

## Slow rusting of bread wheat landraces to *Puccinia striiformis* f.sp. *tritici* under artificial field inoculation

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### Abstract

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Yellow rust caused by *Puccinia striiformis* f. sp. *tritici* is the most devastating fungal disease of wheat, especially in the Central and West Asia and North Africa (CWANA) region. Most of the released cultivars in CWANA have become susceptible to the new virulence Yr27. Growing durable resistance cultivars is the most economical control measure. A field study was conducted to evaluate 500 bread wheat landraces along with the susceptible control 'Morocco' using artificial inoculation under field conditions at Tel Hadia, Syria during 2010/11 and 2011/12 growing seasons. The most prevailing and spreading yellow rust virulence (70E214) was used for artificial inoculation. Disease scoring started when disease severity was more than 50% on the leaves of cv. Morocco and continued for four readings at 7 days intervals. Slow rusting resistance was assessed based on development of the disease over time using the area under disease progress curve (AUDPC), coefficient of infection (CI), final rust severity (FRS), infection rate "r" and relative resistance index (RRI). None of the landraces showed immune reaction and 10% showed the lowest values for all parameters, suggesting that major genes control resistance in these landraces. Approximately 65% of the landraces were marked as having different levels of slow rusting and 25% were highly susceptible. Cluster analysis based on partial resistance parameters of the landraces along with cv. Morocco revealed two major clusters: susceptible and low level of slow rusting were grouped in the first cluster; resistant, high level and moderate level of partial resistance were grouped in the second cluster. These groups were also confirmed using principal coordinate analysis. By comparing the results of RRI and others parameters, it appeared that landraces with very low values exhibited high RRI value of 9, while those that showed high, moderate, and low levels of slow rusting, had RRI ranges of 8-9, 7-8 and 5-7, respectively. Landraces with maximum values from each parameter showed very low RRI values of less than 5. The results also suggest that AUDPC, CI, and FRS are the more appropriate parameters for assessing slow rusting than infection rate. Correlation coefficient and principle component analysis revealed a high and positive correlation between these parameters.

**Keywords:** Disease resistance, yellow rust, bread wheat, landraces.

### Introduction

Wheat is the second most important food crop in the developing world after rice, with annual production of 720 million tons (FAO, 2014). Higher and sustainable production is needed to meet the demand of the world increasing population.

Wheat production is severely affected by many abiotic and biotic stresses (Chen *et al.*, 2013). The development of new tolerant and resistant varieties, is the more efficient approach to ensure sustainable wheat production.

Among the major wheat diseases, yellow rust caused by *P. striiformis* f. sp. *tritici* appears the most devastating worldwide after breakdown of the resistance of most released varieties (Hovmoller, 2001). In recent years, significant yield losses were reported in CWANA region and beyond after the appearance of virulence against Yr27 gene (Solh *et al.*, 2012).

The use of fungicides to control yellow rust is not economical as it significantly increases the costs of production discouraging its use by small farmers. In addition, the excessive use of pesticides is not friendly to environment, and the adoption of an integrated disease management

approach based on use of genetic resistance (Chen, 2005; Singh *et al.*, 2005) is becoming more desirable.

Slow rusting or horizontal resistance or partial resistance is a form of quantitative resistance that can slow the incidence and development of yellow rust in the field (Wang *et al.*, 2000). It is mainly controlled by minor genes having a different mode of action and do not provide immunity (Herrera-Fossel *et al.*, 2007). Therefore, continued access to new sources of resistance in genetic resources is needed (Bux *et al.*, 2011). In this regard, evaluation of gene bank accessions and other germplasm is a key in this direction.

Slow rusting could be assessed through different measures such as the final rust severity (FRS) (Parlevliet & Ommeren, 1975), area under diseases progress curve (AUDPC) (Wilcoxson *et al.*, 1975), infection rate "r" (Broers *et al.*, 1996), coefficient of infection (CI) (Pathan & Park, 2006), and some researchers used relative resistance index (RRI) (Akhtar *et al.*, 2002). Slow rusting has been assessed using only CI and some researchers consider it as the most commonly used parameter for assessment of yellow rust reaction (Ali *et al.*, 2009). Other researchers used AUDPC, "r" and final disease severity to assess slow rusting (Ali *et al.*, 2007). Some scientists use RRI and CI to assess partial

resistance to yellow rust in wheat (Afzal *et al.*, 2009; Mahmoud *et al.*, 2015).

The present study is designed to evaluate a set of 500 bread wheat landraces for slow rusting resistance and to test the efficiency of different slow rusting epidemiological parameters, and assess the relationship among them.

## Materials and Methods

This study was carried out during two seasons 2010/11 and 2011/12 at International Center for Agricultural Research in the Dry Areas (ICARDA) Tel Hadya experiment station, located in Northern Syria at 36° 16'N, 36° 56'E, altitude 284 m.a.s.l. with long-term average annual rainfall of 350 mm (Ryan *et al.*, 1997).

### Plant materials and germplasm sources

A subset of 500 bread wheat landraces collected mainly from CWANA region, were obtained from ICARDA gene bank. The landraces originated from 10 countries (314 accessions from Iran, 98 from Afghanistan, 24 from Syria, 21 from Iraq, 19 from Pakistan, 10 from Egypt and 6 from Morocco). The remaining eight landraces belong to China (6), Russia (1) and Eritrea (1).

### Planting the experiment and disease assessment

During 2010/2011 season, the 500 landraces were grown in one-meter length plot, and subject to artificial inoculation using the race (70E214). The susceptible check "Morocco" was used as disease spreader and planted around the experiment and as susceptible check after each 10 accessions. The disease severity was recorded twice during the season.

During 2011/2012 season, the seeds of selected single heads from each accession along with the susceptible spreader row check variety "Morocco" were planted under irrigated conditions and were subject to artificial inoculation using the same race (70E214). Artificial inoculation was done following the procedure described by (Roelfs *et al.*, 1992) in both seasons.

Only 417 accessions originating from the 500 original landraces were assessed for slow rusting using different parameters: disease severity (DS), final rust severity (FRS), and area under disease progress curve (AUDPC), coefficient of infection (CI), Infection rate (r) and Relative Resistance Index (RRI).

