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Phenotyping selected Australian wheat genotypes for resistance to stem rust and yellow rust and yield performance in Kenya

Cyril Wasike[1]*, Pascal P. Okwiri. Ojwang[1], Michael A. Okiror[2], Godwin K. Macharia[3] and Mandeep S. Randhawa[4]

[1]Department of Crops, Horticulture and Soils, Faculty of Agriculture, Egerton University, P. O. Box 536-20115, Egerton, Kenya.
[2]Department of Biological Sciences, Faculty of Science, Egerton University, P. O. Box 536-20115, Egerton, Kenya.
[3]Kenya Agricultural and Livestock Research Organization (KALRO), Food Crops Research Institute (FCRI), P. O. Box Private Bag-20107, Njoro, Kenya.
[4]International Maize and Wheat Improvement Center (CIMMYT), World Agroforestry Center (ICRAF Campus), United Nations Avenue, P. O. Box 1041-00621, Gigiri, Nairobi, Kenya.

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Stem rust and yellow rust are major diseases of wheat (*Triticum aestivum* L.) caused by *Puccinia graminis* and *Puccinia striiformis*, respectively. In Kenya, although the two diseases occur together, available genetic resistance is limited. Therefore, research for resistance to both diseases is of priority. We therefore evaluated 59 Australian wheat genotypes alongside local checks over three seasons in Njoro, Kenya, for resistance to stem rust, yellow rust and yield performance and one season in Debre Zeit, Ethiopia, for resistance to stem rust in a partially balanced *lattice*-square design with three replicates. Resistance to stem rust isolates *TTKSK* and *TTKTT* was evaluated in the greenhouse. Effect due to genotype, season and genotype-by-season interaction was significant ($p \leq 0.05$) for area under disease progress curve (AUDPC), coefficient of infection (CI), final disease severity (FDS), grain yield (GY), 1000-kernel weight and test weight (TW). AUDPC, CI and FDS were negatively correlated with GY and TW. Broad-sense heritability (H^2) for AUDPC, CI and FDS was 70.2, 60.0 and 68.1% for stem rust and 55.8, 50.0 and 59.7% for yellow rust, respectively. Genotypes Lancer, Sunguard and Gauntlet exhibited stable resistance to stem rust in Njoro and Debre-Zeit while genotypes Sunmax, Steel and Gladius showed stable resistance to yellow rust in Njoro. Genotypes Lancer, Sunguard, Gauntlet, Sunmax, Steel, Gladius, Shield and Magenta, having adult plant resistance to stem rust and yellow rust and seedling resistance to stem rust with superior yield performance are, therefore, recommended as sources of resistance genes and candidates for deployment as varieties.

Key words: adult plant resistance, genotype-by-season interaction, grain yield, seedling resistance.

INTRODUCTION

Common wheat (*Triticum aestivum* L.) is an important cereal crop for food and livelihood (Balk et al., 2019). In sub-Saharan Africa (SSA), its demand continues to increase due to population growth, urbanization and changes in food preference (Shiferaw et al., 2013). However, current levels of wheat production in SSA only serve about 28% of regional requirements while 72% of the demand is met through imports (USDA-FAS, 2021). In 2019, for instance, of the 765.7 million tonnes (t) produced worldwide, SSA contributed a paltry 9.3 million t yet consumption was nearly 33.8 million t (USDA-FAS, 2021). To offset this deficit, a 30% growth in grain yield needs to be realized through annual increases of at least 2% (Ray et al., 2013). However, current levels of genetic gain are insufficient to meet the rising demand (Tadesse et al., 2019).

Wheat production is affected by biotic and abiotic factors (Leonard and Szabo, 2005; Park, 2016; Soko et al., 2018). Among biotic factors, three rust diseases namely: stem rust (caused by fungus *Puccinia graminis* f. sp. *tritici*), yellow rust (*P. striiformis* f. sp. *tritici*) and leaf rust (*P. triticina*) are considered as the most significant foliar diseases of wheat (Olivera et al., 2019; Chen, 2020). They cause shrivelling of kernels and reduce the number of kernels per spike (Dean et al., 2012; Szabo et al., 2014; Soko et al., 2018; Brinton and Uauy, 2019). The evolution of the pathogen and emergence of new races of aggressive nature has resulted in the loss of resistance among a majority of deployed cultivars (Cuomo et al., 2017; Olivera et al., 2019). Therefore, continuous identification, characterization and deployment of genetically diverse sources of resistance in wheat cultivars is essential to achieve durable resistance (Wessels et al., 2019).

Genetic variation is essential for breeding wheat for improved traits and adaptability through classical as well as modern genotyping technologies (Jovovic et al., 2020). Molecular mapping studies have identified quantitative trait loci (QTLs) in diverse germplasm for resistance to rust diseases (Randhawa et al., 2018; Rahmatov et al., 2019). Genetic loci linked to resistance and yield performance have also been identified via marker-trait associations using mapping populations derived from bi-parental crosses and diversity panels using genome-wide association studies (Lopes et al., 2015). A few of these known QTLs have been introgressed into adapted genetic backgrounds through marker assisted backcrossing resulting in cultivars which are adapted to target environments, thus, increasing production from one to three t ha^{-1} (Fedoroff, 2015). Genes for resistance to rust diseases are classified as race specific (seedling resistance) and race non-specific (adult plant resistance). To date, more than 70 genes each for stem rust (Sr) and yellow rust (Yr) have been characterized and formally catalogued in wheat (McIntosh et al., 2017). However, most of these genes are race specific and are often overcome by new races, which harbor virulence, when they are deployed singly (Pretorius et al., 2012; Singh et al., 2015). On the other hand, race non-specific resistance genes reduce the possibility of virulent races emerging (Figueroa et al., 2020). Durable resistance, however, is attained when both classes of genes are combined (Randhawa et al., 2018). In Kenya, the wheat breeding program based at the Kenya Agricultural and Livestock Research Organization (KALRO) in Njoro works in collaboration with the International Maize and Wheat Improvement Center (CIMMYT). This collaboration has resulted in deployment of resistant cultivars with high yield performance (Njau et al., 2013; Macharia and Ngina, 2017; Bhavani et al., 2019). However, evolution of virulence necessitates continuous research for resistance from diverse sources. For instance, stem rust resistance gene *SrTmp* in Kenya Robin which was released in 2011 was broken down by races *TTKTT*, *TKTTF* and *TTKTK* in 2014 (Olivera et al., 2015; Newcomb et al., 2016; Patpour et al., 2016). Consequently, identification of new sources of resistance is a sustainable strategy that potentially confers durable resistance through strategic introgression of resistance genes into adapted cultivars. The objective of our study was therefore to characterize genotypes with resistance to stem rust and yellow rust with acceptable yield performance among wheat genotypes introduced from Australia.

MATERIALS AND METHODS

Experimental sites

The study was performed in 2019 off-season (NJ1), 2019 main-season (NJ2) and 2020 off-season (NJ3) at KALRO, Njoro, Kenya (35° 55′ 60″ E, 0° 19′ 60″ S) and in 2019 main-season (DZ) at Debre Zeit Agricultural Research Center (DZARC), Debre Zeit, Ethiopia (38° 59′ 19″ E, 8° 44′ 38″ N). Njoro is located at an elevation of ~ 2185 metres above sea level (masl) and lies within the Lower Highland III (LH$_3$) Agro-Ecological Zone (AEZ) (Jaetzold et al., 2010). Soils are predominantly well drained volcanic *mollic andosols* which are dark brown to greyish with a thick humic top soil and an average *pH* of 7.0 (Jaetzold and Schmidt, 1983). It receives annual precipitation of approximately 980 mm with average minimum and maximum temperatures of 9.7 °C and 25 °C, respectively. On the other hand, Debre Zeit is located at an elevation of ~ 1900 masl and receives annual precipitation of approximately 851 mm. Average minimum and maximum temperatures are 8.9 °C and 28.3 °C, respectively, while soils are predominantly *vertisols* with an average *pH* of 7.5. These climatic conditions were favorable for cultivation of wheat and occurrence of rust diseases.

Genetic materials

Fifty-nine wheat genotypes introduced from Australia were used in

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*Corresponding author. E-mail: wasikecyril@gmail.com.

this study. They were released cultivars in Australia. Wheat line “Cacuke” and Kenyan cultivar “Kenya Robin” were used as susceptible controls. Cultivar name and pedigree are listed in supplementary Tables 1 to 7

Greenhouse experiment

Five seeds of wheat line “Cacuke” and cultivar “Kenya Robin” were sown in separate plastic pots measuring 6 cm (length) × 6 cm (width) × 6 cm (height) filled with vermiculite mixed with diammonium phosphate (DAP) fertilizer (18:46:0). Pots were labelled and placed in the growth chamber and watered over trays. Seedlings were inoculated at the two-leaf stage with fresh urediniospores collected from corresponding genotypes in the disease nursery following standard procedures (Jin et al., 2007). Urediniospores were suspended in 250 ml of distilled water and two drops of a light mineral oil Soltrol® 130 Isoparaffin (Chevron Phillips Chemical, TX) added and shaken gently before sieving to drain the inoculum in a dispenser (Jin et al., 2007). Seedlings were inoculated by spraying the spore suspension followed by misting using water. Inoculated seedlings were then air-dried for 10-20 minutes and placed in polythene hoods inside a dew cabinet (Percival model I-36, Perry, IA) for incubation at temperatures and relative humidity of 18-20 ºC and ~100%, respectively, in the dark for 48 hours. These conditions were maintained during the day using a humidifier and misting the dew cabinet 3-4 times a day with distilled water using a hand sprayer. After the dew process, fluorescent lights were turned on to provide light to complete the infection process and temperatures raised gradually to 25 ºC for 3 hours. Thereafter, seedlings were transferred to a temperature and water-controlled growth and sporulation chamber at 18-25 ºC under natural light with additional light provided by fluorescent tubes placed at ~1 m above the seedlings and closely monitored for symptoms of disease development.

Fourteen days after inoculation, one fresh and distinct stem rust pustule (large/unique) was collected from an infected stem or leaf from each pot. A sharp razor blade was used to cut out tissues around the pustule. Pustules were carefully placed in a pre-labelled gelatin capsules and sealed. Alcohol-soaked (70%) wipes were used to sterilize the razor blade between collections. The single pustules were washed off in distilled water to prepare inoculum of pure isolates. To bulk the pure isolates, five sets of the two genotypes were planted, inoculated and incubated as early described and bulk inoculum of pure isolates collected separately from each genotype.

Fifty-nine Australian bread wheat introductions and two susceptible controls (Cacuke and Kenya Robin) were evaluated against stem rust isolates *TTKSK* (detected in Kenya in 2001 and virulent on *Sr31*) [purified on Cacuke] and *TTKTT* (detected in Kenya in 2014 and virulent on *SrTmp*) [purified on Kenya Robin] to characterize infection types (ITs) and virulence patterns. Two sets of the experimental materials were planted in the greenhouse as earlier described. At the two-leaf stage, each set of materials was inoculated and incubated separately and monitored for symptoms of disease development. Tests were repeated to clarify ambiguous results.

Field experiment

Five grams of seeds of each genotype were seeded in a 0.7 m double row plot. DAP fertilizer was applied at planting at the rate of 150 kg ha^{-1}. Urea [$CO(NH_2)_2$] (46:0:0) was applied to 1-month old seedlings as top dressing at the rate of 100 kg ha^{-1}. Pre and post emergence herbicides were used to control weeds and a pesticide was used to control insect pests. At booting stage, spreader rows were inoculated with fresh inoculum collected from disease nurseries via needle-injection and foliar spray as described by Njau et al. (2013). Inoculation was repeated after 7 days until the disease had fully developed.

Data collection

Infection types (ITs) in the greenhouse were scored according to Stakman et al. (1962) as 0 (immune), ; (very resistant), 1 (resistant), 2 (moderately resistant), X (mesothetic or heterogenous), 3 (moderately susceptible) and 4 (susceptible). All ITs on stems and leaves were recorded in the order of their prevalence with the most frequent IT recorded first. A comma (,) was used to segregate more than one IT. A forward slash (/) differentiated symptoms on the first and second stem or leaf with letters “n” and “c” indicating more than usual necrosis and chlorosis, respectively. In addition, plus (+) and minus (-) signs described pustules which were relatively larger or smaller, respectively, than is normal. Infection type (IT) 0; was between immune and very resistant. IT 1 was differentiated further into 1-, 1, 1+ while IT 2 was differentiated further into 2-, 2 and 2+. Host responses (HRs) and severity of infection in the field were visually evaluated and first scores taken when spreader rows displayed a severity of ~ 50% as per the modified Cobb scale (Peterson et al., 1948). Three more scores were taken at an interval of seven days. HRs were assessed as immune (I), traces (TR), resistant (R), resistant to moderately resistant (RMR), moderately resistant (MR), moderately resistant to moderately susceptible (MRMS), moderately susceptible (MS), moderately susceptible to susceptible (MSS) and susceptible (S) (Roelfs et al., 1992). Severity was estimated on a scale of 1-100%, where 1% = very low severity and 100% = very high severity (Peterson et al., 1948). The AUDPC was calculated following Wilcoxson et al. (1975) as shown (eq. 1) and AUDPC values of 0-150, 151-300, 301-500 and > 500 represented high, moderate, low and very low levels of resistance, respectively (Jeger and Viljanen-Rollinson, 2001).

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

Where, y_i = % disease severity on the i^{th} scoring; t_i = number of days from sowing to i^{th} scoring; n = total number of scores. FDS is the highest disease severity and FDS values of ≤ 30 and > 30 represent high and low levels of resistance, respectively. CI is the product of FDS and constants for HRs (I = 0.0, R = 0.1, RMR = 0.2, MR = 0.3, MRMS = 0.5, MS = 0.7, MSS = 0.9, and S = 1.0) (Knott, 2012) and CI values of 0-20, 21-40, 41-60, and > 60 represent high, moderate, low, and very low levels of resistance, respectively. Days to heading (DH) is the difference between date of sowing and date at which 50% of plant heads are fully out of flag leaf sheaths. Plant height (PH) is the average height of five tillers each from a randomly selected plant as measured from soil surface to the top of the spikes excluding awns. Spike length (SL) is the average length of five spikes each from a randomly selected plant measured from the top of the peduncle to the top of the spike excluding awns. Kernels per spike (K S^{-1}) is the average number of kernels from five spikes each from a randomly selected plant. Biomass (BM) is the weight of plants as weighed on a Mettler PC 4400 DeltaRange® digital balance. Grain yield (GY) is the weight of cleaned kernels after threshing using ALMACO® Model LPTD, S/No.T09235, winnowing on an electronic winnower (S/No. R78443) and standardizing moisture content to 12%. 1000-kernel weight (TKW) is the weight of 1000 cleaned kernels counted by an electronic grain counter (CONTADOR®, S/No. 14176107). Test weight (TW) is the weight of kernels in a container of a standard volume and HI is the ratio of GY to BM.

Statistical analyses

The AUDPC was square root transformed to obtain a normal frequency distribution before analyses. Data were subjected to a restricted maximum likelihood (REML) estimation in GenStat version 16 (Patterson and Thompson, 1971) using the linear mixed model (LMM) below, with effect due to replicates, seasons and genotypes being fixed and effect due to blocks being random.

$$y_{ijkl} = \mu + r_i + G_j + S_k + GS_{jk} + \beta_{l(i)} + \varepsilon_{m(ijkl)}$$

where, y_{ijkl} is the response, μ is the overall mean, r_i is the effect due to the i^{th} replicate, G_j is the effect due to the j^{th} genotype, S_k is the effect due to the k^{th} season, GS_{jk} is the effect due to interaction between the j^{th} genotype and the k^{th} season, $\beta_{l(i)}$ is the effect due to the l^{th} block nested within the i^{th} replicate and $\varepsilon_{m(ijkl)}$ is the random error component.

