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Effects of environment on epidemics of yellow rust (*Puccinia striiformis* West.) of bread wheat (*Triticum aestivum* L.) in Bale highlands, South-Eastern Ethiopia

[1]Wubishet Alemu T, [2]Chemeda Fininsa G, [3]Bekele Hundie E

[1]Oromia Agricultural Research Institute, Sinana Agricultural Research Centre,
P.O. Box 208, Bale-Robe, Ethiopia
[2]Department of Plant Sciences, Haramaya University, P.O. Box 138, Dire Dawa, Ethiopia
[3]Ethiopian Institute of Agricultural Research, Kulumsa Agricultural Research Centre,
P.O. Box 32, Asella, Ethiopia

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Abstract

Bread wheat is one of the most important cereal crops cultivated in south-eastern Ethiopia. However, the regional wheat production is threatened by yellow rust, which is caused by *Puccinia striiformis* f.sp. *tritic*i. A field experiment was conducted to assess the effects of environment on wheat yellow rust epidemics and wheat varieties' yellow rust resistance at three locations in 2012. Six bread wheat varieties having different levels of resistance to yellow rust were used. Plots were arranged in randomized complete block design in three replications. Yellow rust incidence was significantly different among the highly susceptible variety Kubsa, the resistant and moderately resistant varieties at all locations. There was significant difference ($p \leq 0.05$) in the overall mean of yellow rust severity among the varieties. Yellow rust severity of up to 16.7, 41.9 and 55.5% was recorded on the susceptible variety Kubsa at Agarfa, Ginir and Sinana, respectively. Area under disease progress curve values and disease progress rate exhibited significant difference between the susceptible and resistant varieties. Environmental variability had a significant effect on epidemic development of yellow rust through its effect on growth and progress rate of the pathogen. Yellow rust has now extended its adaptation to lower and warmer altitudes where it did not exist before.

Keywords: AUDPC, environment, epidemics, Puccinia striiformis, resistance, severity, yellow rust

INTRODUCTION

Bread wheat (*Triticum aestivum* L.) is one of the most widely grown and most consumed food crops all over the world. Annually, wheat is produced on 224.53 million hectares of land and 672.2 million metric tons of wheat is produced in the world (USDA, 2010). According to this report the world average wheat production is 2.99 tons /ha. Wheat is largely grown in the highlands of Ethiopia and constitutes 24.6% of the annual cereal production and plays an important role in supplying the population with various nutritional advantages (CSA, 2010/11). Wheat is grown at an altitude ranging from 1500 to 3000 (m.a.s.l.), between 6-16^{o} N latitude and 35-42^{o} E longitude in Ethiopia. The most suitable agro-ecological zones, however, fall between 1900 and 2700 m.a.s.l. (Bekele et al., 2000).

Yellow or stripe rust, caused by *Puccinia striiformis* Westend*.* f.sp*. tritici,* probably occurred long before wheat was grown for food, but Gadd from Europe first described it in 1777 (Eriksson and Henning 1896). Hassebrauk (1965), Stubbs (1985), Line (2002), Li and Zeng (2003) were among those who reported yellow rust and its distributions around the world. Currently, yellow rust of wheat has been reported in more than 60 countries of the world. Yellow rust can cause 100% yield loss if infection occurs very early and the disease continues to develop during the growing season on susceptible cultivars. In most wheat producing areas of

Corresponding author. Email: wubtesema@gmail.com , Mobile: +251-913091568

Table 1. Characteristic features of bread wheat yellow rust experimental sites in Bale highlands, South-eastern Ethiopia

Sites	Location	Altitude (m.a.s.l.)	Total annual rainfall (mm)	Seasonal total rainfall (mm)	Mean minimum temperature (^oC)	Mean maximum temperature (^oC)	Cropping system
Ginir	07^o 15′ N, 40^o 66′ E	1972	600 - 1000	531	13.4	25.5	Monocropping
Sinana	07^o 07′ N, 40^o 10′ E	2400	750 - 1400	562 - 842	9.8	21	Double cropping
Agarfa	07^o 26′ N, 39^o 87′ E	2514	1000 - 1451	434 - 852	7.3	22.8	Double cropping

the world, yield losses due to yellow rust have ranged from 10-70% depending upon the susceptibility of cultivar, earliness of the initial infection, rate of disease development and duration of the disease (Chen, 2005). Yellow rust is an important disease of bread wheat in the highlands of Ethiopia at altitudes ranging from 2150 to 2850 m above sea level. In south-eastern part of Ethiopia, yellow rust is a major threat to wheat production resulting in high yield and quality losses (Mulugeta, 1986; Bekele et al., 2002; Dereje, 2003). Grain yield loss of 71, 28 and 12% on susceptible, moderately resistant and resistant varieties, respectively, were recorded (Dereje, 2003). Epidemics of yellow rust have become more frequent and widespread at higher elevations in south-eastern Ethiopia due to varietal susceptibility, frequent production of mega cultivars, expansion of wheat monocropping, introduction and development of new virulent races and favourable environmental factors prevailing disease development.

Yellow rust used to be limited mainly to high altitude and cooler areas but has now extended its adaptation to lower altitudes and warmer conditions. In recent years, new high temperature tolerant and aggressive strains of yellow rust have occurred in warmer areas (Hovmoller et al., 2008; Milus et al., 2009). Changes in atmospheric composition and the physical climatic factors, including temperature, rainfall pattern and intensity, and humidity with no doubt affect the economic importance, geographical distribution and management of rusts of wheat ultimately affecting wheat production. In Bale highlands, yellow rust has now widened its adaptation from higher, cooler to lower and warmer altitudes. It is now becoming a major threat in areas where it did not exist before.. Therefore, this study was conducted with the objectives to (1) assess the effect of environment on wheat yellow rust epidemics and (2) assess the effect of environment on wheat varieties' yellow rust resistance.

MATERIALS AND METHODS

Field experiments were conducted at three locations; at Sinana Agricultural Research Center (SARC) experimental field station and at Agarfa and Ginir farmers' field under rain fed conditions during the main cropping season in 2012. SARC and Agarfa are located in cool, sub-humid agro climatic zone, while Ginir is in the midlands of Bale, south-eastern Oromia regional state of Ethiopia. SARC and Agarfa experience a bimodal rainfall with reliable two seasons' crop growing period where wheat monocropping is predominant. The two seasons are locally named after the time of crop harvest. The main season, locally called *Bona,* extends from August to December and the other second season, locally called *Ganna* extends from March to July. Ginir experience a mono cropping season (main season) that extends from September to January.

SARC is located at 07^o 07′ N latitude and 40^o 10′ E longitude at 2400 m above sea level. The annual total rainfall ranges from 750 to 1400 mm. The main season receives 270 to 842 mm rainfall, while the short season receives from 250 to 562 mm. The mean annual minimum and maximum temperatures are 9.8 and 21 ^oC, respectively. The soil type is dominated by pellic vertisol which is slightly acidic. Agarfa is located around 07^o 26′ N latitude and 39^o 87′ E longitude at 2514 m above sea level. Its annual total rainfall ranges from 1000 to 1451 mm. Mean annual minimum and maximum temperatures are 7.3 and 22.8 ^oC, respectively. The soil type is pellic vertisol. Ginir is located at 07^o 15′ N latitude and 40^o 66′ E longitude at 1972 m above sea level. The seasonal rainfall is 531 mm and its mean annual minimum and maximum temperatures are 13.4 and 25.5 ^oC, respectively. The soil type is vertisol.