Scoring of the disease severity (%) on each landrace started when the susceptible check reached to 50% severity, then observations were taken at 7 days interval on 9<sup>th</sup> April, 16<sup>th</sup> April, 23<sup>rd</sup> April, and 1<sup>st</sup> May 2012. Disease severities were measured according to the Modified Cobb scale (Peterson *et al.*, 1948).

The coefficient of infection (CI) was calculated by multiplying final disease severity (DS) by constant values (the numerical notation for the host response) of infection type (IT) in as suggested by (Pathan & Park, 2006).

The area under the disease progress curve (AUDPC), was calculated using the software obtained from CIMMYT (Joshi & Chand, 2002). The equation used is given as:

$$AUDPC = \sum_{i=1}^a \{ [Y_i + Y_{(i+1)}] / 2 \} \times [t_{(i+1)} - t_i]$$

Where, a = total number of observations.  $t_i$  = day i (time) expressed as number of days after sowing,  $t_{(i+1)} - t_i$  = Time (days) between two disease observation dates and  $Y_i$  = Number of pustules at time  $t_i$ .

The infection rate "r", which represents the unit leaf area occupied by disease per day, was estimated for the whole epidemic period after the time when "Morocco" showed more than 50% severity, following (van der Plank, 1968). The relative infection rate was worked out for each accession by comparing its "r" value with that of the susceptible check.

The Relative Resistance Index (RRI) was calculated, using a 0 to 9 scale, where 0 represents the most susceptible and 9 the highly resistant accessions. The highest average coefficient of infection (ACI) of an accession is set at 100 and all other accessions are adjusted accordingly. This gives the Country Average Relative Percentage Attack (CARPA). The standard for desirable index was maintained at  $\leq 7$  whereas the value for acceptable index was fixed as 5 (Aslam, 1982). The following formula was used for calculating RRI (Akhtar *et al.*, 2002):

$$RRI = \frac{(100 - CARPA)}{100} \times 9$$

### Statistical analysis

#### Cluster analysis and principal coordinate analysis (PCoA)

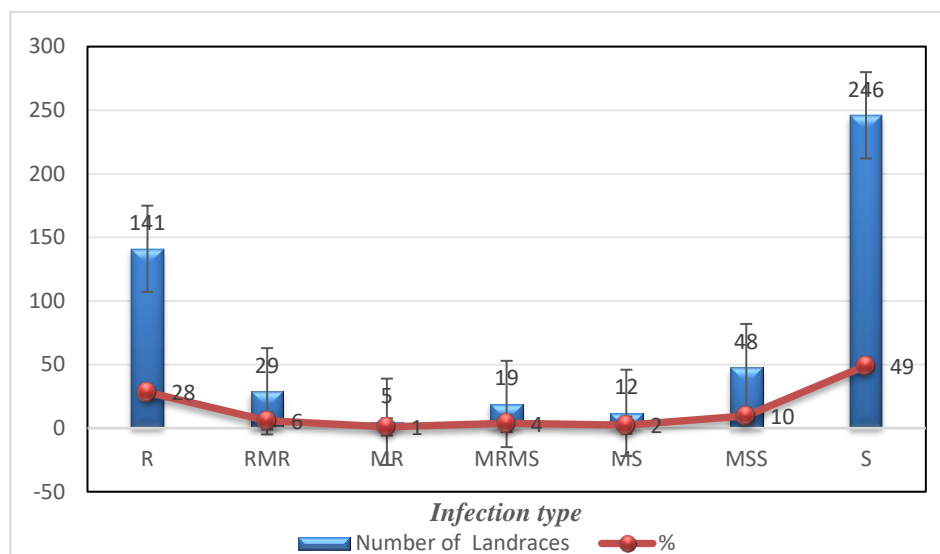
Euclidian distance between landraces was calculated from the standardized data matrix to assess the genetic distance, hierarchical cluster was made by un weighted pair-group average method using arithmetic averages (UPGMA), using DAR win 6 software (Perrier & Jacquemoud-Collet, 2006). The same data matrix was also used to undertake a Principal coordinate analysis (PCoA) with the same software in order to obtain a graphical representation of the genetic diversity patterns for differentiating the landraces.

#### Principle competent analysis (PCA)

For PCA analysis, the function PRCOMP was used from the STATS package in R (R Core Team, 2016) and 3D view of the PCA was drawn using an in house R script. The correlation coefficient between any two traits is approximated by the cosine of the angle between their vectors (Yan & Rajcan, 2002). On this premise, two traits are positively correlated if the angle between their vectors is an acute angle ( $< 90^\circ$ ) while they are negatively correlated if their vectors are an obtuse angle ( $> 90^\circ$ ), and right angles in case of no correlation. A short vector may indicate that the trait is not related to other traits (Yan & Kang, 2003).

## Results

During season 2010/2011, there was a good development of yellow rust and the spreader susceptible check scored 70S to 100S. The 500 landraces showed different reactions to the disease and based on FRS there are 246 S, 48 MSS, 12 MS, 19 MRMS, 5 MR, 29 RMR and 141R (Figure 1).



**Figure 1.** Number of bread wheat landraces for each yellow rust infection type.

### Disease severity (DS) value

A high disease pressure was observed in 2011/12 season as revealed by the susceptible check “Morocco” which exhibited 100S in all the plots, while the mean level of YR severity ranged from 5R (HR) to 100S (HS) for the tested landraces. The landraces were divided into seven groups depending on infection type: 73 landraces (18%) were resistant (R), 75 (18%) were resistant to moderately resistant (RMR), 30 landraces (7%) were moderately resistant (MR), 60 landraces (14%) marked as moderately resistant to moderately susceptible (MRMS), 32 landraces (8%) were moderately susceptible (MS), 22 landraces (5%) were moderately susceptible to susceptible (MSS), and 125 landraces (30%) were susceptible to high susceptible (S).

The disease development over time is presented in Figure 2, depending on the four reading dates assessment and the corresponding severity for each infection type (the landraces were grouped according to their infection type and the value of disease severity for each reading date was calculated, so each landrace in each infection type was represented by four reading dates). Morocco showed high levels of disease severity and almost linear pattern of increase between initial and final scorings. Most of susceptible landraces were having more increase in severity between second and final score, and some of them were very close to the susceptible check at final score. Almost all landraces that belong to infection type R showed the lowest levels of severity over the four scoring dates.