Correlation measured the relationships among AUDPC, CI, FDS, GY, HI, DH, and TKW while the slope of regression indicated the magnitude of the change in GY, TKW, and TW due to change in FDS. Estimates for genetic correlation were determined by coefficient of variation (CV %) and mean. Variance component estimates for genotype (σ_g^2), genotype-by-season interaction (GSI) (σ_{gs}^2), and residual (σ_e^2) were obtained by fitting the LMM using REML in GenStat with effect due to replicates and seasons being fixed and effect due to genotypes and blocks being random. Phenotypic coefficient of variation (PCV) (eq. 2) and genotypic coefficient of variation (GCV) (eq. 3) were computed according to Ogunniyan and Olokayo (2014) as:

$$\text{PCV} = \frac{\sqrt{\sigma_{ph}^2}}{\bar{x}} \times 100\% \qquad (2)$$

$$\text{GCV} = \frac{\sqrt{\sigma_g^2}}{\bar{x}} \times 100\% \qquad (3)$$

Where, σ_{ph}^2 and σ_g^2 are variance due to phenotype and genotype, respectively, and $\bar{x}$ is the mean. Broad-sense heritability (H^2) (%) was estimated as shown (eq. 4) and H^2 values of > 60%, 30-60%, and 0-30% indicated high, moderate, and low heritability, respectively (Johnson et al., 1955).

$$H^2 = \frac{\sigma_g^2}{\sigma_g^2 + \left(\frac{\sigma_{gs}^2}{s} + \frac{\sigma_e^2}{r}\right)} \qquad (4)$$

where, σ_g^2 is variance due to genotype, σ_{gs}^2 is variance due to GSI, s is the number of seasons, σ_e^2 is variance due to error (residual) and r is the number of replications.

Genotypic stability of AUDPC for stem rust and yellow rust was assessed using cultivar superiority (eq. 5) as described by Lin and Binns (1985). In this method, superiority of a genotype's performance was the distance mean square (MS) from the minimum response in each season and was determined as:

$$P_i = \left[n(\bar{X}_{i.} - \bar{M})^2 + \sum_{j=1}^{n}\left(X_{ij} - \bar{X}_{i.} - M_j + \bar{M}\right)^2\right] / (2n) \qquad 5$$

Where, P_i is the superiority measure of the i^{th} genotype, *n* is the number of seasons, X_{ij} is performance of the i^{th} genotype in the j^{th} season and M_j is the minimum seasonal response.

Superiority represented MS of the effect due to genotype $[n(\bar{X}_{i.} - \bar{M})^2]$, GSI $\left[\sum_{j=1}^{n}\left(X_{ij} - \bar{X}_{i.} - M_j + \bar{M}\right)^2\right]$ and genotypes' general adaptability (Lin and Binns, 1985; Lin and Binns, 1988). Critical values for significance of P_i and GSI were the product of pooled residual MS from REML analyses and tabulated F-values for corresponding degrees of freedom (df), where df for P_i and GSI were n and n-1, respectively (Lin and Binns, 1988).

Finlay and Wilkinson (1963) regression (FW) of AUDPC for stem rust and yellow rust on seasons revealed the trend of genotypes' stability across seasons which was useful in identifying resistance based on responsiveness to seasonal potential (Walsh and Lynch, 2014). FW assessed variation in performance as a function of season by regressing each genotype's performance on seasonal means in a two-step ordinary least squares (OLS) procedure of computing seasonal indices and estimating intercepts and slopes (Lian and de Los Campos, 2016). We used the FW package in R (R Development Core Team, 2020) by installing function 1. Function 1 enabled us to analyse AUDPC data for stem rust and yellow rust in RCBD model below to generate ANOVA of 4 seasons for stem rust and 3 seasons for yellow rust.

$$y_{ijkl} = \mu + S_i + G_j + \beta_{k(i)} + SG_{ij} + \varepsilon_{m(ijkl)}$$

Where, y_{ijkl} is the response, μ is the overall mean, S_i is the effect due to the i^{th} season, G_j is the effect due to the j^{th} genotype, $\beta_{k(i)}$ is the effect due to the k^{th} block nested within the i^{th} season, SG_{ij} is the effect due to interaction between i^{th} season and the j^{th} genotype and $\varepsilon_{m(ijk)}$ is the random error component.

We used function 2 to calculate components of variation and function 3 to generate interaction plots for all genotypes across seasons and those of selected genotype's performance on estimated seasonal indices. Function 4 performed ANOVA for seasons and ranked means using Tukey's HSD test at 5% level of significance. The joint regression analysis obtained sensitivities (stability). To visualise this, we used function 5 to plot genotypes identified for superior performance in resistance to stem rust and yellow rust and plots of genotype's stability for mean AUDPC.

```
Function 1:    library(devtools)
                install_github(“lian0090/FW”)
Function 2:    library(lme4)
                install.packages("lme4")
Function 3:    library(HH)
                install.packages("HH")
Function 4:    library("agricolae")
                install.packages("agricolae")
Function 5:    library(ggplot2)
                install.packages("ggplot2")
```

RESULTS

Variance components

Main effects due to genotype and season were significant ($p \leq 0.001$) for all traits except effect due to season on K S^{-1} (S2). Genotype-by-season interaction (GSI) was significant ($p \leq 0.001$) for AUDPC, CI, FDS, GY, TKW, TW and SL. However, GSI was not significant for DH, HI, BM, PH, and K S^{-1}.

Resistance at seedling stage

A majority of genotypes were susceptible to isolates *TTKSK* and *TTKTT* with the former and the latter being

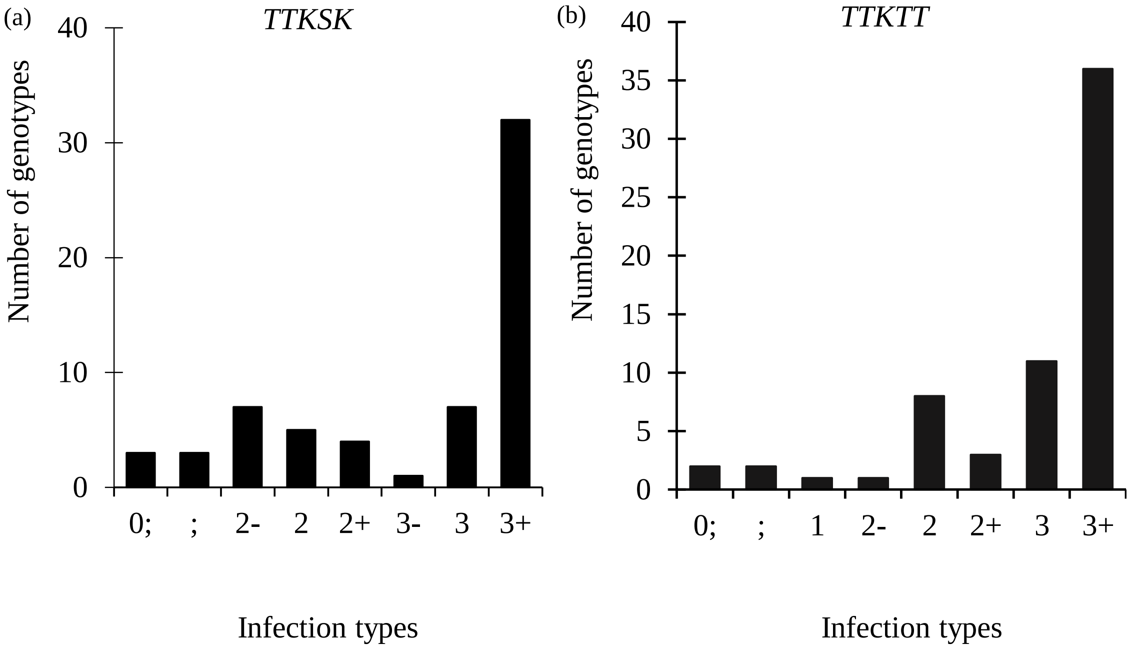

Figure 1. Frequencies of infection types for 61 bread wheat (*Triticum aestivum* L.) genotypes evaluated for seedling resistance to stem rust isolates (a) TTKSK and (b) TTKTT.
Source: Authors

avirulent to seventeen and fourteen genotypes, respectively (Figure 1). Genotypes Lancer, Sunguard, Gauntlet, Scepter, Merlin, Magenta, Spitfire, Coolah, Dart, Janz and Preston exhibited resistance to both isolates (Table 1). However, genotypes Shield, Westonia, Gazelle, Orion, Supreme and Cutlass were resistant to *TTKSK* but susceptible *TTKTT* while genotypes Bolac and Emu Rock were resistant to *TTKTT* but susceptible to *TTKSK*.

Resistance at adult plant stage

For stem rust, AUDPC, CI, and FDS ranged from 13.0-1573.0, 0.1-100.0, and 5.0-100.0 in NJ1, 0.0-1536.0, 0.2-99.1, and 0.0-100.0 in NJ2, 0.0-1776.0, 0.3-80.5, and 1.0-100.0 in NJ3, and 3.0-984.0, 0.2-43.0, and 0.0-80.0 in DZ, respectively (Table 2). For yellow rust, on the other hand, the AUDPC, CI, and FDS values ranged from 0.0-592.0, 0.0-45.5, and 0.0-60.0 in NJ1, 0.0-1029.0, 0.0-76.7, and 0.0-80.0 in NJ2, and 0.0-591.0, 0.1-27.8, and 0.0-50.0 in NJ3, respectively. The trend showed a higher level of stem rust in NJ1 and NJ3 than in NJ2, with the lowest recorded in DZ. However, the level yellow rust in NJ2 was higher than in NJ1 and NJ3. Mean AUDPC was 711.0, 382.0, 421.0 and 401.0, CI was 50.8, 25.9, 16.0 and 14.9, and FDS was 70.0, 41.0, 41.0 and 37.0 for stem rust in NJ1, NJ2, NJ3 and DZ, respectively. On the other hand, mean AUDPC was 95.0, 268.0 and 130.0, CI was 7.2, 18.9 and 5.1 and FDS was 18.0, 29.0 and 17.0 for yellow rust in NJ1, NJ2 and NJ3, respectively. Genotypes Lancer, Sunguard, Gauntlet, Shield and Magenta were identified for low levels of < 300 for AUDPC, ≤ 20 for CI and ≤ 30 for FDS of stem rust in NJ1, NJ2, NJ3 and DZ and yellow rust in NJ1, NJ2 and NJ3 (S3). Resistant genotypes had AUDPC, CI and FDS range of 13.0-194.0, 0.1-7.7 and 5.0-20.0 in NJ1, 0.0-101.0, 0.2-5.5 and 0.0-15.0 in NJ2, 0.0-99.0, 0.9-3.3 and 1.0-10.0 in NJ3, and 3.0-189.0, 0.2-4.4 and 1.0-30.0 in DZ for stem rust, respectively. The range of AUDPC, CI and FDS was 0.0-72.0, 0.2-5.3 and 0.0-10.0 in NJ1, 22.0-241.0, 1.4-18.7 and 5.0-30.0 in NJ2, and 2.0-108.0, 0.1-4.4 and 1.0-10.0 in NJ3 for yellow rust, respectively. In respect to final infection types (FITs), genotypes with a FIT of ≤ MRMS for stem rust were 16 in NJ1, 37 in NJ2, 34 in NJ3 and 23 in DZ with genotypes Lancer, Sunguard, Gauntlet, Magenta, Shield, Merlin, Dart, Spitfire and Beckom displaying a FIT of ≤ MRMS across seasons (S4). Conversely, genotypes with a FIT of ≤ MRMS for yellow rust were 42 genotypes in NJ1, 22 in NJ2 and 47 in NJ3 with genotypes Lancer, Suntop, LRPB Flanker and Gazelle displaying a FIT of ≤ MR across seasons (S5). Genotypes Sunguard, Gauntlet, Shield and Magenta had a FIT of ≤ MRMS for yellow rust.

Yield performance

Mean GY, TKW, TW, HI and BM was higher in NJ1 and NJ3 than in NJ2 while stem rust was higher in NJ1 and

Table 1. Infection types of 61 bread wheat genotypes evaluated for seedling resistance against stem rust isolates TTKSK and TTKTT at KALRO, Njoro.

Genotype	*TTKSK*		*TTKTT*		Genotype	*TTKSK*		*TTKTT*	
	Set 1	**Set 2**	**Set 1**	**Set 2**		**Set 1**	**Set 2**	**Set 1**	**Set 2**
Cacuke	3+	3	3+	3+	Gauntlet	1	1	1+	2-
Kenya Robin	2	2+	3+	3+	Gazelle	2-	2-	3+	3+
Coolah	2-	;	2-	0;	Sunmax	3+	3+	3+	3+
Chara	3+	3+	3+	3+	Janz	2-	2-	2	2
LRPB Flanker	2+	3	3	3	Kiora	3	NG	3	3
LRPB Reliant	3-	3+	3	3	Lancer	0;	0;	0;	0;
Ninja	3+	3+	3+	3+	Livingston	3+	3+	3	3+
Tenfour	3+	3+	NG	3+	Mace	3	3	3	3+
Tungsten	3+	3	3+	3+	Magenta	2-	2-	2-	2
Axe	3+	2	2	3+	Merlin	2+	2	2	2
B53	3-	NG	3+	3	Mitch	3+	3+	3+	3+
Beckom	3+	3+	3+	3+	Orion	2-	2-	3	2+
Bremer	3+	2-	3+	2+	Gladius	3+	3+	3+	3+
Buchanan	3+	3+	3+	3	Preston	2+	2	NG	2+
Calingiri	3+	3	3+	3+	Scepter	2-	NG	2	2-
Cobalt	3+	3+	3+	3+	Scout	3+	3+	3+	3+
Cobra	3+	3+	3+	3+	Shield	1	0;	3	2+
Condo	3+	3+	3+	3+	Spitfire	2	2	2	2
Corack	3	3	3	3	Steel	3+	3+	3+	3+
Correll	3	3	3	3+	Sunguard	0;	NG	0;	0;
Cosmick	3+	3+	3+	3+	Bolac	3-	2	2-	2-
Cutlass	2	2-	3+	3	Suntop	3+	3+	3+	3+
Dart	2	2+	2-	2	Supreme	2-	2-	3	3
Derrimut	3+	3+	3+	3+	Trojan	3	3+	3+	3+
EGA Bounty	3+	3+	3+	3+	Viking	3+	3+	3	3+
EGA Gregory	3	3	3	3	Wallup	NG	3+	3+	3
Baxter	3+	1	3+	3+	Westonia	2-	2-	3-	2
Emu Rock	3+	2+	2	2	Wyalkatchem	NG	NG	3+	3+
Espada	3	2-	3+	3+	Yitpi	NG	NG	1	1
Estoc	3	3+	3+	3+	Zen	NG	3+	3+	3+
Forrest	3+	3+	3+	3+					

NG: Did not germinate.
Source: Authors

NJ3 than NJ2 and yellow rust was higher in NJ2 than in NJ1 and NJ3 (Table 2 and S6). Resistant genotypes Magenta with 4.9, 1.8 and 5.9 t ha^{-1}, Lancer with 3.9, 2.4 and 4.9 t ha^{-1}, Sunguard with 3.6, 1.6 and 4.7 t ha^{-1}, Gauntlet with 2.8, 1.3 and 4.2 t ha^{-1} and Shield with 3.1, 1.1 and 3.5 t ha^{-1} significantly yielded higher than the best control Kenya Robin which yielded 1.3, 0.6 and 0.7 t ha^{-1} in NJ1, NJ2 and NJ3, respectively (S3). Mean TKW and TW was 20.8, 13.7 and 19.8 g, and 64.4, 56.5 and 57.8 kg hL^{-1} in NJ1, NJ2 and NJ3, respectively (Table 2). However, DH, PH, SL and K S^{-1} were not affected by seasons. Among resistant genotypes, GY, HI, TW and TKW ranged from 2.8-4.9 t ha^{-1}, 0.2-0.7, 71.2-77.4 kg hL^{-1} and 23.2-31.2 g in NJ1, 1.1-2.4 t ha^{-1}, 0.15-0.20, 56.4-76.1 kg hL^{-1} and 15.2-24.1 g in NJ2, and 3.5-5.9 t ha^{-1}, 0.23-0.45, 66.2-81.0 kg hL^{-1} and 26.2-33.3 g in NJ3, respectively (S3). GY, HI, TW and TKW values for NJ1 exceeded those of NJ2 by 121, 33, 14 and 52% with NJ3 values exceeding NJ2 values by 132, 29, 2 and 45%, respectively. Stem rust and yellow rust caused a reduction in the quantity and quality of kernels. For instance, resistant genotype Lancer had GY of 3.9, 2.4 and 4.9 t ha^{-1}, HI of 0.74, 0.20 and 0.41, TW of 77.4, 70.9 and 80.2 kg hL^{-1} and TKW of 25.4, 20.8 and 26.4 g in NJ1, NJ2 and NJ3, respectively. However, the susceptible control Kenya Robin recorded GY of 1.3, 0.6 and 0.7 t ha^{-1}, HI of 0.10, 0.10 and 0.03, TW of 56.2, 45.2 and 50.9 kg hL^{-1} and TKW of 20.1, 10.9 and 13.6 g in

Table 2. Range and mean values of disease and yield performance of 61 bread wheat genotypes evaluated for resistance to stem rust, yellow rust and yield performance over three seasons at KALRO, Njoro and resistance to stem rust over one season at DZARC, Debre Zeit..

