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Prevalence and Distribution of Wheat Stem Rust (*Puccinia graminis* f. sp. *tritici*) in Tigray Region, Northern Ethiopia

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Abstract

Wheat stem rust (black rust) is caused by *Puccinia graminis* f. sp. tritici remains one of the most production constraints in all wheat growing areas of the country and worldwide, causing yield losses of up to 100% during epidemic years. Behaviorally, the pathogen have capacity to blow aerially long distances, fast reproduction of infectious uredospores and ability to evolve new pathotypes/races that makes the management option very challenging task. Therefore, this study was initiated to assess information on the current distribution and prevalence of wheat stem rust in the study area. Purposive multi-stage sampling procedure was used to select major wheat growing zones, districts and peasant associations. Assessment was carried out on 95 wheat farms in 7 districts across the three zones of Tigray region. The results of the study showed that wheat stem rust was 70.53% prevalent across the study areas with significantly ($p < 0.01$) varied incidence and severity damage among fields, districts, and zones. The mean prevalence of stem rust was 85.55% in Southern, 62.22% in Eastern and 53.33% in Southeast zones. The highest disease incidence of 78.67, 66.5, and 47.33% were recorded in Kilte Awulaelo, Raya Azebo, and Ofla districts, with corresponding severity of 43.67, 35, and 21.93%, respectively. The overall mean incidence and severity of stem rust was 41.84 and 21.36% respectively, which is higher than the previous reports from the region indicated an increase in its distribution and intensity. Therefore, there is a need to develop a coordinated network on the wheat stem rust assessment program for virulence and/or avirulence updated information in the region.

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Incidence, Prevalence, Puccinia graminis f.sp. tritici, Severity, Stem rust, Wheat.

Introduction

Wheat (*Triticum* spp.) is one of the most important stable cereal crop in temperate zones by production and nutritional value. Worldwide, wheat is the leading source of cereal proteins and primary staple food (Figueroa *et al.*, 2017). It is the second most important crop in the world next to rice in area of production (Ambika and Meenakshi, 2018). It is a source of food and livelihoods for over 1 billion people in developing countries (FAO, 2017a). Ethiopia is the only country in Sub-Saharan Africa where smallholder wheat production meets more than 70% of the national consumption demand (Shiferaw *et al.*, 2011; Tadesse *et al.*, 2018). Tigray is one of the major wheat producing regions of Ethiopia. In this region wheat is the 3rd important cereal crop both in area coverage and production. Even if there is large area of wheat production in the country, the average national yield is estimated at 2.74 t/ha while it is only 1.98 t/ha in Tigray region (CSA, 2018), which is lower than the country's and world's average yield of 3.65 t/ha (FAO, 2017a).

The low productivity is attributed to a number of biotic and abiotic factors that put in a questions the production of wheat. Among the biotic factors, wheat is infected by three rust diseases, stripe, leaf and stem rust (Roelfs *et al.*, 1992; Hailu *et al.*, 2015). Wheat rust pathogens have hindered global wheat production since the domestication of the crop and continue to threaten the world's wheat supply. Wheat stem rust, caused by *Puccinia graminis* f.sp. *tritici* causes one of the most potentially destructive wheat diseases, seriously threatening and remains a constraint to the world's wheat production due to the variability of virulence in the pathogen population, the rapid evolution of new races, the ability of urediniospores to spread over long distances by wind, and an exponential reproduction capacity. It is estimated that global annual losses to wheat rust pathogens range between US$ 4.3 to 5.0 billion and specifically, wheat stem rust estimated that global losses would average 6.2 million metric tonnes per year or higher under severe epidemics (Pardey *et al.*, 2013).

