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Stripe Rust Partial Resistance Increases Spring Bread Wheat Yield in South-eastern Anatolia, Turkey

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Abstract

Stripe rust caused by *Puccinia striiformis* f.sp. *tritici* is the most serious disease of wheat globally including south-eastern Anatolia of Turkey, where wheat originated. In this study, 12 spring wheat genotypes were artificially inoculated and preserved in two locations, Diyarbakır and Adıyaman, during the 2011–2012 season to investigate loss in yield and yield components. Genotypes were evaluated at the adult plant stage using two partial resistance parameters: final disease severity and area under the disease progress curve (AUDPC). AUDPC ranged from 14.8 to 860 in Diyarbakır, and 74 to 760 in Adıyaman. Yield loss ranged from 0.6 to 68.5% in Diyarbakır and 9.8 to 56.8% in Adıyaman. Genotypes G1, G5, G7 and G8 were found to lose less yield, while higher yield loss was observed in G3, G4 (Nurkent), G5 and G9 (Karacadağ-98). The highest loss in thousand kernel weight was observed in a susceptible cultivar Karacadağ-98 in Diyarbakır followed by 43.4 and 24.4% in Adıyaman. Test weight loss reached 8.89% in Diyarbakır and 20.8% in Adıyaman. Yield loss and AUDPC had a positive significant relationship. Based on the values of AUDPC, final disease severity and yield loss, three major clusters were formed for 12 wheat genotypes. Partially resistant genotypes were found to lose less grain yield and seemed to be stronger against severe stripe rust pressure.

Introduction

Wheat is the largest cultivated crop in 27 developing countries including Turkey (Rharrabti et al. 2003) and provides more than half the calorie and nearly half the protein requirements for one-third of the world's population (Dixon et al. 2009). Common diseases limiting wheat yield are leaf (*Puccinia triticina*), stem (*P. graminis* f.sp. *tritici)* and stripe (*P. striiformis* f.sp. *tritici*) rusts. Rust diseases damage the respiratory system, kill foliar parts, stunt growth, reduce yield and worsen quality (Line 2002; Chen 2005). Among rusts, widely distributed stripe rust has become the most threatening wheat disease due to the emergence of aggressive races in the near Himalayan (Hovmøller et al. 2015). Stripe rust causes severe yield loss across the world (Dusunceli et al. 1996; Morgounov et al. 2012). Reduction in wheat grain yield leads to severe economic losses up to 60% under favourable conditions for stripe rust induction (Chen 2005). The south-east of Turkey has a critical role in preventing the spread of wheat stripe rust throughout Turkey as these fungal pathogens first arrive in this region from the Middle East and Africa. This inoculum is then carried north through wind and causes severe rust epidemics (Morgounov et al. 2012).

Yield loss caused by stripe rust depends on several factors such as cultivar susceptibility, infection time, disease development rate and disease duration (Chen 2005). Stripe rust can cause 90–100% grain yield loss (Afzal et al. 2007) if infection occurs at an early stage and remains on susceptible cultivars for a long time under favourable conditions. Therefore, resistant cultivars are economically and environmentally the safest way of managing stripe rust (Singh et al. 2004).

During the 2009–2010 season, a stripe rust epidemic swept across West and Central Asia. Syria and Turkey were most affected countries and they lost half of their wheat harvest in 2010, followed by Ethiopia (45%), Morocco and Uzbekistan (35%) (Yahyaoui and Rajaram 2012). During the 1995–96 season, a similar rust epidemic in Cukurova region, Turkey, decreased yield by 50% (Dusunceli et al. 1996). Rust epidemics in China (Wan et al. 2004), Pakistan and Iran (Bimb and Johnson 1997) caused serious yield losses across different wheat-growing seasons. Singh et al. (2004) reported that rust diseases decreased grain yield in the susceptible cultivars by more than 50%. Similarly, a negative relationship was found to exist between yield, yield components and final disease severity (FDS) (Ali et al. 2007), which suggested that disease pressure significantly affects the yield.

Several yellow rust epidemics that have occurred in Turkey within the last few decades have resulted in more than 10–30% crop losses and an estimated national grain loss of 1–2 million tons (Anonymous 2010). In 2009–2010, stripe rust attacked all of the aboveground portions of wheat grown in Turkey (Aktaş et al. 2012a) causing 50–60% yield loss (1.5–2 million tons) in the south-east of Turkey (Aktas et al. 2012b). During this period, most Turkish wheat cultivars, including some ICARDA and CIMMYT genotypes with different resistant genes, became sensitive (Anonymous 2010). After this epidemic, the farmers in the region realized the importance of resistant cultivars and started to use chemical pesticides even in the absence of rust epidemics.

The aim of this study was to evaluate the reaction and partial resistance level of four commercial cultivars and eight breeding lines against stripe rust under field conditions based on the parameters of grain yield, thousand kernel weight (TKW), test weight (TW) and protein content under protected and infected conditions.

Material and Methods

Plant material

The plant material was 12 wheat genotypes (Table 1) consisting of eight advanced breeding lines, two highly susceptible cultivars (Nurkent and Karacadağ-98) and two commonly grown moderate-resistant cultivars (Cemre and Sagittario). Susceptible cultivar Morocco was filler around for sufficient stripe rust pressures on the experiments.