	Area under disease progress curve									
	Stem rust		Yellow rust		Grain yield (t ha^{-1})		Days to heading		Plant height (cm)	
Season	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean
NJ1	13-1573	711	0-592	95	0.14-4.93	2.01	50-83	69	62.6-95.6	76.2
NJ2	0-1536	382	0-1029	268	0.30-2.44	0.91	54-84	73	50.1-91.1	73.2
NJ3	0-1776	421	0-591	130	0.26-5.94	2.11	57-101	77	50.0-99.0	77.2
DZ	3-984	401	-	-	-	-	-	-	-	-

	Coefficient of infection									
	Stem rust		Yellow rust		Harvest index		1000-kernel weight (g)		Spike length (cm)	
Season	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean
NJ1	0.1-100.0	50.8	0.0-45.5	7.2	0.01-0.74	0.16	10.7-32.9	20.8	7.0-12.3	9.3
NJ2	0.2-99.1	25.9	0.0-76.7	18.9	0.04-0.28	0.12	6.6-24.1	13.7	6.7-11.2	8.9
NJ3	0.3-80.5	16.0	0.1-27.8	5.1	0.01-0.48	0.17	9.2-34.3	19.8	6.3-10.8	8.9
DZ	0.2-43.0	14.9	-	-	-	-	-	-	-	-

	Final disease severity									
	Stem rust		Yellow rust		Kernels per spike		Test weight (kg hL^{-1})		Biomass (t ha^{-1})	
Season	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean
NJ1	5-100	70	0-60	18	24-53	38	40.7-77.4	64.4	6.4-31.2	14.6
NJ2	0-100	41	0-80	29	22-53	38	37.6-76.1	56.5	2.8-14.1	7.8
NJ3	1-100	41	0-50	17	22-51	38	28.6-81.0	57.8	7.0-25.5	14.1
DZ	0-80	37	-	-	-	-	-	-	-	-

NJ1: 2019 off-season at Njoro, NJ2: 2019 main-season at Njoro, NJ3: 2020 off-season at Njoro, DZ: Debre Zeit, –: missing data.
Source: Authors

NJ1, NJ2 and NJ3, respectively.

Correlation and regression analyses

AUDPC, CI and FDS of stem rust and yellow rust were positively correlated (Table 3). However, they were negatively correlated with GY, DH and TKW. Correlation between AUDPC and GY, DH and TKW was -0.5637***, -0.1562 and -0.4418*** for stem rust and -0.1227***, -0.3400*** and -0.0010*** for yellow rust, respectively. GY was positively correlated with TKW (0.9107***) but was negatively correlated with HI (-0.0626***) and DH (-0.2308***). Regression revealed a decrease in GY with an increase in FDS for stem rust and yellow rust (Figure 2).

Heritability and stability

Variance due to genotype exceeded variance due to GSI for all traits except HI while variance due to genotype exceeded variance due to error for all traits but HI, BM and K S^{-1} (Table 4). Lowest and highest estimates of broad-sense heritability (H^2) were recorded for HI at 2.2% and AUDPC for stem rust at 70.2%. Other traits with high H^2 were CI (60%) and FDS (68.1%) for stem rust, GY (61.5%), TKW (67.5%) and TW (62.2%). High (> 50%) PCV and GCV was recorded for disease traits, GY and HI. Based on AUDPC, genotypes varied in reaction to stem rust and yellow rust with seasons. Generally, however, resistance to stem rust was higher during NJ2 and DZ than NJ1 and NJ3 (Figure 3a) while resistance to yellow rust was higher during NJ1 and NJ3 than NJ2 (Figure 3b). Genotypes with superior resistance and stable performance across seasons were Sunguard and Lancer for stem rust and Sunmax, Steel and Gladius for yellow rust (S7). However, genotype Gauntlet, for stem rust, and genotypes Lancer and Magenta, for yellow rust, displayed superior resistance with unstable performance across seasons. Resistance to stem rust of genotypes Lancer and Sunguard was similar across seasons; however, Sunguard marginally outperformed Lancer during the poorer season with Gauntlet being the worst in the poor season and superior in the best season (Figure 4a). On the other hand, resistance to yellow rust of

Table 3. Correlation coefficients of selected traits for 61 bread wheat genotypes evaluated for resistance to stem rust, yellow rust and yield performance over three seasons at KALRO, Njoro.

	AUDPCsr	CIsr	FDSsr	AUDPCyr	CIyr	FDSyr	GY	HI	DH	TKW
AUDPCsr	-									
CIsr	0.9847***	-								
FDSsr	0.5422***	0.53687***	-							
AUDPCyr	-0.0678***	-0.1009***	0.0836***	-						
CIyr	-0.0255**	-0.0568*	0.0989**	0.9816***	-					
FDSyr	0.0595**	0.0775**	0.0526**	0.6228***	0.6176***	-				
GY	-0.5637***	-0.5962***	-0.4718***	-0.1227***	-0.1720***	-0.1869***	-			
HI	0.4356	0.4120***	0.1604***	0.1291**	0.1456***	0.0760***	-0.0626***	-		
DH	-0.1562***	-0.0829***	-0.0429***	-0.3400***	-0.3012***	-0.1045***	-0.2308***	-0.1988***	-	
TKW	-0.4418***	-0.4712***	-0.3401***	-0.0010***	-0.0487***	-0.1069***	0.9107***	0.0482***	-0.4369***	-

$AUDPC_{Sr}$: Area under Disease Progress Curve for Stem Rust, CI_{Sr}: Coefficient of Infection for Stem Rust, FDS_{Sr}: Final Disease Severity for Stem Rust, $AUDPC_{Yr}$: Area under Disease Progress Curve for Yellow Rust, CI_{Yr}: Coefficient of Infection for Yellow Rust, FDS_{Yr}: Final Disease Severity for Yellow Rust, GY: Grain Yield, HI: Harvest Index, DH: Days to Heading, TKW: 1000-Kernel Weight. *, ** and *** = significance at $p \leq 0.05$, $p \leq 0.01$ and $p \leq 0.001$, respectively.
Source: Authors

Table 4. Estimates of variation and heritability of selected traits for 61 bread wheat genotypes evaluated for resistance to stem rust, yellow rust and yield performance over three seasons.

	σ_{ph}^2	σ_g^2	σ_{gs}^2	σ_e^2	H^2 (%)	PCV (%)	GCV (%)	SE
$AUDPC_{Sr}$	181065.0	127098.0	13197.0	40770.0	70.2	87.9	73.7	18.7
CI_{Sr}	771.9	460.8	110.2	200.9	60.0	90.2	70.0	1.3
FDS_{Sr}	773.7	526.9	71.0	175.8	68.1	67.8	56.0	1.3
$AUDPC_{Yr}$	33095.0	18473.0	7111.0	7511.0	55.8	90.9	79.0	8.2
CI_{Yr}	170.3	84.6	49.0	36.7	50.0	93.2	65.7	0.6
FDS_{Yr}	230.1	137.4	39.7	53.1	59.7	96.0	74.2	0.7
DH	103.2	65.3	0.2	37.7	63.3	13.9	11.1	0.4
PH (cm)	89.6	44.8	2.8	42.0	50.0	12.5	8.9	0.4
SL (cm)	1.3	0.9	0.1	0.3	69.2	12.8	10.0	0.0
BM (t ha^{-1})	28.9	7.8	1.9	19.2	27.0	44.1	22.9	0.3
GY (t ha^{-1})	1.3	0.8	0.2	0.3	61.5	67.9	53.2	0.1
HI	0.3	0.0	0.1	0.2	2.2	65.1	52.5	0.1
K S^{-1}	79.8	35.1	7.9	36.8	44.0	23.5	15.6	0.3
TKW (g)	34.5	23.3	4.7	6.5	67.5	32.5	26.7	0.3
TW (kg hL^{-1})	139.4	86.7	14.9	37.8	62.2	19.8	15.6	0.5

σ_{ph}^2: Phenotypic Variance, σ_g^2: Genotypic Variance, σ_{gs}^2: Variance due to Genotype-by-Season Interaction, σ_e^2: Variance due to Error, H^2: Heritability in Broad-sense, PCV: Phenotypic Coefficient of Variation, GCV: Genotypic Coefficient of Variation, SE: Standard Error, $AUDPC_{Sr}$: Area Under Disease Progress Curve for Stem Rust, CI_{Sr}: Coefficient of Infection for Stem Rust, FDS_{Sr}: Final Disease Severity for Stem Rust, $AUDPC_{Yr}$: Area Under Disease Progress Curve for Yellow Rust, CI_{Yr}: Coefficient of Infection for Yellow Rust, FDS_{Yr}: Final Disease Severity for Yellow Rust, DH: Days to Heading, PH: Plant Height, SL: Spike Length, BM: Biomass, GY: Grain Yield, HI: Harvest Index, K S^{-1}: Kernels per Spike, TKW: 1000-Kernel Weight, TW: Test Weight.
Source: Authors

genotypes Sunmax and Gladius was constant across seasons with the former outperforming the latter (Figure 4b). Moreover, resistance of genotype Steel was better in the best season than in the poor season. Detailed results on sensitivity to seasons for stem rust and yellow rust are shown in Figure 5.

DISCUSSION

Emergence of new races limits the deployment of resistant genotypes (Olivera et al., 2019). Nevertheless, APR genes provide broad-spectrum and durable resistance (Moore et al., 2015). AUDPC, CI and FDS are

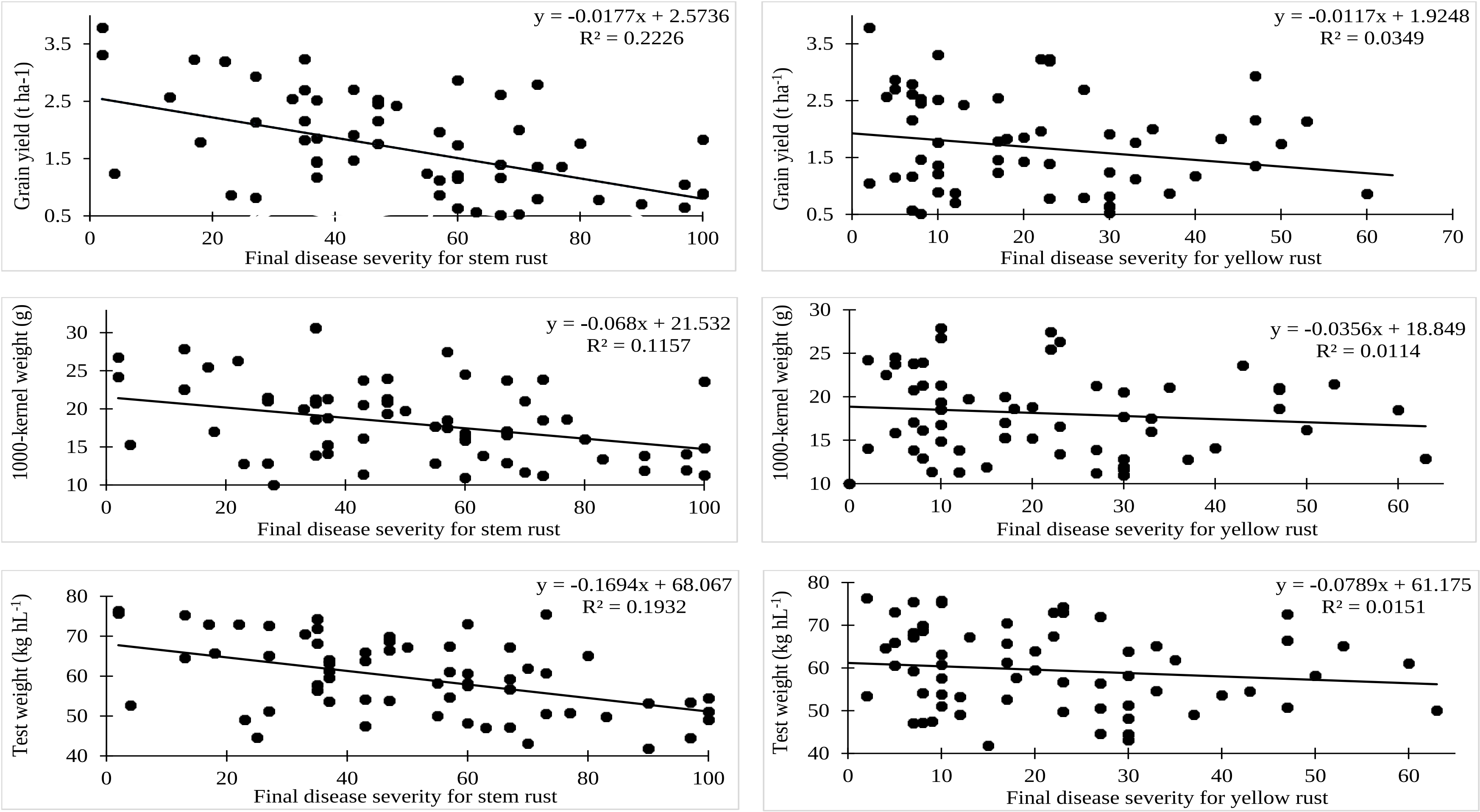

Figure 2. Reaction of wheat genotypes against stem rust and yellow rust for grain yield, 1000-kernel weight and test weight in three seasons at KALRO, Njoro**.**
Source: Authors

reliable measures of APR (Figueroa et al., 2020). In this study, stem rust was higher in NJ1 and NJ3 than in NJ2 and DZ while yellow rust was higher in NJ2 than in NJ1 and NJ3 (Table 1). Genotypes Lancer, Sunguard, Gauntlet, Shield and Magenta were identified for APR due to low levels of AUDPC, CI and FDS (Table 2). These genotypes also displayed low FITs ranging from R to MRMS (S3 and S4). Therefore, APR reduced the rate of infection and development of disease. Differences in reaction to disease seemed to depend on variation in seasons. NJ1 and NJ3 received less and poorly distributed rainfall with higher temperatures while NJ2 received more and well distributed rainfall and lower temperatures (S8).