East African highlands including Ethiopia are considered as hot spots for the emergence of new stem rust pathogen races. The development of new virulent races in East Africa and other parts of the world caused severe losses and continue to pose a threat to global wheat production and food security (Olivera *et al.*, 2015; Singh *et al.*, 2015; Bhavani *et al.*, 2019). Many of the races evolve with corresponding virulence to commercially deployed resistance genes and some have broad virulence spectrum. The races in East Africa including Ug99 (TTKSK) and its lineage, TKTTF ("Digalu"), TRTTF and JRCQC defeated the resistance conferred by many major/ R-genes in breeding lines and commercial cultivars. Continuously emerging races virulent to many of the commercially deployed qualitative resistance genes have caused remarkable loss worldwide and threaten global wheat production (Megerssa *et al.*, 2020).

Due to the constant evolution and mutation of *Puccinia graminis* f. sp. *tritici* races, many resistance genes are rendered ineffective within a relatively short period of time (Rahmatov *et al.*, 2016). Furthermore, some studies that were carried out in Ethiopia showed that most previously identified races were virulent on most of the varieties grown in the country and they are among the most virulent in the world (Admassu *et al.*, 2009). Keeping this in mind, continuous and exhaustive surveys need to be carried out to give a clear picture of the virulence pattern of *Puccinia graminis* f. sp. *tritici* in Ethiopia. It is important to study the evolution of new races, determine virulence and forecasting the virulence shifts in a population (Admassu *et al.*, 2009). Hence, this study was initiated with the objectives of assessing the current distribution of wheat stem rust in the zones of Tigray region, Northern Ethiopia.

Materials and Methods

Description of the Study Area

Wheat stem rust survey was conducted in 2017 main cropping season in the Southern, Southeast and Eastern zones of Tigray regional state in Ethiopia. The survey was conducted in the major wheat growing districts of the Southern zone involved three sample districts: Ofla, Enda-Mekoni, and Raya-Azebo, three districts in the Eastern zone namely, Saesia Tseadaemba, Kilte Awulaelo and Ganta Afeshum, and one district in Southeast zone which was Enderta (Figure 1).

Assessment of Wheat Stem Rust

The study was conducted once at the vital growth stage of the crop per field (milk-hard dough) in mid-October. Stem rust assessments were made at five points along the two diagonals (in an ''X'' pattern) of the field using 0.5 x 0.5 m (0.25 m^2) quadrant. The survey was carried out using purposive multi-stage sampling techniques and also based on wheat area coverage. From each peasant association, five farms were assessed at 5-10 km interval followed by systematic sampling along the main and feeder (accessible) roadsides on pre-planned routes in areas where wheat is predominantly grown. In each field, wheat plants within the quadrant were counted and recorded as diseased/infected and healthy/non-infected and intensity of stem rust was calculated (Hailu *et al.*, 2015). The incidence of wheat stem rust was calculated using the number of infected plants and expressed as a percentage of the total number of plants assessed.

$$\textbf{\textit{DiseaseIncidence}}(\%) = \frac{Number\ of\ diseased\ plants}{Total\ number\ of\ plants\ inquadrant} x100$$

The disease severity was measured as a percentage of leaf/stem area covered by rust disease according to Modified Cobb's Scale as developed by Peterson *et al.*, (1948). The severity of the disease was examined randomly by selecting five plants from a single quadrant and five quadrants were used for the estimation in a single wheat field. Type of infection (plant response) was recorded using the description of Roelfs *et al.,* (1992).

The prevalence of the disease was measured by using the number of fields affected divided by a total number of fields assessed and expressed in percentage (Hailu *et al.,* 2015).

$$\boldsymbol{DiseasePrevalence}(\%) = \frac{Number\ of\ infected\ fields}{Total\ number\ of\ fields\ assessed} x100$$

Data Analysis

Data on disease incidence and severity were analyzed using three-stage nested design. Analysis of variance (ANOVA) was performed using SAS version 9.3 Software package (SAS, 2012). Means were separated using LSD test. The associations of disease incidence and severity with independent variables *viz*. altitude, variety growth stage and weed management were computed using simple correlation analysis to establish their relationships. Each of the independent variableswere tested with incidence and severity of wheat stem rust as the dependent variable. Linear regression analysis was done by plotting disease severity against altitude. Determination of regression intercept, slope and coefficient of determination were computed using Excel microcomputer statistical software.