Table 1 Spring wheat genotypes used in the study including their pedigrees and origins

Genotypes	Pedigree	Origin
G1	MUNIA//CHEN/ALTAR84/3/CHEN/AE. SQUARROSA(TAUS)//BCN	CIMMYT
G2	ZCL/3/PGFN//CNO67/SON64(ES86-8)/ 4/SERI/5/UA-2837/6/BABAX/7/F10S-1	CIMMYT
G3	SITE/MO/4/NAC/TH.AC//3*PVN/3/MIRLO/BUC	CIMMYT
G4	NURKENT	TURKEY
G5	SPN/NAC//ATTİLA	CIMMYT
G6	SHUHA-7//SERI82/SHUHA ‘S2	ICARDA
G7	WH542//GALVEZ/WEAVER	CIMMYT
G8	CEMRE	TURKEY
G9	KARACADAĞ-98	TURKEY
G10	SUNCO/2*PASTOR	CIMMYT
G11	RRNEMSET 0506 QT4118 MX	CIMMYT
G12	SAGITTARIO	ITALY

Field experiments

During the 2011–2012 season, two experiments were performed under infected (experiment 1) and protected (experiment 2) conditions. Yield loss was measured under rainfall conditions in the following two locations in south-eastern Anatolia, Turkey: GAP International Agricultural Research and Training Center in Diyarbakır, and a farmer field in Adıyaman. Diyarbakır is at 37°54′N latitude, 40°14′E longitude and 660 m asl, and Adıyaman is located at 38°11′N latitude, 39°14′E longitude and 669 m asl. The mean rainfall was 580 mm in Diyarbakır and 498 mm in Adıyaman, during 2011–12 cropping season. For the experiments, a randomized block design was used with four replicates. Infected and protected plots (control plots) genotypes were sown into six rows of 1.2 × 5 m using a sowing machine leaving 20 cm between the rows. The seedling rate was 400 seed/m^2. Optimum nutrient (160 N: 80 P: 0 K) was applied.

Stripe rust inoculation and evaluation

In both locations, for experiment 1, the plots were artificially inoculated with equal doses of the mixed inoculum of urediniospores of *P. striiformis tritici (Pst)* collected from different locations in the south-east of Turkey. This pathogen is virulent to stripe rust resistance genes: *Yr2, Yr6, Yr6+1, Yr7, Yr9, Yr18, Yr-20, YrA, APR, Yr27, Yr28, Yr29, Yr31* and *Yr32.* These genes were determined by an international yellow rust standard differential set. The inoculum was collected during the 2009–2010 season when a severe yield and quality loss occurred on a 1.3-million ha of wheat acreage in the region. Artificial inoculation was performed with a mix containing 250 mg uredin-iospores suspended in one litre of distilled water and two drops of Tween-20 (Roelfs et al. 1992). Starting from the tillering stage, Zadoks 29 (Zadoks et al. 1974), plots were inoculated twice a week until flowering time (Zadoks 61).

For experiment 2, the plots in both locations were protected by the fungicide Opera® (containing 12.5% active ingredients, pyraclostrobin and epoxiconazole; Nufarm Ltd, Laverton North, Vic.) at the concentration and rate recommended by the manufacturer. The fungicide was applied to the plots in Diyarbakır and Adıyaman on 20 March and 2 April 2012 and resulted in complete protection.

Partial resistance parameters, namely area under the disease progress curve (AUDPC) and final rust severity, were evaluated in both locations. The stripe rust severity data were recorded on 19th and 26th April and 4th May, at 7-day intervals following the modified Cobb's scale (Peterson et al. 1948). The first observation was made when the severity of the susceptible spreader cultivar Morocco was 50% and then repeated twice more every 7 days until it reached 90%. Area under the disease progress curve was calculated using the method described by Bjarko and Line (1988) and the computer programme developed at CIMMYT.

The yield loss due to stripe rust was determined based on AUDPC, which was calculated by the trapezoidal integration of the disease severity in time considering the whole period observed as follows:

$$\mathrm{AUDPC} = \sum_{i=1}^{n-1} \left(1 \frac{X_i + X_{i+1}}{2} \right) (t_{i+1} - t_1)$$

where X is the disease severity (percentage of plants diseased), n is the number of observations and (t_{i+1} – t_i; ti = time (day) at the ith observation) represents the time interval (days) between two consecutive observations (Campbell and Madden 1990).

The relative loss was determined based on grain yield, TKW and TW as the percentage of the protected plots of the respective genotypes. Yield loss for each genotype was calculated as follows:

$$\mathrm{RL}(\%) = \frac{(\mathrm{Y1} - \mathrm{Y2})}{\mathrm{Y1}} \times 100$$

where RL (%) is the relative loss (reduction in the grain yield, TKW and TW), Y1 is the mean value of the respective parameter in the protected plots and Y2 is the mean value of the respective parameter in the unprotected plots.

TKW (g), TW (kg/hl) and grain yield (kg/ha) were recorded according to Taye et al. (2015) and protein content (%) was calculated following the standard procedure of AACC-39-10 (Anonymous 1990).

Statistical analyses

Combined analysis of variance based on random complete block design (RCBD), correlation and regression analyses were carried out using SAS (1999) version 8.2. Comparison of the means was calculated by LSD test ($P < 0.01$ and $P < 0.05$).