Treatments, Experimental Design and Management

Six bread wheat varieties namely, Madda Walabu (HAR-1480), Digalu (SHA 7/ KAUZ or HAR 3116), Sofumar (HAR-1889), Kubsa (HAR 1685), Millennium (ETBW-4921) and Dure (HAR-1008) currently under production and having different level of resistance to yellow rust were used. Kubsa is highly susceptible to yellow rust while Dure and Millennium are susceptible and moderately susceptible, respectively. Madda Walabu and Digalu are late maturing varieties and resistant to yellow rust while Sofumar is moderately resistant. Other wheat diseases, such as leaf rust (*Puccinia triticina* f.sp. *tritici*), septoria (*Stagonospora nodorum*) and powdery mildew (*Blumeria graminis* f.sp. *tritici*) are not important on bread wheat in Bale. Yellow rust was allowed to develop naturally in each variety without any artificial inoculation.

The experiment was laid out in randomized complete block design in three replications at the three locations.

Table 2. Characteristic features of bread wheat test varieties for assessing epidemics of yell]ow rust in Bale highlands

Variety	Pedigree	Yield at time of release (ton ha^{-1})		Year of release	Releasing Center	Reaction to rusts		
		Research field	Farmers Field			Yellow rust	Stem rust	Leaf rust
Madda Walabu	HAR-1480	4.2	3.14	2000	SARC	R	S	R
Digalu	SHA 7/KAUZ or HAR-3116	4.0	3.1	2005	KARC	R	MS	R
Sofumar	HAR-1889	3.8	NA	2000	SARC	MR	MR	R
Millennium	ETBW-4921	4.42	3.2	2007	KARC	MS	MR	R
Dure	HAR-1008	3.5	2.97	2001	SARC	S	MS	MS
Kubsa	HAR-1685	5.8 - 6.3	4 - 4.5	1995	KARC	S	S	MS

R= resistant, MR= moderately resistant, MS= moderately susceptible, S= susceptible, NA= Not available
Source: Ministry of Agriculture. Animal and Plant Health Regulatory Directorate. Crop Variety Register. 1995-2007. Addis Ababa, Ethiopia.

Eight-rowed plots of 1.6 m x 5 m and 0.2 m spacing between rows were used. Each plot was spaced 1 m apart and distance between blocks was 1.5 m. Seed rate of 150 kg ha^{-1} was used. Plots were sown manually in rows on 8 August 2012 at Agarfa, on 29 August 2012 at Sinana and on 22 September 2012 at Ginir. At planting, recommended rates of 41 kg ha^{-1} N and 46 kg ha^{-1} P_2O_5 were applied. Land preparation was done manually by using rake after tractor plough. Weeds were removed manually two times at the three locations. Plots were harvested on 2 January 2013 at Agarfa, on 27 January 2013 at Ginir and on 30 January 2013 at Sinana.

Disease Assessment

Yellow rust incidence, expressed as percentage of leaves of the main stems of the ten plants that exhibited any symptom of yellow rust, was assessed from each plot. Disease incidence was assessed once at flowering stage (GS 61-69) to distinguish yellow rust development among the varieties.

Yellow rust severity was assessed at ten days interval by estimating the approximate percentage of leaf area affected using modified Cobb scale (Peterson et al., 1948) on all tillers of 10 randomly selected plants of the central rows of each plot starting from the disease appearance. During disease assessment, the growth stage of the crop was recorded to observe onset and progress of the disease in relation to wheat phenology. Crop growth stage was assessed based on the decimalized key developed by Zadoks et al. (1974). The ten randomly selected plants were tagged with colored thread before the disease appearance. After flag leaf emergence (7 and 28 October 2012 at Agarfa and Sinana, respectively, and 20 November 2012 at Ginir), yellow rust severity was assessed at 10 days interval on flag (F) and penultimate (F-1) leaves of the main stems of the ten random plants in each plot. Disease severity was assessed seven times on all tillers and five times on both flag and penultimate leaves at Sinana and six times on all tillers and 5 times on both flag and penultimate leaves at Agarfa. Similarly, five times on all tillers and four times on both flag and penultimate leaves at Ginir. For all assessments, yellow rust severity was averaged for the ten plants in each plot. Yellow rust head (spike) infection was assessed on 14 December 2012 at Sinana and 1 January 2013 at Ginir on spikes of five random main stems from each plot using 0-5 scale where 0 = no disease symptom on the spike and 5 = 100% of the spike infected by yellow rust. At Agarfa there was no head infection by yellow rust and hence data was not collected.

The field severity score and response for the yellow rust was converted into coefficient of infection (CI) by multiplying severity with constant value for field response as described by Stubbs et al. (1986), Roelf et al. (1992), Yadav (1985).

Meteorological Data

Weather data like daily maximum and minimum temperature (^{o}C) and daily precipitation (mm) were collected from Sinana Agricultural Research Center and Ginir Meteorology Stations. Since Agarfa Technical, Vocational, Education and Training (TVET) College meteorology station was not fully functional in the season, daily maximum and minimum temperatures data were not collected. Instead, only daily precipitation was collected. The weekly mean maximum and minimum temperature and monthly total rainfall distribution of the seasons were presented in (Figure 1 to 3).

Analysis of Disease Progress

The integral models, i.e. area under the disease progress curve (AUDPC), and growth curve functions were used. AUDPC values were calculated for each plot using the following formula (Wilcoxson et al., 1975).

AUDPC = $\sum_{i=1}^{n-1}[0.5(X_{i+1}+X_i)][t_{i+1}-t_i]$

Where x_i is the disease severity expressed in percentage at i^{th} observation, t_i is the time (days after

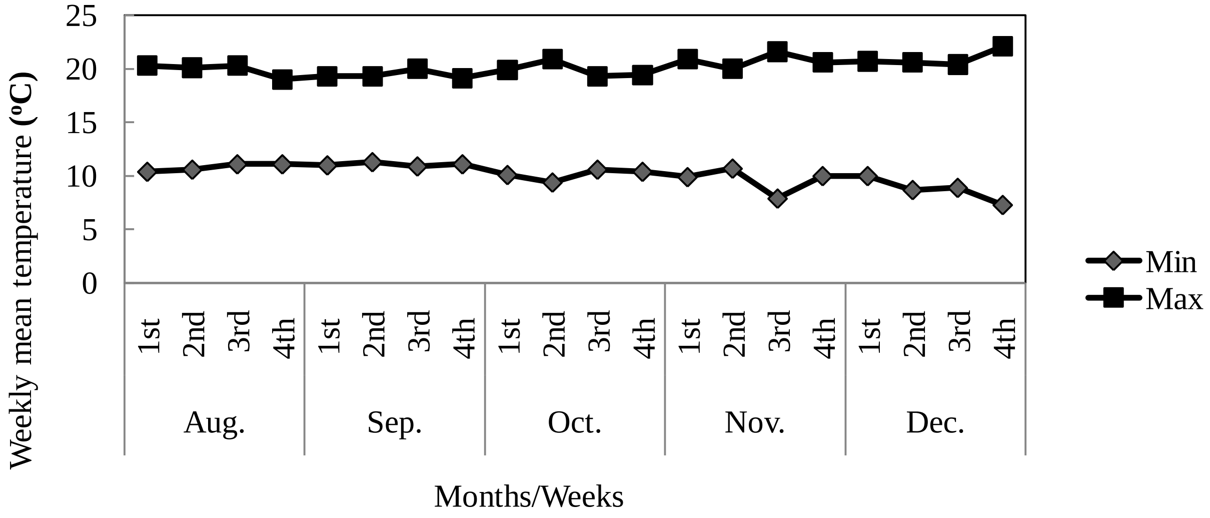
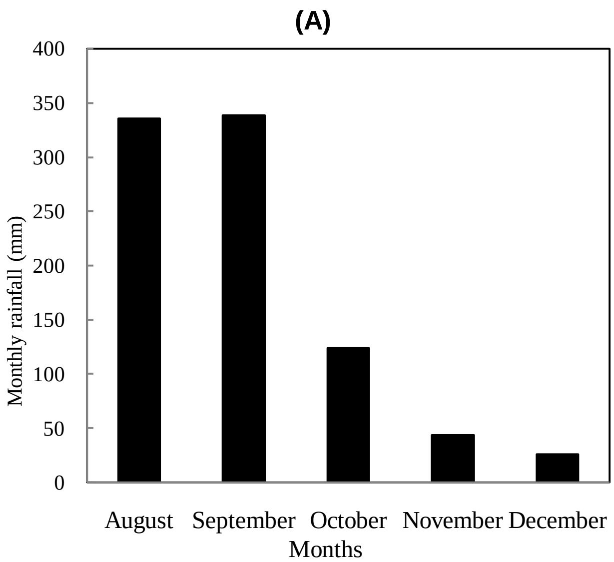