The curve showed slow progress of the disease for landraces showing, MR and/or MS and MSS infection types. These results were in accordance with all studies that showed that varieties rated as MR or MRMS or MS and MSS generally exhibit slow rusting.

The quantitative resistance (race-nonspecific) usually behave in a stable manner compared to the race-specific resistance, because of that, the selection for quantitative resistance is expected to be more durable. To assess the slow rusting, bread wheat landraces were grouped in to three main

categories of slow rusting (low, medium and high) based on the results from different slow rusting parameters, in addition to the susceptible group and the race-specific resistant group

### Race-specific resistant group

None of the bread wheat landraces were recorded as resistant, however 39 landraces with scores of 5R, 10R, 20R showed the lowest values of different slow rusting parameters (FRS <20, AUDPC value less than 50, CI value less than 3, and r-value less than 10, and RRI the value was 9). This group is believed to have race-specific resistance, and may carry a single or combination of major genes of resistance.

According to the landraces origin, the accessions from Iran (which representing the highest number of accessions in this study) had the biggest number with 22 resistant landraces, 6 from Afghanistan, 4 from Iraq and 3 from Syria and Pakistan, and one from Morocco.

### Slow rusting groups

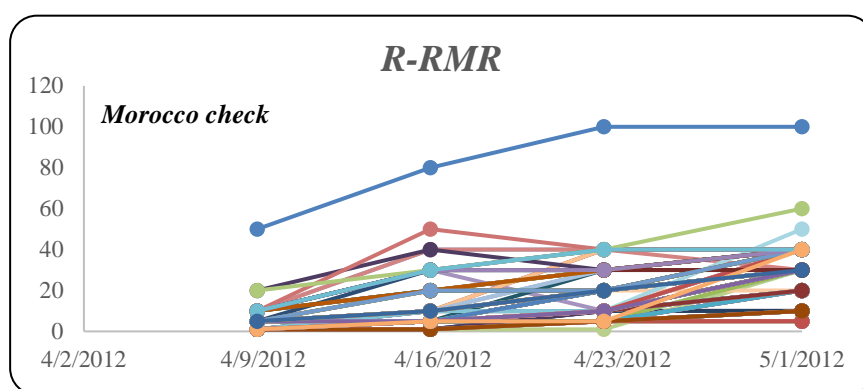
The landraces with slow rusting were divided into three groups based on the slow-rusting parameters, Group 1: The landraces in this group have low level of FRS value of (0-30), AUDPC value  $\leq 200$ , CI value were (0-20) and with r-value less and equal to 30, and are marked as having high level of slow rusting. Different numbers of landraces in each category for different parameters were detected. A total of 51 landraces showed high level of partial resistance with FRS value less than 30, 128 landraces had  $CI \leq 20$ , 126 with  $AUDPC \leq 200$  and 121 with  $r \leq 30$ . Group 2: The landraces in this group showed low level of FRS value of (31-50) (104 landraces), CI value (21-40) (65 landraces), AUDPC value (201-500) (69 landraces), and with “r” value (31-50) (35 landraces), and are marked as having a moderate level of slow rusting resistance. This group showed moderate level of severity and moderately resistant to moderately susceptible reaction type. Group 3: The landraces in this group had high level of slow rusting parameters and were

characterized as having low level of slow rusting. This group showed high levels of disease severity and moderately susceptible to susceptible reaction, with FRS value (51-70), CI value (41-60), AUDPC value ranging between (501 and 900) and with r-value range of (51-90).

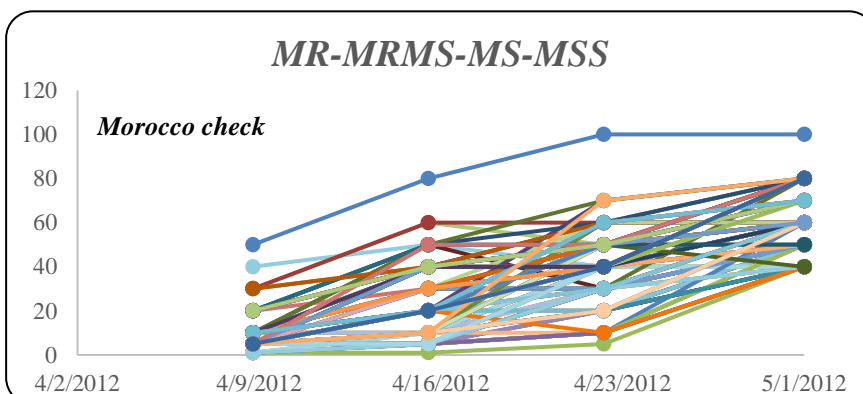
A total of 73 landraces were classified in this category based on FRS parameter, 43 landraces based on CI, 74 landraces based on AUDPC values, and 56 landraces based on r-value.

### Susceptible group

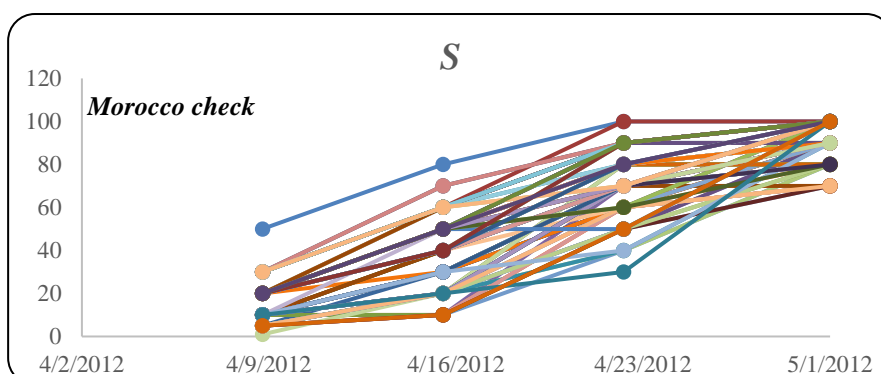
This group showed high level of severity and susceptibility (80S to 100S) and had greater values for all slow-rusting parameters than the other groups, and includes the susceptible check "Morocco". Based on the parameters, 150 landraces had FRS>70, 142 landraces had CI value of more than 60, 109 landraces with AUDPC value exceeding 900, and 166 landraces had r-value higher than 90. According to the landraces origin, 73 accessions belongs to Iran, 19 from Afghanistan, 5 from Iraq and 5 from Syria.



