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Identification of Resistance Sources to Wheat Stem Rust from Introduced Genotypes in Kenya

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Abstract

Stem rust *Puccinia graminis* Pers. f. sp. *tritici* of wheat is the most important disease in Kenya. Emergence of race Ug99 and other variants virulent to host resistance genes including *Sr31* has rendered 95% of Kenyan cultivars susceptible. This study aimed to identify new sources of resistance to stem rust in a collection of exotic genotypes. Three hundred and sixteen wheat genotypes were screened at the Kenya Agricultural and Livestock Research Organization (KALRO) in Njoro for two seasons in 2015. The host reaction to disease was evaluated based on the modified Cobb scale. The relative Final Rust Severity (rFRS), Average Coefficient of Infection (ACI) and relative Area Under Disease Progress Curve (rAUDPC) were used to characterize the genotypes for stem rust resistance. Agronomic traits were also recorded. Six genotypes namely ALBW-100, ALBW- 204, EPCBW-261, EPCBW-295, PCHP-309 and PCHPBW-310 with significantly low ACI, rAUDPC and rFRS were identified. Thirty five genotypes showed Pseudo-Black Chaff (PBC) phenotype associated with resistant gene *Sr2*, a source of partial resistance in wheat. The genotypes also showed low disease severity (20-25%) and Moderately Susceptible (MS) – Susceptible (S) infection types in both seasons. Genotypes had significant differences ($p \leq 0.05$) on plant height, 1000-kernel weight and number of tillers indicating genetic variation which could be exploited in breeding for resistance to stem rust. The negative relationship between agronomic variables involving plant height, spikelet length and 1000-kernel weight showed harmful effects of stem rust on plant characteristics including yield. The stem rust resistant genotypes with good agronomic traits could be introgressed into adapted Kenyan backgrounds while the genotypes showing presence of PBC could be utilized to develop durable stem rust resistant wheat. Inheritance studies to elucidate the exact genes conferring resistance to stem rust could be conducted for breeders to exploit their genetic variability.

Keywords: adult plant resistance (APR), introduced genotypes, *Sr2* genes, stem rust

1. Introduction

Wheat (*Triticum aestivum* spp. *aestivum* L.) is an important food grain source worldwide. Its demand in developing countries is rising in recent decades and is expected to reach 60% by 2050 (FAO, 2016). However, climate change associated with erratic temperatures, droughts, floods, pests and disease epidemics will reduce wheat production by 29% (Rosegrant et al., 1995). Ever since wheat was introduced in Kenya-nearly a century ago, stem rust has remained a key production challenge. Strategic introgression and deployment of resistance genes in commercial varieties throughout the 1950s greatly circumvented major stem rust epidemics. However, in more recent years, the evolution and selection for new races with increased virulence has become undesirably frequent (Velu & Singh, 2013). In the last decade, the threats due to stem rust disease have re-emerged owing to a new set of races, called the "Ug99 family". The first recognizable variant in this family is the initially characterized race Ug99, also designated as TTKSK, based on its effects on select host resistance genes differentials (Jin et al., 2008). First reported in Uganda in 1998, the race TTKSK was found in Kenya in 2001. This race has unique virulence to *Sr31* and *Sr38* resistance genes widely utilized in wheat worldwide and for which virulence had not been reported previously in the world (Pretorius et al., 2000).

Globally, since the discovery of Ug99, about 80% to 90% of the wheat grown is susceptible to stem rust often leading to up to 70% yield losses (Singh et al., 2006). In Kenya, stem rust associated yield losses of 100%, have been reported (Njau et al., 2010). Over 95% of local commercial varieties are susceptible or highly susceptible, while only a few older varieties showing some level of 'adult plant resistance' (APR) (Wanyera et al., 2006; Njau et al., 2010) have been identified. Currently, more than 15 confirmed races in the Ug99 lineage have been reported in Africa and beyond (Singh et al., 2015). Through airborne transmission, Ug99 and its variants have reached Asia one of the main global wheat bread baskets; having been reported in Yemen in 2006, Iran in 2007 and Pakistan in 2009 (Hodson et al., 2009; Nazari et al., 2009; Admassu et al., 2009).

While chemicals can be used to manage stem rust, the main challenge is the high costs and the detrimental effects posed on the environment (Beard et al., 2006). Genetic resistance is the most economically viable method of controlling stem rust. To date over 70 genes have been designated for resistance to stem rust (McIntosh et al., 2014). Of those, 34 are ineffective against race Ug99 (Singh et al., 2015). Among the adult plant resistance genes, *Sr2* gene is the only well studied. A combination of *Sr2* gene and other unknown slow rusting resistance genes forms the "*Sr2* complex" which provides durable resistance to stem rust (McIntosh, 1988). The concept-"breeding for durable resistance in wheat" championed by Dr. Norman Borlaug has led to a global search for new genes or gene combinations to combat the new stem rust race Ug99 that could be released as new varieties.

A shuttle breeding scheme with the goal of phenotyping breeding populations for adult plant resistance to Ug99 family of races was initiated in 2005 between KALRO-Njoro and the International Maize and Wheat Improvement Centre (CIMMYT) (http://www.globalrust.org/). Through the initiative, several genotypes, with potentially good sources of APR genes have been identified. A study conducted at KALRO-Njoro on elite advanced CIMMYT bread wheat indicated that 30% of the materials were susceptible at the seedling stage while various levels of APR were identified in the field tests (Njau et al., 2010). Invariably, all APR in the studied material was associated with the *Sr2* complex. Bhavani et al. (2011) reported detection of *Sr2* gene based on mapping studies on six CIMMYT parental lines. These reports indicate that exotic wheat genotypes could be good sources of resistance to stem rust that could be deployed in the national wheat improvement program at KALRO-Njoro. A study on 30 vintage Kenyan varieties for resistance to stem rust both at the seedling and adult plant growth stage revealed that none of them except variety *Bonny* was resistant at the seedling stage, while a few had APR attributed to *Sr2* gene in their backgrounds (Njau et al., 2009).

Given the devastating nature of Ug99 family of stem rust races to wheat productivity regionally, effort to explore for resistance sources and incorporation of effective genes into new high yield commercial varieties is paramount. Accordingly, the objective of this study was to identify suitable sources of resistance to stem rust among exotic wheat genotypes.

2. Materials and Methods

2.1 Experimental Site

The research was carried at KALRO-Njoro which is about 2185 meters above sea level, approximately 0°20′S; 35°56′E. Average temperatures ranges between 9.7 °C and 23.5 °C. Mean annual precipitation is 900 mm (Ooro et al., 2009). KALRO-Njoro hosts the global phenotyping facility for characterizing and selection of wheat genotypes resistant to stem rust (Singh et al., 2006), under the auspices of the BGRI project (http://www.globalrust.org/).

2.2 Genotypes

Three hundred and sixteen exotic genotypes namely: 250 "Aluminum Bread Wheat (AL BW)", 47 "Elite Bread Wheat (EPC BW)" and 19 "PC-Harvest plus Bread Wheat (PCHP BW)". These are genetically fixed lines, bred targeting high yields and superior grain quality including specific nutritional needs (Velu & Singh, 2013). The universally stem rust susceptible genotype CACUKE was included to monitor proliferation of the disease epidemic. A mixture of seven rust susceptible genotypes including Morocco, Robin, and PBW343 were used.