Figure 1: Weekly mean maximum and minimum temperatures at Sinana in 2012 main cropping season.



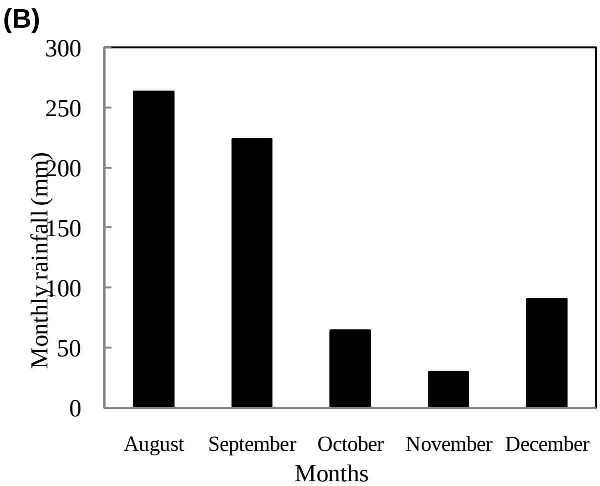


Figure 2: Monthly total rainfall distribution at Sinana (A) and Agarfa (B) in 2012 main cropping season.

planting) at the ith observation and n is total number of days. AUDPC was calculated separately for disease assessments made on different leaves of the plant (i.e. all leaves, flag leaves and penultimate leaves). Since AUDPC values on the different leaves and over the locations were of different epidemic duration, the values were standardized through dividing the values by the total duration (t_n - t_1) of the epidemic.

Disease progress rates were estimated from the logistic functions, ln [(Y/1-Y)] (Van der Plank, 1963). Comparison of the goodness of fit with the Gompertz model, -ln [-ln(Y)] (Berger, 1981) showed that the logistic function is superior as indicated by higher coefficients of determination (R^2). The transformed data were regressed over time (number of days after planting) and the apparent rates of disease increase were derived.

Statistical Analysis

Data on yellow rust incidence, severity, AUDPC and rate of disease increase were subjected to analysis of variance (ANOVA). ANOVA and regression analysis were done using SAS GLM Procedure (SAS version 9.00, Inst. 2002). Comparison of treatment means was made using least significant difference test (LSD).

RESULTS AND DISCUSSION

Disease on set and incidence

At the three locations (Sinana, Agarfa and Ginir) yellow rust appeared first on the highly susceptible variety, Kubsa. At Sinana it appeared on Kubsa, Madda Walabu, Digalu, Millennium and Dure at about tillering growth stage (GS 21-26) of the crop. The disease appeared on the variety Sofumar at the end of tillering

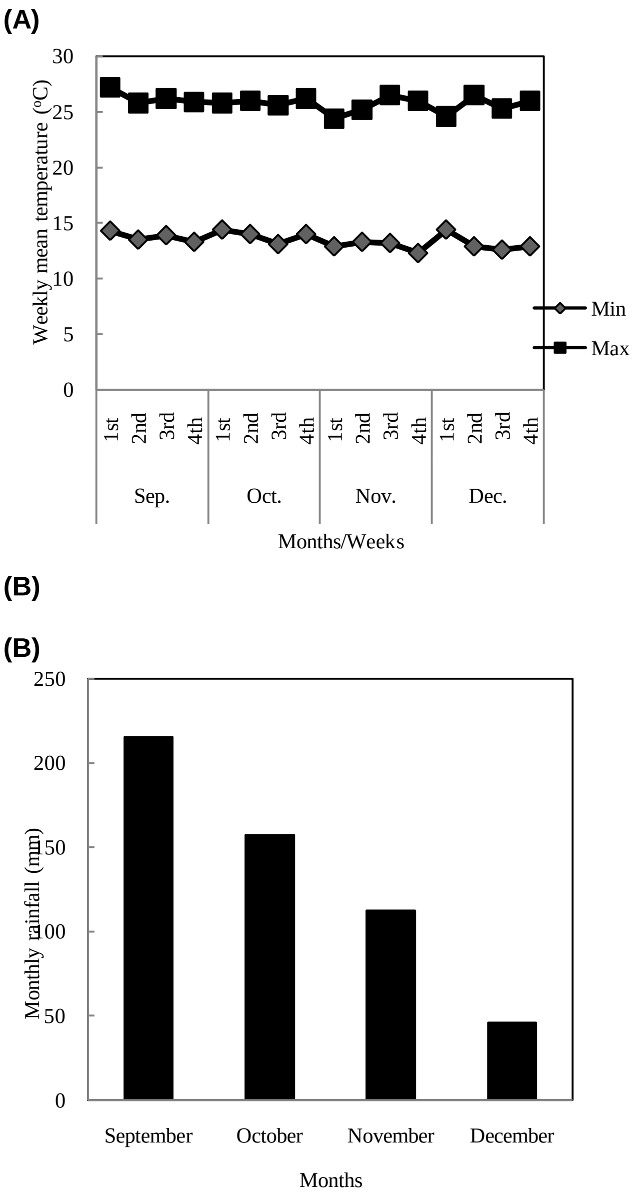


Figure 3: Weekly mean maximum and minimum temperatures (A) and monthly total rainfall (B) at Ginir in 2012 main cropping season.

(GS 28) even though the intensity was very low for further progression of the disease. At Agarfa on set of yellow rust was relatively late as compared to Sinana and Ginir. Likely, it appeared on Kubsa, Millennium and Dure at about ear emergence (GS 51) of the crop. Yellow rust was not observed on the resistant and moderately resistant varieties Madda Walabu, Digalu and Sofumar, respectively. The disease appeared on Kubsa, Millennium and Sofumar at about tillering (GS 21-26) of the crop at Ginir. On the variety Dure, the disease appeared at stem elongation (GS 31-36), while on Digalu at about booting (GS 41-49) of the crop. The disease was not observed on Madda Walabu variety in this district during the growing period.

Yellow rust appeared on different growth stages of the host plant at different locations at different times.