Results

Reaction of wheat genotypes to artificial stripe rust infection

In infected plots, the reaction of genotypes to stripe rust varied, while the protected plots were almost free from stripe rust in both locations (Table 2). Disease severity ranged from 5 to 90% in Diyarbakır (Table 2) with the lowest values being obtained from G1, G6 and G7 (5MR) followed by G10 and G12 (10MR and 20MS, respectively). In Adıyaman, disease severity ranged from 10 to 90% (Table 2) with the lowest reaction observed in G1 (10MS) followed by G10 (20MR) and G2, G6, G7, Cemre and Sagittario (20MS). The remaining genotypes had a higher range of disease severity from 30 to 90%. G6, which had the lowest severity (5MR) in Diyarbakır, was found to be susceptible to infection in Adıyaman (20%).

Data for AUDPC

In both experimental locations, the genotypes with the highest AUDPC had the highest yield loss, while those with the lowest AUDPC less yield loss (Table 2). In Diyarbakır, the highest AUDPC was found in Nurkent, Karacadağ-98, G3 and G5 with the values of 860, 825, 810 and 455, respectively. G2, G11 and Sagittario had moderate values of AUDPC (324, 202 and 162, respectively). The lowest values of AUDPC were 14.8, 14.8, 14.8, 37.0 and 38.4 observed in G1, G6, G7, G10 and G8, respectively. In Adıyaman, AUDPC ranged from 74 to 740. The highest AUDPC was seen in G4, G3, G9 and G5 with the values of 740, 690, 690 and 590, respectively, while G2, G6, G11, G10, G12 and Sagittario had moderate and G1, G6, G7 and G8 had the lowest AUDPC value. In both locations, the genotypes were divided into low, moderate and high partial resistance groups according to their AUDPC value.

Table 2 Partial resistance traits and grain yield of spring wheat genotypes in Diyarbakır and Adıyaman during the 2011–12 season

	Diyarbakır							Adıyaman						
	Protected experiment Grain yield (kg/ha)	Infected experiment Grain yield (kg/ha)	FDS (%)	Reaction type	AUDPC	Yield loss (kg/ha)	Yield loss (%)	Protected experiment Yield (kg/ha)	Infected experiment Yield (kg/ha)	FDS (%)	Reaction type	AUDPC	Yield loss (kg/ha)	Yield loss (%)
G1	5490	5460 ac	5	MR	14.8	30	0.6	5250 c	4410 a	10	MS	76.8	840	16.0
G2	5720	3750 e	40	MS	324	1970	34.4	4470 d	4030 ac	20	MS	162	440	9.8
G3	5830	2010 f	80	S	810	3820	65.5	5670 bc	2860 ef	80	S	690	2810	49.6
G4	6580	2120 f	90	S	860	4460	67.8	6280 ab	2710 f	90	S	740	3570	56.8
G5	5260	4240 e	50	S	455	1020	19.4	5440 c	3230 de	60	S	590	2210	40.6
G6	6460	5750 a	5	MR	14.8	710	11.1	6320 a	4330 ab	20	MS	162	1990	31.5
G7	5140	4990 cd	5	MR	14.8	150	2.9	5180 c	3650 cd	20	MS	162	1530	29.5
G8	5650	5100 bd	10	10MR	38.4	550	9.8	5460 c	3870 bc	20	MS	162	1590	29.1
G9	6510	2050 f	90	S	825	4460	68.5	5070 cd	2700 f	80	S	690	2370	46.7
G10	5910	5520 ab	10	MR	37	390	6.7	5330 c	3610 cd	20	MR	74	1720	32.3
G11	6330	4850 d	30	MS	202	1480	23.4	5280 c	3620 cd	30	S	355	1660	31.4
G12	5440	4140 e	20	MS	162	1300	23.9	5250 c	3690 cd	20	MS	162	1560	29.7
Mean	5861 a	4164 b				1697	29	5416 a	3559 b				1858	34
LSD	1010 ns	503**						639**	473**					
CV (%)	11.9	8.4						8.1	9.24					

G 1-12, genotype; TW, test weight (kg/hl); FDS, final disease severity; *significant at level 0.05; **significant at the level 0.01; MR, moderately resistant MS, moderately sensitive; S, susceptible; AUDPC, area under disease progress curve. Different letter indicate different statistical group.

Relationship between AUDPC and percentages of loss in grain yield, TKW and TW

A positive and significant relationship (Figs 1 and 2) was found between AUDPC and grain yield loss (%) in both Diyarbakır and Adıyaman (R^2 = 0.92 and 0.71). Furthermore, in Diyarbakır and Adıyaman, AUDPC had a high correlation with TKW loss (R^2 = 0.92 and 0.65, respectively; Figs 3 and 4) and a significant relationship with TW loss (R^2 = 0.45 and 0.62, respectively; Figs. 5 and 6). The highest loss in grain yield was observed in the genotypes with the highest disease severity and AUDPC.

Grain yield loss caused by stripe rust

In Diyarbakır, the grain yield loss (%) ranged from 0.6 to 68.5% (Table 2). G3, G4 and G9 had the highest percentage of grain yield loss (65.5, 67.8 and 68.5%, respectively), followed by G2, G5, G11 and G12 (34.4, 19.4, 23.4 and 23.9%, respectively). The lowest yield loss was obtained from G1 (0.6%), G6 (11.1%), G7 (2.91%), G8 (9.8%) and G10 (6.7%). In Adıyaman, the yield loss ranged from 9.8 to 56.8% with the highest loss obtained from genotypes G3, G4, G5 and G9 (49.6, 56.8, 40.6 and 46.7%, respectively), followed by G6, G7, G8, G10, G11 and G12 (31.5, 29.5, 29.1, 32.1, 31.4 and 29.7%, respectively). The lowest yield loss was observed in G1 (16%) and G2 (9.8%).