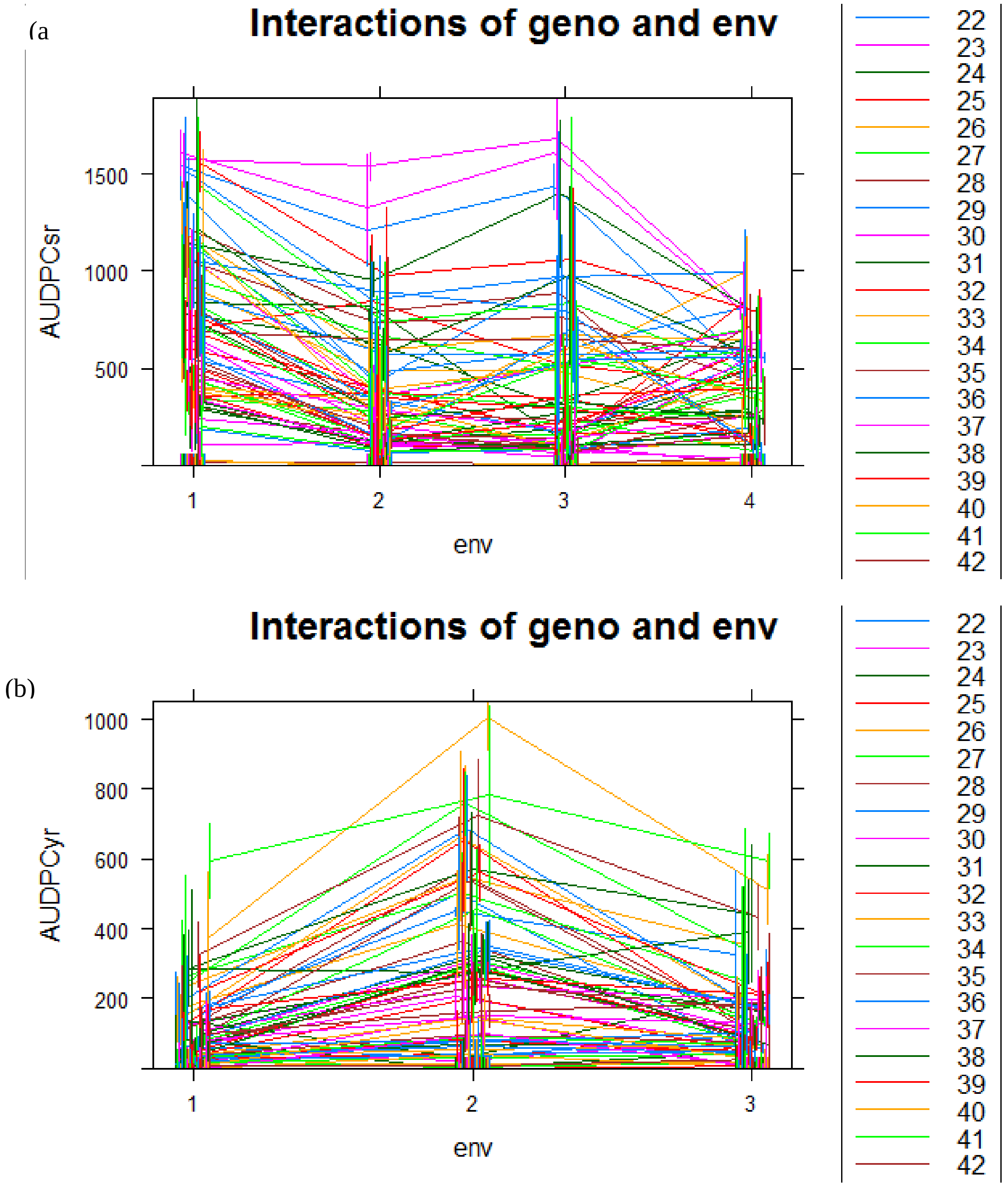

Figure 3. Interaction plots of all genotypes for AUDPC of (a) stem rust and (b) yellow rust in different seasons. AUDPC$_{sr}$: Area Under Disease Progress Curve for Stem Rust, AUDPC$_{yr}$: Area under Disease Progress Curve for Yellow Rust. Each coloured line represents a genotype; 1: 2019 off-season in Njoro, 2: 2019 main-season in Njoro, 3: 2020 off-season in Njoro, 4: Debre Zeit.
Source: Authors

Therefore, NJ1 and NJ3 favored infection and development of stem rust whereas NJ2 favored infection and development of yellow rust. A number of genotypes identified for APR were susceptible at seedling stage and *vice versa*. Seedling susceptibility of APR genotypes indicates resistance conferred by minor genes

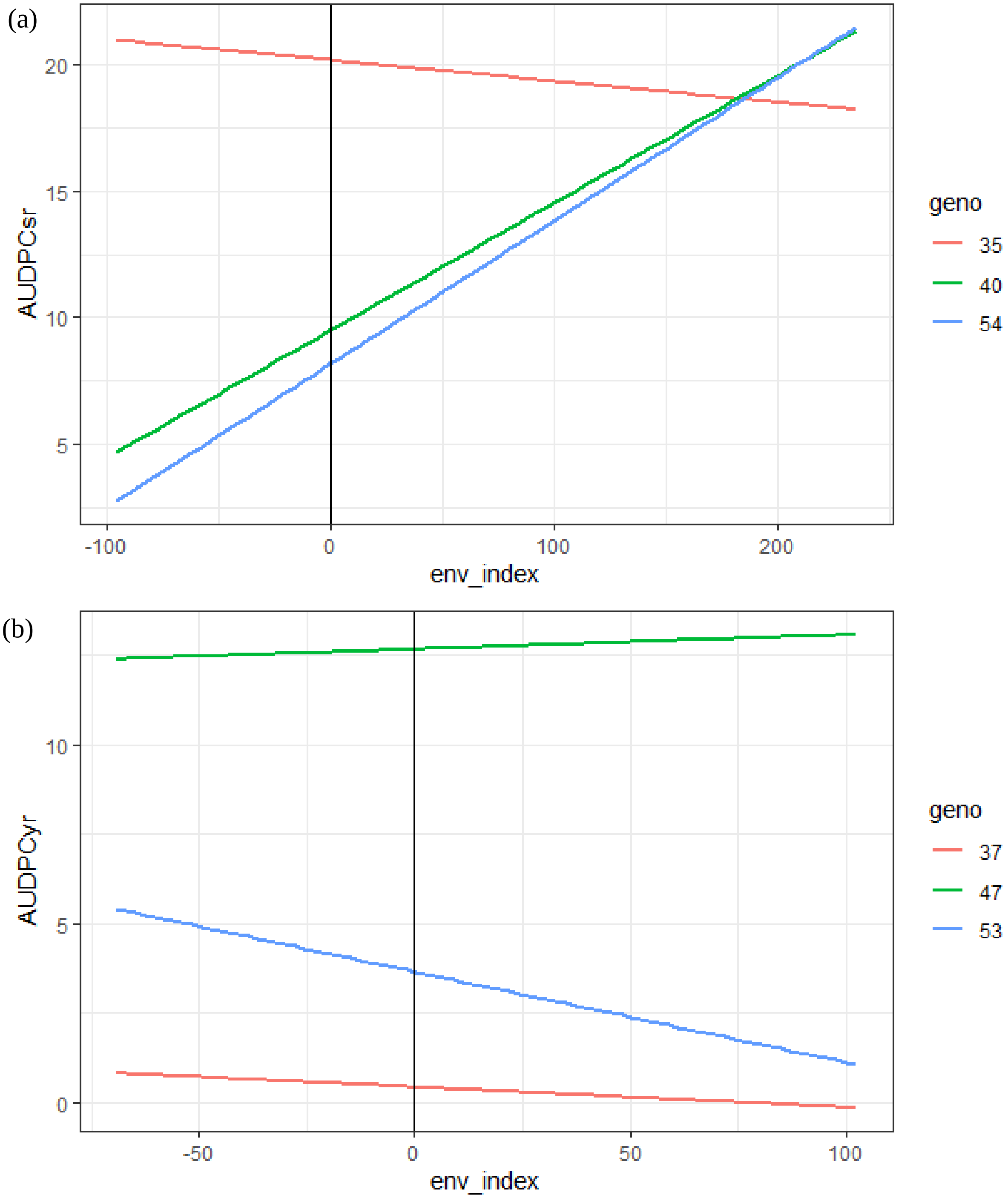

Figure 4. Performance of selected genotypes on estimated seasonal indices. $AUDPC_{sr}$: Area under disease progress curve of stem rust, $AUDPC_{yr}$: Area under disease progress curve of yellow rust. Each coloured line represents fitted values for means of genotype by season interaction: 35 = Gauntlet, 37 = Sunmax, 40 = Lancer, 47 = Gladius, 53 = Steel and 54 = Sunguard.
Source: Authors

(Rahmatov et al., 2019). They provide field resistance (slow rusting) resulting from diverse gene combinations. (Bhavani et al., 2019; Randhawa et al., 2018; van der Plank, 2012). This resistance prolongs the latent period and reduces the duration of sporulation, number and size of uredinia to lower the severity of infection (Figueroa et

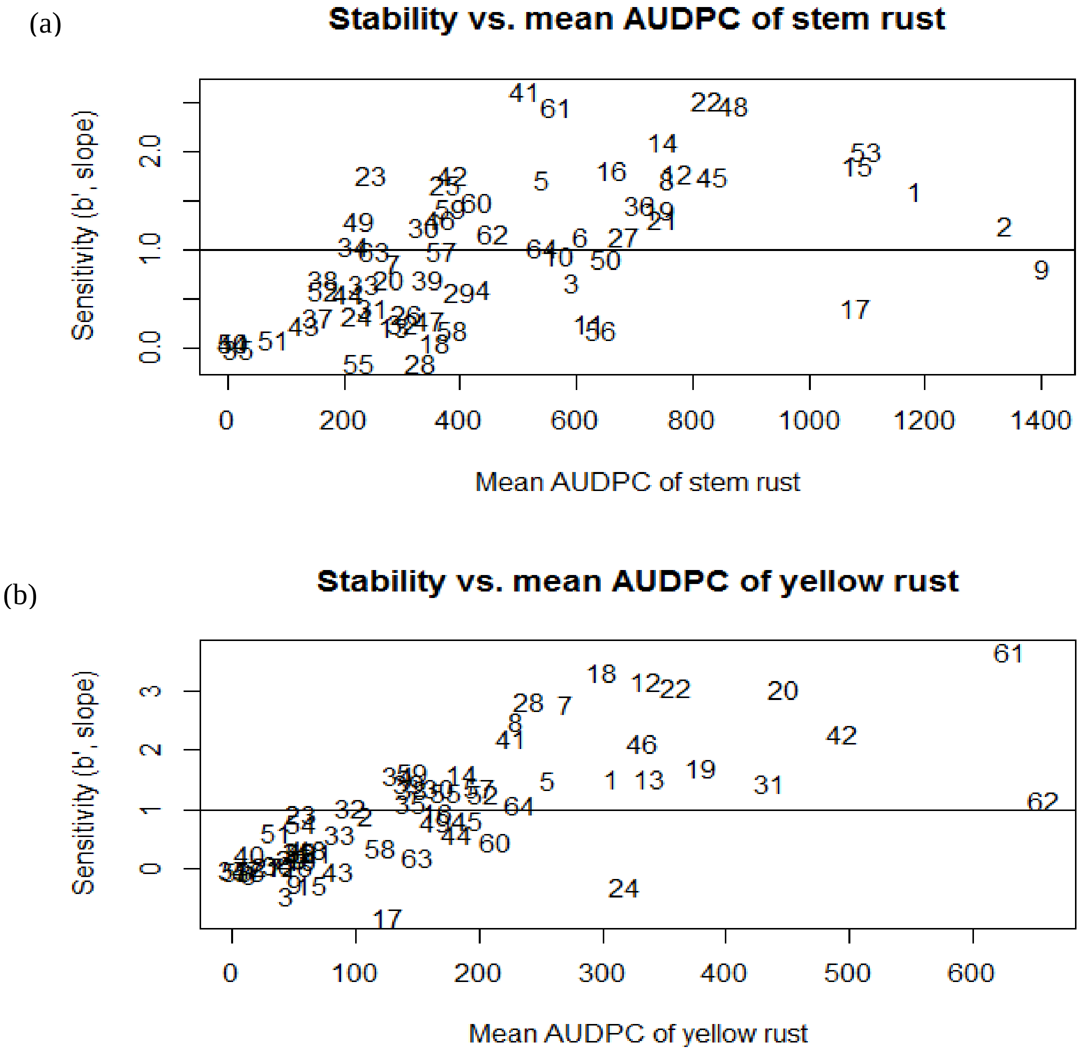

Figure 5. A plot of stability vs mean AUDPC of (a) stem rust and (b) yellow rust AUDPC, area under disease progress curve.
Source: Authors

al., 2020). APR genes are known to confer partial resistance to different races where each gene contributes small to intermediate effects to the phenotype (Huerta-Espino et al., 2020). On the other hand, seedling resistance among genotypes lacking APR such as Scepter, Spitfire, Merlin, Coolah, Janz, Dart and Preston indicate resistance conferred by major genes. It occurs when a pathogenic attack signals defense mechanisms resulting in cell death to restrict the spread of infection and is associated with hypersensitive responses (Singh et al., 2014). Yield performance was not only related to stem rust and yellow rust but also on seasonal variation. The trend showed a reduction in yield with a reduction in stem rust and an increase in yellow rust (Table 1). A similar trend was observed for HI, BM, PH and SL. The reduction in yield with an increase in rust highlights the impact of the two diseases on photosynthesis and mobilization of water and essential nutrients. The high yield among early maturing genotypes is attributed to disease escape. In addition, the high yield among shorter plants which headed early compared to tall plants which headed late is attributed to more tillers and spikelets and a reduction in losses to lodging (Berry and Spink, 2012; Singh et al., 2015). Brinton and Uauy (2019) and Leonardo et al. (2017) found that variation in seasons significantly affect yield performance because yield is a quantitative trait under a polygenic system.

Phenotypic variance was largely attributed to variance due to genotype. Since phenotypic variance is due to variance in genotype, season and GSI, however, seasonal variation causes positive or negative variation in genotypic performance (Falconer and Mackay, 1996;

Acquaah, 2012). H^2 values indicated moderate to high heritability for a majority of variables. Therefore, it was worthwhile to rely on their phenotypic performance to identify resistance and yield performance. PCV and GCV values for AUDPC, CI, FDS, GY and HI were > 50 % thus indicating high variability for these traits. Reaction to stem rust and yellow rust varied across seasons with a higher number of genotypes exhibiting resistance to stem rust during NJ2 and DZ compared to NJ1 and NJ3. However, for yellow rust, a higher number of genotypes were resistant during NJ1 and NJ3 than in NJ2. Therefore, an increase in stem rust caused a decrease in yellow rust and *vice versa*. Genotypes Lancer and Sunguard were superior and stable in resistance to stem rust across three seasons in Njoro and one season in Debre Zeit. Conversely, genotypes Sunmax, Steel and Gladius were superior and stable in resistance to yellow rust across three seasons in Njoro. This is because they were consistently well ranked across seasons (Tables 2 and 4). Genotypes Sunguard and Lancer emerged as the most resistant to stem rust in the poor season with the performance of the former being marginally better than that of the latter. Therefore, both genotypes could be used in breeding for resistance to stem rust during this season. However, during the best season, genotype Gauntlet outperformed genotypes Sunguard and Lancer, and could be used during this season. On the other hand, genotype Sunmax could be utilised in breeding for resistance to yellow rust across seasons since it was the best performing and stable across seasons.

Conclusion

Genetic variation existed for resistance to stem rust and yellow rust and yield performance. However, reaction to disease and yield performance was significantly affected by season and GSI. Genotypes Lancer, Sunguard, Gauntlet, Shield and Magenta were identified for APR to stem rust and yellow rust and were also among the best performing for yield performance. In addition, the study established the existence of seedling resistance with genotypes Lancer, Sunguard, Gauntlet, Scepter, Merlin, Magenta, Spitfire, Coolah, Dart, Janz and Preston exhibiting resistance to isolates *TTKSK* and *TTKTT*. These genotypes present a good source of resistance to stem rust and yellow rust that could be exploited in breeding for resistance. Genotypes Lancer, Sunguard and Gauntlet were well ranked and superior in terms of resistance to stem rust with genotypes Lancer and Sunguard showing stability of performance across seasons. Genotypes Sunguard and Gauntlet emerged as the most resistant to stem rust during poor and best seasons, respectively. On the other hand, genotypes Sunmax, Gladius and Steel were well ranked and superior in terms of resistance to yellow rust with Sunmax being the most resistant and stable across all seasons.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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Supplementary (S) Table 1. Genotypes.