2.3 Experimental Procedures

The study was undertaken twice; off-season (January to June 2015) and main-season nursery (July to November 2015). Experiments in both seasons were established based on augmented alpha lattice square design with no replication. Experimental plots were 6 rows by 2 m length and 20 cm inter-row spacing. Diammonium phosphate (DAP) was applied at the rate of 125 kg/ha while planting, followed by an application of Urea (75 kg/ha) as a source of Nitrogenn at late tillering and booting stages of the plants.

2.4 Data Collection

2.4.1 Agronomic Traits

These included: plant height (cm), spike length (cm) and 1000-kernel weight (g) evaluated at harvest maturity. Presence of *Sr2* gene was recorded by observing occurrence of pseudo-black chaff (PBC) on the stems and heads of the plant. A plus (+) was used to indicated presence of PBC while a minus (-) indicated absence of PBC.

2.4.2 Disease Scoring

This was done in season one and two when the susceptible check CACUKE expressed 50% rust severity, and 70% severity respectively. The stem rust severity was recorded based on the modified Cobb's scale on a 0-100% scale (Peterson et al., 1948). The host response which included the trace (TR), resistant (R), moderately resistant (MR), moderately susceptible (MS), and susceptible (S) were recorded based on Roelfs et al. (1992) scale. The disease severity scores were converted into area under the disease progress curve (AUDPC) values following Wilcoxson et al. (1975) Equation 1.

$$AUDPC = \sum_{i=1}^{n} \frac{(y_i + y_{i+1})}{2}(t_{i+1} - t_i) \tag{1}$$

Where, y_i = average coefficient of infection of the i^{th} reading; y_{i+1} = average coefficient of infection of i + 1^{th} reading; (t_{i+1} - t_i) = number of days between the i^{th} and the i + i^{th} reading, and n = number of observations.

The susceptible check CACUKE was used as a reference to obtain the relative AUDPC (rAUDPC) in Equation 2, as well as relative Final Rust Severity (rFRS), in Equation 3.

$$rAUDPC = \frac{AUDPC\ of\ Genotypes}{AUDPC\ of\ Susceptible\ Check} \times 100 \tag{2}$$

$$rFinal\ Rust\ Severity = \frac{Final\ Rust\ Severity\ of\ Genotype}{Final\ Rust\ Severity\ of\ Susceptible\ Check} \times 100 \tag{3}$$

The coefficient of infection (CI) was obtained by multiplying the final disease severity for each individual score by the numerical value where TR = 0.1; R = 0.2; MR = 0.4; M = 0.6; MS= 0.8; and averaged to give average coefficient of infection (ACI) (Roelfs et al., 1992).

2.5 Data Analysis

The analysis of variance (ANOVA) was used to discern differences among genotypes. Genotypes were considered fixed while the seasons were considered as random effects. Genotypic means were separated based on Fisher's protected least significance difference (LSD) at $p \leq 0.05$. A Pearson correlation coefficient test was done to determine the relationship between the different disease parameters and the agronomic traits.

3. Results

3.1 Reactions of Genotypes to Weather Conditions across the Seasons

There was high disease pressure among the genotypes during both seasons. The susceptible check, CACUKE showed 90% and 100% final rust severity in season one and two respectively.

3.2 Reaction of Genotypes to Stem Rust and Other Agronomic Traits

ANOVA revealed significant differences at $p \leq 0.05$ among the genotypes for all the agronomic traits, apart from TKW (Table 1). Seasonal variations were significant at ($p \leq 0.05$) for AUDPC, rAUDPC, TKW and PH. Significant genotypes × season interactions were revealed among the disease parameters but not the agronomic traits. Dwarf genotypes with heights ranging from 62.5 to 68.2 cm relative to the tallest genotype (ALBW-135) - 94 cm tall were identified in both seasons. These were: ALBW-38, ALBW-65, ALBW-72, ALBW-81, ALBW-82, ALBW-99, ALBW-108, ALBW-207, ALBW-208, ALBW-210, EPCBW-292, PCHP-300, PCHP-312 and PCHP-316. They also recorded high TKW ranging between 32.7 to 39.2 g in both seasons (Table 2). The longest spikes averaged from 12.4 cm among the ALBW genotypes. ALBW-98 had the highest average TKW (47.4 g). Notably, rust susceptible genotypes ALBW-16 depicting high disease severities of 40% and 50% in season one and two respectively also had a relatively low average TKW of 24.4 g, only slightly higher than that of the susceptible check CACUKE 20.2 g in season 2 (Table 2).

Genetic variations for resistance to stem rust within each season were observed. Six genotypes: ALBW-100, ALBW-204, EPCBW-261, EPCBW-295, PCHP-309 and PCHPBW-310, showed R-MR response in season one and trace responses to stem rust in season two. Among the ALBW, ACI ranged from 1-60, while the AUDPC ranged from 15-455 in season one and 0-795 in season two. Over half (54%) of the two hundred and fifty ALBW recorded moderately susceptible-susceptible (MSS) response with AUDPC, ranging from 90-650, in season two, lower than the susceptible check CACUKE, whose AUDPC was 700 in season two. Only 6 genotypes from the ALBW set namely ALBW-4, ALBW-100, ALBW-106, ALBW-173, ALBW-174 and ALBW-204 showed R or MR infection types in both seasons (Table 2).

Among the 47 genotypes in the EPCBW set, the AUDPC ranged from 20-230 in season one and 0-605 in season two. EPCBW genotypes depicted lower rAUDPC, than ALBW genotypes ranging between 0-46 in season one and 0-86 in season two. The EPCBW genotypes had the highest number of intermediate infection type (M) in (twenty two genotypes) (Table 2). Among the PCHP accessions, AUDPC ranged from 78-303 in season one and 0-415 in season two lower than those in the ALBW set. The rFRS ranged from 14-35 in season one and 0-42 in season two. Fourteen of the 19 PCHPBW genotypes evaluated (74%) showed moderately susceptible to susceptible infection types.

Across all test material thirty five wheat genotypes depicted the pseudo black chaff (PBC) on the spikes and the necks of the plants in season two.

3.3. Correlation Coefficients among Disease Parameters and Agronomic Traits

The Pearson Correlation coefficients considered between pairs of the respective disease parameters were highly significant ($p \leq 0.05$) (Table 3). Among the agronomic traits, negative values for Pearson correlation coefficient were observed with respect to stem rust severity. Specifically, Pearson's correlation coefficients with rust severity were -0.0475, -0.0253 and -0.3401 respectively for plant height, spikelet length and TKW (Table 4). This indicated that as the stem rust severities increased, this had negative effects on the agronomic traits. There were significant differences in the relationships between spikelet length and plant height; thousand kernel weight and spikelet length and stem rust and thousand kernel weights ($p \leq 0.05$). The p-values of all the other agronomic traits were not significantly different from each other (Table 4).

Table 1. ANOVA table highlighting levels of significance observed among various disease and agronomic parameters

SOURCE	Df	AUDPC	rAUDPC	ACI	rFRS	TKW (g)	PH (cm)	SL (cm)
Genotype	316	20167*	411.6*	126.7*	320.2*	34.46	67.79*	1.441*
Season	1	37712*	769.6*	83.27	360.2	4037.23*	687.7*	0.3222
Genotype by Season	316	13136*	268.1*	69.09*	208.4*	33.08	18.02	0.5211
Residual	316	8943	182.5	52.38	134.6	27.72	33.22	0.8384
Total	633							

Note. * Significance at $p \leq 0.05$. df = degree of freedom; AUDPC = area under the disease progress curve; rAUDPC = relative area under the disease progress curve; ACI = average coefficient of infection; rFRS = relative final rust severity; TKW = thousand kernel weight in grams; PH = plant height; SL = spikelet length in centimeters.