TKW and TW loss caused by stripe rust

In Diyarbakır and Adıyaman, TKW decreased by 0.64 to 43.4% and 0.3 to 24.4%, respectively, with the highest percentages of loss obtained from genotypes G3, G4 and G9 in both locations. G5, G7, G10 and G11 had a moderate loss of TKW ranging from 4.5 to

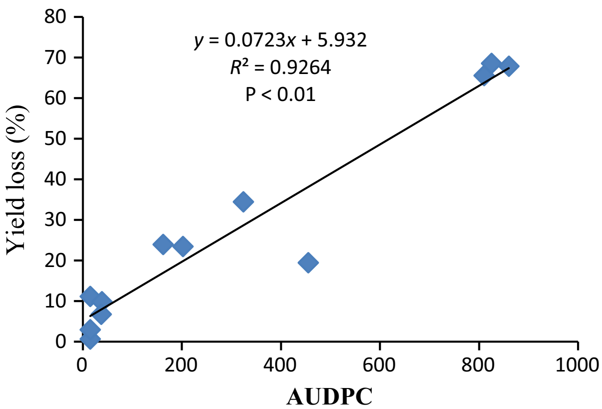

Fig. 1 Regression graph showing the relationship between AUDPC and grain yield loss (%) in Diyarbakır. [Colour figure can be viewed at wileyonlinelibrary.com].

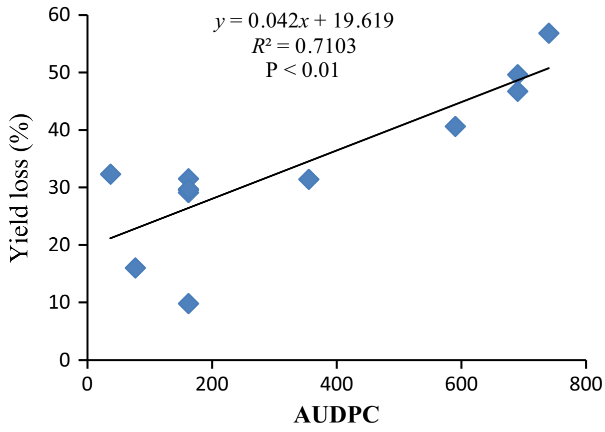

Fig. 2 Regression graph showing the relationship between AUDPC and grain yield loss in Adiyaman. [Colour figure can be viewed at wileyonlinelibrary.com].

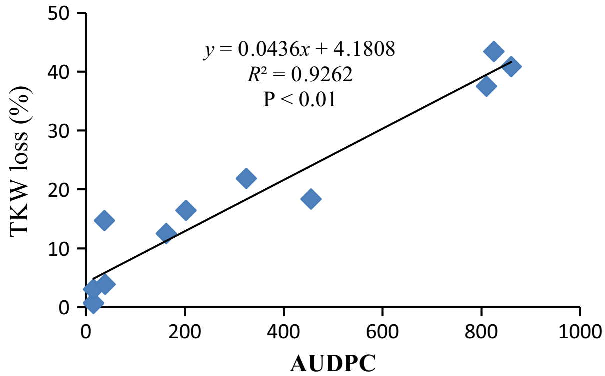

Fig. 3 Regression graph showing the relationship between AUDPC and TKW loss (%) in Diyarbakır. [Colour figure can be viewed at wileyonlinelibrary.com].

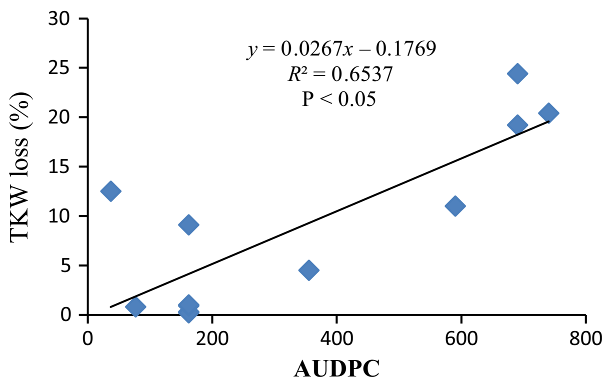

Fig. 4 Regression graph showing the relationship between AUDPC and TKW loss (%) in Adiyaman. [Colour figure can be viewed at wileyonlinelibrary.com].

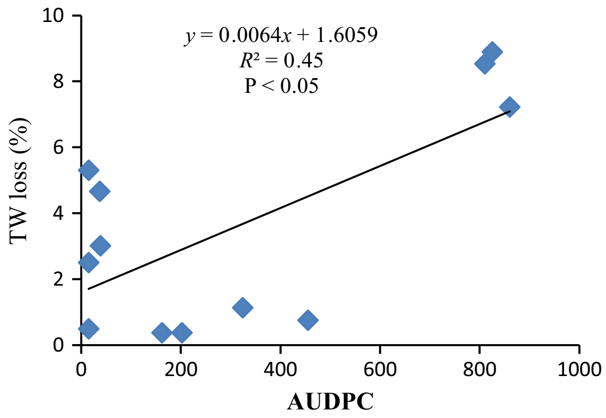

Fig. 5 Regression graph showing the relationship between AUDPC and TW loss (%) in Diyarbakir. [Colour figure can be viewed at wileyonlinelibrary.com].