Table 3. Yellow rust incidence and head infection on six bread wheat varieties at Sinana, Agarfa and Ginir in 2012 main cropping season

Variety	Yellow rust incidence (%)			Head (spike) infection (0-5 scale)	
	Sinana	Agarfa	Ginir	Sinana	Ginir
Kubsa	100.00	100.00	100.00	4.43	2.93
Millennium	100.00	100.00	100.00	1.50	0.27
Dure	80.00	3.33	100.00	0.67	0.00
Madda Walabu	13.33	0.00	0.00	0.37	0.00
Sofumar	13.33	0.00	3.33	0.03	0.00
Digelu	13.33	0.00	3.33	0.00	0.00
Mean	53.33	33.89	51.11	1.17	0.53
SE[1]	4.08	1.18	1.49	0.41	0.27
LSD (0.05)	7.43	2.14	2.71	0.75	0.49

[1]standard error of means

This is due to variation in the environmental factors for epidemic development of the disease. Even though the test locations were different in their environmental factors, the disease appeared first on the susceptible varieties (Kubsa and Dure) at all locations. However, the degree of susceptibility varied across locations. This might be due to variation in virulence spectra of the pathogen and climatic conditions for the build up of disease pressure.

Disease incidence on the highly susceptible variety Kubsa, was significantly different from the resistant and moderately resistant varieties at Sinana and Agarfa. However, there was no significant difference between the susceptible and moderately susceptible varieties. The resistant and moderately resistant varieties showed insignificant difference among themselves in their yellow rust incidence at both locations (Table 3). A significant difference in yellow rust incidence was observed between the susceptible variety and moderately resistant and resistant varieties except that there was no significant difference among Kubsa, Millennium and Dure at Ginir. Disease incidence of 100% on Kubsa, Millennium and Dure, 0% on Madda Walabu and 3.3% on Sofumar and Digalu was recorded at Ginir (Table 3).

Disease Severity

Sinana

Yellow rust assessments made on all leaves revealed that a maximum of 55.5, 20.8, 4.2, 1.7, 0.6 and 0.03% yellow rust severities were recorded on Kubsa, Millennium, Dure, Digalu, Madda Walabu and Sofumar, respectively at Sinana (Figure 4). The highest disease severity was consistently observed on the susceptible variety, Kubsa. After 41 DAP, the disease increased sharply on all leaves of Kubsa, while the increment was seen after 61 DAP on Millennium and Dure. The disease severity increment was stable on the resistant varieties Madda Walabu and Digalu and the moderately resistant variety Sofumar. Yellow rust severities recorded on the resistant and moderately resistant varieties for all assessment dates were not significantly different among each other. But there was a significant

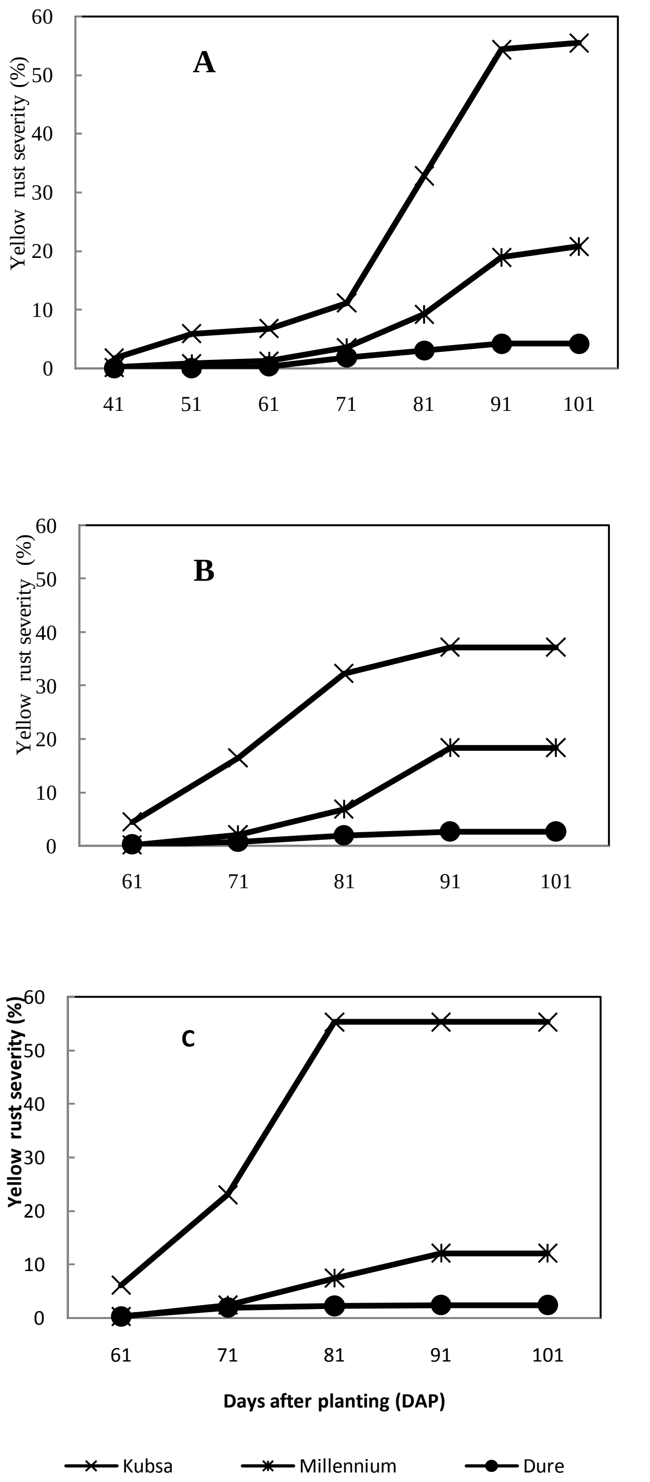


Figure 4: Yellow rust severity progress curves on bread wheat varieties at Sinana in 2012. Disease assessment was made on all leaves (A) and flag leaves (B) and Penultimate leaves (C) of each variety at 10-days interval.

difference (p≤ 0.05) in severities among susceptible, moderately resistant and resistant varieties.

Disease severities recorded on flag leaves were lower compared to the severities on all leaves for all the test varieties. The susceptible variety Kubsa had the maximum disease severity values consistently for all assessment dates. On flag leaves, a maximum of 37.1, 18.3, 2.6, 1.3, 0.5 and 0% severities were recorded on Kubsa, Millennium, Dure, Digalu, Madda Walabu and Sofumar, respectively, at Sinana (Figure 4). The sharp increment of the disease was observed after 61 DAP on flag leaves of Kubsa and Millennium, 71 DAP on Dure and Digalu, while a stable increment was observed on Madda Walabu. The resistant and moderately resistant varieties were not significantly different among each other in disease severity recorded on all assessment dates. There was significant difference (p≤ 0.05) in yellow rust severities on flag leaves among susceptible, moderately resistant and resistant varieties.