Table 2. Means among different disease and agronomic traits parameters among 316 tested genotypes

Genotype	ACI	AUDPC	rAUDPC	rFRS	Stem rust season 1		Stem rust season 2		TKW (g)	PH (cm)	SL (cm)	PBC
					Severity	FR	Severity	FR				
AL BW-1	6	114	32.6	11.8	10	MSS	10	MR	32.2	77.4	8.5	-
AL BW-2	10	134	38.3	14.7	5	MSS	20	MSS	37.6	73.7	9.2	-
AL BW-3	44	627.5	179.3	44.1	60	MSS	15	MSS	37.3	73.5	8.5	-
AL BW-4	4	47.5	13.6	5.9	10	MSS	0	TR	39.3	61.5	7.2	-
AL BW-5	9	105	30	14.7	20	MSS	5	MR	36.8	71.5	6.5	-
AL BW-6	8	141.5	40.4	11.8	10	MSS	10	MS	44.9	72.3	6.8	-
AL BW-7	11	170	48.6	17.6	20	MSS	10	M	33.8	76.9	7.7	-
AL BW-8	18	256.5	73.3	26.5	15	MSS	30	MSS	35.1	81.7	8.9	-
AL BW-9	18	229	65.4	26.5	15	MSS	30	MSS	39.2	76.5	7.6	-
AL BW-10	20	285	81.4	29.4	30	MSS	20	MSS	35.4	73.5	9.2	-
AL BW-11	18	247.5	70.7	26.5	5	MSS	40	MSS	29.8	80.9	8.8	-
AL BW-12	19.5	274	78.3	26.5	15	S	30	MSS	31.6	86.5	8.6	-

Genotype	ACI	AUDPC	rAUDPC	rFRS	Stem rust season 1		Stem rust season 2		TKW (g)	PH (cm)	SL (cm)	PBC
					Severity	FR	Severity	FR				
AL BW-13	24	360	102.9	35.3	30	MSS	30	MSS	33.1	72.4	8.6	-
AL BW-14	28	397.5	113.6	41.2	20	MSS	50	MSS	35	64.5	7.8	-
AL BW-15	30	419	119.7	44.1	25	MSS	50	MSS	33	79.5	7.6	-
AL BW-16	40	521.5	149	52.9	40	S	50	MSS	24.4	75.2	8.1	-
AL BW-17	20	275	78.6	29.4	10	MSS	40	MSS	35.5	78.4	8.4	-
AL BW-18	22	286.5	81.9	32.4	15	MSS	40	MSS	28.2	81	7.3	-
AL BW-19	20	275.5	78.7	29.4	20	MSS	30	MSS	27.3	83.9	8.5	-
AL BW-20	20	294	84	29.4	10	MSS	40	MSS	29.6	73.3	8.7	-
AL BW-21	18	320	91.4	26.5	5	MSS	40	MSS	33.5	89.5	8.4	-
AL BW-22	15	191.5	54.7	23.5	10	M	30	MSS	29.6	68.3	8.8	-
AL BW-23	9.5	151.5	43.3	14.7	5	M	20	MS	29.7	74.4	8.1	-
AL BW-24	16	191.5	54.7	23.5	10	MSS	30	MSS	33.6	71.5	8.1	-
AL BW-25	14	190	54.3	20.6	5	MSS	30	MSS	29.7	79	8.5	-
AL BW-26	13.5	192	54.9	20.6	5	M	30	MSS	32.2	78.4	9.3	-
AL BW-27	28	406.5	116.1	41.2	20	MSS	50	MSS	33	80.2	7.9	-
AL BW-28	16	272.5	77.9	23.5	20	MSS	20	MSS	28.3	76.7	7.9	-
AL BW-29	10	170.5	48.7	14.7	5	MSS	20	MSS	31.3	69.7	9.5	-
AL BW-30	19	294	84	29.4	10	M	40	MSS	36.9	74	9	-
AL BW-31	16	200	57.1	23.5	10	MSS	30	MSS	29.4	73.5	8.1	-
AL BW-32	16	227.5	65	23.5	20	MSS	20	MSS	34.5	81.2	8.8	-
AL BW-33	12	216.5	61.9	17.6	20	MSS	10	MSS	28.3	77.9	9.2	-
AL BW-34	15	219	62.6	23.5	30	MSS	10	M	32.6	84.3	9.3	-
AL BW-35	16	245	70	23.5	25	MSS	15	MS	35.5	83.8	7.7	-
AL BW-36	28	305.5	87.3	35.3	40	S	20	MS	37	69.7	9	-
AL BW-37	11	153	43.7	17.6	20	MSS	10	M	30.1	67.5	8.7	-
AL BW-38	14	207.5	59.3	20.6	20	MSS	15	MS	34.2	66	10.2	-
AL BW-39	8	124	35.4	14.7	15	MSS	10	MR	36.7	75.7	8.5	+
AL BW-40	22	331.5	94.7	32.4	15	MSS	40	MSS	28.1	74.5	8.1	-
AL BW-41	18	229	65.4	26.5	15	MSS	30	MSS	33.6	77.5	8.8	-
AL BW-42	16	227.5	65	23.5	10	MSS	30	MSS	32.8	81.7	9.8	-
AL BW-43	12.5	226.5	64.7	20.6	20	MSS	15	M	31.8	71.3	8.6	-
AL BW-44	18	229	65.4	26.5	15	MSS	30	MSS	32.3	76.2	8.9	-
AL BW-45	4.3	55	15.7	6.5	10	M	10	MS	38	80.7	8.8	-
AL BW-46	6	104	29.7	8.8	5	MS	10	MS	29.8	81.5	7.9	-
AL BW-47	22	312.5	89.3	32.4	15	MSS	40	MSS	29.6	80.3	8.6	-
AL BW-48	5.5	104	29.7	8.8	5	M	10	MS	32.2	77	9.6	-
AL BW-49	22	276.5	79	29.4	40	S	10	MR	35.7	71.4	9.3	+
AL BW-50	14	255.5	73	23.5	20	M	20	MSS	34.2	81.2	8.7	-
AL BW-51	6	131.5	37.6	8.8	10	MSS	5	MS	37.2	76.9	8.7	-
AL BW-52	9	114	32.6	11.8	10	S	10	MSS	34.4	72.5	9.2	-
AL BW-53	5	104	29.7	8.8	5	MSS	10	M	35.3	80	8.1	-
AL BW-54	12	161.5	46.1	17.6	10	MSS	20	MSS	33.4	76	8.6	-
AL BW-55	5.5	112.5	32.1	8.8	5	M	10	MS	37.7	84.5	8.2	-
AL BW-56	38	490	140	55.9	25	MSS	70	MSS	25.8	73.5	8.5	-
AL BW-57	3.5	131.5	37.6	8.8	10	MR	5	M	37.7	78.2	9.9	+
AL BW-58	14	171.5	49	20.6	15	MSS	20	MSS	26.9	73.2	8.5	-
AL BW-59	8	95	27.1	11.8	10	MS	10	MS	39.6	79.5	7.8	-
AL BW-60	13	134	38.3	17.6	10	S	20	MSS	35.6	80.7	9.1	-
AL BW-61	4.5	114	32.6	11.8	5	M	15	MR	34.2	85.5	8.8	+
AL BW-62	8	122.5	35	11.8	10	MSS	10	MSS	28.4	77.4	8.6	-