A



B



C

**Figure 2.** Yellow rust progress curves on bread wheat landraces obtained by plotting disease severity (DS) against the number of days after sowing. (A) Yellow rust progress curves of R-RMR. (B) Yellow rust progress curves of MR-MRMS-MS-MSS. (C) Yellow rust progress curves of S.

### Relative Resistance Index (RRI)

The relative resistance index RRI was determined using the obtained data from both seasons, after calculating the ACI. Based on RRI values, out of 417 landraces, 90 landraces had highest RRI value of 9, 143 exhibited RRI value  $\geq 7 < 9$  and all were within the desirable range for adequate resistance to yellow rust. Another 75 landraces were included among the acceptable range of resistance having RRI value  $\geq 5 < 7$ , but 107 landraces showed RRI value of less than 5 and placed under undesirable range. Only two landraces collected from Afghanistan showed RRI value of 0 like Morocco.

By comparing the results obtained from RRI and others parameters we found out that landraces with infection type (R-MR) and with very low values for all parameters, exhibited RRI values of 9, while those that showed high, and moderate and low levels of partial resistance had RRI value ranges of between 8-9, 7-8 and 5-7, respectively. The landraces that have susceptible infection type S and maximum values for each parameter showed very low value of RRI < 5.

### Association between slow rusting parameters

Field assessment for partial resistance was evaluated through FRS, AUDPC, CI and r-value. The results suggested that the landraces which are characterized as having slow disease development (low AUDPC, FRS, CI and “r”) could be considered as having partial resistance to yellow rust.

In the present study, an attempt was made to elucidate the relationships between these parameters by using Pearson’s correlation coefficients. High and significant positive correlations were found among all disease assessment parameters (Figure 4). The highest correlation coefficient was between AUDPC and CI ( $r = 0.99$ ), and the lowest value was between “r” and AUDPC ( $r = 0.86$ ). However, all measured parameters seem to be good estimators of partial resistance to yellow rust in wheat (Table 1).

**Table 1.** Correlation coefficients between yellow rust slow parameters in bread wheat landraces.

	AUDPC	CI	FRS	r-value
AUDPC	—			
CI	0.99	—		
FRS	0.92	0.94	—	
“r”	0.86	0.87	0.96	—

FRS: Final Rust Severity, AUDPC: Area under Disease Progress Curve, r-value:

Infection Rate, ACI: Average coefficient of Infection, RRI: Relative resistance Index

### Principal component analysis (PCA)

Biplot analysis using Principal Component Analysis is used to show graphically the relationships between all partial resistance parameters including RRI. The first two PCAs accounted for about 99.2% of total variation. The most

prominent relations are shown in Figure (4). Significant and positive correlations were found between ACI and AUDPC; between FRS and “r”, as indicated by the small obtuse angles between their vectors. Good and positive correlations were also confirmed between AUCPC, ACI and FRS. There was a near zero correlation between AUDPC and “r”, between ACI and “r”, as indicated by the near perpendicular vectors. There were negative correlations between AUDPC and RRI, and between ACI and RRI, as indicated by the angle of approximately 180 degrees.

### Diversity analysis

#### Cluster analysis

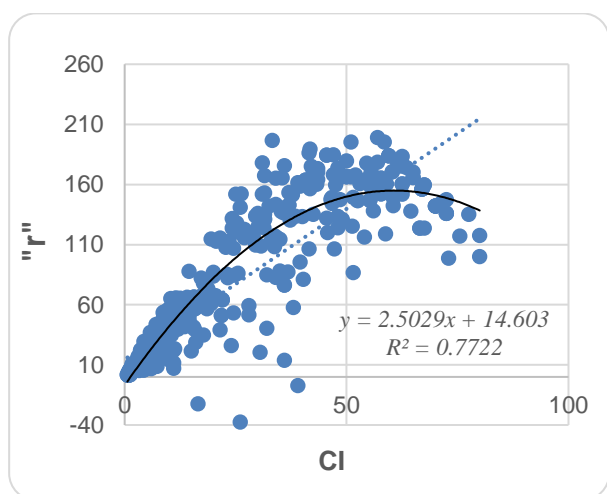
Cluster analysis based on partial resistance parameters of bread wheat landraces along with Morocco, revealed two major clusters. Susceptible and low level of slow rusting landraces was grouped in the first cluster. Resistant, high level and moderate level of partial resistance were grouped in the second cluster (Figure 5). The first cluster included one sub-cluster with Morocco and two landraces from Afghanistan with maximum distance from all the other landraces and having the highest values of all parameters and “0” value of RRI. The other sub-cluster include landraces in two groups: The first group consist of all landraces marked as susceptible, and the second group included two sub-groups one of them having low level of partial resistance and the second as moderate to low level of partial resistance, with infection type (MS-S).

The second cluster comprises landraces having better level of slow rusting. This cluster is divided into two main sub-clusters, the first one includes moderate level of partial resistance, and the second sub-cluster consist of two groups: the first group has two different sub-groups, one consisting of landraces with lowest values of all parameters and “9” value of RRI, which could carry a major gene or a combination of major genes for resistance to yellow rust. The second sub-group includes landraces with high level of partial resistance, with low values of all parameters and “9” value of RRI.