Genotype number	Genotype	Pedigree
1	Cacuke	Canadian/Cunningham/Kennedy
2	Kenya Robin	Babax/*Lr42*//Babax*2/3/Tukuru
3	Coolah	EGA Gregory/VQ2791//EGA Gregory
4	Chara	BD225/CD87
5	LRPB Flanker	EGA Gregory//EGA Gregory/Lang
6	LRPB Reliant	LRPB Crusader/EGA Gregory
7	Ninja	Calingiri/Wyalkatchem derivative
8	Sunmax	CRW142.16/2*SunzellA
9	Tenfour	N/A
10	Tungsten	Axe with a European winter wheat background
11	Axe	-0AUS/DT29361//RAC820/Excalibur/3/-0AUS/DT29361//RAC820/Excalibur
12	B53	N/A
13	Beckom	N/A
14	Bremer	DM02-25-SB02-167/Correll// Mace
15	Buchanan	Frederick/Sprague
16	Calingiri	Chino/Kulin//Reeves
17	Cobalt	N/A
18	Cobra	Westonia/W29
19	Condo	WW-80/2*WW-15
20	Corack	Wyalkatchem/Silverstar A// Wyalkatchem
21	Correll	CHA/Mengavi8156//CNO67/GLL//Bezostaya2/4/N10/BVR14//5*Burt/3/3*Raven/5/Sr2 1/4*Lance//4*Bayonet/6/C 8 MM/C 8 HMM/4/M-8-DAG-3-B19-H9-/Dagger/3/Sabre/MEC 3//Insignia
22	Cosmick	N/A
23	Cutlass	RAC1316/2*Fang
24	Dart	Sunbrook/Janz//Kukri
25	Derrimut	N/A
26	EGA Bounty	Batavia/2*Leichhardt
27	EGA Gregory	Pelsart/2*Batavia DH
28	Baxter	QT2327/Cook//QT2804
29	Emu Rock	96W657-37/Kukri
30	Espada	CO5583*B117/NH5441*F03//RAC875-2/-0AUS/3/-0AUS/DT29361//RAC820/EXCALIBUR
31	Estoc	Trident/Molineux/4/VPM 1/5*COOK//3*Spear/3/Sabre/MEC 3//Insignia/5/VM931/RAC935
32	Forrest	96 WFHB 5568/2*Kohika
33	Gauntlet	Kukri/Sunvale
34	Gazelle	24K1056/VPM/3*Vasco
35	Janz	3-AG-3/4*Condor//Cook
36	Kiora	N/A
37	Lancer	VII84/Chara//Chara/3/Lang
38	Livingston	SUN129A/Sunvale
39	Mace	Wyalkatchem/Stylet//Wyalkatchem
40	Magenta	Carnamah/Tammin-18
41	Merlin	Calidad//Yecora F 70/Ciano F 67/3/76ECN44/4/Hartog*3/Quarrion
42	Mitch	QT10422/GILES

(S) Table 1. Cont'd

43	Orion	TATIARA/QAL2000
44	Gladius	CO5583*B117/NH5441*F03//RAC875-2/-0AUS/3/-0AUS/DT29361//RAC820/Excalibur
45	Preston	N/A
46	Scepter	RAC1480/2*Mace
47	Scout	Sunstate/QH71-6//Yitpi
48	Shield	AGT-Scythe/CO-7138(CO-7412)//(CO-7413)RAC-1105/CO-7165
49	Spitfire	Drysdale/Kukri
50	Steel	Composite cross of unknown germplasm
51	Sunguard	SUN289E/*Sr2*Janz
52	Bolac	Nesser/2*VI252
53	Suntop	Sunco/2*Pastor//SUN436E
54	Supreme	LoPh-Nyabing.3*Calingiri/4*VPM Arrino
55	Trojan	LPB 00LR000041/Sentinel3R
56	Viking	(S) Early-Baart[113];
57	Wallup	Chara/Wyalkatchem
58	Westonia	Spica/Timgalen//Tosca/3/Cranbrook//Bob-White*2/Jacup
59	Wyalkatchem	Machete/W84-129*504
60	Yitpi	C8MMC8HMM/Frame
61	Zen	Calingiri/Wyalkatchem

N/A: Not available.
Source: Authors

Supplementary (S) table 2. Combined REML variance component analyses for selected traits of 61 bread wheat genotypes evaluated for resistance to stem rust, yellow rust and yield performance over three seasons at KALRO, Njoro and resistance to stem rust over one season at DZARC, Debre Zeit.

(i) Response variate: Area under disease progress curve for stem rust

Fixed model:	constant + replicate + genotype + season + genotype.season
Random model:	replicate.block
Number of units:	576

Estimated variance components

Random term	**component**	**s.e.**
Replicate. Block	-0.71	789

Residual variance model

Term	**Model (order)**	**Parameter**	**Estimate**	**s.e**
Residual	Identity	Sigma2	40837	3040

Deviance: -2*Log-Likelihood

Deviance = 4657.58, d.f.= 380

Tests for fixed effects

Fixed term	**Wald statistic**	**n.d.f.**	**F statistic**	**Wald/d.d.f.**	**F pr**
replicate	17.09	2	0.73	8.55	<0.001
genotype	1902.29	63	22.81	30.20	<0.001
season	305.71	3	295.16	152.86	<0.001
genotype.season	247.95	360	1.77	1.97	<0.001

Dropping individual terms from full fixed model

Fixed term	**Wald statistic**	**n.d.f.**	**F statistic**	**d.d.f.**	**F pr**
replicate	247.95	2	0.73	8.55	<0.001
genotype.season	17.09	360	1.77	1.97	<0.001

	Replicate	**Season**	**Genotype**	**Genotype.Season**
Average	20.19	0.4393	164.9	3.504
Maximum			164.9	3.514
Minimum			164.8	3.503

Standard errors of differences

(ii) Response variate: Coefficient of infection for stem rust

Fixed model:	constant + replicate + genotype + season + genotype.season
Random model:	replicate.block
Number of units:	576

Estimated variance components

Random term	**component**	**s.e.**
replicate.block	6.3	5.9

Residual variance model

Term	**Model (order)**	**Parameter**	**Estimate**	**s.e**
Residual	Identity	Sigma2	201.8	15.0

Deviance: -2*Log-Likelihood

Deviance = 2638.24, d.f. = 380

Tests for fixed effects

Fixed term	Wald statistic	n.d.f.	F statistic	d.d.f.	F pr
replicate	7.3	2	2.1	3.65	0.026
genotype	1367.08	60	15.71	21.7	<0.001
season	616.17	3	249.33	308.08	<0.001
genotype.season	331.81	360	2.57	2.63	<0.001

Dropping individual terms from full fixed model

Fixed term	Wald statistic	n.d.f.	F statistic	d.d.f.	F pr
replicate	7.3	2	2.1	3.65	0.026
genotype.season	331.81	360	2.57	2.63	<0.001

	Replicate	Season	Genotype	Genotype.Season
Average	1.351	0.9436	5.425	7.61
Maximum			5.435	7.618
Minimum			5.403	7.549
Average variance of differences			29.43	

Standard errors of differences

(iii) Response variate: Final disease severity for stem rust

Fixed model:	constant + replicate + genotype + season + genotype.season
Random model:	replicate.block
Number of units:	576

Estimated variance components

Random term	**component**	**s.e.**
replicate.block	2.50	4.30

Residual variance model

Term	**Model (order)**	**Parameter**	**Estimate**	**s.e**
Residual	Identity	Sigma2	176.3	13.1

Deviance: -2*Log-Likelihood

Deviance = 2582.41, d.f. = 380

Tests for fixed effects

Fixed term	**Wald statistic**	**n.d.f.**	**F statistic**	**d.d.f.**	**F pr**
replicate	8.14	2	0.87	4.07	0.017
genotype	1761.49	60	19.78	27.96	<0.001
season	510.7	3	403.94	455.35	<0.001
genotype.season	277.84	360	2.5	2.21	<0.001

Dropping individual terms from full fixed model

Fixed term	**Wald statistic**	**n.d.f.**	**F statistic**	**d.d.f.**	**F pr**
replicate	8.14	2	0.87	4.07	0.017
genotype.season	277.84	360	2.5	2.21	<0.001

Cont'd

	Replicate	Season	Genotype	Genotype.Season
Average	2.007	1.298	7.513	10.5
Maximum			7.534	10.52
Minimum			7.47	10.38
Average variance of differences			56.44	110.3

Standard errors of differences

(iv) Response variate: Area under disease progress curve for yellow rust

Fixed model:	constant + replicate + genotype + season + genotype.season
Random model:	replicate.block
Number of units:	576

Estimated variance components

Random term	component	s.e.
replicate.block	-0.71	789

Residual variance model

Term	Model (order)	Parameter	Estimate	s.e
Residual	Identity	Sigma2	40837	3040

Deviance: -2*Log-Likelihood

Deviance = 4657.80, d.f. = 380

Tests for fixed effects

Fixed term	Wald statistic	n.d.f.	F statistic	Wald/d.d.f.	F pr
replicate	17.09	2	0.73	8.55	<0.001
genotype	1902.29	120	22.81	30.2	<0.001
season	305.71	2	295.16	1562.86	<0.001
genotype.season	247.95	120	1.77	1.97	<0.001

Dropping individual terms from full fixed model

Fixed term	Wald statistic	n.d.f.	F statistic	d.d.f.	F pr
replicate	247.95	2	0.73	1.97	0.51
genotype.season	17.09	120	1.77	8.55	0.001

	Replicate	Season	Genotype	Genotype.Season
Average	0.5109	0.4393	2.47	3.504
Maximum			2.474	3.514
Minimum			2.469	3.503

Standard errors of differences

(v) Response variate: Coefficient of infection for yellow rust

Fixed model:	constant + replicate + genotype + season + genotype.season
Random model:	replicate.block
Number of units:	576

Estimated variance components

Random term	component	s.e.
replicate.block	6.3	5.9

Residual variance model

Term	Model (order)	Parameter	Estimate	s.e
Residual	Identity	Sigma2	201.8	15.0

Deviance: -2*Log-Likelihood

Deviance = 2638.24, d.f. = 380

Tests for fixed effects

Fixed term	Wald statistic	n.d.f.	F statistic	d.d.f.	F pr
replicate	7.3	2	2.1	3.65	0.026
genotype	1367.08	60	15.71	21.7	<0.001
season	616.17	2	249.33	308.08	<0.001
genotype.season	331.81	120	2.57	2.63	<0.001

Cont'd.

Dropping individual terms from full fixed model					
Fixed term	**Wald statistic**	**n.d.f.**	**F statistic**	**d.d.f.**	**F pr**
replicate	7.3	2	2.1	3.65	0.026
genotype.season	331.81	120	2.57	2.63	<0.001

	Replicate	Season	Genotype	Genotype.Season
Average	1.351	0.9436	5.425	7.61
Maximum			5.435	7.618
Minimum			5.403	7.549
Average variance of differences			29.43	

Standard errors of differences

(vi) Response variate: Final disease severity for yellow rust

Fixed model:	constant + replicate + genotype + season + genotype.season
Random model:	replicate.block
Number of units:	576

Estimated variance components

Random term	component	s.e.
replicate.block	2.50	4.30

Residual variance model

Term	Model (order)	Parameter	Estimate	s.e
Residual	Identity	Sigma2	176.3	13.1

Deviance: -2*Log-Likelihood

Deviance = 2582.41, d.f. = 380

Tests for fixed effects					
Fixed term	**Wald statistic**	**n.d.f.**	**F statistic**	**d.d.f.**	**F pr**
replicate	8.14	2	0.87	4.07	0.017
genotype	1761.49	60	19.78	27.96	<0.001
season	510.7	2	403.94	455.35	<0.001
genotype.season	277.84	120	2.5	2.21	<0.001

Dropping individual terms from full fixed model					
Fixed term	**Wald statistic**	**n.d.f.**	**F statistic**	**d.d.f.**	**F pr**
replicate	8.14	2	0.87	4.07	0.017
genotype.season	277.84	120	2.5	2.21	<0.001

	Replicate	Season	Genotype	Genotype.Season
Average	2.007	1.298	7.513	10.5
Maximum			7.534	10.52
Minimum			7.47	10.38
Average variance of differences			56.44	110.3

Standard errors of differences

(vii) Response variate: Grain yield (t ha^{-1})

Fixed model:	Constant + replicate + genotype + season + genotype.season
Random model:	replicate.block
Number of units:	383 (1 unit excluded due to missing value)

Estimated variance components

Random term	component	s.e.
replicate.block	0.0102	0.0110

Residual variance model

Term	Model (order)	Parameter	Estimate	s.e
Residual	Identity	Sigma2	0.262	0.0243

Deviance: -2*Log-Likelihood

Deviance = 69.85,d.f. = 251

(vii) Cont'd

Tests for fixed effects					
Fixed term	**Wald statistic**	**n.d.f.**	**F statistic**	**d.d.f.**	**F pr**
replicate	1.26	2	0.63	12.2	0.55
genotype	842.61	60	13.36	227.8	<0.001
season	446.03	1	446.03	232.1	<0.001
genotype.season	266.95	60	4.24	232.1	<0.001
Dropping individual terms from full fixed model					
Fixed term	**Wald statistic**	**n.d.f.**	**F statistic**	**d.d.f.**	**F pr**
replicate	1.26	2	0.63	12.2	0.548
genotype.season	266.95	60	4.24	232.1	<0.001

	Replicate	**Season**	**Genotype**	**Genotype.Season**
Average	0.08157	0.05231	0.303	0.4235
Maximum	0.08162		0.3214	0.4736
Minimum	0.08147		0.3007	0.4176
Average variance of differences			0.09183	0.1794

Standard errors of differences

(viii) Response variate: Biomass (t ha^{-1})

Fixed model:	constant + replicate + genotype + season + genotype.season
Random model:	replicate.block
Number of units:	576

Estimated variance components

Random term	component	s.e.
replicate.block	0.02	0.55

Residual variance model

Term	Model (order)	Parameter	Estimate	s.e
Residual	Identity	Sigma2	17.96	1.66

Deviance: -2*Log-Likelihood

Deviance = 1137.07, d.f. = 252.

Tests for fixed effects					
Fixed term	**Wald statistic**	**n.d.f.**	**F statistic**	**d.d.f.**	**F pr**
replicate	21.61	2	10.8	9.4	0.004
genotype	182.26	60	2.88	199.8	<0.001
season	242.92	1	242.92	233	<0.001
genotype.season	75.73	60	1.2	233	0.166
Dropping individual terms from full fixed model					
Fixed term	**Wald statistic**	**n.d.f.**	**F statistic**	**d.d.f.**	**F pr**
replicate	21.61	2	10.8	9.4	0.004
genotype.season	75.73	60	1.2	233	0.166

	Replicate	**Season**	**Genotype**	**Genotype.Season**
Average	0.5354	0.4325	2.449	3.462
Maximum			2.45	3.462
Minimum			2.449	3.46

Standard errors of differences

(ix) Response variate: Harvest index

Fixed model:	constant + replicate + genotype + season + genotype.season
Random model:	replicate.block
Number of units:	383 (1 unit excluded due to missing value)

Estimated variance components

Random term	component	s.e.
replicate.block	0.00013	0.00043

Residual variance model

Term	Model (order)	Parameter	Estimate	s.e
Residual	Identity	Sigma2	0.0129	0.00120

Deviance: -2*Log-Likelihood

Deviance = -696.41, d.f. = 251

Tests for fixed effects

Fixed term	Wald statistic	n.d.f.	F statistic	d.d.f.	F pr
replicate	4.53	2	2.26	10.2	0.154
genotype	164.31	60	2.6	209.7	<0.001
season	12.72	1	12.72	232.1	<0.001
genotype.season	70.57	60	1.12	232.1	0.272

Dropping individual terms from full fixed model

Fixed term	Wald statistic	n.d.f.	F statistic	d.d.f.	F pr
replicate	4.6	2	2.3	10.2	0.15
genotype.season	70.57	60	1.12	232.1	0.272

	Replicate	Season	Genotype	Genotype.Season
Average	0.01535	0.01162	0.06627	0.09334
Maximum	0.01536		0.07022	0.1043
Minimum	0.01532		0.06601	0.09279
Average variance of differences				0.008714

Standard errors of differences

(x) Response variate: Days to heading

Fixed model:	Constant + replicate + genotype + season + genotype.season
Random model:	replicate.block
Number of units:	576

Estimated variance components

Random term	component	s.e.
replicate.block	3.02	1.54

Residual variance model

Term	Model (order)	Parameter	Estimate	s.e
Residual	Identity	Sigma2	20.60	1.91

Deviance: -2*Log-Likelihood

Deviance = 1191.36, d.f. = 252

Tests for fixed effects

Fixed term	Wald statistic	n.d.f.	F statistic	d.d.f.	F pr
replicate	5.31	2	2.65	15.9	0.101
genotype	1053.4	60	16.72	241.5	<0.001
season	46.44	1	46.44	233	<0.001
genotype.season	11.57	60	0.18	233	1

Dropping individual terms from full fixed model

Fixed term	Wald statistic	n.d.f.	F statistic	d.d.f.	F pr
replicate	5.31	2	2.65	15.9	0.101
genotype.season	11.57	60	0.18	233	1

	Replicate	Season	Genotype	Genotype.Season
Average	1.038	0.4632	2.75	3.798
Maximum			2.766	3.81
Minimum			2.718	3.705
Average variance of differences			7.563	14.42

Standard errors of differences

(xi) Response variate: Plant height (cm)

Fixed model:	constant + replicate + genotype + season + genotype.season
Random model:	replicate.block
Number of units:	576

Estimated variance components

Random term	component	s.e.
replicate.block	0.25	1.57

Residual variance model

Term	Model (order)	Parameter	Estimate	s.e
Residual	Identity	Sigma2	49.62	4.60

Deviance: -2*Log-Likelihood

Deviance = 1396.06, d.f. = 252

Tests for fixed effects

Fixed term	Wald statistic	n.d.f.	F statistic	d.d.f.	F pr
replicate	3.75	2	1.87	9.7	0.205
genotype	325.99	60	5.16	204.8	<0.001
season	17.7	1	17.7	233	<0.001
genotype.season	66.29	60	1.05	233	0.385