Genotype	ACI	AUDPC	rAUDPC	rFRS	Stem rust season 1		Stem rust season 2		TKW (g)	PH (cm)	SL (cm)	PBC
					Severity	FR	Severity	FR				
AL BW-63	12	180	51.4	17.6	10	MSS	20	MSS	36.9	79.3	8	-
AL BW-64	13.5	190	54.3	20.6	5	M	30	MSS	30.2	80.4	8.4	-
AL BW-65	22	295.5	84.4	32.4	15	MSS	40	MSS	33	66.9	8.7	-
AL BW-66	7	141.5	40.4	11.8	10	MSS	10	M	29.5	75.7	9.8	-
AL BW-67	8	114	32.6	11.8	15	MSS	5	MS	31	71.9	9	-
AL BW-68	24	314	89.7	35.3	30	MSS	30	MSS	32.1	77	8.8	-
AL BW-69	18	275	78.6	26.5	15	MSS	30	MSS	36.3	81.4	7.3	-
AL BW-70	17	218	62.3	20.6	30	S	5	MSS	34	77.5	8.8	-
AL BW-71	7	141.5	40.4	11.8	10	M	10	MSS	29.8	73.4	7.1	-
AL BW-72	4.5	112.5	32.1	8.8	10	M	5	M	35.7	62.5	8.1	-
AL BW-73	5	86.5	24.7	11.8	10	M	10	MR	37.5	84.5	8.3	+
AL BW-74	8	105.5	30.1	11.8	15	MSS	5	MS	37.2	71.9	8.1	-
AL BW-75	20	294	84	29.4	35	MSS	15	MSS	26.8	76.5	8.3	-
AL BW-76	12	161.5	46.1	17.6	20	MSS	10	MSS	26.7	86.5	7.8	-
AL BW-77	13	209	59.7	20.6	25	MSS	10	M	28.9	74.2	9.2	-
AL BW-78	14	190	54.3	20.6	15	MSS	20	MSS	25.4	79.9	10.2	-
AL BW-79	8.5	163	46.6	20.6	15	M	20	MR	33.3	80.9	7.9	+
AL BW-80	12.5	190.5	54.4	20.6	20	MSS	15	M	32	71.9	10.2	-
AL BW-81	16	209	59.7	23.5	20	MSS	20	MSS	26.6	66.7	9	-
AL BW-82	9	151.5	43.3	14.7	15	MSS	10	M	38.2	68.8	8.6	-
AL BW-83	14	217.5	62.1	20.6	15	MSS	20	MSS	32.1	77	8.7	-
AL BW-84	14	218	62.3	20.6	15	MSS	20	MSS	28.4	76.3	8.1	-
AL BW-85	23	266.5	76.1	29.4	40	S	10	M	35	81.7	8.5	-
AL BW-86	28	341.5	97.6	35.3	40	S	20	MSS	39.7	85.4	7.7	-
AL BW-87	18	303	86.6	29.4	20	M	30	MSS	28.4	82.5	8.9	-
AL BW-88	10	153	43.7	17.6	20	M	10	MS	26	83.3	9.7	-
AL BW-89	12	255	72.9	23.5	20	M	20	M	31.4	78.9	8	-
AL BW-90	12	216.5	61.9	17.6	20	MSS	10	MSS	35.6	73.4	8.3	-
AL BW-91	10	179	51.1	14.7	20	MS	5	MS	30	87.2	9.3	-
AL BW-92	5	76.5	21.9	8.8	10	M	5	MS	31.7	71.3	9.6	-
AL BW-93	3.5	58	16.6	5.9	5	M	5	M	29.3	77.9	9.1	-
AL BW-94	5	78	22.3	11.8	10	M	10	MR	31.8	81.3	8.2	+
AL BW-95	3.5	95.5	27.3	8.8	5	M	10	MR	34.1	73	8.7	+
AL BW-96	5.5	54.5	15.6	8.8	5	M	10	MS	36.9	73	8.1	-
AL BW-97	3.5	68	19.4	8.8	10	MR	5	M	34.2	71.7	8.5	+
AL BW-98	3.5	104	29.7	8.8	10	MR	5	M	47.4	72	8.1	+
AL BW-99	2.5	47.5	13.6	5.9	5	MR	5	M	30.7	64.7	8.4	+
AL BW-100	3	40	11.4	5.9	10	M	0	TR	30.2	72.3	9.1	-
AL BW-101	8	105.5	30.1	11.8	10	MSS	10	MS	32.6	79.8	8.9	-
AL BW-102	12	227.5	65	23.5	20	M	20	M	32.6	86.5	10.1	-
AL BW-103	10	124	35.4	14.7	5	MSS	20	MSS	28.7	71.3	8.7	-
AL BW-104	12	171.5	49	17.6	15	MSS	15	MS	29.1	81.7	9.8	-
AL BW-105	8	141.5	40.4	11.8	10	MSS	10	MS	28.6	76.3	8	-
AL BW-106	8	123	35.1	11.8	20	MSS	0	TR	34.5	62.8	7.5	-
AL BW-107	5.5	85	24.3	8.8	10	MSS	5	M	36.6	71.2	8.5	-
AL BW-108	11	197.5	56.4	17.6	10	M	20	MSS	30.9	61.5	9.1	-
AL BW-109	20	320	91.4	29.4	20	MSS	30	MSS	32.2	82	8.6	-
AL BW-110	14	218	62.3	20.6	30	MSS	5	MS	37.8	83.8	8.9	-
AL BW-111	7	141.5	40.4	11.8	10	M	10	MS	33.4	81.5	9.2	-
AL BW-112	12	189	54	17.6	25	MSS	5	MS	30	84.7	8.3	-