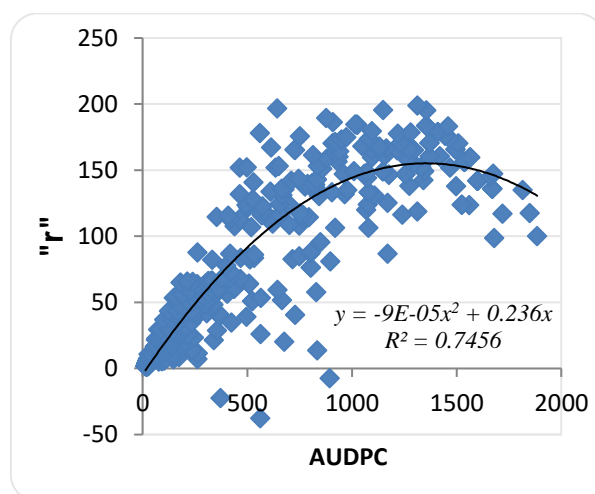
The second group comprised also two sub-groups: the first one consists of landraces marked as having high level of partial resistance and “8” for RRI parameter, and the last sub-group consisted of landraces scored as high to moderate level of partial resistance. The landraces in this sub-group are classified as having moderate to high levels of partial resistance and infection type (MR-MS).

### Principal coordinates analysis (PCoA)

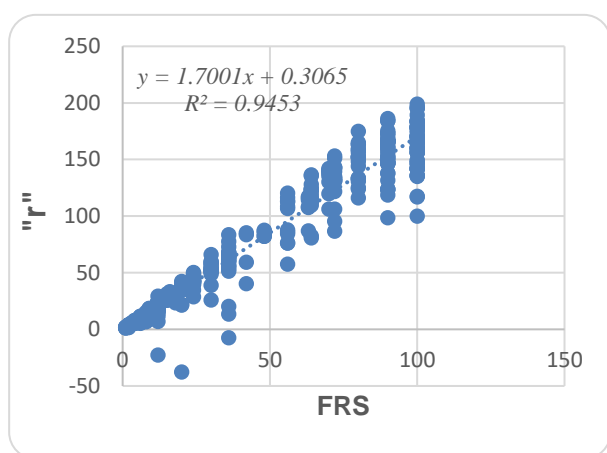
Principal coordinates analysis (PCoA) has been performed for a clear separation among the groups having different levels of resistance (Figure 6). In accordance with the dendrogram, the first two components explained 99.5% of the total variation. The first principal coordinate clearly separated the landraces having susceptible and low level of partial resistance on the left side of the diagram and the landraces with better level of partial resistance and resistance clustered on the right side.



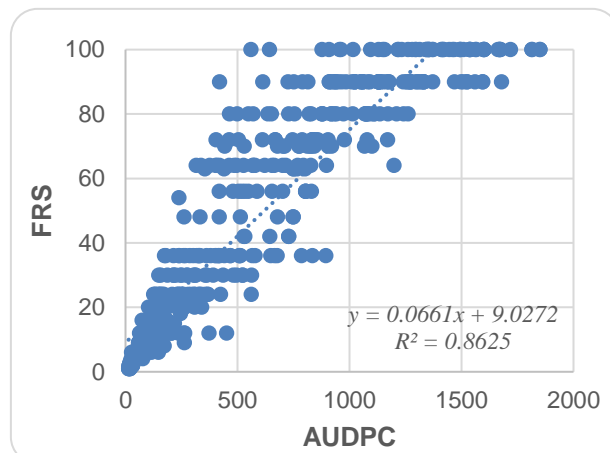
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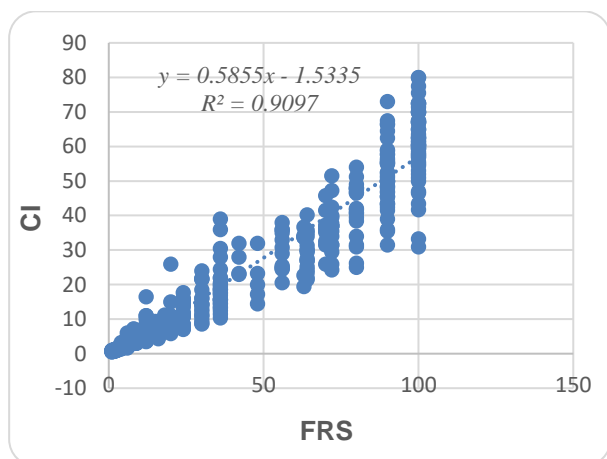
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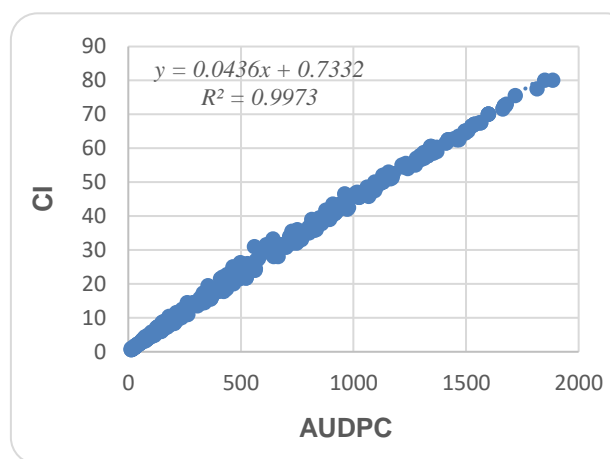
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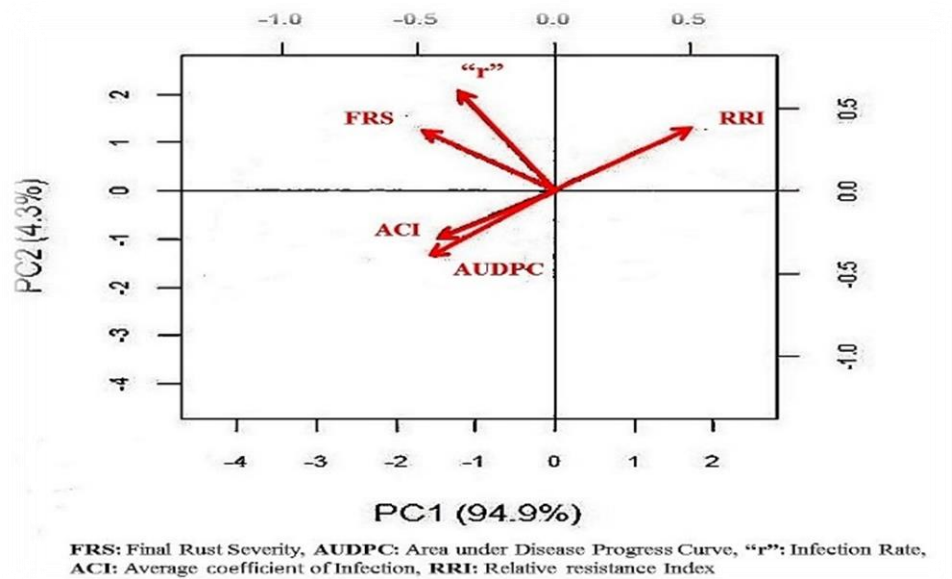
**E**