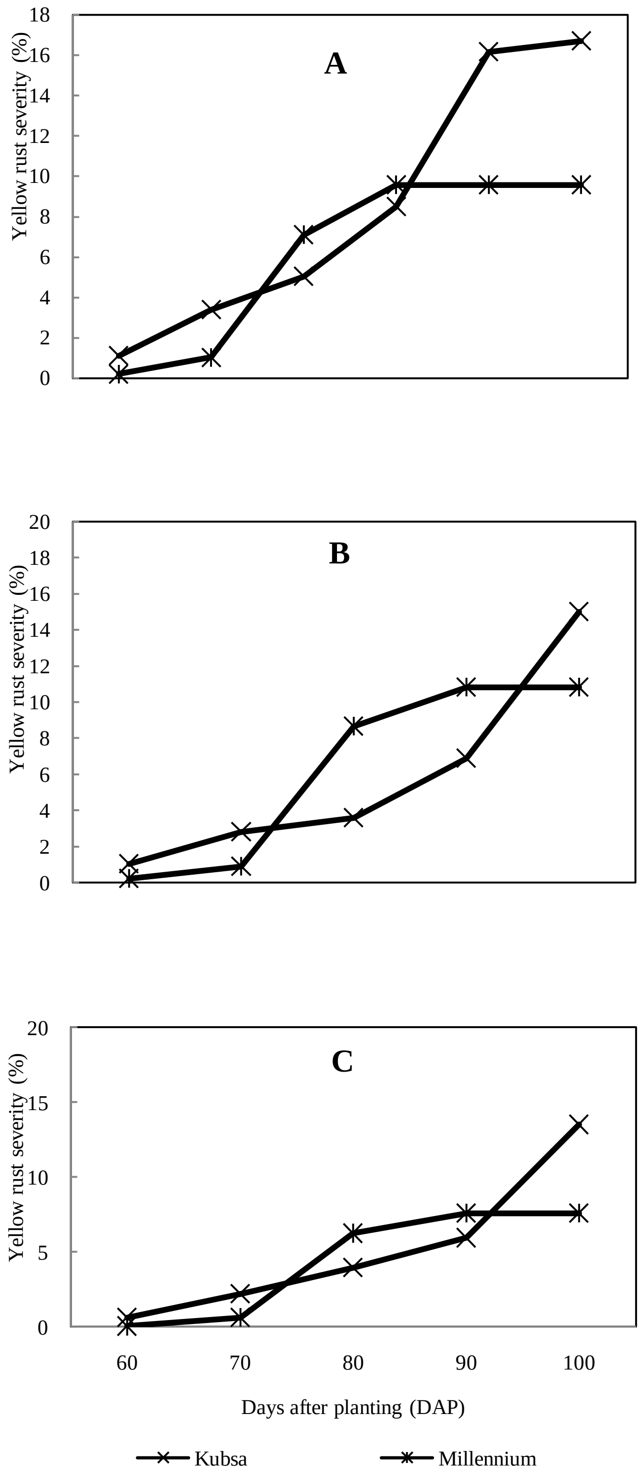
Yellow rust severity on F-1 leaves revealed that the highest severity was recorded on the susceptible variety Kubsa at Sinana. On 91 DAP the highest (55.3%) disease severity was recorded on F-1 leaves of Kubsa whereas variety Millennium, Dure, Digalu, Madda Walabu and Sofumar had 12.03, 2.4, 0.43, 0.05 and 0.03%, respectively, at Sinana (Figure 4).

Agarfa

Generally disease severity at Agarfa was lower compared to Sinana for all the varieties on all assessment dates. Out of the six test varieties, yellow rust epidemic developed only on the susceptible and moderately susceptible varieties, Kubsa and Millennium, respectively. The maximum mean disease severity on all leaves was 16.7% on the susceptible variety Kubsa and 9.6% on Millennium (Figure 5). The disease increased sharply after 70 and 60 DAP on all leaves of Millennium and Kubsa, respectively. There was significant difference (p≤ 0.05) in yellow rust severity between the susceptible variety Kubsa and resistant varieties (Madda Walabu and Digalu). But there was no significant difference among the resistant and moderately resistant varieties. A significant difference severity level on all leaves was also observed between Kubsa and Millennium on the final date of disease assessment.

On flag leaves disease severity increased after 70 and 60 DAP on Millennium and Kubsa, respectively (Figure 5). The mean disease severity on flag leaves of Kubsa was lower than that of all leaves, while the severity on flag leaves of Millennium was higher than that of all leaves. Maximum of 15 and 10.8% disease severities were recorded on flag leaves of Kubsa and Millennium, respectively, at Agarfa. After 80 DAP a significant difference in yellow rust severity was observed between Kubsa and Millennium.

Yellow rust severity assessed on F-1 leaves of Kubsa and Millennium was lower than the severity assessed on all and flag leaves. Disease severity on F-1 leaves increased sharply after 60 and 70 DAP on Kubsa and Millennium, respectively. Maximum mean disease severities of 13.5 and 7.6% were recorded on Kubsa and Millennium, respectively (Figure 5). Kubsa and Millennium showed significant difference in yellow rust severity during all the assessment dates except on 80 DAP. There was significant difference in yellow rust



severities on F-1 leaves between the susceptible variety Kubsa and the resistant varieties at Agarfa during all the assessment dates.

Ginir

Based on the assessments made on all leaves, disease severity was lower on the susceptible variety Kubsa at Ginir than at Sinana, while the severity was higher than at Agarfa. A maximum of 41.9, 14.9 and 21.5% yellow rust severities were recorded on Kubsa, Millennium and Dure, respectively, at Ginir (Figure 6). A sharp increment of the disease was observed after 49 DAP on all leaves of the three test varieties. At the time of disease onset (49 and 59 DAP), yellow rust severity on all leaves was not significantly different among Kubsa, Millennium and Dure. But the severities were significantly different among Madda Walabu, Digalu and Sofumar. The varieties showed significant difference in yellow rust severity at 69 DAP. The final date of disease severity (89 DAP) on the highly susceptible variety Kubsa was significantly different from the rest of the test varieties.

Yellow rust severities recorded on flag leaves of Kubsa, Millennium and Dure were lower than the severities recorded on all leaves. On flag leaves, maximum of 40.6, 9.1 and 21.3% yellow rust severities were recorded on Kubsa, Millennium and Dure, respectively (Figure 6). The disease increased sharply after 59 DAP on flag leaves of Kubsa and Dure, while the increment was pronounced after 69 DAP on Millennium. A significant difference in yellow rust severities on flag leaves was observed between the highly susceptible variety Kubsa and Millennium and Dure at 59 and 89 DAP.

Disease severities assessed on F-1 leaves of Kubsa and Dure were lower than the severities recorded on all and flag leaves on the same varieties, whereas yellow rust severity recorded on F-1 leaves of Millennium was higher than that of the flag leaf. The disease severity increment on F-1 leaves was observed after 59 DAP on Kubsa, Millennium and Dure. Maximum mean disease severities of 19.2, 12 and 9.9% were recorded on Kubsa, Millennium and Dure, respectively, at Ginir (Figure 6). The highly susceptible variety Kubsa showed significant difference in yellow rust severity as compared to the other varieties during all the assessment dates.

The present study indicated that yellow rust epidemic development on all leaves, flag leaves and F-1 leaves was different for different varieties at different environments. This is explained by changes in environmental variables and aggressiveness of the pathogen over locations. Andrivon (1993) stated that aggressiveness of an isolate is influenced by both host plant response and environment. Changes in environmental factors also modify host morphology, physiology and resistance. This is in agreement with Yanez-Lopez et al. (2012) who reported that climate change modifies host physiology and resistance, and alter the stages and rates of the development of pathogens. The result of the current study also showed that rate of yellow rust development was different for the test varieties at different locations.