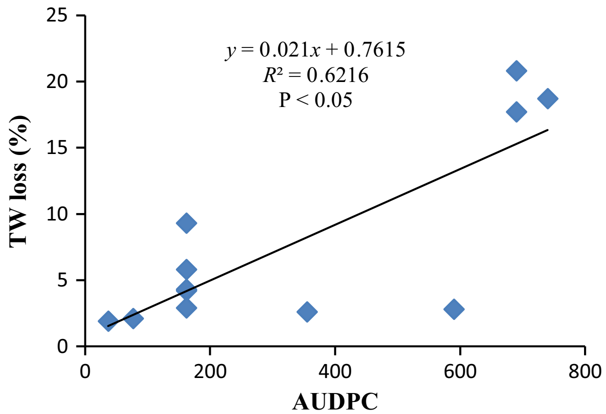

Fig. 6 Regression graph showing the relationship between AUDPC and TW loss (%) in Adıyaman. [Colour figure can be viewed at wileyonlinelibrary.com].

12.5%, while G1, G2, G6, G8 and G1 had the lowest TKW loss varying between 0.3 and 1% (Table 3).

In Diyarbakır, TW loss ranged from 0.37 to 8.89% with G3, G4 and G9 having the highest loss at the percentages of 8.53, 7.22 and 8.89, respectively, followed by G7 and G10 (5.30 and 4.66%, respectively). The remaining genotypes had lower TW loss ranging from 0.37 to 2.5% (Table 4). In Adıyaman, TW loss ranged from 1.9 to 20.8% with the highest value obtained from G2, G3, G4 and G9 (9.3, 20.8, 18.7 and 17.7%, respectively). G6, G7 and G8 had a moderate TW loss and the remaining genotypes had the lowest TW loss ranging from 1.9 to 2.9% (Table 4).

Effect of stripe rust on grain protein content

In this study, grain protein content increased (Table 5) in parallel with the increase in genotypes' susceptibility to stripe rust. Grain protein contents of susceptible genotypes G3, Nurkent and Karacadağ-98 in infected plots were 6.3, 5 and 2.3%, respectively, and were higher than protected plots. In Adıyaman, the highest grain protein contents were found in susceptible genotypes, G4, G9, G11 and G3 at the values of 25, 8.4, 8.1 and 5.5%, respectively, in comparison with control genotypes.

Cluster analysis based on AUDPC, FDS and grain yield loss

Cluster analysis on wheat genotypes formed three major clusters based on AUDPC, FDS and percentage of grain yield loss in both locations (Figs. 7 and 8). In Diyarbakır, G1, G6, G7, Cemre and G10 were in the first cluster; G2, G5, G11 and G12 were in the second cluster; and G3, Nurkent and Karacadağ-98 were in the third cluster. In Adıyaman, G1 and G2 were in the first cluster; G6, Sagittario, G7, Cemre, G10 and G11 were in the second cluster; and G3, Nurkent, G5 and Karacadağ-98 were in the third cluster. The genotypes located in the first, second and third clusters can be considered to have high partial resistance – low yield loss, moderate partial resistance – moderate yield loss and low partial resistance – high yield loss, respectively.

Discussion

Reaction of wheat genotypes to artificial stripe rust infection

Stripe rust is one of the most destructive wheat diseases causing severe yield losses (Wan et al. 2004; Chen 2005). In this study, the genotypes had different reaction and severity levels (90%) against stripe rust in the infected plots in Diyarbakır and Adıyaman, while the protected plots remained almost free from stripe rust in both locations (Table 2). Variability among the wheat genotypes under the pressure of stripe rust may be attributed to their diverse genetic background.

In both locations, G1, G6, G7, Cemre, G10 and G12 showed the lowest rust severity from 5 to 20%, while disease severity of the most susceptible genotypes (Nurkent and Karacadağ-98) was high at 90%. Similarly, Aktaş et al. (2012a) reported that during the 2009–2010 season, Nurkent and Karacadağ-98 were the most susceptible genotypes and Cemre was moderately resistant. The results concerning the susceptible Nurkent and Karacadağ-98 cultivars being similar is due to the inoculum source of the present study belonging to the 2009–2010 season. Most cultivars

Table 3 Partial resistance traits and thousand kernel weight of spring wheat genotypes in Diyarbakır and Adıyaman during the 2011–12 season

	Diyarbakır							Adıyaman						
	Protected experiment TKW (g)	Infected experiment TKW (g)	FDS (%)	Reaction type	AUDPC	TKW loss (g)	TKW loss (%)	Protected experiment TKW (g)	Infected experiment TKW (g)	FDS (%)	Reaction type	AUDPC	TKW loss (g)	TKW loss (%)
G1	33.3 ef	33.0 b	5	MR	14.8	0.2	0.73	37.4 b	37.1 b	10	MS	76.8	0.30	0.8
G2	34.0 de	26.5 f	40	MS	324	7.4	21.85	36.7 cd	36.6 b	20	MS	162	0.10	0.3
G3	32.3 f	20.2 g	80	S	810	12.1	37.50	36.7 bc	29.7 e	80	S	690	7.03	19.2
G4	32.3 f	19.1 g	90	S	860	13.2	40.84	35.8 cd	28.5 e	90	S	740	7.33	20.4
G5	36.4 ab	29.7 e	50	S	455	6.7	18.36	36.7 bc	32.6 d	60	S	590	4.03	11.0
G6	36.0 bc	35.7 a	5	MR	14.8	0.2	0.64	39.3 a	39.2 a	20	MS	162	0.07	0.2
G7	32.4 f	31.4 d	5	MR	14.8	1.0	3.05	35.8 cd	32.5 d	20	MS	162	3.28	9.1
G8	34.0 de	32.7 bc	10	10MR	38.4	1.3	3.88	35.0 de	34.7 c	20	MS	162	0.32	0.9
G9	34.5 d	19.5 g	90	S	825	15.0	43.40	34.0 e	25.7 f	80	S	690	8.30	24.4
G10	37.1 a	31.6 cd	10	MR	37	5.5	14.70	37.4 b	32.7 d	20	MR	74	4.68	12.5
G11	35.0 cd	29.3 e	30	MS	202	5.8	16.43	34.0 e	32.5 d	30	S	355	1.53	4.5
G12	37.1 a	32.4 cd	20	MS	162	4.6	12.51	37.5 bc	37.1 b	20	MS	162	0.38	1.0
Mean	34.5 a	28.5 b				6.1	17.6	36.4 a	33.2 b				3.11	8.6
LSD	1.2**	1.1**						1.14**	1.8**					
CV (%)	2.3	2.7						2.2	3.6					