Genotype	ACI	AUDPC	rAUDPC	rFRS	Stem rust season 1		Stem rust season 2		TKW (g)	PH (cm)	SL (cm)	PBC
					Severity	FR	Severity	FR				
AL BW-113	13.5	181.5	51.9	20.6	30	MSS	5	M	36.3	79.8	9.2	-
AL BW-114	20	230.5	65.9	29.4	30	MSS	20	MSS	32.6	71.4	9.7	-
AL BW-115	23	257.5	73.6	29.4	30	S	20	MSS	30.3	76.7	10	-
AL BW-116	8.5	134	38.3	14.7	15	M	10	MS	33.4	71.5	9.8	-
AL BW-117	12.5	209	59.7	20.6	15	M	20	MSS	31.9	80	8.2	-
AL BW-118	16	229	65.4	23.5	20	MSS	20	MSS	26.7	76	10.6	-
AL BW-119	14	190.5	54.4	20.6	20	MSS	15	MSS	29.2	72.3	8.4	-
AL BW-120	10	170.5	48.7	14.7	20	MSS	5	MS	33.6	79.9	9.8	-
AL BW-121	16	200.5	57.3	23.5	20	MSS	20	MSS	26.3	72.7	9.9	-
AL BW-122	8	151.5	43.3	14.7	10	MR	15	MSS	30.2	84.5	8.6	-
AL BW-123	16	219	62.6	23.5	10	MSS	30	MSS	32.9	75	9.1	-
AL BW-124	4	104	29.7	8.8	5	MS	10	MR	27.8	74.2	9	+
AL BW-125	10	132.5	37.9	14.7	15	MSS	10	MSS	36.3	76.2	8.4	-
AL BW-126	14	226.5	64.7	20.6	25	MSS	10	MSS	31.9	83.7	9.5	-
AL BW-127	16	228	65.1	23.5	25	MSS	15	MSS	28.3	82.7	9.2	-
AL BW-128	11	180.5	51.6	17.6	20	MSS	10	M	36.2	81.2	7.9	-
AL BW-129	20	247.5	70.7	29.4	20	MSS	30	MSS	37.8	88.3	8.1	-
AL BW-130	6.5	160.5	45.9	11.8	15	M	5	MS	31.1	85.5	9.1	-
AL BW-131	7	141.5	40.4	11.8	10	M	10	MSS	34.1	79.8	9.2	-
AL BW-132	12	216.5	61.9	17.6	20	MSS	10	MSS	32.5	76.9	8.6	-
AL BW-133	9	199	56.9	17.6	20	M	10	M	36.5	77.7	8.9	+
AL BW-134	11	207.5	59.3	17.6	10	M	20	MSS	28.7	79.5	7.7	-
AL BW-135	9	245.5	70.1	17.6	20	M	10	M	34.1	94	9.8	-
AL BW-136	9.5	218	62.3	20.6	25	M	10	MR	29.8	88.5	10.5	+
AL BW-137	24.5	304	86.9	32.4	25	S	30	MSS	30.8	77.2	9.1	-
AL BW-138	14.5	180	51.4	17.6	25	S	5	MS	29.5	82.2	8.7	-
AL BW-139	10	143	40.9	14.7	15	MSS	10	MS	32.9	78.5	8.2	-
AL BW-140	16	200.5	57.3	23.5	30	MSS	10	MS	29.4	73.7	9.3	-
AL BW-141	14	173	49.4	20.6	25	MSS	10	MS	30.4	67.2	8	-
AL BW-142	5.5	76.5	21.9	8.8	5	M	10	MS	37.5	72.5	9.6	-
AL BW-143	7	114	32.6	11.8	10	M	10	MSS	33.8	71.7	8.4	-
AL BW-144	32	435	124.3	41.2	40	S	30	MSS	31.2	83.5	9.5	-
AL BW-145	9.5	153	43.7	14.7	5	M	20	MSS	30.4	84.7	10.4	-
AL BW-146	10	151.5	43.3	14.7	15	MSS	10	MS	34.1	85	8.7	-
AL BW-147	24.5	321.5	91.9	32.4	25	S	30	MSS	35.6	72.9	7.5	-
AL BW-148	26	360.5	103	35.3	20	S	40	MSS	32.3	76.9	9.8	-
AL BW-149	12	180.5	51.6	17.6	10	MS	20	MSS	35	75.7	8.5	-
AL BW-150	16	237.5	67.9	23.5	20	MSS	20	MSS	31.1	81.5	10	-
AL BW-151	6	133	38	11.8	10	M	10	M	30	73.7	9.7	-
AL BW-152	3.5	85.5	24.4	5.9	5	MSS	5	M	36	77.9	9.6	-
AL BW-153	4	75	21.4	5.9	5	MSS	5	MS	38.4	83.5	10.3	-
AL BW-154	6	105.5	30.1	11.8	10	M	10	M	39.4	83.7	9.7	-
AL BW-155	4	95.5	27.3	8.8	10	M	5	MR	34.8	79.4	8.2	+
AL BW-156	7	124	35.4	11.8	15	MSS	5	MR	30	70.5	8.6	-
AL BW-157	15.5	218	62.3	20.6	25	S	10	M	30.4	76.7	8.4	-
AL BW-158	6	133	38	11.8	15	M	5	M	29.1	76.4	9.4	+
AL BW-159	10	114	32.6	14.7	15	MSS	10	MS	35.5	76.2	10.6	-
AL BW-160	5	112.5	32.1	8.8	10	M	5	MSS	36.6	82	8.3	-
AL BW-161	8.5	143	40.9	14.7	15	M	10	MSS	36.4	80.4	7.9	-
AL BW-162	7.5	151.5	43.3	14.7	15	M	10	M	40.1	89.5	9.5	+

Genotype	ACI	AUDPC	rAUDPC	rFRS	Stem rust season 1		Stem rust season 2		TKW (g)	PH (cm)	SL (cm)	PBC
					Severity	FR	Severity	FR				
AL BW-163	5.5	85	24.3	8.8	5	M	10	MSS	37.2	63.4	7.4	-
AL BW-164	6.5	105.5	30.1	11.8	15	M	5	MS	38.4	88.2	8.5	-
AL BW-165	13.5	200.5	57.3	20.6	30	MSS	5	M	32.7	80.2	8.4	-
AL BW-166	11.5	197.5	56.4	17.6	25	MSS	5	M	33.3	79.8	8.5	-
AL BW-167	11.5	199	56.9	20.6	25	M	10	MS	27.5	74.2	8.3	-
AL BW-168	31	371.5	106.1	41.2	30	S	40	MSS	30.7	81.2	9	-
AL BW-169	18	116	33.1	23.5	20	S	20	MSS	36.4	87.5	9	-
AL BW-170	7	133	38	11.8	10	M	10	MS	30.7	91.7	9.7	-
AL BW-171	5.5	76.5	21.9	8.8	10	MSS	5	M	37.7	88.9	9.9	-
AL BW-172	5	104	29.7	8.8	10	M	5	MSS	37.2	84.2	8.9	-
AL BW-173	1.5	29	8.3	2.9	5	M	0	TR	38.9	74.7	8.4	-
AL BW-174	3	66.5	19	5.9	10	M	0	TR	35.1	71.8	8.7	-
AL BW-175	6	76.5	21.9	8.8	10	MSS	5	MSS	39.2	64.4	9.2	-
AL BW-176	15.5	163	46.6	20.6	15	S	20	MSS	35.7	72.9	10.2	-
AL BW-177	3	85.5	24.4	5.9	5	M	5	M	36.4	74	9.2	-
AL BW-178	18	275	78.6	26.5	15	MSS	30	MSS	30.5	81.7	9.7	-
AL BW-179	8	114	32.6	11.8	10	MSS	10	MS	31.9	85.3	8.8	-
AL BW-180	7	114	32.6	11.8	10	MS	10	M	34.4	81	8.7	-
AL BW-181	9	190.5	54.4	17.6	10	M	20	M	33.7	73.5	8.2	+
AL BW-182	6.5	187.5	53.6	11.8	15	M	5	MS	30.9	69.9	9	-
AL BW-183	14	217.5	62.1	20.6	15	MSS	20	MSS	26.7	79.5	9.4	-
AL BW-184	9	161.5	46.1	17.6	10	M	20	M	32.2	86.7	8.5	-
AL BW-185	12	180.5	51.6	17.6	20	MSS	10	MSS	30.5	85.2	9.8	-
AL BW-186	7.5	105.5	30.1	11.8	15	MSS	5	M	32.7	74.8	9.6	-
AL BW-187	16	246.5	70.4	23.5	20	MSS	20	MSS	41.4	86.3	9.3	-
AL BW-188	16	219	62.6	23.5	20	MSS	20	MSS	32.5	77.5	8.9	-
AL BW-189	24	331.5	94.7	35.3	30	MSS	30	MSS	31.3	71.5	9	-
AL BW-190	16	227.5	65	23.5	20	MSS	20	MSS	26.2	79.7	10.8	-
AL BW-191	35	455	130	47.1	30	S	50	MSS	25	79	10.2	-
AL BW-192	37.5	511.5	146.1	50	35	S	50	MSS	26.9	72.9	8.4	-
AL BW-193	7	133	38	11.8	10	MS	10	M	34.4	79	8.4	-
AL BW-194	5	95.5	27.3	8.8	5	MS	10	M	34.6	75.2	8.6	-
AL BW-195	8	114	32.6	11.8	10	MSS	10	MSS	34.8	78	8.4	-
AL BW-196	24	367.5	105	35.3	10	MS	50	MSS	27.1	81.2	9.2	-
AL BW-197	5.5	104	29.7	8.8	5	M	10	MSS	31.9	78.9	9.3	-
AL BW-198	11	134	38.3	17.6	10	M	20	MSS	28.8	72.5	8.5	-
AL BW-199	11	125.5	35.9	17.6	10	M	20	MSS	29.1	87.8	8	-
AL BW-200	14	164	46.9	23.5	20	M	20	MSS	32.2	71.7	7.4	-
AL BW-201	16.5	229	65.4	26.5	15	M	30	MSS	36.2	77.4	7.7	-
AL BW-202	12.5	209	59.7	20.6	15	15M	20	MSS	34.4	77.5	9.9	-
AL BW-203	5	114	32.6	11.8	10	M	10	MR	30.9	80	10.2	+
AL BW-204	4.5	76.5	21.9	8.8	15	M	0	TR	40	76.7	8.4	-
AL BW-205	11	153	43.7	17.6	10	M	20	MSS	32.6	75	8.4	-
AL BW-206	17	265	75.7	26.5	5	MR	40	MSS	36.8	73.8	7.3	-
AL BW-207	14	245	70	23.5	20	M	20	MSS	32.7	67.5	8.3	-
AL BW-208	8	122.5	35	11.8	10	MSS	10	MSS	33.8	68.2	9	-
AL BW-209	9	151.5	43.3	14.7	15	MSS	10	M	33	74	8.3	-
AL BW-210	7	114	32.6	11.8	15	MSS	5	MR	35.7	65	8.4	-
AL BW-211	10	160	45.7	14.7	15	MSS	10	MSS	31.7	78.2	10.2	-
AL BW-212	16	161.5	46.1	23.5	20	MSS	20	MSS	32.9	72.4	9.7	-