Yellow rust progress curves on different leaf positions for the three locations generally attained typical sigmoid shape for Kubsa, Millennium and Dure. Such disease progress curves are characteristic of polycyclic diseases (Van der Plank, 1963). The yellow rust epidemic development showed that disease progress curves vary depending on the resistance level of the

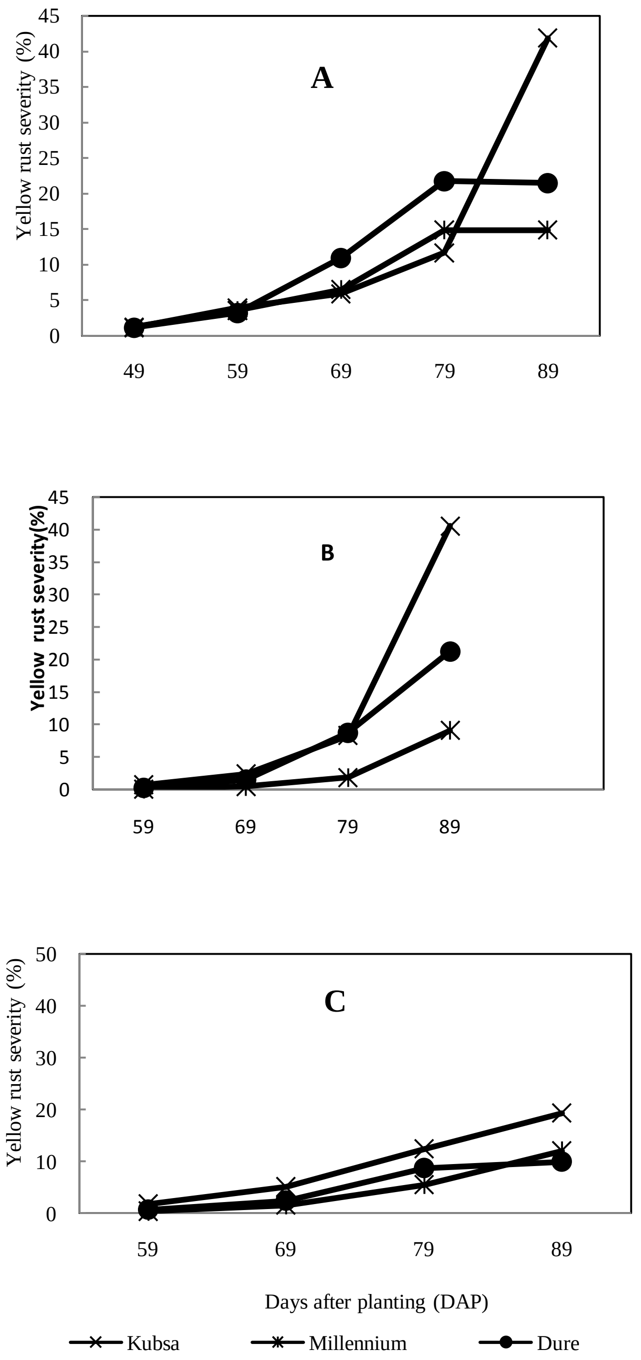


Figure 6. Yellow rust severity progress curves on bread wheat varieties at Ginir in 2012. Disease assessment was made on all leaves (A) and flag leaves (B) and Penultimate leaves (C) of each variety at 10-days interval

variety and the prevailing environmental factors. The difference in magnitude and shape of yellow rust progress curves at Sinana, Agarfa and Ginir shows the effects of environmental factors on disease progress and final disease development as stated by Campbell and Madden (1989).

Yellow rust epidemics lasted to the end of crop maturity and resulted in head infection on Kubsa, Millennium, Dure, Madda Walabu and Sofumar at Sinana and on Kubsa and Millennium at Ginir. The maximum head infection was observed on the susceptible variety Kubsa at both Sinana and Ginir locations (Table 3). There was significant difference between the susceptible and moderately resistant and resistant varieties in head infection at both locations. However, there was no significant difference among the moderately resistant and resistant varieties in terms of head infection at these locations (Sinana and Ginir). On the highly infected variety Kubsa, the grains were shrivelled and resulted in losses in yield, yield components and hectolitre weight at Sinana. This current result is consistent with the findings of Purdy and Allan (1965) who indicated that head infection by yellow rust, which influences yield is an important factor.

Little infection on the moderately resistant and resistant varieties did not result in shrivelling of kernels and corresponding losses in yield and yield components at Sinana. Moderately resistant and resistant varieties were free of yellow rust head infection at all locations except that at Sinana insignificant little infection was observed on these varieties. Higher head infection was recorded at Sinana than that of Ginir, whereas at Agarfa there was no head infection at all even on the highly susceptible variety.

The current study clearly showed that environmental variability had a significant effect on epidemic development of yellow rust through its effect on growth and progress rate of the pathogen. The test locations were different in their weather variables and created significant difference in yellow rust severity among the varieties. Due to these weather variables across locations, the same variety responded differently to yellow rust severities at different locations.

Area under Disease Progress Curve (AUDPC)

The area under disease progress curve exhibited highly significant difference ($p \leq 0.01$) between the susceptible and moderately resistant and resistant varieties at Sinana, Agarfa and Ginir. The highest AUDPC was calculated on the susceptible variety Kubsa both at Sinana and Agarfa, while at Ginir the highest value was calculated on Dure. At the three locations, AUDPC values on moderately resistant and resistant varieties were very low (Figure 7 to 9).

At Sinana, the highest standardised AUDPC values (21.4, 26.6 and 41.4%-days) on all, flag and F-1 leaves, respectively were observed on the highly susceptible variety, Kubsa (Figure 7). These values were significantly reduced by planting resistant varieties, Madda Walabu and Digalu. On the highly susceptible variety, Kubsa, the highest AUDPC value was calculated on F-1 leaves. From this study it was observed that higher AUDPC value was calculated on flag and F-1 leaves than on all leaves for the test varieties at Sinana.

At Agarfa, AUDPC was calculated only for Kubsa and Millennium, whereas the rest of the test varieties exhibited zero values. Even though there was no significant difference between Kubsa and Millennium in

