Severity for wheat stem rust onset, planting date, and resistance index.

Factors	**Factor levels**							
Planting date	Early		Optimum		Late		Very late	
Mean H = 5.81	37.08		46.30		50.33		55.73	
Chi P = 0.121								
Resistance index	Bahar/20	Baharan/50	Chamran II/10	Parsi/30	Pishgam/40	Pishtaz/80	Sirwan/60	Sivand/5
Mean H = 6.44	52.64	42.29	49.43	54.07	40.50	38.75	43.07	57.21
Chi P = 0.489								
Stem rust onset	Early				Late			
Mean H = 68.24	70.18				26.67			
Chi P< 0.001								

The *H*-test ranked the effects of disease onset time, planting date, and resistance index on wheat yield. The yield in the eight cultivars of wheat was not affected (*Chi* $P > 0.05$) by the resistance index factor **(Table 4)**. For the planting date factor, the highest yield ranking was obtained for early plantings which affected the (*Chi* $P < 0.001$; mean $H = 32.93$) yield. Then, the yield rankings were reduced as the planting was delayed from optimum to late and very late plantings. This suggested that the yield ranking in very late plantings improved by 184.55% in early planting in October over the four growing seasons. Planting wheat cultivars at an optimum date in November increased yield ranking by 153.09% compared to the very late planting. For stem rust onset factor affecting (*Chi* $P = 0.008$; mean $H = 7.02$) wheat yield, the early onset of disease corresponded with a 27% greater yield ranking in comparison with the late onset.

Table 4. Ranking yield levels for wheat stem rust onset, planting date, and resistance index.

Factors	**Factor levels**							
Planting date	Early		Optimum		Late		Very late	
Mean H = 32.93	66.67		59.30		39.33		23.43	
Chi P< 0.001								
Resistance index	Bahar/20	Baharan/50	Chamran II/10	Parsi/30	Pishgam/40	Pishtaz/80	Sirwan/60	Sivand/5
Mean H = 8.97	64.29	35.57	49.21	54.43	31.30	47.21	51.50	44.29
Chi P< 0.255								
Stem rust onset	Early				Late			
Mean H = 7.02	55.28				40.36			
Chi P< 0.008								

Factor analysis

From the results of FA, the four principal factors explained 76.27% of variations in the maturity duration, planting date, resistance index, weather, stem rust progress, and yield datasets **(Table 5)**. The first principal factor, justifying 37.06% of the data variance, evidenced the significant loading values for the contributions of the predictor of mean min. Temperature in the second month of spring (-0.45), number of rainy days in spring (-0.43), and the disease onset (0.39). Thus, this factor was defined as the factor of stem rust progress in association with the air temperature and rainy days predictors. The AUSRPC (-0.38), planting date (0.41), and yield (-0.58) predictors were linked significantly to the second principal factor which explained 19.25% of data variance. Thus, the second principal factor was defined as the factor of disease, planting date, and wheat yield. The third principal factor, justifying 11.58% of the data variance, provided a highly negative loading (0.62) for the index of resistance to stem rust, suggesting it was the wheat resistance factor. The fourth factor provided high and moderate contributions of the exponential parameters *b* (0.80) and *r* (0.42), defining it as the stem rust progress factor. The FA outcomes simplified the selection of predictors for the regression model according to the predictive values of the crop, stem rust, and weather descriptors tested at field plot scale during four seasons of wheat growth.

Table 5. Factor analysis of stem rust progression in wheat cultivars differing in planting date, resistance index, and maturity time.

Variables		**Principal components**			
		1	**2**	**3**	**4**
Maturity time		-0.33	0.34	-0.26	0.05
Planting date		-0.24	**0.41**	-0.28	-0.19
Resistance index		0.05	0.18	**0.62**	-0.25
Stem rust	The area under the stem rust progress curve	-0.28	**-0.38**	-0.21	-0.07
	Disease onset	**0.39**	0.26	-0.12	-0.02
	Exponential parameter *b*	0.11	0.01	0.13	**0.80**
	Exponential parameter *r*	0.10	0.03	-0.29	**0.42**
	Max. disease severity	-0.32	-0.28	-0.32	-0.02
Weather	Nd min temp 5-20°C& max RH ≥ 60%	-0.31	0.24	0.27	0.22
	Number of rainy days in spring	**-0.43**	0.00	0.24	0.09
	Mean min. temperature in spring	**-0.45**	-0.04	0.23	0.13
Yield (kg/ha)		0.06	**-0.58**	0.15	-0.02
Eigenvalues		4.45	2.31	1.39	1.01
Variation (%)		37.06	19.25	11.58	8.38
Accumulated variation (%)		37.06	56.31	67.89	76.27

Bold numbers indicate significant loadings ≥ 0.35.

Model development

The current multivariate model explained 96% of variations in yield (*F* prob. = 0.001; $R^2 = 0.96$) of wheat treated with cultivar and planting date across 282 plots during the four growing seasons **(Table 6)**. The stem rust onset, planting date, mean min. Temperature for the second month of spring and the number of rainy days for the second and third months of spring were identified as the most predictive variables describing wheat yield variations across cultivars, planting dates, and growing seasons. The resistance index in interaction with the AUSRPC significantly corresponded with the yield of wheat. Disease onset, planting date, and number of rainy days in spring were negatively related to wheat yield. The mean min. The temperature in spring and the two-way interaction of AUSRPC and resistance index were associated positively with yield. The response data for wheat yield was significantly associated with the data fitted by the model **(Figure 1)**. Thus, this model suggested that higher yield levels corresponded with earlier planting date and stem rust onset, fewer rainy days in spring months, warmer spring, and greater wheat resistance index when interacting with a greater AUSRPC.