Results and Discussion

Distribution and Occurrence of Wheat Stem Rust

Wheat stem rust was observed in all surveyed zones of the region at variable levels. The results of the assessments revealed that the intensity of stem rust varied from slight to complete infection in wheat fields depending on the varietygrown and agro-ecological divergence. During the assessment, the disease was observed on 67 (70.53%) of the 95 wheat fields inspected. It was prevalent in all assessed zones of the region. The number of fields assessed in the Southern, Eastern and Southeast zones were 40, 40 and 15, respectively. Of which, 34 (85%), 25 (62.50%) and 8 (53.33%) were affected by stem rust, respectively.

Wheat stem rust was prevalent in all assessed districts of the zones and its intensity among the districts was significantly different ($p < 0.01$). The disease was more prevalent at Ofla and Kilte Awulaelo districts with a similar prevalence value of 93.33% while the lowest disease prevalence 33.33% was recorded at Ganta Afeshum district (Table 1). Besides the locational variations in disease intensity, the field assessment results showed that there was a wide distribution of stem rust across the districts of the zones in the season.

The distribution and extent of damage caused by the wheat stem rust varied significantly ($p < 0.01$) among the zones. The overall mean incidence in the zones was 41.88% in the season. The highest disease incidence was recorded in Southern followed by Eastern zone with the mean values of 49.61% and 37.00%, respectively whereas the lowest disease incidence was recorded in Southeast zone (34.33%). Similarly, the highest disease severity was recorded in the Southern zone (24.22%) followed by Eastern zone (20.06%). The lowest was observed in Southeast with 16.67% disease severity (Figure 2). The overall mean disease severity of the zones was 21.36% in the season.

Crop rotation practice was used to minimize inoculum build-up, however, it was not practiced well in the study area. This might be contributed more chance of disease occurrence in the areas than where crop rotation practice was done. Crop rotation practice probably contributed to the low wheat stem rust disease incidence and severity. It also limits the genetic diversity of the pathogen population and to minimize the number of urediniospores produced. According to Joseph *et al.,* (2007), crop rotation improves management of plant diseases through manipulation of host factors such as crop and cultivar selection; interruption of disease cycles through crop rotation, fungicide application, and removal of weeds and volunteer crop plants.

The reasons for more widespread of wheat stem rust disease in the Southern zone than in the Eastern and Southeast zones might be due the contribution of the agro-ecological divergence.

In the Southern zone the altitude ranges from 1567-2520 m.a.s.l (meter above sea level) which was suitable or important for the pathogen development and warmer temperature compared to the other zones. According to this study, stem rust development varied from place to place depending on agroecological divergence and variety grown. This is probably due to the differences in relative humidity and temperature (Mideksa *et al.,* 2018).

Bars with the same letter(s) are not signi2ficantly different at p<0.05.

There was a significant difference ($p < 0.01$) among districts in the incidence of wheat stem rust. The disease incidence ranged between 22 and 64% in Ofla, 62-71% in Raya Azebo, 16-46% in Enda Mehoni, 64-92% in Kilte Awulaelo, 0-26% in Ganta Afeshum, 10-32% in Saesia Tsaedaemba and 24-39% in Enderta districts. The mean disease incidence was ranged from minimum of 11% to maximum of 78.67% within the districts (Table 2).The highest wheat stem rust mean incidence was recorded in Kilte Awulaelo (78.67%) followed by Raya Azebo district (66.5%) and the lowest disease incidence was recorded at Ganta Afeshum district (11%).