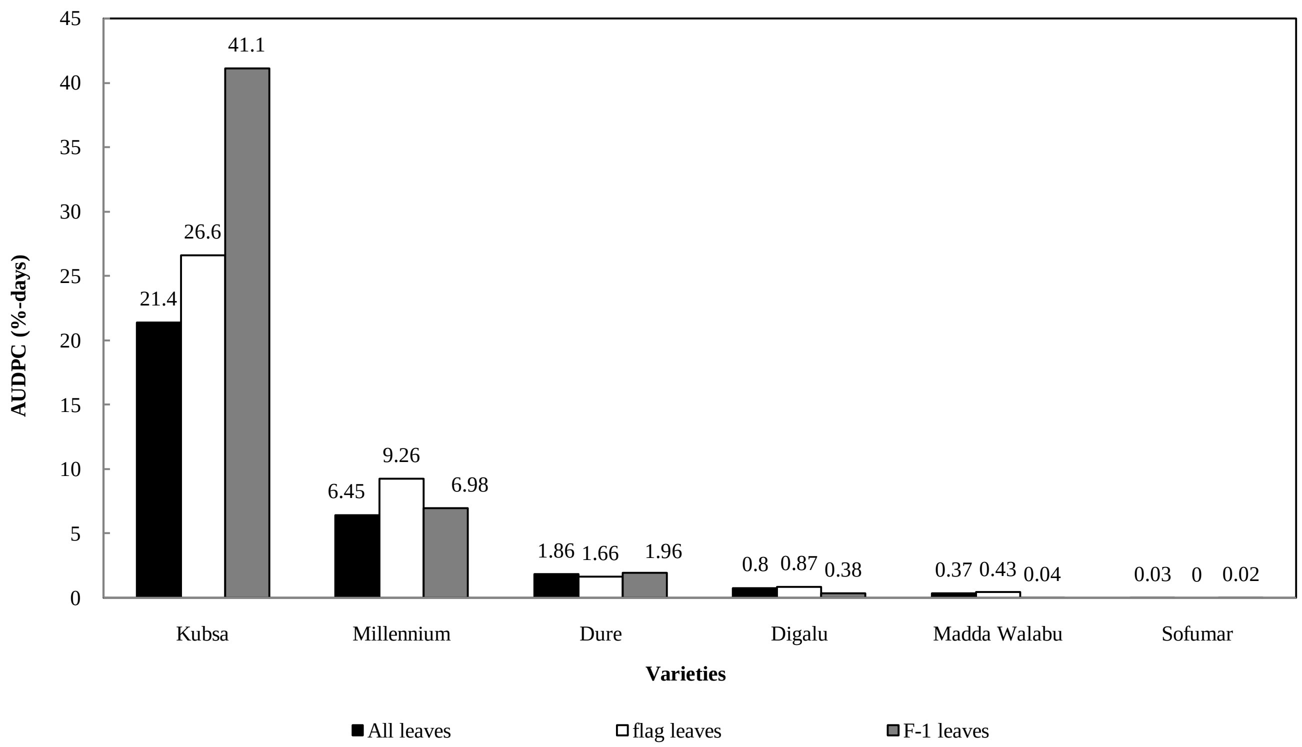


Figure 7: Area under disease progress curve (AUDPC) for yellow rust severity assessed on all leaves, flag leaves and Penultimate (F-1) leaves on six bread wheat varieties at Sinana in 2012 main cropping season.

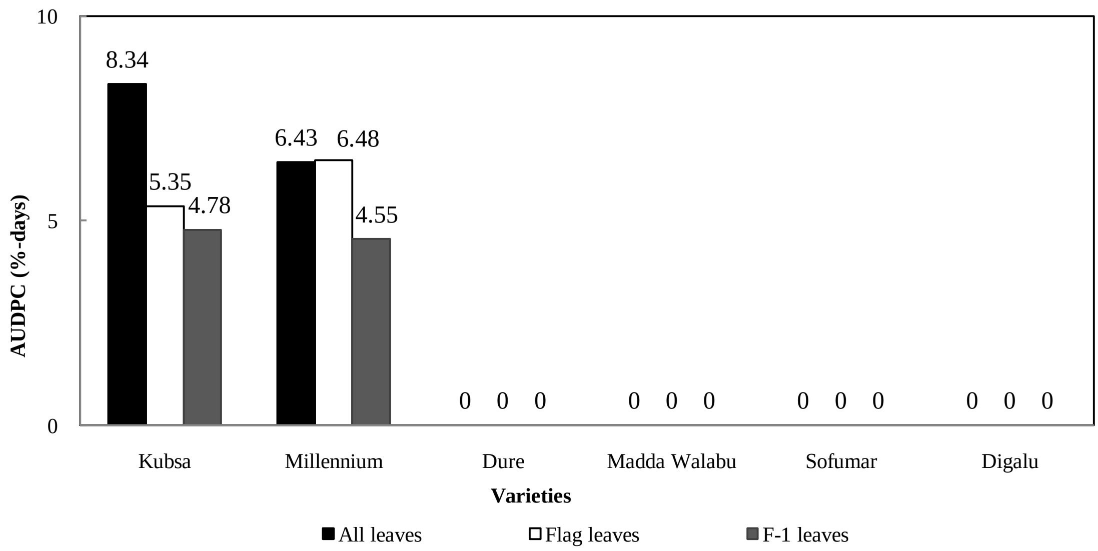


Figure 8: Area under disease progress curve (AUDPC) for yellow rust severity assessed on all leaves, flag leaves and Penultimate (F-1) leaves on six bread wheat varieties at Agarfa in 2012 main cropping season.

their AUDPC values on all and F-1 leaves, the highest AUDPC value (8.34%-days) was recorded on the susceptible variety, Kubsa, whereas on flag leaves, the highest value (6.48%-days) was observed on Millennium in spite of insignificant difference between the two varieties. The AUDPC values of 8.34, 5.35 and 4.78%-days were recorded on all, flag and F-1 leaves, respectively, on Kubsa. Similarly, maximum AUDPC values of 6.43, 6.48 and 4.55%-days were calculated on all, flag and F-1 leaves, respectively, on Millennium Agarfa (Figure 8). At this location the maximum AUDPC values were calculated on all leaves and flag leaves of Kubsa and Millennium, respectively.

Since the resistant and moderately resistant varieties exhibited zero levels of disease incidence, AUDPC was calculated for Kubsa, Millennium and Dure at Ginir. A significant difference in AUDPC values calculated on all, flag and F-1 leaves were observed between Kubsa

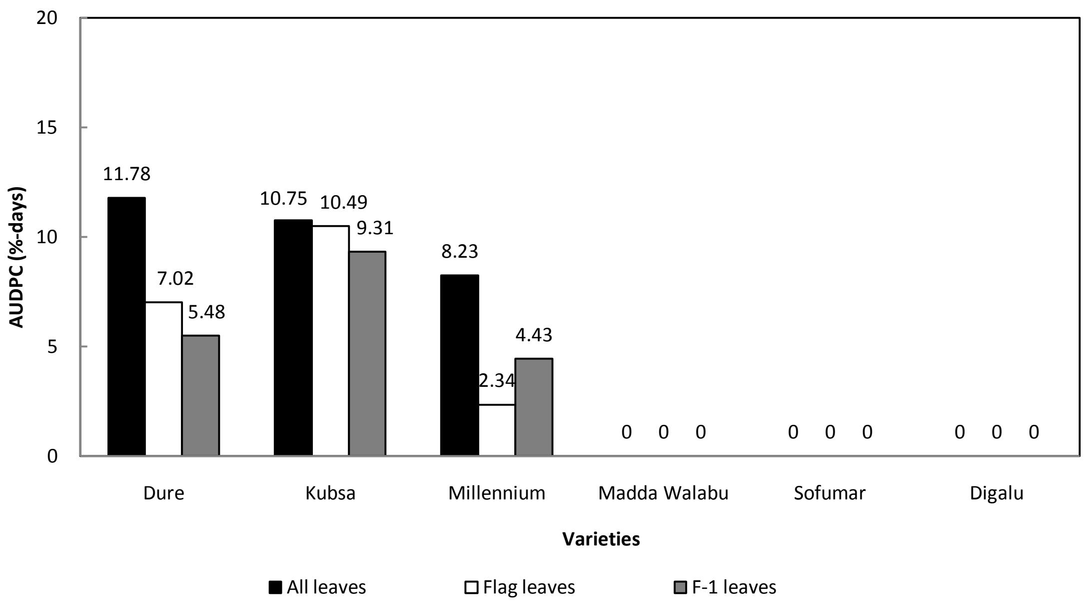


Figure 1: Area under disease progress curve (AUDPC) for yellow rust severity assessed on all leaves, flag leaves and Penultimate (F-1) leaves on six bread wheat varieties at Ginir in 2012 main cropping season.

and Millennium and Dure except that on all leaves of Dure insignificant difference was observed. Higher AUDPC values were recorded on all leaves of the three varieties than on flag and F-1 leaves. Likewise, maximum AUDPC values of 11.78, 10.75 and 8.23%-days were calculated on all leaves of Dure, Kubsa and Millennium, respectively (Figure 9). This figure showed that higher AUDPC was recorded on Dure than the susceptible variety, Kubsa. Based on the analysis, AUDPC values of 10.49, 7.02 and 2.34%-days were recorded on flag leaves of Kubsa, Dure and Millennium, respectively, at this location. The area under disease progress curves calculated on F-1 leaves of Kubsa and Dure were lower than that of all and flag leaves at Ginir. The maximum AUDPC values were 9.31, 5.48 and 4.43%-days on F-1 leaves of Kubsa, Dure and Millennium, respectively.