Dropping individual terms from full fixed model

Fixed term	Wald statistic	n.d.f.	F statistic	d.d.f.	F pr
replicate	3.75	2	1.87	9.7	0.205
genotype.season	66.29	60	1.05	233	0.385

	Replicate	Season	Genotype	Genotype.Season
Average	0.9152	0.719	4.084	5.764
Maximum			4.086	5.765
Minimum			4.08	5.752
Average variance of differences				

Standard errors of differences

(xii) Response variate: Spike length (cm)

Fixed model:	constant + replicate + genotype + season + genotype.season
Random model:	replicate.block
Number of units:	576

Estimated variance components

Random term	component	s.e.
replicate.block	0.0149	0.0131

Residual variance model

Term	Model (order)	Parameter	Estimate	s.e
Residual	Identity	Sigma2	0.285	0.0264

Deviance: -2*Log-Likelihood

Deviance = 93.92,d.f. = 252

Tests for fixed effects

Fixed term	Wald statistic	n.d.f.	F statistic	d.d.f.	F pr
replicate	12.48	2	6.24	12.9	0.013
genotype	1353.72	60	21.47	232.9	<0.001
season	44.48	1	44.48	233	<0.001
genotype.season	133.65	60	2.12	233	<0.001

Dropping individual terms from full fixed model

Fixed term	Wald statistic	n.d.f.	F statistic	d.d.f.	F pr
replicate	12.48	2	6.24	12.9	0.013
genotype.season	133.65	60	2.12	233	<0.001

	Replicate	Season	Genotype	Genotype.Season
Average	0.09049	0.05451	0.3174	0.4425
Maximum			0.3185	0.4433
Minimum			0.3152	0.4361
Average variance of differences				

Standard errors of differences

(xii) Response variate: Kernels spike^{-1}

Fixed model: constant + replicate + genotype + season + genotype.season
Random model: replicate.block
Number of units: 576

Estimated variance components

Random term	component	s.e.
replicate.block	-1.23	0.77

Residual variance model

Term	Model (order)	Parameter	Estimate	s.e
Residual	Identity	Sigma2	37.30	3.46

Deviance: -2*Log-Likelihood

Deviance = 1313.39, d.f. = 252

Tests for fixed effects

Fixed term	Wald statistic	n.d.f.	F statistic	d.d.f.	F pr
replicate	1.26	2	0.63	4.9	0.57
genotype	414.35	60	6.45	88.4	<0.001
season	0.65	1	0.65	233	0.42
genotype.season	6.22	60	0.1	233	1

Dropping individual terms from full fixed model

Fixed term	Wald statistic	n.d.f.	F statistic	d.d.f.	F pr
replicate	1.26	2	0.63	4.9	0.57
genotype.season	6.22	60	0.1	233	1

	Replicate	Season	Genotype	Genotype.Season
Average	0.5253	0.6234	3.363	4.874
Maximum			3.405	4.987
Minimum			3.343	4.859
Average variance of differences			11.31	23.76

Standard errors of differences

(xiii) Response variate: Test weight (kg hL^{-1})

Fixed model: constant + replicate + genotype + season + genotype.season
Random model: replicate.block
Number of units: 350 (34 units excluded due to missing values)

Estimated variance components

Random term	component	s.e.
replicate.block	1.09	1.05

Residual variance model

Term	Model (order)	Parameter	Estimate	s.e
Residual	Identity	Sigma2	20.47	2.05

Deviance: -2*Log-Likelihood

Deviance = 1024.78, d.f. = 218

Tests for fixed effects

Fixed term	Wald statistic	n.d.f.	F statistic	d.d.f.	F pr
replicate	4.25	2	2.13	12.4	0.161
genotype	1057.53	60	16.77	197.7	<0.001
season	332.94	1	332.94	200.6	<0.001
genotype.season	125.46	60	1.99	201.2	<0.001

Dropping individual terms from full fixed model

Fixed term	Wald statistic	n.d.f.	F statistic	d.d.f.	F pr
replicate	3.15	2	1.57	12.4	0.246
genotype.season	125.46	60	1.99	201.2	<0.001

	Replicate	Season	Genotype	Genotype.Season
Average	0.8018	0.5107	2.938	4.09
Maximum	0.8063		4.337	6.539
Minimum	0.7931		2.671	3.694
Average variance of differences	0.643		8.746	17.07

Standard errors of differences

(xiv) Response variate: 1000-kernel weight (g)

Fixed model:	constant + replicate + genotype + season + genotype.season
Random model:	replicate.block
Number of units:	382 (2 units excluded due to missing values)

Estimated variance components

Random term	component	s.e.
replicate.block	0.114	0.169

Residual variance model

Term	Model (order)	Parameter	Estimate	s.e
Residual	Identity	Sigma2	4.446	0.414

Deviance: -2*Log-Likelihood

Deviance = 781.44, d.f. = 250

Tests for fixed effects

Fixed term	**Wald statistic**	**n.d.f.**	**F statistic**	**d.d.f.**	**F pr**
replicate	8.32	2	4.16	11.4	0.044
genotype	1643.71	60	26.04	220.8	<0.001
season	1103.8	1	1103.08	231.3	<0.001
genotype.season	311.15	60	4.94	231.3	<0.001

Dropping individual terms from full fixed model

Fixed term	**Wald statistic**	**n.d.f.**	**F statistic**	**d.d.f.**	**F pr**
replicate	9.04	2	4.52	11.4	0.036
genotype.season	311.15	60	4.94	231.3	<0.001

	Replicate	**Season**	**Genotype**	**Genotype.Season**
Average	0.314	0.2161	1.244	1.743
Maximum	0.3144		1.387	2.133
Minimum	0.3138		1.234	1.722
Average variance of differences			1.547	3.041

Standard errors of differences

Supplementary (S) table 3. Means of selected traits for resistant genotypes (AUDPC ≤ 300, CI ≤ 20 and FDS ≤ 30) and controls evaluated for resistance to stem rust, yellow rust and yield performance over three seasons at KALRO, Njoro and resistance to stem rust over one season at DZARC, Debre Zeit.

Genotypes	Stem rust														
	AUDPC				CI				FDS				Harvest index		
	NJ1	NJ2	NJ3	DZ	NJ1	NJ2	NJ3	DZ	NJ1	NJ2	NJ3	DZ	NJ1	NJ2	NJ3
Lancer	13	0	0	8	1.1	1.1	3.1	0.4	5	0	1	1	0.70	0.20	0.41
Sunguard	16	0	4	3	2.7	0.2	0.9	0.2	5	0	1	0	0.20	0.15	0.33
Gauntlet	13	10	5	31	0.1	0.4	1.0	0.8	5	5	1	10	0.20	0.16	0.33
Shield	94	101	85	23	4.7	5.5	2.0	0.6	20	15	5	1	0.20	0.15	0.23
Magenta	194	59	99	189	7.7	3.4	3.3	4.4	20	10	10	30	0.30	0.20	0.45
Controls															
Cacuke[a]	1496	1201	1519	545	97.0	95.3	68.0	17.6	100	100	100	60	0.22	0.13	0.22
Kenya Robin[b]	1573	1329	1684	790	97.8	96.8	75.5	34.6	100	100	100	70	0.10	0.10	0.03
Mean[c]	711	382	421	401	50.8	25.9	16.0	14.9	70	41	41	37	0.16	0.12	0.17
LSD$_{0.05}$	5.4	5.8	7.1	4.5	26.6	20.1	18.1	7.7	19.1	17.6	22.8	11.4	0.46	0.04	0.13
CV (%)	8.0	8.2	5.2	2.2	17.4	13.9	15.7	8.9	12.8	15.1	13.0	7.1	4.10	0.20	1.40

	Yellow rust									Grain yield (t ha^{-1})			Test weight (kg hL^{-1})			1000-kernel weight (g)		
	AUDPC			CI			FDS											
	NJ1	NJ2	NJ3	NJ1	NJ2	NJ3	NJ1	NJ2	NJ3	NJ1	NJ2	NJ3	NJ1	NJ2	NJ3	NJ1	NJ2	NJ3
Lancer	**0**	**22**	**2**	**0.2**	**1.4**	**0.1**	**0**	**5**	**1**	**3.9**	**2.4**	**4.9**	**77.4**	**70.9**	**80.2**	**25.4**	**20.8**	**26.4**
Sunguard	5	123	12	1.1	6.7	0.4	5	20	5	3.6	1.6	4.7	73.1	76.1	78.8	23.3	24.1	33.1
Gauntlet	64	241	108	5.3	18.7	4.4	10	30	10	2.8	1.3	4.2	74.5	68.7	81.0	23.2	17.3	30.6
Shield	0	102	3	0.3	4.9	0.1	1	10	1	3.1	1.1	3.5	71.2	56.4	66.2	26.3	15.2	26.2
Magenta	72	65	101	4.8	3.2	3.4	10	10	10	4.9	1.8	5.9	76.4	69.6	80.0	31.2	19.2	33.3
Controls																		
Cacuke[a]	132	470	304	12.0	43.4	14.5	30	50	50	2.4	0.7	2.5	64.6	55.4	43.9	32.5	14.7	23.6
Kenya Robin[b]	53	212	70	1.0	8.8	1.0	5	20	5	1.3	0.6	0.7	56.2	45.2	50.9	20.1	10.9	13.6
Mean[c]	95	268	131	7.2	18.9	5.1	18	29	17	2.0	0.9	2.1	64.4	56.5	57.8	20.8	13.7	19.8
LSD$_{0.05}$	5.4	5.1	5.8	10.3	11.7	7.5	12.3	11.8	11.9	1.1	0.5	1.1	5.7	8.3	14.0	3.4	3.4	5.5
CV (%)	6.1	0.7	2.6	17.2	6.5	10.0	15.7	5.8	6.7	4.5	4.7	13.0	2.9	1.7	1.4	3.2	2.4	1.8

AUDPC: area under disease progress curve, CI: coefficient of infection, FDS: final disease severity, NJ1: 2019 off-season in Njoro, NJ2: 2019 main-season in Njoro, NJ3: 2020 off-season in Njoro, DZ: Debre Zeit.

[a] Control for stem rust and yellow rust

[b] Control for yield performance

[c] Means stated are for all the 61 genotypes evaluated

Supplementary (S) table 4. Disease means and final infection types of 61 bread wheat genotypes evaluated for resistance to stem rust over three seasons at KALRO, Njoro and one season at DZARC, Debre Zeit

	Area under disease progress curve				Coefficient of infection				Final disease severity				Final infection type			
Genotype	**NJ1**	**NJ2**	**NJ3**	**DZ**	**NJ1**	**NJ2**	**NJ3**	**DZ**	**NJ1**	**NJ2**	**NJ3**	**DZ**	**NJ1**	**NJ2**	**NJ3**	**DZ**
Cacuke	1496	1201	1519	545	97.0	95.3	68.0	17.6	100	100	100	60	S	S	S	S
Kenya Robin	1573	1329	1684	790	97.8	96.8	75.5	34.6	100	100	100	70	S	S	S	S
Coolah	750	620	336	619	55.5	47.9	9.2	28.2	80	60	40	70	S	S	MRMS	S
Chara	907	472	493	235	75.3	39.7	9.2	4.9	100	60	60	30	S	S	MRMS	MRMS
LRPB Flanker	861	341	499	682	59.4	16.1	17.6	28.8	90	40	50	50	S	MRMS	MSS	S
LRPB Reliant	497	148	102	371	46.3	10.5	3.0	14.2	60	30	15	40	MSS	MRMS	MS	S
Ninja	1174	417	494	823	87.2	22.9	18.3	34.3	90	50	70	80	S	MSS	S	S
Tenfour	1537	1536	1776	790	97.6	99.1	80.5	33.0	100	100	100	60	S	S	S	S
Tungsten	808	800	152	484	64.9	60.3	5.5	16.2	90	90	20	40	S	S	MRMS	MRMS
Axe	702	826	553	392	47.6	53.4	13.8	11.7	70	70	50	30	S	S	MRMS	S
B53	1196	579	666	620	84.1	51.2	24.4	28.5	90	60	60	60	S	S	MRMS	S
Beckom	343	237	103	395	19.8	13.2	3.4	17.0	50	50	10	60	MRMS	MRMS	MRMS	MRMS
Bremer	1240	792	867	76	84.3	57.7	35.2	1.3	90	60	90	15	S	MSS	S	S
Buchanan	1492	839	844	972	95.9	62.6	41.9	42.8	100	70	100	80	S	S	S	S
Calingiri	1104	343	476	674	86.0	28.5	13.7	29.4	90	50	60	70	S	MSS	MS	S
Cobalt	1089	944	1415	818	85.5	75.8	64.9	34.2	100	90	100	60	S	S	S	S
Cobra	374	81	89	856	25.4	6.5	2.5	35.9	50	20	10	70	MRMS	MRMS	MRMS	S
Condo	1058	380	499	984	72.0	16.8	11.7	43.0	100	40	40	60	S	MRMS	MRMS	S
Corack	440	135	159	347	19.7	5.5	2.8	8.9	50	15	15	30	MRMS	MRMS	MRMS	S
Correll	1036	745	722	426	81.7	60.5	27.0	12.9	100	60	60	40	S	S	MSS	MRMS
Cosmick	1403	385	941	535	95.1	31.6	34.9	12.3	100	60	70	40	S	S	S	I
Cutlass	632	187	96	3	46.6	14.9	1.5	0.3	80	40	10	0	S	MRMS	MS	MRMS
Dart	286	104	142	283	11.0	3.0	1.3	5.9	40	10	20	20	RMR	MRMS	MRMS	MRMS
Derrimut	760	355	190	158	53.5	26.8	6.4	3.4	60	60	20	10	S	S	MRMS	MS
EGA Bounty	297	155	135	711	14.6	10.0	2.9	30.3	40	20	15	60	MRMS	MRMS	MRMS	S
EGA Gregory	498	316	160	522	36.8	14.7	2.7	21.3	80	40	20	50	S	MRMS	MRMS	S
Baxter	580	106	43	546	40.1	7.1	1.8	24.0	90	15	5	50	S	MRMS	MRMS	MRMS
Emu Rock	345	113	257	255	16.6	5.1	6.0	5.5	40	10	30	30	MRMS	MRMS	MRMS	MS
Espada	360	302	301	116	27.9	23.2	9.0	3.0	50	50	40	20	MSS	MS	MS	MS
Estoc	393	303	86	119	36.1	15.4	3.5	4.0	50	50	10	20	MSS	MRMS	MS	MRMS
Forrest	450	94	183	79	31.6	6.8	9.2	1.3	50	15	40	10	MRMS	MRMS	MSS	MRMS