Genotype	ACI	AUDPC	rAUDPC	rFRS	Stem rust season 1		Stem rust season 2		TKW (g)	PH (cm)	SL (cm)	PBC
					Severity	FR	Severity	FR				
AL BW-213	20	285	81.4	29.4	20	MSS	30	MSS	33.7	76.3	9.3	-
AL BW-214	28	389	111.1	41.2	30	MSS	40	MSS	35.8	77.2	8.8	-
AL BW-215	32	329	94	47.1	30	MSS	50	MSS	27.3	75.9	8.6	-
AL BW-216	26	452.5	129.3	41.2	20	M	50	MSS	29.5	77.2	8.1	-
AL BW-217	12	209	59.7	23.5	20	M	20	M	32.6	73.9	8.1	+
AL BW-218	4	131.5	37.6	8.8	10	M	5	MR	37.5	76.5	7.2	+
AL BW-219	6.5	143	40.9	14.7	15	M	10	MSS	40.2	80.9	9.7	+
AL BW-220	6	114	32.6	11.8	10	M	10	M	37.7	83.5	9.4	-
AL BW-221	4.5	104	29.7	8.8	5	M	10	M	36.2	74.2	9	-
AL BW-222	3.5	76.5	21.9	8.8	5	M	10	MR	35.9	74.2	8.2	+
AL BW-223	6.5	143	40.9	14.7	15	M	10	MR	29.8	78	8.6	+
AL BW-224	12	180.5	51.6	17.6	15	MS	15	MSS	36.5	70	8.7	-
AL BW-225	14	209	59.7	20.6	15	MSS	20	MSS	30.6	67.7	8.2	-
AL BW-226	18	246.5	70.4	26.5	15	MSS	30	MSS	26.6	76	8.8	-
AL BW-227	16	190	54.3	23.5	20	MS	20	MSS	26.5	78.5	10.3	-
AL BW-228	15	220.5	63	23.5	10	M	30	MSS	34.5	74.4	10	-
AL BW-229	20	275.5	78.7	29.4	20	MSS	30	MSS	24.9	80	8.9	-
AL BW-230	7.5	95	27.1	11.8	5	M	15	MSS	40.9	79.7	8.1	-
AL BW-231	21	246.5	70.4	26.5	30	S	15	MSS	35.3	80.2	8.1	-
AL BW-232	14	209	59.7	20.6	5	MSS	30	MSS	28.3	84	8.7	-
AL BW-233	16	191.5	54.7	23.5	10	MSS	30	MSS	34.1	78.2	10	-
AL BW-234	6	133	38	11.8	10	M	10	M	33.6	81.7	9.2	-
AL BW-235	3	20	5.7	5.9	5	M	5	M	33.7	80.8	8.3	-
AL BW-236	2.5	66.5	19	5.9	5	M	5	MR	30.2	75.5	7.3	+
AL BW-237	2.5	66.5	19	5.9	5	M	5	MR	32.6	78	8.3	+
AL BW-238	12	170	48.6	17.6	20	MSS	10	MS	34	81.4	8	-
AL BW-239	16	246.5	70.4	23.5	20	MSS	20	MSS	38.7	76.2	10.4	-
AL BW-240	15	237.5	67.9	23.5	10	M	30	MSS	32.2	74	9.8	-
AL BW-241	6	133	38	11.8	10	M	10	M	38	73.7	8.1	-
AL BW-242	5.5	85	24.3	8.8	10	MSS	5	M	40.8	74.7	8.9	-
AL BW-243	5	85	24.3	8.8	10	M	5	MS	32.1	76.2	8.6	-
AL BW-244	10	151.5	43.3	14.7	15	MSS	10	MSS	29.1	77.8	9.4	-
AL BW-245	16	246.5	70.4	23.5	20	MSS	20	MSS	30.4	68	9.7	-
AL BW-246	4.5	104	29.7	8.8	5	M	10	M	30.9	78.9	9.2	-
AL BW-247	8	114	32.6	11.8	10	MSS	10	MS	33.7	71.2	9.7	-
AL BW-248	6	85	24.3	8.8	10	MSS	5	MSS	31.2	79.4	12.1	-
AL BW-249	2.5	66.5	19	5.9	5	M	5	MR	30.4	77.7	8.4	+
AL BW-250	5	95.5	27.3	8.8	10	M	5	MS	33.2	72.5	8.8	-
EPC BW-251	4	68	19.4	8.8	10	M	5	MR	33.5	70.3	8.4	+
EPC BW-252	11	180	51.4	17.6	10	M	20	MSS	25.9	77.9	10.1	-
EPC BW-253	15	274	78.3	23.5	10	M	30	MSS	29.6	77.9	9.8	-
EPC BW-254	13.5	162.5	46.4	20.6	5	M	30	MSS	26.6	79.3	9.7	-
EPC BW-255	15	191.5	54.7	23.5	10	M	30	MSS	26.7	78.2	9.7	-
EPC BW-256	12	285	81.4	29.4	10	M	40	M	30	76.4	10.3	+
EPC BW-257	8	141.5	40.4	11.8	10	MSS	10	MS	25.8	70.8	8.7	-
EPC BW-258	4.5	104	29.7	8.8	10	M	5	M	25.4	77.9	9.2	+
EPC BW-259	6	141.5	40.4	11.8	10	M	10	M	26	79.7	10.6	+
EPC BW-260	10	151.5	43.3	14.7	20	MSS	5	MS	33	72.9	8.4	-
EPC BW-261	8	114	32.6	11.8	20	MSS	0	TR	30.1	83.5	9.5	-
EPC BW-262	4	76.5	21.9	8.8	10	M	5	MR	37.4	69.5	10.5	+