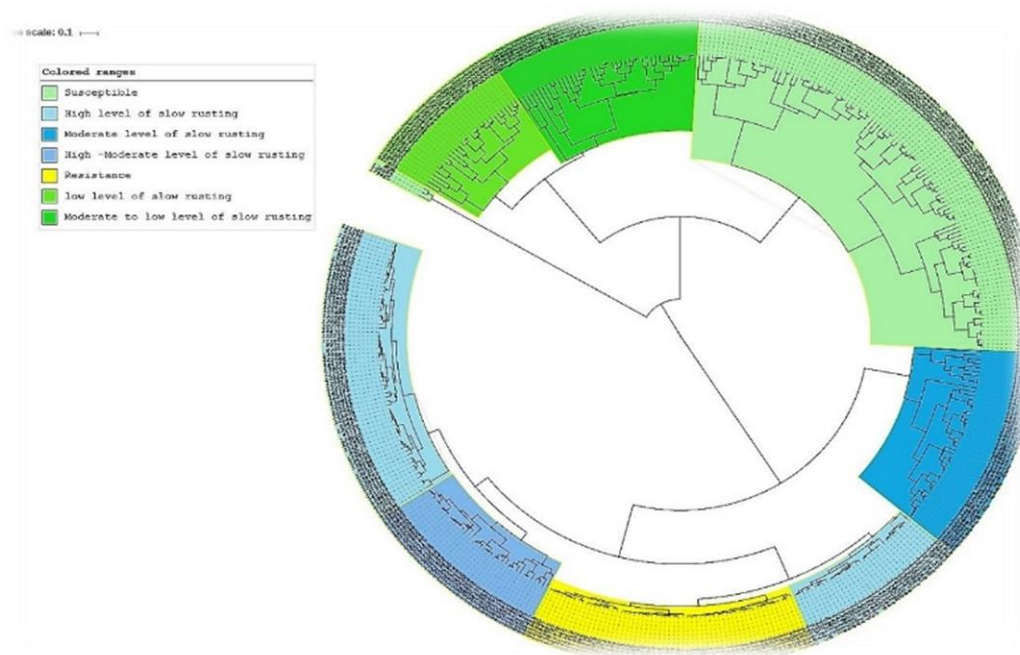
**F**

**Figure 3.** Associations between different yellow rust parameters used to assess partial resistance to yellow rust in bread wheat: (A) “r” with CI. (B) “r” with AUDPC. (C) “r” with FRS. (D) FRS with AUDPC. (E) CI with FRS. (F) CI with AUDPC.

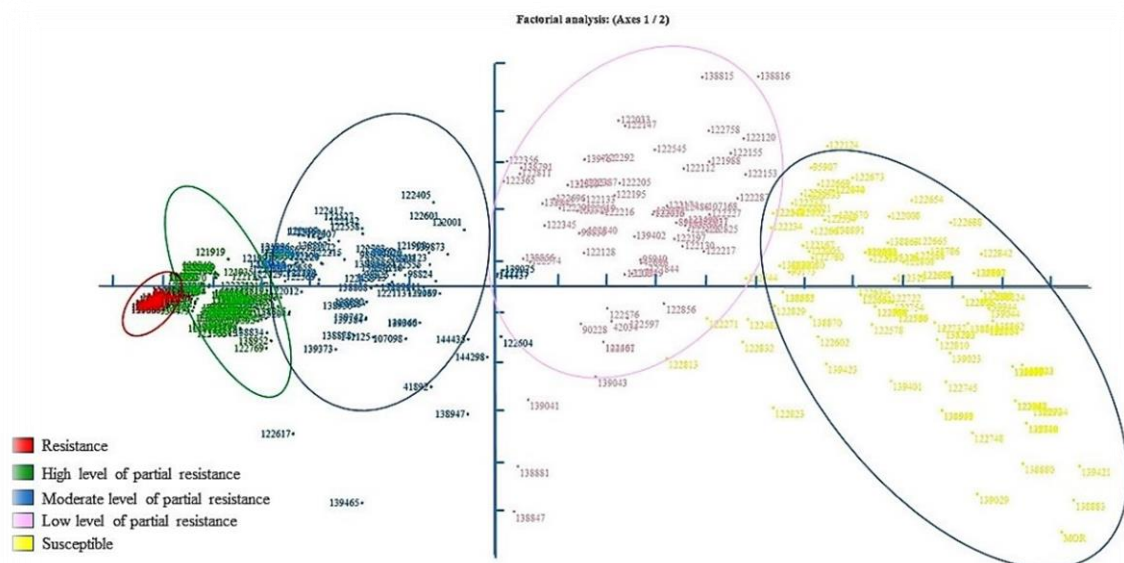




**Figure 4.** Correlations between slow rusting parameters using Principal component analysis (PCA)



**Figure 5.** The dendrogram of landraces generated from UPGMA using Neighbor-joining analysis



**Figure 6.** Factorial coordinate analysis for bread wheat landraces as generated by DARwin Software using dissimilarity coefficient matrix calculated from all partial resistance parameters.

## Discussion

Improving resistance to yellow rust has become an important target for bread wheat breeding programs at ICARDA and around the world, after most of the varieties grown by the farmers as well as most elite germplasms have become susceptible to the new virulence (70E214). During both seasons, epidemics of yellow rust are widely spread in CWANA countries after the wide spread of (70E214) virulent populations. The climatic conditions during 2010-2012 seasons were favorable for the development of the disease and the success of artificial inoculation with (70E214) virulent population. The high susceptibility of Morocco used as spreader row showed the uniformity of inoculation, which has allowed effective screening of the accessions, planted, including good assessment of slow rusting resistance. The focus of this study was on identification of genetic sources with slow rusting resistance in bread wheat accessions.