Table S4. Cont'd

Gauntlet	13	10	5	31	0.1	0.4	1.0	0.8	5	5	1	10	RMR	RMR	R	MR
Gazelle	1028	877	744	96	86.6	63.0	29.4	2.1	100	60	60	15	S	S	S	MSS
Sunmax	228	150	37	166	18.7	13.4	0.3	6.8	40	40	5	20	MSS	MRMS	MRMS	S
Janz	311	109	87	114	17.2	7.6	2.8	2.5	50	20	30	20	MRMS	MRMS	MS	MRMS
Kiora	485	109	179	506	29.5	8.1	3.8	22.2	60	30	20	50	MSS	MRMS	MS	S
Lancer	13	0	0	8	1.1	1.1	3.1	0.4	5	0	1	1	R	I	R	TR
Livingston	1128	341	309	239	87.9	15.9	10.5	5.1	90	40	40	20	S	MRMS	MRMS	MRMS
Mace	806	258	248	254	71.0	13.6	8.4	7.7	80	30	30	30	S	MRMS	MRMS	MS
Magenta	194	59	99	189	7.7	3.4	3.3	4.4	20	10	10	30	MR	MRMS	MRMS	MRMS
Merlin	325	101	162	252	9.6	4.6	4.7	5.2	40	10	15	20	MR	MRMS	MRMS	MRMS
Mitch	1176	573	988	556	84.6	29.4	39.3	20.3	100	50	100	50	S	MSS	S	S
Orion	643	319	302	164	57.1	23.4	10.7	4.8	90	50	30	15	S	MSS	MS	MSS
Gladius	385	172	693	129	31.4	10.9	23.1	3.0	40	40	50	20	MSS	MRMS	MS	MS
Preston	1438	706	672	401	94.7	38.1	32.1	12.0	100	70	100	60	S	S	S	S
Scepter	479	133	95	160	39.3	4.9	5.1	3.7	80	15	10	20	S	MRMS	MRMS	MRMS
Scout	831	557	587	601	74.2	34.3	34.6	25.5	90	60	50	50	S	S	MRMS	S
Shield	94	101	85	23	4.7	5.5	2.0	0.6	20	15	5	5	MRMS	MRMS	MRMS	MR
Spitfire	312	69	114	180	12.5	3.9	3.3	3.8	30	10	10	20	MR	MRMS	MRMS	MRMS
Steel	1560	969	1026	783	100.0	71.4	47.4	32.8	100	100	90	60	S	S	S	S
Sunguard	16	0	4	3	2.7	0.2	0.9	0.2	5	0	1	1	R	I	R	TR
Bolac	175	76	69	557	5.6	4.6	1.4	17.3	30	15	10	50	MR	MRMS	MRMS	S
Suntop	684	592	601	605	41.6	46.0	21.6	25.1	70	60	50	50	S	S	MSS	S
Supreme	553	121	607	76	44.6	5.4	39.4	1.0	60	15	90	10	MSS	MRMS	S	RMR
Trojan	447	293	168	636	40.2	17.2	4.9	28.3	50	30	30	60	MSS	MRMS	MRMS	S
Viking	722	252	308	228	64.9	14.6	8.2	5.8	80	30	40	30	S	MRMS	MRMS	MRMS
Wallup	764	191	352	393	48.3	8.9	8.3	10.9	80	20	30	30	S	MRMS	MRMS	S
Westonia	1082	184	603	316	69.4	6.8	13.5	6.7	100	20	50	20	S	MRMS	MRMS	MRMS
Wyalkatchem	680	199	495	366	52.5	8.4	11.6	8.8	90	15	60	30	S	MRMS	MRMS	MS
Yitpi	496	164	35	259	55.0	12.2	0.6	12.4	70	20	15	30	S	MRMS	MRMS	S
Zen	766	295	468	565	59.4	18.4	16.8	22.6	90	30	60	40	S	MSS	S	S

I: immune, TR: traces, R: resistant, RMR: resistant to moderately resistant, MR: moderately resistant, TRMS: traces to moderately susceptible, MRMS: moderately resistant to moderately susceptible, MS: moderately susceptible, MSS: moderately susceptible to susceptible, S: susceptible, NJ1: 2019 off-season in Njoro, NJ2: 2019 main-season in Njoro, NJ3: 2020 off-season in Njoro, DZ: Debre Zeit.

Supplementary (S) table 5. Disease means and final infection types of 61 bread wheat genotypes evaluated for resistance to yellow rust over three seasons at KALRO, Njoro.

	Area under disease progress curve			Coefficient of infection			Final disease severity			Final infection type		
Genotype	**NJ1**	**NJ2**	**NJ3**	**NJ1**	**NJ2**	**NJ3**	**NJ1**	**NJ2**	**NJ3**	**NJ1**	**NJ2**	**NJ3**
Cacuke	132	470	304	12.0	43.4	14.5	30	50	50	MS	MSS	MS
Kenya Robin	53	212	70	1.0	8.8	1.0	5	20	5	MRMS	MRMS	MRMS
Coolah	77	0	40	5.2	0.0	1.5	20	1	10	MRMS	R	MS
Chara	163	413	183	7.8	28.3	7.4	20	40	20	MS	MSS	MS
LRPB Flanker	10	1	15	0.7	0.7	0.1	5	5	5	MR	MR	R
LRPB Reliant	96	556	146	5.1	34.0	5.0	15	50	15	MRMS	MSS	MRMS
Ninja	102	473	42	10.7	36.8	1.8	30	50	10	MSS	MSS	MRMS
Tenfour	47	21	77	2.3	4.4	1.7	10	10	15	RMR	MS	MR
Tungsten	33	73	64	1.6	2.9	0.5	5	10	10	MRMS	MR	MR
Axe	25	42	44	2.4	1.6	1.3	5	5	10	MS	S	MS
B53	135	675	198	11.0	49.4	9.7	15	70	20	MRMS	MSS	MRMS
Beckom	249	505	216	16.2	30.9	9.2	40	40	40	MSS	MSS	MS
Bremer	82	340	82	13.8	23.4	3.0	40	50	10	MRMS	MR	MRMS
Buchanan	40	20	71	2.5	0.9	2.8	15	5	15	MS	MSS	MRMS
Calingiri	115	252	102	11.9	16.2	4.1	30	30	10	MS	MR	MRMS
Cobalt	67	15	148	10.4	1.3	8.1	40	10	40	MS	MSS	MS
Cobra	121	647	123	10.3	45.5	5.4	20	60	10	MRMS	S	MRMS
Condo	222	516	342	13.0	40.2	12.7	40	70	40	MSS	MSS	MSS
Corack	200	759	280	19.8	49.3	17.9	50	60	50	R	MR	MRMS
Correll	33	92	76	0.4	4.7	1.5	5	15	10	MSS	S	MRMS
Cosmick	195	650	168	18.7	55.3	7.2	40	70	30	MRMS	MRMS	MRMS
Cutlass	3	139	1	0.0	7.1	0.2	5	20	1	MS	MSS	MS
Dart	280	242	385	17.9	19.4	14.7	40	30	40	MRMS	MRMS	MRMS
Derrimut	22	86	44	1.0	3.9	0.8	5	15	5	MR	MRMS	MR
EGA Bounty	68	563	106	4.7	36.7	3.5	15	50	15	R	MRMS	MRMS
EGA Gregory	33	45	40	0.4	3.3	0.3	5	15	5	MRMS	MS	MRMS
Baxter	80	309	104	4.5	18.7	3.6	15	30	15	MS	MSS	MRMS
Emu Rock	261	555	431	19.0	46.4	17.4	40	60	40	MRMS	MRMS	MRMS
Espada	23	199	32	1.5	8.0	1.0	5	20	5	RMR	MS	MR
Estoc	33	134	81	1.5	8.5	2.6	5	20	5	MS	MSS	MS
Forrest	33	272	70	1.7	20.9	2.3	5	40	10	MS	MS	MS
Gauntlet	64	241	108	5.3	18.7	4.4	10	30	10	RMR	MRMS	MRMS
Gazelle	19	28	47	0.3	1.2	0.7	5	5	10	R	I	I
Sunmax	0	0	0	0.3	0.0	0.3	1	0	0	MR	MS	MRMS
Janz	63	266	86	3.9	17.4	3.2	10	30	10	MS	MS	MS
Kiora	47	266	87	2.0	17.4	1.7	10	30	10	MS	MS	MRMS
Lancer	0	22	2	0.2	1.4	0.1	0	5	1	I	MR	R
Livingston	86	452	133	5.4	27.6	4.6	10	40	15	MRMS	MSS	MRMS

Table S5. Cont'd

Mace	323	723	428	26.8	49.3	20.5	40	60	40	MS	MSS	MS
Magenta	72	65	101	4.8	3.2	3.4	10	10	10	MRMS	MRMS	MRMS
Merlin	104	249	192	8.8	18.6	8.5	20	30	20	MS	MS	MS
Mitch	129	285	162	9.4	16.0	6.4	30	20	20	MRMS	MS	MS
Orion	215	553	214	14.1	40.7	6.7	30	50	20	MRMS	MSS	MRMS
Gladius	3	6	6	0.7	1.6	0.3	5	5	5	R	MRMS	R
Preston	17	71	44	2.3	5.6	2.1	10	15	20	MRMS	MRMS	MRMS
Scepter	72	244	155	6.3	15.7	6.3	20	30	20	MS	MSS	MS
Scout	25	82	58	0.5	4.2	0.8	5	10	5	RMR	MRMS	MRMS
Shield	0	102	3	0.3	4.9	0.1	1	10	1	R	MRMS	R
Spitfire	97	334	178	6.7	24.0	7.2	15	30	20	MRMS	MS	MRMS
Steel	0	0	6	0.0	0.0	0.3	1	0	5	R	I	MRMS
Sunguard	5	123	12	1.1	6.7	0.4	5	20	5	R	MRMS	R
Bolac	82	304	136	4.8	18.6	4.9	10	30	10	MRMS	MS	MRMS
Suntop	4	2	22	0.4	0.7	0.1	5	5	5	R	MR	MR
Supreme	58	340	124	5.6	27.4	7.0	20	40	30	MRMS	MSS	MRMS
Trojan	63	152	112	5.7	12.0	3.8	20	20	20	MRMS	MS	MRMS
Viking	48	304	69	2.6	17.7	1.4	5	30	5	MR	MSS	MR
Wallup	166	273	204	10.7	14.6	7.6	30	30	30	MRMS	MS	MRMS
Westonia	362	1029	510	26.9	76.7	20.3	50	80	50	MSS	S	MS
Wyalkatchem	592	756	591	45.5	67.9	27.8	60	80	50	MSS	S	MSS
Yitpi	86	158	160	7.2	8.9	6.8	30	20	30	MRMS	MS	MRMS
Zen	180	342	169	17.5	30.3	6.7	30	40	20	MSS	MSS	MRMS

I: immune, R: resistant, RMR: resistant to moderately resistant, MR: moderately resistant, MRMS: moderately resistant to moderately susceptible, MS: moderately susceptible, MSS: moderately susceptible to susceptible, S: susceptible, NJ1: 2019 off-season in Njoro, NJ2: 2019 main-season in Njoro, NJ3: 2020 off-season in Njoro.

Supplementary (S) table 6. Means of yield performance for 61 bread wheat genotypes evaluated for resistance to stem rust and yellow rust over three seasons at KALRO, Njoro.

	Grain yield			Biomass			Harvest index			Kernels spike^{-1}		
	t ha^{-1}											
Genotype	NJ1	NJ2	NJ3	NJ1	NJ2	NJ3	NJ1	NJ2	NJ3	NJ1	NJ2	NJ3
Cacuke	2.40	0.67	2.48	11.1	6.9	9.9	0.22	0.13	0.22	41	40	41
Kenya Robin	1.28	0.57	0.72	14.2	5.9	14.1	0.10	0.10	0.03	48	47	51
Coolah	1.57	0.78	1.35	16.4	8.5	16.2	0.10	0.09	0.08	37	36	36
Chara	0.79	0.57	1.05	13.0	7.1	13.1	0.06	0.08	0.08	36	40	36
LRPB Flanker	1.94	0.81	0.83	16.9	11.3	17.4	0.16	0.08	0.04	42	40	42
LRPB Reliant	3.34	1.10	3.68	21.4	6.6	19.2	0.16	0.16	0.19	49	43	49
Ninja	0.32	0.45	0.75	10.1	6.8	10.1	0.03	0.07	0.06	31	33	33
Tenfour	0.60	0.59	0.39	11.8	5.1	13.2	0.10	0.13	0.07	42	39	38
Tungsten	0.71	0.41	0.64	12.3	7.5	12.3	0.06	0.06	0.06	39	39	38
Axe	2.83	0.94	2.40	11.0	6.8	10.5	0.26	0.14	0.25	39	38	38
B53	1.64	0.46	1.64	13.9	4.7	13.8	0.15	0.10	0.14	41	41	39
Beckom	2.38	0.96	1.94	11.7	5.3	12.1	0.20	0.19	0.17	44	41	41
Bremer	0.72	0.40	1.14	18.2	6.8	18.2	0.05	0.06	0.08	32	33	34
Buchanan	1.76	0.93	1.54	11.0	9.0	10.9	0.18	0.11	0.14	36	35	37
Calingiri	0.61	0.38	1.04	11.2	6.1	11.1	0.06	0.06	0.12	34	33	33
Cobalt	0.69	0.50	1.20	10.0	6.1	10.0	0.07	0.09	0.13	31	36	29
Cobra	2.13	0.78	2.21	20.5	6.2	19.1	0.10	0.12	0.12	32	34	33
Condo	3.01	1.14	2.37	11.4	5.9	11.1	0.27	0.20	0.23	50	48	48
Corack	1.73	1.02	1.45	13.9	4.6	13.9	0.14	0.28	0.15	36	34	36
Correll	1.95	0.40	1.67	15.7	9.1	16.8	0.13	0.04	0.10	29	29	30
Cosmick	0.23	0.34	0.58	9.4	4.3	9.7	0.02	0.08	0.11	32	32	33
Cutlass	0.91	0.45	1.19	16.5	9.3	17.0	0.07	0.04	0.07	28	28	30
Dart	3.32	1.00	3.05	8.5	6.3	9.0	0.48	0.14	0.38	43	42	44
Derrimut	2.51	1.18	2.74	14.7	10.6	14.5	0.18	0.12	0.21	44	44	41
EGA Bounty	3.07	1.46	3.19	12.9	9.1	11.6	0.27	0.17	0.32	38	38	39
EGA Gregory	2.39	0.87	2.22	15.5	10.8	16.3	0.15	0.08	0.13	35	34	35
Baxter	3.45	1.73	3.63	17.9	8.8	18.2	0.20	0.21	0.20	46	45	36
Emu Rock	2.28	0.95	1.96	13.5	5.7	15.1	0.18	0.17	0.14	30	30	28
Espada	3.16	1.24	3.11	17.2	10.5	17.6	0.18	0.11	0.19	44	43	42
Estoc	2.26	0.83	2.29	20.5	9.0	19.2	0.12	0.09	0.14	38	38	41
Forrest	1.41	0.50	1.53	16.0	10.2	16.0	0.09	0.05	0.08	32	33	32
Gauntlet	2.79	1.33	4.21	16.0	8.9	14.8	0.20	0.16	0.33	43	43	50

Table S6. Cont'd

Gazelle	0.41	0.30	0.64	13.2	6.6	13.6	0.06	0.04	0.06	36	36	36
Sunmax	0.58	1.10	0.85	31.2	11.7	25.5	0.02	0.09	0.03	51	51	49
Janz	3.19	1.15	3.23	17.2	8.2	16.7	0.19	0.14	0.20	37	36	36
Kiora	1.79	0.76	1.75	21.3	9.8	21.4	0.08	0.08	0.08	43	43	43
Lancer	3.86	2.44	4.86	16.0	12.6	13.9	0.74	0.20	0.41	38	38	47
Livingston	2.65	1.69	1.57	13.0	7.3	12.9	0.22	0.23	0.13	44	44	44
Mace	2.79	0.68	2.90	13.6	5.2	13.4	0.22	0.14	0.21	37	37	38
Magenta	4.93	1.81	5.94	16.8	9.1	14.7	0.31	0.20	0.45	42	41	50
Merlin	4.02	1.23	4.38	14.9	7.6	13.3	0.39	0.17	0.48	38	37	45
Mitch	0.68	0.66	0.95	12.4	7.4	11.8	0.05	0.09	0.07	46	42	47
Orion	1.34	0.56	1.55	11.7	7.0	9.2	0.15	0.09	0.18	29	28	35
Gladius	3.28	1.44	3.40	19.7	10.6	19.2	0.18	0.13	0.19	40	39	40
Preston	0.14	0.37	0.78	7.0	3.9	7.5	0.01	0.09	0.07	35	34	31
Scepter	3.60	1.81	4.25	15.5	10.4	14.6	0.23	0.18	0.29	38	37	43
Scout	1.26	0.61	1.50	12.8	7.4	12.0	0.10	0.08	0.10	43	42	45
Shield	3.07	1.13	3.54	18.1	7.8	15.8	0.19	0.15	0.23	45	43	47
Spitfire	3.86	1.36	4.48	13.5	7.5	10.6	0.31	0.18	0.43	40	40	44
Steel	1.20	0.77	1.18	10.8	10.2	11.8	0.10	0.08	0.08	53	53	51
Sunguard	3.64	1.63	4.73	20.9	10.5	15.8	0.19	0.15	0.33	43	41	51
Bolac	2.25	1.05	2.08	24.8	7.4	20.2	0.10	0.15	0.11	37	36	37
Suntop	3.10	1.52	3.91	13.7	14.1	13.1	0.26	0.10	0.32	38	37	43
Supreme	1.61	0.62	1.43	6.8	5.9	9.3	0.28	0.11	0.15	37	37	34
Trojan	1.65	0.87	1.77	14.4	7.4	14.0	0.12	0.12	0.13	38	38	38
Viking	2.97	1.29	3.18	16.1	9.6	16.5	0.21	0.14	0.23	34	33	34
Wallup	2.28	1.22	2.37	13.0	8.2	12.6	0.19	0.15	0.21	38	38	35
Westonia	0.66	0.73	1.18	6.4	4.9	7.0	0.12	0.15	0.20	28	27	29
Wyalkatchem	0.35	0.41	0.35	8.1	2.8	9.1	0.07	0.16	0.05	24	22	22
Yitpi	0.26	0.81	0.26	16.3	7.5	16.5	0.02	0.11	0.01	33	33	32
Zen	0.81	0.39	0.69	10.4	5.0	10.7	0.08	0.09	0.07	33	32	30

NJ1: 2019 off-season in Njoro, NJ2: 2019 main-season in Njoro, NJ3: 2020 off-season in Njoro.