Genotype	ACI	AUDPC	rAUDPC	rFRS	Stem rust season 1		Stem rust season 2		TKW (g)	PH (cm)	SL (cm)	PBC
					Severity	FR	Severity	FR				
EPC BW-263	4	76.5	21.9	8.8	10	M	5	MR	33.4	75.5	7.9	+
EPC BW-264	18	284	81.1	26.5	15	MSS	30	MSS	25.9	80.3	8.4	-
EPC BW-265	18	246.5	70.4	26.5	25	MSS	20	MSS	29.5	83.8	10.7	-
EPC BW-266	5.5	85	24.3	8.8	5	M	10	MSS	33.8	71.7	9.2	-
EPC BW-267	28	425	121.4	41.2	20	MSS	50	MSS	25	73.4	8.3	-
EPC BW-268	22	312.5	89.3	32.4	15	MSS	40	MSS	28.3	74.8	9.7	-
EPC BW-269	18	246.5	70.4	26.5	15	MSS	30	MSS	32.9	79.2	9.2	-
EPC BW-270	12	254	72.6	17.6	20	MSS	10	MSS	38.1	74.4	7.7	-
EPC BW-271	12	216.5	61.9	17.6	20	S	10	MR	32.3	75	8.8	-
EPC BW-272	12	189	54	17.6	20	MSS	10	MSS	32.2	78.7	8.3	-
EPC BW-273	6	122.5	35	11.8	10	MSS	10	MR	31.5	82	8.5	-
EPC BW-274	9.5	151.5	43.3	14.7	20	MSS	5	M	28.5	76.7	9.8	-
EPC BW-275	5.5	141.5	40.4	11.8	15	MSS	5	MR	35	69.7	8.7	+
EPC BW-276	9	170	48.6	14.7	20	MSS	5	MR	37.2	84.9	7.9	-
EPC BW-277	10	160	45.7	14.7	20	MSS	5	MS	34.6	77.9	8	-
EPC BW-278	5	104	29.7	8.8	10	M	5	MS	33	69.3	9.3	-
EPC BW-279	4	47.5	13.6	5.9	5	MSS	5	MSS	25.9	80.7	9.9	-
EPC BW-280	4	66.5	19	5.9	5	MSS	5	MSS	27	73.9	10.3	-
EPC BW-281	15	219	62.6	23.5	10	M	30	MSS	27.9	71.9	9.1	-
EPC BW-282	26	416.5	119	38.2	25	MSS	40	MSS	25.7	73	8.5	-
EPC BW-283	5	85	24.3	8.8	10	M	5	MSS	32.7	82.4	9.2	-
EPC BW-284	12.5	217.5	62.1	20.6	15	M	20	MSS	28	72.3	10.2	-
EPC BW-285	8	133	38	11.8	15	MSS	5	MS	32.5	77.7	10	-
EPC BW-286	14	217.5	62.1	20.6	15	MSS	20	MS	31.8	80.4	10.7	-
EPC BW-287	8	160	45.7	14.7	20	M	5	MS	41.6	79.8	8.8	-
EPC BW-288	8.5	151.5	43.3	14.7	15	M	10	MSS	32.2	82.4	9.2	-
EPC BW-289	20	375	107.1	29.4	20	MSS	30	MSS	29	74.2	7.8	-
EPC BW-290	15	227.5	65	23.5	10	M	30	MSS	32.1	80.2	8.2	-
EPC BW-291	12.5	190	54.3	20.6	15	M	20	MSS	28.8	71.8	8.8	-
EPC BW-292	12	216.5	61.9	17.6	20	MSS	10	MS	27.8	63.8	8	-
EPC BW-293	10.5	161.5	46.1	17.6	15	M	15	MSS	29.8	72.5	8.6	-
EPC BW-294	9	151.5	43.3	14.7	15	MSS	10	M	28.9	77.4	9.7	-
EPC BW-295	6	122.5	35	11.8	20	M	0	TR	30.5	73.4	9.4	-
EPC BW-296	8	133	38	11.8	15	MSS	5	MS	31.4	80.2	8	-
EPC BW-297	10	124	35.4	14.7	20	MSS	5	MS	31.3	74.7	9.9	-
PCHP BW-298	12	180.5	51.6	17.6	20	MSS	10	MSS	35.8	79.5	10.1	-
PCHP BW-299	18	284	81.1	26.5	25	MSS	20	MSS	31.3	77.5	8.2	-
PCHP BW-300	18	238	68	26.5	15	MSS	30	MSS	36.4	68.4	7.9	-
PCHP BW-301	14	217.5	62.1	20.6	15	MSS	20	MSS	35.7	71.9	7.8	-
PCHP BW-302	7	141.5	40.4	11.8	10	M	10	MSS	31.8	79.4	9.2	-
PCHP BW-303	16	246.5	70.4	23.5	20	MSS	20	MSS	32.3	72.7	9.3	-
PCHP BW-304	20	312.5	89.3	29.4	20	MSS	30	MSS	30.7	83.9	11	-
PCHP BW-305	14	209	59.7	20.6	15	MSS	20	MSS	34.2	74.4	10.4	-
PCHP BW-306	7	141.5	40.4	11.8	10	M	10	MS	34.6	77.4	8.9	-
PCHP BW-307	8.5	151.5	43.3	14.7	15	M	10	MSS	38.3	69.2	8.5	-
PCHP BW-308	6	133	38	11.8	10	M	10	M	32.7	74.2	8.7	+
PCHP BW-309	4	39	11.1	5.9	10	MSS	0	TR	29.3	74.7	9.6	-
PCHP BW-310	8	114	32.6	11.8	20	MSS	0	TR	32.3	71	8.2	-
PCHP BW-311	10	151.5	43.3	14.7	20	MSS	5	MS	36.5	77.2	7.4	-
PCHP BW-312	12	197.5	56.4	17.6	20	MSS	10	MSS	40.6	62.5	8.6	-

Genotype	ACI	AUDPC	rAUDPC	rFRS	Stem rust season 1		Stem rust season 2		TKW (g)	PH (cm)	SL (cm)	PBC
					Severity	FR	Severity	FR				
PCHP BW-313	10	151.5	43.3	14.7	15	MSS	10	MS	40.9	81	9.4	-
PCHP BW-314	12	197.5	56.4	17.6	20	MSS	10	MS	34.9	78.5	10.1	-
PCHP BW-315	9	179	51.1	17.6	20	M	10	M	34	78	8.7	+
PCHP BW-316	18	238	68	26.5	25	MSS	20	MSS	36.4	67.5	9.1	-
CACUKE	56	350	100	100	90	MSS	100	MSS	20.2	60.7	9.5	-
Grand Mean	12.3	187	26.7	22.9	15.7		20		32.5	76.8	8.8	
LSD	10.7	139.8	19.97	17.15	12		16		7.7	8.2	1.4	
CV (%)	8.8	5.6	5.6	5.7	5.7		7.2		16.2	7.5	10.4	

Note. ACI = average coefficient of infection; AUDPC = area under the disease progress curve; rAUDPC = relative area under the disease progress curve; rFRS = relative final rust severity; Disease Severity based on Modified Cobb's (0-100%) scale (Peterson et al., 1948); IT = Infection Type based on (Roelfs et al., 1992); TR = trace , R = resistant, MR = moderately resistant, RMR = resistant to moderately resistant, MRMS (M) = moderately resistant to moderately susceptible, MSS = moderately susceptible to susceptible, MS = moderately susceptible and S = susceptible; TKW = thousand kernel weight in grams; PH = Plant Height in centimeters; SL = Spike length in centimeters TKW = thousand kernel weight; PBC = Pseudo Black Chaff, (+) predictive of Sr2 gene, (-) absence of Sr 2 gene; LSD = Least Significant Difference CV (%) = Percentage Coefficient of Variation.