The evaluated accessions exhibited a wide range of reaction to yellow rust ranging from high susceptible to highly resistant and most of the entries showed better resistance than Morocco. Most of the accessions were more resistance under high disease pressure as compared to the susceptible check. Similar diversity in reaction to yellow rust is found by other researchers for other sets of germplasm showing the possibility of finding new sources of resistance to emerging virulence's (Ali *et al.*, 2009; Sthapit *et al.*, 2014).

Field-based assessment of partial resistance is essential for the development of new varieties with long lasting resistance. Different parameters, FRS, AUDPA, CI, "r" were used in this study to assess the slow rusting in bread wheat landraces along with RRI. These parameters showed large

ranges which have allowed classifying the landraces into five groups: one group with potentially vertical resistance, one group with susceptible reaction and three groups with low, medium and high slow rusting reactions.

None of the tested landraces showed resistant reaction and some landraces showed even higher susceptibility than Morocco which used frequently around the world as rust spreader. The group with race-specific type of resistance included 39 landraces (10%) traced to different geographic areas and their resistance is controlled by major genes. Other researchers reported, that the lines having resistant reaction at adult plant stage and low value of slow rusting parameters may carry major genes along with minor genes of resistance, and the accessions with CI up to 5% are probably carrying major genes (Ali *et al.*, 2009; Safavi *et al.*, 2010). The duration of the effectiveness of major genes is often limited by the selection of new virulent races as reported by many authors (Safavi *et al.*, 2010; Chen *et al.*, 1993; Wan & Chen, 2012). The protection using this type of resistance can be extended through either using the different genes sequentially or through their pyramiding and within an integrated disease management approach. These findings confirm the value of genetic resources held ex situ in gene banks to continuously supply needed diversity to overcome major challenges including the new virulence's for major diseases such as yellow rust. This study has shown the existence of large number of accessions with partial resistance which could be used within the strategy for more durable protection against the disease, as it is believed to be race non-specific. Approximately (55-65%) of the tested landraces showing infection types (R-MR, MR, MR-MS, MS, and MS-S) can be classified into different levels of slow rusting as the rust development was slower and the spores were surrounded by necrosis and chlorosis. Landraces with slow rusting mechanism of resistance are expected to possess



several genes that confer partial and durable resistance (Dehghani & Moghaddam, 2004; Tabassum, 2011) or could be combined to provide near resistance (Angus & Fenwick, 2008).

According to all used partial resistance parameters, landraces with slow rusting were divided into three groups with high, moderate, and low slow rusting, with the infection types MR, MS and MSS. These results were in accordance with (Brown *et al.*, 2001) and (Singh *et al.*, 2005), who mentioned that the cultivars with MS or MR infection type may carry durable resistance genes. Several parameters were used to assess the slow rusting type of resistance.

Landraces with CI values of 0-20, 21-40, 41-60 were regarded as possessing high, moderate, and low levels of slow rusting (Ali *et al.*, 2007; Pathan & Park, 2006). Safavi *et al.* (2010) used the same parameters to classify wheat germplasm into groups with low to high levels of slow rusting and classified the accessions that showed CI value greater than 60 as susceptible. Although values of (61–80) with (MS-MSS) infection type could reflect the presence of minor genes. CI values within this range may have also resulted from variation in environment and/or growth stage at the time of scoring.

Considering high disease pressure maximum FRS (100%) was recorded for Morocco and 98 landraces showed FRS 90-100%. Depending on this parameter, the tested landraces were divided into three groups of partial resistance, i. e., high, moderate, low levels of partial resistance having 1-30%, 31-50%, and 51-70% FRS, respectively. This parameter is also used for assessment of slow rusting by other authors (Herrera-Fossel *et al.*, 2007; Safavi *et al.*, 2010).

Landraces were also categorized into three groups of partial resistance using AUDPC. This parameter is the most widely used to assess disease development and slow rust (Ali *et al.*, 2008; Broers *et al.*, 1996; Bux *et al.*, 2012); other studies (Mahmoud *et al.*, 2015; Saleem *et al.*, 2015) classified cultivars with AUDPC of less than 300 as having high level of slow rusting.

The infection rate “r” seemed not a reliable estimate of slow rusting resistance compared to FRS, ACI, and AUDPC, due to its estimation depends on the linear regression of disease severity across the four readings. During the period of reading, 164 landraces showed disease development and “r” values superior to the check, although the actual infection rate for “Morocco” may even be more. Some landraces showed even negative r-values, because they showed MS infection type at the early stage and R to MR infection types at the advanced stages, indicating that the rate of disease development didn’t change with the host developmental stages. Indeed, it is possible the growth rate will be negative while the disease is increasing, if the host grows faster than the pathogen (Kushalappa & Ludwig, 1982). In other words, the value of this parameter does not reflect the final infection type of the studied landrace, but only the degree of disease development during the time of the study. Similar results and

justifications were also reported for yellow rust on 20 wheat-breeding lines in Pakistan (Ali *et al.*, 2007).

Overall, AUDPC and CI showed high and positive correlation that was confirmed using principal component analysis. Similar relationships among the two parameters were found by other researchers (Safavi *et al.*, 2010; Sandoval-Islas *et al.*, 2007). Field selection of partial resistance trait preferably using low AUDPC and terminal rating CI is feasible in situations, where greenhouse facilities are inadequate (Singh *et al.*, 2007). In the present study a high correlation (0.99) was found between FRS and AUDPC which is consistent with previous studies made on yellow rust of wheat by (Safavi, 2015; Tabassum, 2011) in Pakistan.

Since AUDPC, CI and FRS parameters are strongly and positively correlated, they can then be used interchangeably to assess slow rusting, as also suggested by other researchers (Safavi *et al.*, 2010; Safavi & Afsari, 2012; Sandoval-Islas *et al.*, 2007).

However, FRS and CI are requiring less labor and time for recording in contrast with AUDPC and infection rate, as also reported by (Safavi *et al.*, 2013). Other studies also privileged FRS as a parameter to measure the resistance levels over other slow rusting parameters (Tabassum, 2011; Taye *et al.*, 2014), FRS is assumed to represent the cumulative result of all resistance factors during the progress of epidemics (Parlevliet & Ommeren, 1975). Ali *et al.* (2008) recommended the use of CI to assess slow rusting.