Table 6. Regression modeling wheat yield (kg/ha) based on factor analysis of planting date, resistance index, weather, and stem rust progress predictors ($R^2 = 96\%$; $P < 0.001$).

Predictors	**Parameter estimates**	**Standard errors**	***t*-probability**
Disease onset	-2875.00	392.00	<0.001
Number of rainy days in spring	-934.00	109.00	<0.001
Mean min. temperature in spring	2499.00	154.00	<0.001
Planting date	-1174.00	145.00	<0.001
Resistance index × Area under stem rust progress curve	0.10	0.04	0.010

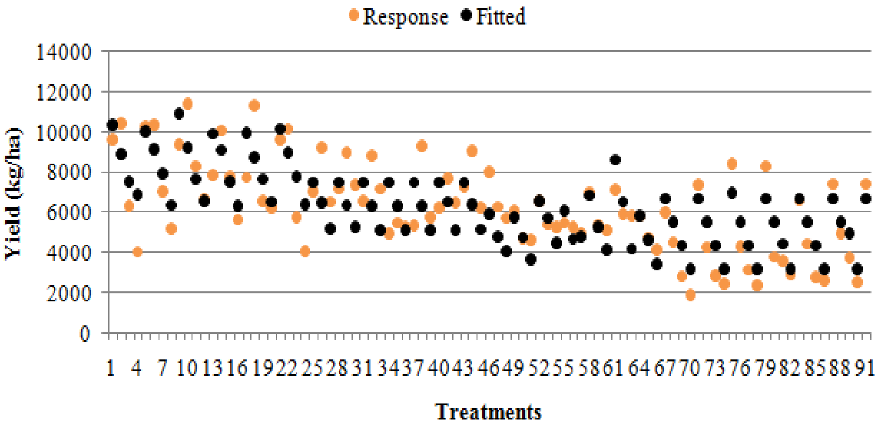

Figure 1. Fitted values regressed to response values of wheat yield in eight cultivars treated with planting date and affected with stem rust; the Treatments axis defines mean values of yield for three replicate plots.

The present observations improved the accuracy of yield estimated by epidemiological and agroecological predictors of wheat cropping systems impacted by highly diverse levels of stem rust. Moreover, the stem rust progress curve elements had been specifically defined for the disease epidemics developed in wheat cultivars planted at different dates and seasons. This experimental design diversified stem rust intensity and spread across 282 field plots (Naseri & Sabeti, 2021). Such high variability in stem rust progress curves increased the predictive values of the disease descriptors to model wheat yield (Kranz, 2003; Naseri, 2022a). This resulted in the present predictive model which explained the main part (96%) of yield variations in wheat treated with cultivar and planting date during four growing seasons. Reviewing earlier findings (Soko *et al*., 2018) demonstrated that it is hard to explain 96% variations in wheat yield by using only general stem rust progress curve elements. Further investigations may elucidate how other agronomic and environmental factors impact stem rust progress and wheat yield.

Roelfs *et al*. (1992) reported that *P. graminis* f. sp. *Tritici* sporulates on the leaf of wheat with an optimum temperature of 30°C. Recently, Naseri and Sabeti (2021) added associations of average monthly min. Temperature and rainy days in spring, autumn-winter-spring days with 5-20°C(min.) temperature and max. RH above 60% with stem rust onset to our knowledge. In the next step, Naseri (2022a, 2022b) introduced accurate, specific, and easy-to-measure disease curve elements as follows: AUSRPC, max. Disease incidence, and exponential parameters *b* and *r*. However, the concise estimation of wheat yield according to these weather and stem rust progress predictors is still required. Therefore, the current four-year investigation predicted wheat yield based on the number of rainy days and mean monthly min. Temperature in spring as a weather variable in conjunction with the AUSRPC and stem rust onset as the disease variables. This appears to be the first report of step-by-step selected weather and disease predictors used as independent variables to estimate wheat yield.

In addition to the weather and stem rust progress, the present research also evaluated the predictive values of maturity duration, cultivar resistance, and planting date to model wheat yield. Because the productivity of wheat is affected by not only stem rust epidemics but also agronomic and weather parameters. Mapuranga *et al*. (2022) reviewed the literature to highlight the impacts of appropriate planting dates on improving the durability of genetic resistance to wheat rusts. Naseri and Sabeti (2021) indicated a significant association of genetic resistance with air temperature and wetness. Thus, a manageable number of pathosystem and agroecosystem predictors were evaluated to predict wheat production under field conditions. This research explained 96% of the variability in yield levels determined in 282 experimental plots treated with the cultivar and planting date over four seasons. Such a remarkable fitness of the disease, climatic, and crop predictors in the yield model appears to be the first report for the stem-rust-wheat interplay. Although Soko *et al*. (2018) predicted wheat yield reductions due to stem rust using non-specific disease variables, they obtained a lower fitness of their model possibly because of excluding influential agroecological factors.

CONCLUSION

This research assists with predicting yield in wheat cultivars differing in maturity and planting date, and resistance to stem rust over four seasons. The highest yield ranking was detected for early plantings in October with yield improved by 184.55% compared to late plantings in January. Early onset of the disease increased stem rust by 62%. Factor analysis simplified the selection of predictors for the yield model according to the crop, stem rust, and weather descriptors examined at the field plot scale. Higher yield corresponded with earlier planting date and stem rust onset, fewer rainy days in spring months, warmer spring, and greater wheat resistance index when interacting with a greater area under the stem rust progress curve.

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