There was a significant ($p < 0.01$) difference among districts in terms of wheat stem rust severity. The disease severity ranged between 9 and 29% in Ofla, 32-38% in Raya Azebo, 7-25% in Enda Mehoni, 33-56% in Kilte Awulaelo, 0-12% in Ganta Afeshum, 5-18% in Saesia Tsaedaemba and 10-20% in Enderta districts. The highest mean disease severity was recorded in Kilte Awulaelo (43.67%) followed by Raya Azebo district were 35% severity was recorded. (Table 2). Enda Mehoni and Enderta districts had moderate levels of disease severities 20.67% and 17%, respectively and were not significantly different from each other. On the other hand, Saesia Tsaedaemba district had a mean disease severity of 11.5%. The lowest disease severity was recorded from Ganta Afeshum district (5%).

Abebe *et al.,* (2012) reported that the highest mean incidence of 42.3% and 26.7% severity of stem rust was recorded in Raya-Azebo district from Southern zone during 2010 main cropping season. The highest severity of 80% was recorded where the highest incidence 100% was noted at Raya-Azebo district. The present study showed increased disease incidence of wheat stem rust in major wheat growing zones of Tigray region, with mean values of 49.61% in the Southern zone; 37% in Eastern zone and 34.33% in Southeast, as compared to results of previous surveys.

According to Abebe *et al.,* (2012), the mean percent incidence of wheat stem rust was 15.60 in the Southern zone during 2010 cropping season. Correspondingly, mean incidence of 33% and 10.80% severity of wheat stem rust in the West and Southwest Shoa zones of Oromia region were reported by Hailu *et al.,* (2015) during 2014 main cropping season. The increment in the intensity of wheat stem rust in this report emanated from the rapid expansion of new pathogen races such as TKTTF (Digalu race), TTTTF and extensive planting of the susceptible varieties.

The detection of TKTTF race was the first report of virulence to SrTmp in the country. This non-effective gene is present in the most popular and widely grown bread wheat variety Digalu (Hodson, 2015). Digalu variety was resistant to the Ug99 race group became susceptible to race TKTTF (not a member of the Ug99 lineage) after planting by many growers in the 2013/14 season (CSA, 2014, Olivera *et al.,* 2015). The continuous wheat production and favorable microclimates in the major wheat production areas could be the main reasons for the rapid evolution of the pathogen. The recent climatic changes like warm temperature and moist (amount and duration of rainfall) have reasonably predisposed and favoured the wheat crop to be infected by stem rust pathogen (Admassu *et al.,* 2009; Hailu *et al.,* 2015; Singh *et al.,* 2015). Similarly, sexual recombination may have also contributed to the high virulence diversity of *Puccinia graminis* f. sp. *tritici* because *Berberry holstii*is present in proximity to wheat production areas of Ethiopia and the pathogen is able to complete its life cycle in the country (Woldeab *et al.,* 2016).

Distribution and intensity of wheat stem rust across peasant associations

The within district comparison of wheat stem rust distribution indicated that, highest prevalence (100%) of the disease were recorded in the peasant associations of Ofla (Hashange and Menkere), Raya Azebo (Kara Adishabo), Kilte Awulaelo (Genfel and Aynalem) districts. However, these peasant associations recorded different mean percent of incidence and severity of stem rust. The disease was more important in Genfal, Agulae, Kara Adishabo, Aynalem, Hashange, and Wargiba localities with mean incidences of 92, 80, 71, 64, 64 and 62% in the order listed. The lowest disease incidence was recorded in Betahawaryat, Guamse and Maichew peasant associations with their mean value of 8, 10, and 16%, respectively (Table 3).