G 1-12, genotype; TKW, test kernel weight (g); FDS, final disease severity; *significant at the level 0.05; **significant at the level 0.01; MR, moderately resistant; MS, moderately sensitive; S, susceptible; AUDPC, area under disease progress curve. Different letter indicate different statistical group.

Table 4 Partial resistance traits and test weight of spring wheat genotypes in Diyarbakır and Adıyaman during the 2011–12 season

	Diyarbakır							Adıyaman						
	Protected experiment TW (kg/hl)	Infected experiment TW (kg/hl)	FDS (%)	Reaction type	AUDPC	TW loss (kg/hl)	TW loss (%)	Protected experiment TW (kg/hl)	Infected experiment TW (kg/hl)	FDS (%)	Reaction type	AUDPC	TW loss (g)	TW loss (%)
G1	81.5 ab	81.1 a	5	MR	14.8	0.4	0.49	80.6 ab	78.9 a	10	MS	76.8	1.7	2.1
G2	79.7 d	78.8 bc	40	MS	324	0.9	1.13	77.7 fg	70.5 f	20	MS	162	7.2	9.3
G3	82.1 a	75.1 ef	80	S	810	7	8.53	81.2 a	64.3 h	80	S	690	16.9	20.8
G4	80.3 cd	74.5 f	90	S	860	5.8	7.22	77.5 g	63.0 l	90	S	740	14.5	18.7
G5	80.4 cd	79.8 ab	50	S	455	0.6	0.75	79.6 d	77.4 b	60	S	590	2.2	2.8
G6	79.9 d	77.9 cd	5	MR	14.8	2	2.50	78.5 e	75.2 de	20	MS	162	3.3	4.2
G7	81.2 ac	76.9 de	5	MR	14.8	4.3	5.30	79.7 cd	76.3 c	20	MS	162	3.4	4.3
G8	79.7 d	77.3 cd	10	10MR	38.4	2.4	3.01	79.7 cd	75.1 e	20	MS	162	4.6	5.8
G9	82.1 a	74.8 f	90	S	825	7.3	8.89	80.3 bc	66.1 g	80	S	690	14.2	17.7
G10	81.6 a	77.8 cd	10	MR	37	3.8	4.66	79.3 d	77.8 b	20	MR	74	1.5	1.9
G11	80.6 bc	80.3 ab	30	MS	202	0.3	0.37	80.8 ab	78.7 a	30	S	355	2.1	2.6
G12	80.1 d	79.8 ab	20	MS	162	0.3	0.37	78.3 ef	76.0 cd	20	MS	162	2.3	2.9
Mean	80.8 a	77.8 b				2.9	3.6	79.4 a	73.3 b				6.2	7.8
LSD	1.14**	1.82*						1.1**	0.82**					
CV (%)	2.2	1.6						2.3	1.1					

G 1-12, genotype; TW, test weight (kg/hl); FDS, final disease severity; *significant at the level 0.05; **significant at the level 0.01; MR, moderately resistant MS, moderately sensitive; S, susceptible; AUDPC, area under disease progress curve. Different letter indicate different statistical group.

with different genes resistant to stripe rust became sensitive due to the strong epidemics of the 2009–2010 growing season in the south-east of Turkey (Aktas et al. 2012b; Mert et al. 2014). It was reported by earlier researchers (Hodson and Nazari 2010; Morgounov et al. 2012) that severe outbreaks occurred across Central and West Asia and North Africa in 2009 and 2010 wheat-growing seasons.

Stripe rust severity and reaction of G6, G7 and Cemre were found to be low in Diyarbakır (5MR, 5MR, and 10MR, respectively), while the same genotypes had a higher disease severity and reaction in

Table 5 Effect of stripe rust infection on grain protein content in Diyarbakır and Adıyaman during the 2011–12 season