Yellow Rust Progress Rate

At Sinana, there was significant difference in yellow rust progress rate between the susceptible variety Kubsa and the resistant varieties on the three leaf positions. On the susceptible variety Kubsa, yellow rust was increasing at a rate of 0.073, 0.070 and 0.078 units per day on all, flag and F-1 leaves, respectively, at Sinana (Table 4 to 6). These rates were reduced by about 3 times on all and flag leaves by the use of resistant variety Madda Walabu and by about 5 and 4 times by planting Digalu variety. Planting of resistant varieties like Madda Walabu and Digalu slowed the rate to 0.022 and 0.014 units day^{-1} on all leaves and 0.026 and 0.018 units day^{-1} on flag leaves, respectively. The rates of yellow rust development on the moderately susceptible variety Millennium were 0.078, 0.101 and 0.103 units day^{-1} on all, flag and F-1 leaves, respectively, at Sinana. These rates were about 4 times faster than the rates on all and flag leaves of Madda Walabu and about 6 times faster than the rates on all and flag leaves of Digalu. The results showed that planting resistant varieties has significant effect on disease development. At Sinana, based on the assessments made on all, flag and F-1 leaves, yellow rust developed at the rates of 0.067, 0.035 and 0.031 units day^{-1}, respectively, on the susceptible variety, Dure. The current study demonstrated that the faster rate of yellow rust progress occurred on the variety Millennium, followed by Kubsa, Dure, Madda Walabu and Digalu, respectively, at Sinana.

Disease progress rate on all, flag and F-1 leaves of Kubsa and Millennium were about the same at Agarfa. However, relatively the highest disease progress rate was recorded on Millennium. Based on the analysis, yellow rust progress rates of 0.066, 0.082 and 0.079 units day^{-1} on all, flag and F-1 leaves were recorded on Kubsa, while it was 0.078, 0.106 and 0.090 units day^{-1} on Millennium at Agarfa (Table 4 to 6).

At Ginir, even though there was no significant difference in disease progress among Kubsa, Millennium and Dure on all, flag and F-1 leaves, there was variation in their resistance to slow the disease. Yellow rust progress rates of 0.096, 0.144 and 0.096 units day^{-1} on all, flag and F-1 leaves, respectively, were observed on Kubsa. Similarly, based on the assessments made on all, flag and F-1 leaves, yellow rust progress rates of 0.069, 0.147 and 0.124 units day^{-1}, respectively, were recorded on Millennium, while it was 0.089, 0.158 and 0.109 units day^{-1} on all, flag and F-1 leaves, respectively, on the variety Dure at Ginir (Table 4 to 6). At this location, relatively faster disease progress rate was observed on flag leaves, followed by F-1 and all leaves. Generally, the fastest yellow rust progress rate was exhibited at Ginir, followed by Sinana and Agarfa. Relatively, the disease developed at a faster rate on flag and F-1 leaves than on all leaves.

Table 4: Yellow rust disease progress rate on all leaves of bread wheat varieties under natural disease epidemic at Sinana, Agarfa and Ginir districts in 2012 main cropping season

Location and Variety	Disease progress rate[a] (units day^{-1})	Standard error of disease progress rate	R^{2b} (%)	Significance level (*p*)
Sinana				
Kubsa	0.073	0.004	93.5	0.00
Millennium	0.078	0.005	92.1	0.00
Dure	0.067	0.013	62.4	0.00
Agarfa				
Kubsa	0.066	0.010	72.4	0.00
Millennium	0.078	0.011	74.3	0.00
Ginir				
Kubsa	0.096	0.009	89.8	0.00
Millennium	0.069	0.007	89.5	0.00
Dure	0.089	0.010	85.2	0.00

[a] calculated based on 10-days interval assessments of disease severity
[b] coefficient of determination

Table 5: Yellow rust disease progress rate on flag leaves of bread wheat varieties under natural disease epidemic at Sinana, Agarfa and Ginir districts in 2012 main cropping season

Location and Variety	Disease progress rate[a] (units day^{-1})	Standard error of disease progress rate	R^{2b} (%)	Significance level (*p*)
Sinana				
Kubsa	0.070	0.014	65.8	0.00
Millennium	0.101	0.014	82.1	0.00
Agarfa				
Kubsa	0.082	0.017	64.5	0.00
Millennium	0.106	0.014	81.4	0.00
Ginir				
Kubsa	0.144	0.023	81.1	0.00
Millennium	0.147	0.018	88.5	0.00
Dure	0.158	0.011	95.4	0.00

[a] calculated based on 10-days interval assessments of disease severity
[b]coefficient of determination

Table 6: Yellow rust disease progress rate on F-1 leaves of bread wheat variety under natural disease epidemic at Sinana, Agarfa and Ginir districts in 2012 main cropping season

Location and Variety	Disease progress rate[a] (units day^{-1})	Standard error of disease progress rate	R^{2b} (%)	Significance level (*p*)
Sinana				
Kubsa	0.078	0.015	69.1	0.00
Millennium	0.103	0.017	72.7	0.00
Agarfa				
Kubsa	0.079	0.011	80.8	0.00
Millennium	0.090	0.018	70.5	0.00
Ginir				
Kubsa	0.096	0.019	72.3	0.00
Millennium	0.124	0.009	94.4	0.00
Dure	0.109	0.018	79.4	0.00

[a] calculated based on 10-days interval assessments of disease severity
[b] coefficient of determination

The results of this study clearly showed that variation in yellow rust progress rate occurred due to the resistance level of the varieties, leaf positions and environment. Yellow rust progress rate was faster on susceptible varieties than on the moderately resistant and resistant varieties. The current results are inconsistent with findings of earlier works reported by Rapilly (1979), Kurt (2002), Dereje (2003) who showed that rate of disease progress depends on the resistance level of varieties used. The result also revealed that yellow rust progress rate was different at the three locations, the highest rate being at Ginir. This shows that yellow rust has now extended its adaptation to lower and warmer altitudes. Earlier works also confirmed that, in recent years, new and high temperature tolerant, aggressive strains of yellow rust are moving into warmer areas (Hovmoller et al., 2008; Milus et al., 2009).

CONCLUSION

Onset of yellow rust was relatively late in relation to the crop growth stage, and the disease pressure was lower than that of the previous years at the test locations. Changes in environmental factors and race structure of the pathogen delayed early infection and epidemics of yellow rust. Yellow rust can cause head infection on wheat whenever the disease pressure is higher and more aggressive. The varieties showed different levels of susceptibility and resistance to yellow rust over different environments. Diverse nature of the rust pathogen and changes in weather variables made the varieties to respond differently at different environments. Disease progress curves varied with the resistance level of the variety and the prevailing environmental factors. Logistic model best described the rate of yellow rust progress. Variation was clearly observed in yellow rust progress rate due to the resistance level of the varieties, leaf positions and environments. Yellow rust has now extended its adaptation to lower and warmer altitudes where it did not cause severe damage before. Yellow rust epidemic development was observed up to a maximum temperature of 26 ˚C. This demonstrates adaptation of *P. striiformis* f.sp. *tritici* to warmer temperatures to cause severe epidemics in previously unfavourable environments.

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