Similarly, the severity of wheat stem rust in the surveyed peasant associations didn't show a similar trend to that of incidence. The highest mean disease severity of 56% was recorded in Genfel, followed by Aynalem, Kara Adishabo, Agulae and Wargiba with mean values of 42, 38, 33, and 32% in the same order. However, the lowest severity was recorded in Bethawaryat (3%) followed by

Guamse and Maichew with mean values of 5 and 7%, respectively. In the localities of Ganta Afeshum district, the disease severity was very low as compared to others districts. Stem rust disease was not recorded in any of wheat fields of Hager Selam locality in Ganta Afeshum district. The zero disease prevalence in this locality might be due to the fact that wheat stem rust is more important at mid-altitude than at high altitude and lower temperature at higher altitude in the area during the survey. The annual rainfall and temperature were low in the district of this locality comparing to other districts assessed in the season and also the locality fall in the altitude range of 2965-3008 m.a.s.l. Dagnatchew (1967) reported that due to a lower temperature at higher altitude stem rust disease is not a threat to the wheat crop.

Peterson (2001) who reported that stem rust is favored by warm temperature with six or more hours of moisture and develops to devastating levels if such conditions prevail during early reproductive phase prior to dough stage of the crop growth stage. Mideksa *et al.,* (2018) also reported that temperature (minimum, maximum and average); rainfall and relative humidity interacted simultaneously in nature and contributed collectively to make the environment favorable for the stem rust development, which showed the existence of multicollinearity among them. When the effects of these weather factors were assessed individually, it was found that there existed no significant positive impact between stem rust development and individual weather factors except with a few weather variables. If one of these weather factors was missed, the disease would not develop. However, if disease develops, its severity fluctuates with changing environmental conditions. Eventually, environmental conditions, amount of inoculum, host susceptibility, host physiological growth stage and timing of the epidemic are all factor that affects the degree of damage significantly (Duveiller, 2007).

Where: K/Awulaelo-Kilte Awulaelo, G/Afeshum-Ganta Afeshum, S/Tseadaemba–Saesia Tseadaemba, H/T/haymanot-Hizba Teklahaymanot, H/hiwot-Hadush hiwot, B/hawaryat- Beta hawaryat and K/Adishabo- Kara Adishabo.

Distribution and prevalence of wheat stem rust across altitude ranges

Wheat stem rust survey was carried out at altitude ranges of 1567-3008 m.a.s.l particularly, 1567-2520 m.a.s.l in Southern, 1950-3008 m.a.s.l in Eastern and 1981-2332 m.a.s.l in Southeast zones of Tigray region. According to the traditional classification system of agro ecological zones of Ethiopia; 500-1500 m lowlands, 1500-2300 m midlands and 2300-3200 m highlands (Ferede *et al.,* 2013). Based on this altitude classification, from the total fields inspected, 41.05% of the fields assessed were fall in mid altitudes ranging from 1567 to 2300 m.a.s.l while the remaining 58.95% were fall in the high altitude ranged from 2301-3008 m.a.s.l (Table 4). There was a significant ($p < 0.01$) difference among two altitude classes in terms of incidence and severity of wheat stem rust. Out of 39 wheat fields inspected in the altitude ranges 1567-2300 m.a.s.l stem rust was observed in 32 (82.05%) wheat fields with 62.05% mean incidence and 33.59% mean severity.

Similarly, out of 56 wheat fields surveyed in the high altitudes, wheat stem rust was recorded in 35 (62.5%) wheat fields with mean incidence and severity of 27.77 and 12.5%, respectively. The highest prevalence (82.05%) of stem rust was recorded at the mid altitude (1567-2300 m.a.s.l) where as a prevalence of 62.5% was recorded at the high altitudes (2301-3008 m.a.s.l). However, disease prevalence was not recorded at above 2585 m.a.s.l during the assessment. This study showed that stem rust has been more important in the mid-altitude agroecologies.

The survey results revealed that mean incidence and severity of wheat stem rust decreased from mid-altitude to high-altitude and markedly very low at high altitude >2500 m.a.s.l. The maximum stem rust disease severity recorded at mid-altitude was 90% while the maximum disease severity at high altitude was 50% on the farms. The highest disease severity 90% was recorded at 1950 m.a.s.l from Kilte Awulaelo district, Genfel locality. Stem rust incidence of 100% was recorded both at mid and high-altitude ranges. According to Badebo *et al.,* (2008), the highest level of stem rust infection has been reported in the altitude ranges from 1600 to 2500 m.a.s.l. Similarly, 50% disease severity and 100% disease incidence were recorded below 2473 m.a.s.l in the present study.