	Diyarbakır				Adıyaman			
Genotypes	FDS (%)	Protected experiment PC (%)	Infected experiment PC (%)	Change in PC (%)	FDS (%)	Protected experiment PC (%)	Infected experiment PC (%)	Change in PC (%)
G1	5MR	10.28 de	10.56 ef	+ 2.7	10MS	10.48 de	11.20 ce	+ 6.7
G2	40MS	10.62 ce	10.66 de	+ 0.3	20MS	10.42 de	10.47 g	+ 0.5
G3	80S	11.11 bd	11.81 b	+ 6.3	80S	10.08 e	10.64 fg	+ 5.6
G4	90S	11.01 bd	11.56 bc	+ 5.0	90S	10.08 e	12.61 a	+ 25
G5	50S	11.86 ab	11.18 ce	− 5.7	60S	11.77 ab	11.41 be	− 3.1
G6	5MR	11.02 bd	11.10 ce	+ 0.7	20S	10.31 de	11.04 df	+ 7.1
G7	5MR	11.65 ab	11.56 bc	− 0.8	10MR	11.15 ad	10.91 eg	− 2.2
G8	10MR	11.45 bc	11.43 bc	+ 0.1	10MR	11.47 ac	11.95 b	+ 7.2
G9	90S	12.50 a	12.79 a	+ 2.3	80S	10.82 ce	11.73 bc	+ 8.4
G10	10MR	9.77 e	9.95 f	+ 1.8	20MR	11.23 ad	11.74 b	+ 4.5
G11	30MS	11.00 bd	11.19 bd	+ 1.7	30S	10.94 be	11.84 b	+ 8.2
G12	20MS	11.21 bc	11.02 ce	+ 1.7	20MS	11.98 a	11.51 bd	+ 3.9
Mean		11.12 a	11.23 a	+ 0.99		10.90 a	11.43 b	+ 4.9
$LSD_{(genotype)}$		0.9**	0.62**			0.94**	0.54**	
CV (%)		4.5	3.8			4.3	3.2	

PC, protein content; *significant at the level 0.05; **significant at the level 0.01; FDS, final disease severity. Different letter indicate different statistical group.

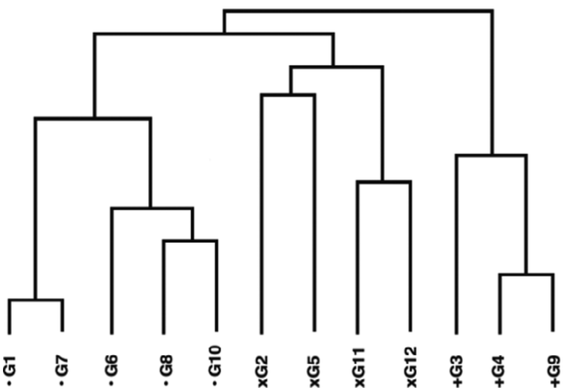

Fig. 7 Dendrogram of similarity index cluster analysis of wheat genotypes based on AUDPC, final disease severity and yield loss in Diyarbakır.

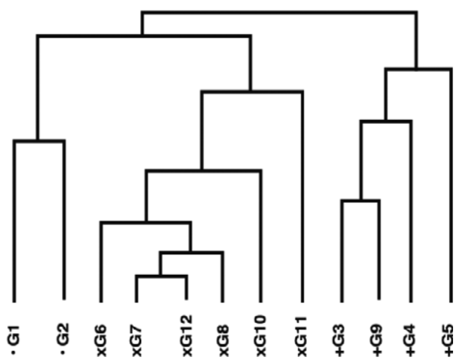

Fig. 8 Dendrogram of similarity index cluster analysis of wheat genotypes based on AUDPC, final disease severity and yield loss in Adıyaman.

Adıyaman (20S, 20MS, and 20MS, respectively). These results may indicate that Adıyaman was more suitable for stripe rust development or different stripe rust races were present. Similarly, Herrera-Foessel et al. (2007) reported that final disease severities of all slow-rusting resistant wheat genotypes were higher at El Batán than in the two field experiments at Ciudad Obregón due to a more favourable environment for the development of the disease in the former location. Several researchers have also suggested that environmental factors play an important role in the spread of stripe rust (Chen 2005; Dereje and Fininsa 2007; Zeng and Luo 2008; Milus et al. 2009).

Relationship between AUDPC, yield and yield components

Generally, the genotypes with the highest AUDPC lost the highest yield, while those with the lowest AUDPC had the lowest lost in both locations (Table 2). Susceptible genotypes (Nurkent and Karacadağ-98) had the highest AUDPC and yield loss in both locations. According to our results, the genotypes were clustered into low, moderate and high AUDPC groups. Area under the disease progress curve reached 860 in Diyarbakır and 690 in Adıyaman. Several authors indicated that cultivars with lower AUDPC usually had less yield loss; on the other hand, higher AUDPC values resulted in higher grain yield loss (Ochoa and Parlevliet 2007; Irfaq et al. 2009).

The results of regression analysis showed a positive and statistically significant relationship between AUDPC and percentage of grain yield, TKW and TW loss. A 250-unit increase in AUDPC for stripe rust resulted in a 5.2% yield loss in Diyarbakır (R^2 = 92%; Fig. 1.), while a 200-unit increase incurred a 22% yield loss in Adıyaman (R^2 = 66%; Fig. 2). Similarly, Ali et al. (2008) found a positive relationship between yield loss and AUDPC (R^2 = 0.94) and Ahmad et al. (2010) reported that AUDPC for leaf rust increased the yield and yield component loss reflecting a positive and highly significant relationship between yield loss and AUDPC (for yield, R^2 = 0.78; for TKW, R^2 = 0.81). Furthermore, Poudyal and Chen (2010) reported that wheat genotypes with higher partial resistance prevent significant yield loss.