In wheat breeding program, lines are tested over several years and locations and the use of the Relative Resistance Index (RRI) could be more appropriate in assessing partial resistance. Similarly, many researchers defined the desirable and acceptable values of RRI between 7 and 5, respectively to determine germplasm with partial resistance (Afzal *et al.*, 2009; Akhtar *et al.*, 2002). Most recently, Mahmoud *et al.* (2015) used the RRI parameter along with CI to identify wheat genotypes resistant to yellow rust in (RILs) derived from a cross between two Egyptian landraces.

Partial resistance is desired by plant breeders to combat the fast evolving diseases such as rusts. Based on AUDPA, FRS and CI along with RRI, 250 landraces out of 417 landraces, were supposed to be having varying degree of slow rusting. However, these landraces should be tested at seedling growth stage in the greenhouse to confirm the presence of major genes.

These findings confirm the value of genetic resources held ex situ in gene banks to continuously supply breeding programs around the world with needed diversity to overcome major challenges including the new virulence’s for major diseases such as yellow rust. The high number of sources of resistance and their geographic spread could reflect the diversity of genes controlling resistance to yellow rust. Slow rusting and adult plant resistance is highly needed to cope with the rapidly evolving and expanding virulence’s of yellow rust.

## المخلص

علاو، فدا، وليد السعيد، مايكل بوم، هشام العطوانى وأحمد عمري. 2018. المقاومة البطيئة لمدخلات القمح الطري للصدأ الأصفر الذي يسببه الفطر *Puccinia striiformis* f.sp. *tritici* تحت ظروف العدوى الحقلية الإصطناعية. مجلة وقاية النبات العربية، 36(2): 36-40.

يعد الصدأ الأصفر الذي يسببه فطر *Puccinia striiformis* f.sp. *tritici* من الأمراض الفطرية الأكثر تدميراً للقمح وبخاصة في منطقة وسط شرق آسيا وشمال أفريقيا /CWANA، حيث أصبحت معظم الأصناف التي تم تطويرها في هذه المنطقة قابلة للإصابة بالسلالة الجديدة Yr27. ولذلك فإن زراعة الأصناف ذات المقاومة البطيئة هي من أكثر الطرائق الإقتصادية الناجحة. أجريت دراسة حقلية لتقويم 500 صنفاً محلياً من القمح الطري مع الصنف القابل للإصابة "Morocco" في ظل الظروف الحقلية في تل حديا، سورية خلال الموسمين 2011/2010 و 2012/2011، وتم استخدام سلالات الصدأ الأكثر انتشاراً (70E214) لإجراء الإعداء الاصطناعي. أخذت القراءات عندما كانت شدة الإصابة على أوراق نبات الشاهد Morocco أكثر من 50%، حيث تم أخذ أربع قراءات بفواصل سبعة أيام بين كل قراءتين. قومت مقاومة الصدأ البطيئة على أساس تطور المرض مع مرور الوقت باستخدام معامل المساحة تحت منحنى تطور المرض (AUDPC)، معامل العدوى (CI)، شدة الإصابة النهائية (FRS)، معدل الإصابة "r"، infection rate و معامل المقاومة النسبية (RRI) Ralative Resistnce Index. لم يظهر أي من الأصناف المقاومة رد فعل مقاوم جداً، بينما أظهرت 10% من الأصناف قيماً صغيرة للمؤشرين السابقين، وهذا ما يدعو للإعتقاد بوجود مورث رئيس مسؤول عن صفة المقاومة في هذه الأصناف المحلية. وامتلك حوالي 65% من الأصناف مستويات مختلفة من المقاومة البطيئة و 25% كانت حساسة جداً. وبالاعتماد على نتائج المؤشرات السابقة تم انشاء شجرة القرابة للأصناف مع الصنف Morocco والتي أظهرت وجود مجموعتين رئيسيتين: الأصناف القابلة للإصابة مع الأصناف ذات مستوى منخفض من المقاومة البطيئة في المجموعة الأولى، والأصناف المقاومة والأصناف ذات المستوى العالي والمتوسط من المقاومة البطيئة في المجموعة الثانية. وتم تأكيد هذه النتائج باستخدام تحليل العناصر (المكونات الأساسية) PCA، وبمقارنة نتائج مؤشر المقاومة النسبية RRI مع نتائج المؤشرات الأخرى، تبين أن الأصناف المحلية والتي تمتلك أقل قيم للمؤشرات تظهر قيمة عالية لـ RRI (RRI=9)، بينما الأصناف التي أظهرت مستويات مختلفة من المقاومة البطيئة عالية، متوسطة ومنخفضة تراوحت قيم RRI 8-9، 7-8 و 5-7، على التوالي. أما الأصناف التي أظهرت أعلى قيم لجميع المؤشرات كانت قيم RRI أقل من 5. والذي تم حسابه من خلال حساب متوسط معامل العدوى (ACI) للنتائج المسجلة في سنتي الدراسة، أن 44 صنفاً من الأصناف المدروسة أعطت درجة مقاومة جيدة بقيمة (RRI=9)، 143 درجة مقاومة مرغوبة (RRI= 8-7)، 75 صنف محلي كانت مقاومتها مقبولة (RRI= 6-5) بينما كانت بقية الأصناف حساسة إلى شديدة الحساسية مع قيمة RRI أقل من 5. وتمكن نتائج هذه الدراسة من امداد برامج التحسين الوراثي في سورية والعالم بمصادر وراثية مقاومة التي ستمكن من حماية القمح الطري من عدوى الصدأ الأصفر لسنوات طويلة. وتشير النتائج أيضاً إلى أن معامل الـ AUDPC، معامل الـ CI وشدة الإصابة النهائية (FRS) هي مؤشرات يعتمد عليها لتقويم مقاومة الصدأ البطيئة أكثر من مؤشر معدل الإصابة "r". هذا وأظهرت النتائج أن الارتباط بين جميع المؤشرات كان قوياً وإيجابياً.

كلمات مفتاحية: مقاومة النبات، الصدأ الأصفر، القمح الطري، مدخلات وراثية.

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