Abebe *et al.,* (2012) also reported that the highest prevalence of 68% of stem rust was recorded at altitude range 1494-1800 m.a.s.l followed by 66.1% prevalence at 1801-2300 m.a.s.l and none in higher altitudes >2300 m.a.s.l during 2010 cropping season in Southern Tigray region. Dagnatchew (1967) also stated that stem rust of wheat disease was very important at an altitude below

2300 m.a.s.l. The reports were contradicted with the current results where stem rust was observed at altitudes above 2300 m.a.s.l. This indicated that although stem rust has been more important at low and mid-altitude, it is now occurring at higher elevations. This might be associated with climate change, widespread cultivation of susceptible commercial varieties and appearance of new virulent races.

Prevalence and distribution of wheat stem rust by wheat variety

The survey results indicated that all farmer in the study areas were engaged in bread wheat production. The farmers were growing both improved and/or local varieties while the proportion of improved varieties were 81.05% and the rest 18.95% grown local varieties. They obtained wheat seed from formal and/or informal sources including non-governmental organizations, governmental organizations and their own seeds (local varieties). The highest seed provider to farming communities were Agricultural Bureau Offices of the study area, Agricultural Transformation Agency, Mekelle Agricultural Research Center and Alamata Agricultural Research Center. The majority of wheat crop was solely cultivated on small-scale farms with size ranged from 0.01-2.5 ha coverage whereas farmers grown barley, teff and field pea in the previous cropping season.

Fourteen wheat varieties were grown by farmers in the study area namely; Kakaba, Shehan (Local), Dashen, Mekelle I, Hidassie, Mekelle III, Ares (local), Danda'a, Pavon-76, Kingbird, Mekelle II, Mekelle IV, Gambo and Fentale. Out of 95 wheat fields inspected, 20 (21.1%), 12 (12.6%), 11 (11.58%), 9 (9.5%), 9 (9.5%), 7 (7.37%), 6 (6.3%) and 5 (5.3%) fields were covered by Kakaba, Shehan (Local), Dashen, Mekelle I, Hidassie, Mekelle III, Ares (Local) and Danda'a, respectively. Pavon-76 and Kingbird were sown in four fields (4.2%) each. Similarly, two varieties (Mekelle IV and Gambo) were planted in 2 (2.1%) of the fields assessed for each whereas Mekelle II and Fentale were sown in 3 (3.2%) and 1 (1%) farms, respectively.

However, wheat stem rust was observed in 4 (100%), 2 (100%), 1 (100%), 8 (89%), 10 (83%) and 4 (67%) of wheat fields covered by varieties Pavon-76, Gambo, Fentale, Mekelle I, Shehan local and Ares local, respectively (Figure 3). The lowest disease prevalence was recorded from Danda'a variety 1 (20%). However, zero disease prevalence of wheat stem rust was observed on Mekelle IV variety during the assessment.

The study indicated that, out of 67 (70.53%) infected wheat fields, 53 (79.1%) fields were sown with improved wheat varieties whereas 14 (20.9%) fields were covered by the local varieties. Most improved wheat varieties have shown the susceptible type of reaction to stem rust disease in surveyed areas in 2017 main crop growing season. The host response to infection in the field was scored using 'R' to indicate resistance or miniature uredinia; 'MR' to indicate moderate resistance, expressed as small uredinia; 'MS' to indicate moderately susceptible, expressed as moderate sized uredinia somewhat smaller than the fully compatible type (Figure 4) and 'S' to indicate full susceptibility (Roelfs *et al.,* 1992).The most widely grown wheat variety was Kakaba and it covered 21.05% of surveyed wheat fields in the zones of Tigray region with 0 to 70% disease severity ranges in the fields. It showed susceptible to moderately resistant reactions with 52% mean incidence and 25.25% mean severity. The second commonly grown variety was Shehan (local) and this variety showed susceptible to moderately susceptible stem rust reaction with mean incidence and severity of 50.83 and 24.17%, respectively (Table 5).