Table S6. Cont'd

Genotype	Days to heading			Plant height			Spike length			1000-kernel weight			Test weight		
						cm					g			kg hL^{-1}	
	NJ1	NJ2	NJ3	NJ1	NJ2	NJ3	NJ1	NJ2	NJ3	NJ1	NJ2	NJ3	NJ1	NJ2	NJ3
Cacuke	59	60	68	78.0	75.4	86.9	11.1	10.7	10.6	32.5	14.7	23.6	64.6	55.4	43.9
Kenya Robin	69	72	72	77.3	86.3	93.2	12.3	11.2	10.8	20.1	10.9	13.6	56.2	45.2	50.9
Coolah	78	81	81	82.7	81.7	82.7	10.6	10.4	9.0	18.6	13.7	18.4	62.1	56.8	52.8
Chara	76	77	84	76.3	65.9	71.4	9.4	8.5	7.6	13.1	9.2	12.0	56.6	49.4	45.9
LRPB Flanker	75	79	81	81.2	89.1	90.5	10.4	10.5	9.8	19.5	10.7	17.7	67.9	48.5	65.4
LRPB Reliant	76	79	80	95.6	84.3	89.3	10.5	10.1	9.9	22.9	16.8	24.3	71.8	66.9	75.4
Ninja	79	81	78	66.6	72.0	80.1	9.3	9.5	9.5	12.7	10.2	12.6	40.7	42.0	45.4
Tenfour	51	54	60	62.6	65.9	67.3	7.0	8.1	7.7	15.6	13.1	9.7	56.2	48.7	38.0
Tungsten	73	78	88	76.6	71.5	76.6	9.6	9.2	9.3	17.9	10.2	13.5	52.0	47.9	41.8
Axe	52	56	62	69.5	69.0	71.7	8.4	7.6	6.9	27.9	16.8	18.4	67.9	54.1	63.1
B53	74	78	83	81.1	75.0	90.3	10.7	9.2	8.5	17.6	8.4	16.4	59.4	52.0	51.8
Beckom	71	75	75	68.7	67.1	65.5	8.1	7.6	7.4	17.9	14.2	16.2	68.5	59.8	67.4
Bremer	74	77	85	78.4	73.2	78.3	9.8	8.9	8.9	16.5	8.2	17.0	58.4	46.8	53.6
Buchanan	70	73	69	87.8	86.3	84.3	9.9	10.0	8.5	21.9	13.4	14.6	62.7	52.8	54.5
Calingiri	81	83	94	81.6	72.7	73.2	8.9	8.5	8.3	14.4	8.9	13.0	51.0	42.7	41.2
Cobalt	69	72	67	79.8	80.4	81.5	10.4	9.9	9.3	14.5	9.5	13.9	56.3	52.7	45.1
Cobra	73	81	87	76.7	63.9	72.4	10.5	8.8	9.1	18.7	12.7	16.7	61.0	57.4	55.0
Condo	71	70	63	76.3	72.4	75.0	9.8	9.2	9.3	27.6	14.6	22.2	69.2	61.2	65.3
Corack	66	68	75	72.7	60.8	64.9	8.5	7.6	7.8	22.0	13.4	20.3	65.0	60.1	59.0
Correll	72	74	77	80.8	71.9	76.7	8.7	8.7	7.9	23.6	9.1	23.0	58.8	39.0	53.4
Cosmick	68	72	73	79.5	69.6	83.4	9.2	8.1	8.6	12.8	9.4	12.0	47.9	46.7	48.0
Cutlass	79	84	101	84.0	79.8	80.5	10.1	9.7	9.2	14.5	9.2	14.6	54.2	48.2	45.0
Dart	51	54	57	70.2	69.1	69.0	8.7	8.8	8.3	24.5	15.5	23.9	72.5	61.3	72.6
Derrimut	62	67	72	72.3	67.4	70.2	7.3	7.4	6.4	24.7	15.7	21.3	72.9	63.9	66.5
EGA Bounty	65	66	76	90.9	86.8	89.6	11.7	10.0	10.2	27.7	15.7	28.9	74.8	59.7	76.1
EGA Gregory	80	83	85	86.9	85.4	90.7	10.5	10.4	9.3	22.9	11.9	22.0	71.2	55.0	64.6
Baxter	69	74	79	73.7	79.1	85.3	9.0	8.8	8.6	24.4	16.3	22.6	75.3	69.0	73.7
Emu Rock	57	60	57	66.9	58.7	58.5	7.6	6.9	7.1	23.0	15.3	19.7	64.5	54.8	41.5
Espada	66	70	66	71.4	70.6	76.3	7.9	8.3	7.9	24.6	15.0	24.4	71.0	54.8	62.5
Estoc	72	74	85	67.7	71.1	73.0	7.8	8.4	7.9	21.4	12.3	21.3	66.4	51.2	55.8
Forrest	82	84	97	67.8	71.6	70.8	11.4	10.2	8.9	18.7	9.6	16.8	63.1	41.8	51.9
Gauntlet	77	75	77	72.0	66.9	69.5	9.1	8.9	8.1	23.2	17.3	30.6	74.5	68.7	81.0
Gazelle	74	76	87	84.4	69.8	77.6	9.2	8.7	8.8	11.4	7.2	11.2	47.8	37.6	35.3

Table S6. Cont'd

Sunmax	79	82	97	87.0	80.1	90.8	10.7	10.6	10.6	10.7	12.4	10.8	47.5	53.9	43.6
Janz	64	69	82	78.2	74.2	73.7	8.6	8.3	8.5	24.0	13.0	22.5	74.2	69.2	67.0
Kiora	69	72	77	76.8	81.5	80.5	9.3	8.7	8.5	16.5	12.9	15.8	63.4	59.6	60.1
Lancer	76	78	84	70.4	69.2	66.1	8.3	9.0	8.1	25.4	20.8	26.4	77.4	70.9	80.2
Livingston	53	57	70	69.3	72.3	72.5	7.4	8.1	8.6	31.4	20.9	29.6	74.5	67.2	61.4
Mace	70	74	82	70.5	65.2	74.6	8.8	8.2	8.2	25.9	12.7	23.5	69.8	59.2	69.2
Magenta	68	77	76	80.1	71.8	78.8	8.6	8.7	9.1	31.2	19.2	33.3	76.4	69.6	80.0
Merlin	64	66	62	73.0	72.4	74.9	8.5	8.2	8.6	28.6	18.9	31.9	77.1	66.0	77.8
Mitch	73	78	84	82.5	76.0	78.4	11.3	9.6	9.4	12.0	10.3	17.9	48.1	46.2	53.7
Orion	71	75	81	83.3	74.1	99.0	10.6	9.8	9.8	20.0	14.3	18.8	57.1	51.7	56.6
Gladius	65	69	61	73.4	75.9	71.4	7.6	8.1	7.5	27.4	19.3	24.7	69.4	61.6	67.5
Preston	70	72	71	69.9	68.1	75.6	8.7	8.0	8.3	13.5	11.6	11.1	50.3	48.3	28.6
Scepter	50	55	67	66.4	73.0	78.5	8.0	8.9	8.5	32.9	23.9	34.3	71.4	70.6	80.6
Scout	72	76	81	74.0	73.9	79.8	9.6	8.9	8.9	19.7	10.5	20.6	67.6	51.5	57.6
Shield	74	79	83	73.3	67.6	72.8	8.0	8.1	7.6	26.3	15.2	26.2	71.2	56.4	66.2
Spitfire	62	65	62	78.2	70.7	70.3	8.5	8.5	8.3	27.8	18.0	30.6	76.1	69.7	74.0
Steel	73	77	78	80.9	84.5	89.5	9.4	9.8	8.5	16.3	9.0	16.8	59.8	43.7	56.4
Sunguard	77	82	90	80.4	75.9	77.2	8.1	8.3	8.2	23.3	24.1	33.1	73.1	76.1	78.8
Bolac	72	76	80	78.5	73.3	82.1	8.5	8.7	8.1	19.0	15.7	16.5	65.5	65.6	66.1
Suntop	66	69	70	76.1	91.1	92.6	9.9	10.0	9.2	26.5	18.8	28.4	73.2	68.1	76.6
Supreme	54	59	73	63.6	57.7	59.9	8.6	8.2	7.9	20.9	13.8	18.2	67.5	57.3	51.8
Trojan	74	78	85	77.2	69.9	72.2	10.1	9.1	8.6	17.0	11.7	17.0	65.8	56.0	58.2
Viking	71	75	78	83.4	74.0	86.1	9.5	8.8	9.1	22.0	16.7	20.8	72.2	66.1	64.5
Wallup	61	62	60	79.1	70.6	70.1	8.6	8.4	8.0	21.6	17.8	22.5	68.3	65.1	59.6
Westonia	60	63	61	72.6	71.6	73.5	9.9	8.3	9.2	20.9	15.9	19.3	70.9	64.7	51.1
Wyalkatchem	61	62	58	66.1	50.1	50.0	7.5	6.7	6.3	14.7	13.0	11.5	60.4	56.7	36.1
Yitpi	71	74	76	75.0	78.6	80.5	9.9	9.5	9.5	12.8	15.1	13.9	64.8	64.4	43.4
Zen	83	84	84	69.2	64.3	73.3	7.4	7.7	7.2	13.6	8.6	11.4	60.9	47.0	40.0

NJ1: 2019 off-season in Njoro, NJ2: 2019 main-season in Njoro, NJ3: 2020 off-season in Njoro.

Supplementary (S) table 7. Superiority measure (P_i) and mean squares (MS) of genotype-by-season interaction (GSI) of AUDPC for 61 bread wheat genotypes evaluated for resistance to stem rust over three seasons at KALRO, Njoro and one season at DZARC, Debre Zeit and resistance to yellow rust over three seasons at KALRO, Njoro.

Stem rust					Yellow rust				
	Genotype	Mean	P_i	MS(GSI)		Genotype	Mean	P_i	MS(GSI)
Rank[a]	Minimum response	8	0.20	0.19	Rank[a]	Minimum response	6	0.07	0.07
1	Lancer	9	0.20	0.19	1	Sunmax	10	0.07	0.07
2	Sunguard	8	0.32	0.21	2	Steel	7	1.08	0.75
3	Gauntlet	20	3.64*	1.56	3	Gladius	6	2.43	0.10
4	Shield	80	28.61*	4.83*	4	Lancer	14	3.93*	2.95
5	Magenta	132	50.69*	1.56	5	LRPB Flanker	9	4.32*	1.06
6	Sunmax	155	55.78*	4.88*	6	Suntop	17	4.69*	1.57
7	Janz	165	58.89*	2.95*	7	Gazelle	43	15.57*	0.75
8	Spitfire	166	64.25*	2.86*	8	Shield	33	17.53*	13.52*
9	Forrest	215	78.98*	9.98*	9	Axe	39	18.39*	0.43
10	Dart	222	80.88*	2.25*	10	EGA Gregory	57	19.40*	0.11
11	Merlin	208	83.29*	1.95	11	Coolah	43	19.43*	8.87*
12	Scepter	225	85.25*	7.91*	12	Buchanan	81	21.88*	1.90
13	Bolac	225	89.64*	21.96*	13	Preston	59	21.89*	2.25
14	Estoc	235	92.28*	10.63*	14	Sunguard	43	23.24*	11.37*
15	Cutlas	247	93.22*	40.11*	15	Cutlas	67	23.71*	17.99*
16	Yitpi	253	94.88*	15.43*	16	Tenfour	63	24.10*	2.22
17	Emu Rock	250	98.75*	2.21	17	Derrimut	60	25.34*	2.64
18	Corack	277	109.84*	4.59*	18	Scout	64	27.36*	2.15
19	Beckom	286	111.69*	6.52*	19	Tungsten	70	28.12*	1.11
20	LRPB Reliant	285	113.38*	9.41*	20	Correll	76	33.39*	2.05
21	Espada	300	114.33*	7.40*	21	Cobalt	133	38.11*	8.68*
22	Baxter	337	130.03*	29.41*	22	Magenta	56	39.56*	0.55
23	Kiora	343	131.85*	11.32*	23	Estoc	81	41.21*	4.31*
24	EGA Bounty	331	137.23*	20.22*	24	Espada	97	42.23*	13.24*
25	Supreme	367	144.48*	30.61*	25	Trojan	111	54.23*	2.44
26	Cobra	355	147.01*	38.32*	26	Robin	119	55.64*	7.75*
27	Gladius	347	149.59*	23.73*	27	Forrest	121	62.21*	15.79*
28	Orion	366	151.45*	9.66*	28	Kiora	146	66.56*	12.04*
29	Derrimut	375	154.39*	17.36*	29	Yitpi	156	67.24*	1.85
30	EGA Gregory	397	159.15*	7.46*	30	Gauntlet	136	68.76*	7.43*
31	Viking	383	159.29*	8.75*	31	Janz	140	69.07*	10.14*
32	Mace	386	164.95*	11.78*	32	Viking	128	70.06*	16.32*
33	Trojan	388	165.13*	10.36*	33	Calingiri	161	78.00*	5.00*
34	Wallup	430	180.08*	8.54*	34	Scepter	173	78.35*	6.38*
35	Wyalkatchem	456	186.31*	7.31*	35	Baxter	166	82.10*	10.91*
36	Livingston	512	216.72*	24.88*	36	Bremer	188	83.82*	14.77*
37	Zen	542	227.45*	4.00*	37	Bolac	190	86.71*	9.22*
38	Chara	542	230.60*	14.30*	38	Supreme	185	86.92*	15.25*
39	Westonia	566	236.24*	25.72*	39	Merlin	182	90.77*	4.01*
40	Tungsten	570	248.10*	25.92*	40	Mitch	191	95.92*	4.14*
41	Coolah	594	257.14*	5.21*	41	Spitfire	195	101.37*	8.95*
42	LRPB Flanker	608	261.23*	4.93*	42	Ninja	217	102.79*	31.95*
43	Suntop	643	277.19*	0.40	43	Wallup	214	107.02*	1.67
44	Axe	619	278.05*	9.74*	44	Livingston	219	111.77*	20.31*
45	Calingiri	660	284.70*	11.05*	45	Zen	233	114.84*	4.71*
46	Scout	652	286.63*	0.49	46	EGA Bounty	252	122.55*	35.36*
47	Gazelle	708	310.69*	51.79*	47	Chara	257	126.22*	8.67*

Supplementary (S) table 7.

48	Ninja	757	321.56*	11.16*	48	LRPB Reliant	285	132.80*	27.28*
49	Condo	743	323.56*	12.74*	49	Cobra	306	148.18*	34.56*
50	Correll	749	329.14*	9.43*	50	Cacuke	321	150.80*	13.09*
51	Bremer	748	336.76*	64.85*	51	Dart	312	150.97*	2.16
52	B53	773	341.62*	6.04*	52	Beckom	334	161.34*	8.90*
53	Preston	874	360.29*	21.45*	53	Orion	326	163.47*	13.14*
54	Cosmick	826	364.47*	22.91*	54	B53	341	167.73*	29.55*
55	Mitch	832	370.81*	10.48*	55	Cosmick	339	168.59*	24.33*
56	Buchanan	1082	471.30*	4.57*	56	Condo	378	179.82*	7.64*
57	Cobalt	1079	491.12*	9.30*	57	Corack	444	206.22*	25.31*
58	Steel	1098	495.29*	7.68*	58	Emu Rock	431	207.58*	6.95*
59	Cacuke	1183	550.07*	27.41*	59	Mace	493	245.37*	10.43*
60	Robin	1339	623.98*	17.88*	60	Westonia	633	316.46*	22.78*
61	Tenfour	1402	657.28*	22.31*	61	Wyalkatchem	650	323.02*	1.68

AUDPC: area under disease progress curve, [a]Ranking of genotypes is based on Pi values.