Effect of stripe rust on yield and yield components

The susceptible cultivars with the highest AUDPC values, Nurkent and Karacadağ-98 had a yield loss of about 65.8 and 56.8% in Diyarbakır and Adıyaman, respectively, while the partially and moderately partial resistant genotypes G1, G6, G7, Cemre and G10 with lower AUDPC values had less than 12% yield loss in both locations. The synthetic-derived wheat genotype G1 (Munia//Chen/Altar84/3/Chen/Ae.Squarrosa (Taus)//Bcn) had lower disease severity, AUDPC value and yield loss in both locations. Several authors agree that synthetic wheat carries different resistant genes against biotic and abiotic stress including rust diseases (Hussain et al. 1999; Rizwan et al. 2007). Increased AUDPC and disease severity cause greater yield loss (Afzal et al. 2007; Asmmawy et al. 2013; Taye et al. 2015). Yield loss is strongly correlated with AUDPC, which means that partial resistance prevents significant yield loss (Ahmad et al. 2010).

In the present study, higher AUDPC and disease severity resulted in a decrease in TKW and TW in both locations. The higher loss in TKW and TW reached 40.8 and 8.89% in Diyarbakır, 20.4 and 20.8% in Adıyaman, respectively. The highest TKW and TW loss occurred in Nurkent, G3 and Karacadağ-98 in both locations. Similarly, Safavi (2015) reported a TKW loss of 40.1% in the susceptible cultivar Morocco and a TW loss of 19% in susceptible genotypes (Everts et al. 2001). Stripe and leaf rust decreased the photosynthesis area and consequently lowered the percentages of yield and yield components (Herrera-Foessel et al. 2007). Decreased TW reduced flour yield loss and profitability in the flour industry. Stripe rust results in reduced TW, TKW and flour yield, but increases grain protein content (Ozberk et al. 2006).

Our findings were similar to those reported by other researchers in that stripe rust may cause grain yield loss up to 40–78% under normal conditions and 84% under favourable conditions for stripe rust (Padmakar et al. 2001; Singh and Tewari 2001; Chen 2005; Safavi et al. 2012).

Effect of stripe rust on grain protein content

In the present study, the genotypes with higher disease severity and AUDPC were found to have higher protein content. Compared to the protected plots, grain protein content of the most susceptible genotypes G3, Nurkent and Karacadağ-98 in the infected plots was significantly higher in Diyarbakır and Adıyaman locations (Table 5). Similarly, Dereje and Fininsa (2007) reported an increase in grain protein content of severely rusted plots. However, this was not an advantage due to the high infection resulting in shriveled kernels. Decreased photosynthesis reduced starch biosynthesis and seed size (Hailu 2003; Devadas et al. 2014). In contrast to our results, Kumar and Raghavaiah (2004) reported that when leaf and stripe rust covered or killed the flag leaf area, grain-filling period is shortened, which resulted in lowered protein content in kernels.

Cluster analysis based on the three parameters

A cluster analysis was performed on the data based on two partial resistance parameters (AUDPC and final disease severity) and yield loss percentage (Figs 7 and 8). A significant diversity was observed for partial resistance among the wheat genotypes, most likely due to their different genetic backgrounds. In both locations, the genotypes were divided into three major groups (Figs 7 and 8). In Diyarbakır, G1, G6, G7, Cemre and G10 were in the first group, which had a higher level of partial resistance and lower yield loss than susceptible genotypes (Nurkent and Karacadağ-98). Genotypes G2, G5, G11 and Sagittario remained in the second cluster, which had a moderately partial resistance, and genotypes G3, Nurkent and Karacadağ-98 were in the third cluster, which had a lower level of partial resistance and a higher yield loss. The results were similar in Adıyaman except for the cluster position of certain genotypes such as G5 and G2. The first cluster in Adıyaman consisted of G1 and G2, the second cluster contained G6, G7, Cemre, G10, G11 and G12, and the last group comprised G3, Nurkent, G5 and Karacadağ-98. The third group had a highest yield loss per cent and a lowest level of partial resistance in Adıyaman. Similarly, Ali et al. (2008) grouped Pakistani breeding lines against stripe rust pressure into three clusters. Some genotypes remained in the same group, while some others were in different groups in different locations. In Diyarbakır, G2 and G5 were in the moderately partially resistant group, whereas in Adıyaman, G2 was in the partially resistant group and G5 was in the low partially resistant group. This was most likely due to the effect of environmental differences on genotypes in terms of rust development. Milus et al. (2009) similarly reported that environmental factors were important for the level of stripe rust pressure. Previously, Ali et al. (2007) demonstrated the presence of a varying degree of partial resistance to stripe rust in the lines tested against slow rusting. Safavi (2015) observed a considerable diversity in slow-rusting resistance (partial resistance) among the Iranian genotypes.

Conclusion

The genotypes with higher partial resistance to stripe rust were found to result in a negligible yield loss, whereas those with high disease severity and AUDPC caused serious loss in grain yield. In this study, the genotypes fell into one of the three groups: the first group with low partial resistance consisted of Nurkent, Karacadağ-98, G3 and G5 and had the highest AUDPC and yield loss. The second group with moderate partial resistance (moderate rusting) contained G2, G11 and G12, which displayed a moderately high level of AUDPC and the last group with high partial resistance (slow rusting) comprised genotypes G1, G6, G7 and G10 and displayed the lowest AUDPC values. Genotypes G1, G6, G7 and Cemre seemed to be better resistant to stripe rust than Nurkent and Karacadağ-98.

Using genotypes with low partial resistance (fast rusting) or high AUDPC values could cause significant yield loss under intensive stripe rust epidemics. Improving slow-rusting genotypes can greatly contribute to local and international food security. Therefore, plant breeding departments should focus on improving slow stripe rusting cultivars.

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