Table 3. Pearson's correlation coefficient for the disease parameters among the wheat genotypes across seasons

	ACI	AUDPC	rAUDPC	rFRS
ACI	-			
AUDPC	0.9242***	-		
rAUDPC	0.9242***	1.0000***	-	
rFRS	0.9745***	0.8982***	0.8982***	-

Note. ***: large positive relationship between the variables at $p \leq 0.05$; ACI = average coefficient of infection; AUDPC = area under the disease progress curve; rAUDPC = relative area under the disease progress curve; rFRS = relative final rust severity.

Table 4. Pearson's correlation coefficient for the different agronomic traits among the wheat genotypes across seasons

	Number of tillers	Plant height	Spikelet length	Thousand kernel weight	Stem rust
Number of tillers	-				
Plant height	0.0475	-			
Spikelet length	-0.0924	0.1472	-		
Thousand kernel weight	0.0848	0.0269	-0.2167	-	
Stem rust severity	0.0559	-0.0475	-0.0253	-0.3401	-

4. Discussion

Seasonal effects of temperature and precipitation on disease development were discernible. In season one when the temperatures were higher and the precipitation was lower, the infection rate was apparently lower. Abiotic stresses such embodied in high temperatures and drought in general induce the plant defense pathway leading to increased plant resistance to stem rust (Mittler, 2006). During the second season in which relatively lower temperatures and high precipitation were recorded, higher disease pressure was noted. Besides supporting vigorous plant growth, providing increased surface area for spore landing and infection, lower temperatures and "free water" through precipitation favors rust infection process per se. Similar findings have been extensively reported in rust epidemiology literature *e.g.* as highlighted in GRDC (2011). The present results underscores that KALRO-Njoro sits in an environment conducive to stem rust proliferation. In the larger East African region stem rust epidemics are driven by a combination of factors including favorable weather conditions for the disease, volunteer host plants, and presence of a green crop of wheat at any one time, also referred to as a "green bridge" that enhance survival build-up and spread of the stem rust pathogen through the seasons. In combination with growing of stem rust susceptible varieties especially among the small scale resource poor farmers, these factors have aggravated the Ug99 threat in the region leading to seasonal stem rust outbreaks (GRDC, 2011).

Different reactions to stem rust observed between the genotypes suggested that the material had diverse genetic backgrounds. It can be inferred that the six genotypes namely ALBW-106, ALBW-204, EPCBW-261, EPCBW-295, PCHPBW-309 and PCHPBW-310 that only showed trace response to the diseases (TR) with no visible stem rust infections could either be carrying single effective major genes or a combination of those. Singh et al. (2005) reported that a combination of 4-5 minor effect genes with race non-specific responses provided near immunity reaction to leaf rust. Accordingly, the 6 highly resistant lines could also be harboring a combination of minor effect genes. Leonard and Szabo (2005) suggested that the presence of effective major genes in a variety limit infection process by triggering necrosis of the host cells in the neighborhood of the infective structures.

Among the 250 ALBW accessions, 22 and 26 genotypes were susceptible during season one and two respectively, while 135 genotypes showed moderately susceptible (MS) response. Their severities however were low, compared to the susceptible check variety CACUKE whose final severity was 90 S and 100 S during season one and two respectively. The ALBW are among old varieties bred between the 70s and the 80s by CIMMYT Mexico (Kohli & Rajaram, 1988). The high frequency of MS to S genotypes among the ALBW genotypes suggested presence of ineffective stem rust resistance genes in their backgrounds, probably *SrTmp*, *Sr24*, *Sr31*, to which the current family of Ug99 races are highly virulent. Results on previous rust resistance studies on genotypes within the ALBW set are consistent with the present study. For instance, Chaves et al. (2011) reported high frequency of moderately susceptible to susceptible infection types within Brazilian genotypes with aluminium tolerance backgrounds. Notably, 19 genotypes among the ALBW set showed resistant to moderately resistant (RMR) infection types. Among those, 6 genotypes (ALBW-4, ALBW-100, ALBW-106, ALBW-173, ALBW-174 and ALBW-204) showed resistant (R) infection type with no visible or compatible interaction between the host genotypes and the stem rust fungus despite the heavy disease pressure in season two. This suggests that these lines could be carrying stem rust resistance genes which are still effective against the Ug99 and its variants.

Among the 47 EPCBW genotypes, nearly half showed intermediate infection type (M), and relatively low severities ranging from 5% to 20% during both seasons implying that these genotypes could be containing effective stem rust resistance genes in their backgrounds. Despite, some level of disease, which in fact suggests incomplete resistance, these lines produced plump grain with no apparent stem rust associated yield loss.

While over 70% of the 19 PCHPBW genotypes evaluated during both seasons, showed MSS infection types, those nonetheless depicted lower severities. Moreover, those genotypes expressed the pseudo black chaff phenotype, implying the presence of the adult plant resistance gene-*Sr2*. These lines could serve as useful genetic resources in breeding for durable resistance to the prevailing stem rust races, especially when combined with effective major genes. Such a strategy will not only counteract the wheat yield losses currently common in many wheat growing zones of Kenya but equally important, it will counter the rapid evolution of new stem rust races due to delayed step-wise mutations triggered by over cultivation of single resistance varieties over extensive acreages and across seasons (Tsilo et al., 2010).

Across the two seasons of evaluation, 14 genotypes exhibiting dwarfing traits also had relatively high TKW values. The TKW is considered a “yield component” and a good proxy for yield potential of a genotype (Dill-Macky et al., 1990). The semi-dwarf stature of these genotypes suggested presence of dwarfing genes (*Rht*), which reduce height. Semi dwarf genotypes unlike the traditionally taller varieties are tolerant to lodging, and hence are more responsive to high nitrogen-fertilization and irrigated cropping systems especially under intensive management. Development of semi-dwarf types of wheats was initiated at CIMMYT by Norman Borlaug in the early 1960s through crosses made between the double-dwarf Japanese cultivar Norin and taller breeding lines (Gale et al., 1981; Kihara, 1984). A report by Sayre et al. (1997) indicated that there has been an annual increase in yield by 1% among semi-dwarf wheat varieties due to incorporation of dwarfing genes in their backgrounds.

The large negative correlation between TKW and stem rust can be attributed to the fact that the fungus damages the vascular system of the susceptible host plant extensively limiting transportation of water and nutrients from the soil to the developing kernel and other organs as well as interfering with translocation of photosynthates, which leads to shrivelled grains (Singh et al., 2006; Everts et al., 2001). Similar results have been reported by numerous previous research groups (Tadesse et al., 2010; Taye et al., 2015). Among the highly susceptible varieties, the endosperm barely forms and resultant grains are invariably completely shrivelled.

5. Conclusion

The six exotic wheat genotypes with high resistance to stem rust could be used as donors for introgression of resistance to the adapted Kenyan wheat backgrounds. This will also help improve Kenyan germplasm with regard to aluminum tolerance and micronutrient fortification (Velu & Singh, 2013). The 35 genotypes with low MSS response and which also showed presence of PBC could be integrated in the Durable Rust Resistance Wheat (DRRW) pipeline to develop durable sources of resistance to stem rust. Further greenhouse studies involving seedlings coupled with marker assisted selection needs be carried out to identify the exact genes conferring the resistance to stem rust among the exotic varieties. Inheritance studies could also be done among the elite wheat genotypes to elucidate the exact genes and their effects especially in conditioning the stem rust resistance. This will ensure the effective utilization of the resistance sources in the wheat breeding program through their deployment into adapted but susceptible wheat varieties.

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