There was a significant difference ($p < 0.01$) in disease incidence among the grown varieties. The highest mean disease incidence was recorded from Fentale variety (100%) followed by Gambo and Pavon-76 which recorded 80 and 75%, respectively. They were not significantly different with the highest disease incidence. Zero-disease incidence was recorded from Mekelle IV variety followed by Danda'a variety which registered 2%. Similarly, there was a significant difference ($p < 0.05$) among varieties grown in disease severity. The highest mean disease severity was recorded from Fentale variety (60%) followed by Gambo and Pavon-76 which recorded 40% for each and statistically par with the highest disease severity. Zero-disease severity was recorded from Mekelle IV variety followed by Danda'a which recorded 1% and they were statistically similar (Table 5).

Where: R- resistant, MR- moderately resistant, MS- moderately susceptible and S- susceptible.

Table.1 Prevalence of wheat stem rust across districts in 2017 main cropping season

Zones	Districts	Altitude ranges (m.a.s.l)	No of fields assessed	No of fields infected	Prevalence (%)
Southern	Ofla	2432-2497	15	14	93.33
	Raya Azebo	1567-1762	10	9	90.00
	Enda Mehoni	2303-2520	15	11	73.33
Subtotal/Mean		1567-2520	40	34	85.00
Eastern	Kilte Awulaelo	1950-2194	15	14	93.33
	Ganta Afeshum	2444-3008	15	5	33.33
	S/Tsaedaemba	2018-2584	10	6	60.00
Subtotal/Mean		1950-3008	40	25	62.50
Southeast	Enderta	1981-2332	15	8	53.33
Mean/range		1567-3008	95	67	70.53

Table.2 Mean incidence and severity of wheat stem rust across the districts during 2017 main cropping season in the zones of Tigray

Zones	Districts	Disease incidence (%)		Disease severity (%)	
		Range	Mean	Range	Mean
Southern	Ofla	0-100	47.00[c]	0-50	20.67[c]
	Raya Azebo	0-100	66.50[b]	0-60	35.00[b]
	Enda Mehoni	0-100	35.00[d]	0-50	17.00[c]
Eastern	Kilte Awulaelo	0-100	78.67[a]	0-90	43.67[a]
	Ganta Afeshum	0-60	11.00[f]	0-40	5.00[e]
	Saesia Tsaedaemba	0-100	21.00[e]	0-60	11.50[d]
Southeast	Enderta	0-100	34.00[d]	0-50	16.67[cd]
Over all mean			41.88		21.36
LSD (0.05)			9.45**		5.39**
CV %			12.82		25.49

*Means with the same letter(s) within the column are not significantly different at $p<0.05$.

Table.3 Prevalence and distribution of wheat stem rust across different peasant associations of the districts in 2017 main cropping season

Zones	Districts	Peasant Association	Field Assessed	Prevalence (%)	Incidence (%)	Severity (%)
Southern	Ofla	Hashenge	5	100	64[c]	27[de]
		Adigolo	5	80	22[gij]	9[ij]
		Menkere	5	100	56[cd]	29[d]
	Raya Azebo	K/Adishabo	5	100	71[bc]	38[bc]
		Wargiba	5	80	62[c]	32[cd]
	Enda Mehoni	Machiew	5	60	16[ijk]	7[ijk]
		Mehan	5	80	46[de]	25[def]
		H/T/haymanot	5	80	43[de]	19[fg]
Eastern	Kilte Awulaelo	Genfal	5	100	92[a]	56[a]
		Aynalem	5	100	64[c]	42[b]
		Agulae	5	80	80[ab]	33[cd]
	G/Afeshum	B/hawaryat	5	40	8[kl]	3[jk]
		Sasun	5	60	26[fghi]	12[ghi]
		H/selam	5	0	0[l]	0[k]
	S/Tseadaemba	Guamse	5	60	10[jkl]	5[ijk]
		H/hiwot	5	60	32[f]	18[fgh]
Southeast	Enderta	Ilala	5	60	39[efg]	20[efg]
		Kelamino	5	40	40[ef]	20[efg]
		Kihen	5	60	24[ghij]	10[hij]
LSD					15.32**	8.73

*Means with the same letter(s) within the column are not significantly different at $p<0.05$.

Table.4 The intensity of wheat stem rust across altitude ranges in 2017 main cropping season

Altitude range	Class name	No of field Inspected	Prevalence (%)	Incidence (%)		Severity (%)	
				Range	Mean	Range	Mean
1567-2300	Mid-altitude	39	82.05	0-100	62.05[a]	0-90	33.59[a]
2301-3008	High-altitude	56	62.50	0-100	27.77[b]	0-50	12.50[b]
Range		95		0-100		0-90	
LSD (0.05)					14.39**		7.53
CV %					4.72		3.25

*Means with the same letter(s) within the column are not significantly different at $p<0.05$.

Table.5 Mean incidence and severity of wheat stem rust across varieties in zones of Tigray region in 2017 main cropping season

Varieties	Variety response at fields	Number of field assessed	Disease Incidence (%)	Disease Severity (%)
Kakaba	MR-MS-S	20	52.00[abcd]	25.25[bcd]
Shehan (local)	MS-S	12	50.83[abcde]	24.17[bcd]
Danda'a	MS	5	2.00[de]	1.00[d]
Hidassie	MS-S	9	49.44[abcde]	24.44[bcd]
Dashen	MR-MS-S	11	21.82[cde]	11.36[cd]
Mekelle I	MS-S	9	51.67[abcd]	25.00[bcd]
Mekelle II	MS-S	3	10.00[cde]	6.67[cd]
Mekelle III	MS-S	7	21.43[cde]	10.00[cd]
Mekelle IV	-	2	0.00[e]	0.00[d]
Gambo	S	2	80.00[a]	40.00[ab]
Fentale	S	1	100.00[a]	60.00[a]
Kinbird	MR-S	4	23.75[bcde]	12.50[bcd]
Pavon 76	MS-S	4	75.00[ab]	40.00[ab]
Ares (local)	MS-S	6	55.00[abc]	33.33[abc]
LSD (0.05)			51.43**	28.16
CV%			4.94	3.51

*Means with the same letter(s) within the column are not significantly different at p<0.05.

Table.6 Occurrence of wheat stem rust by wheat growth stage during 2017 growing season

Growth stages	Number of fields	Incidence (%)		Severity (%)	
		Range	Mean	Range	Mean
Milk	10	0-30	5.00[c]	0-10	2.00[c]
Early dough	45	0-100	47.89[ab]	0-90	23.56[ab]
Soft dough	25	0-100	31.00[b]	0-60	16.80[b]
Hard dough	15	40-100	66.33[a]	20-60	34.00[a]
LSD (0.05)			23.58**		13.00
CV (%)			5.05		3.61

*Means with the same letter(s) within the column are not significantly different at p<0.05.

Table.7 Pearson's correlation coefficients between major factors, and incidence and severity of stem rust in 2017 main cropping season

Variables	DI	DS	ALT	GS	WIL
DI	1	0.94***	-0.44***	0.26*	0.74***
DS		1	-0.50***	0.27**	0.66***
ALT			1	-0.33**	-0.25*
GS				1	0.21*
WM					1

DI - Disease incidence, DS - Disease severity, ALT - Altitude, GS - Growth stage and WIL- Weed infestation level. *Significant level at $p<0.05$; **Significant level at $p<0.01$ and ***Significant level at 0.001.

Fig.1 Geographical location of wheat stem rust survey areas in the zones of Tigray region

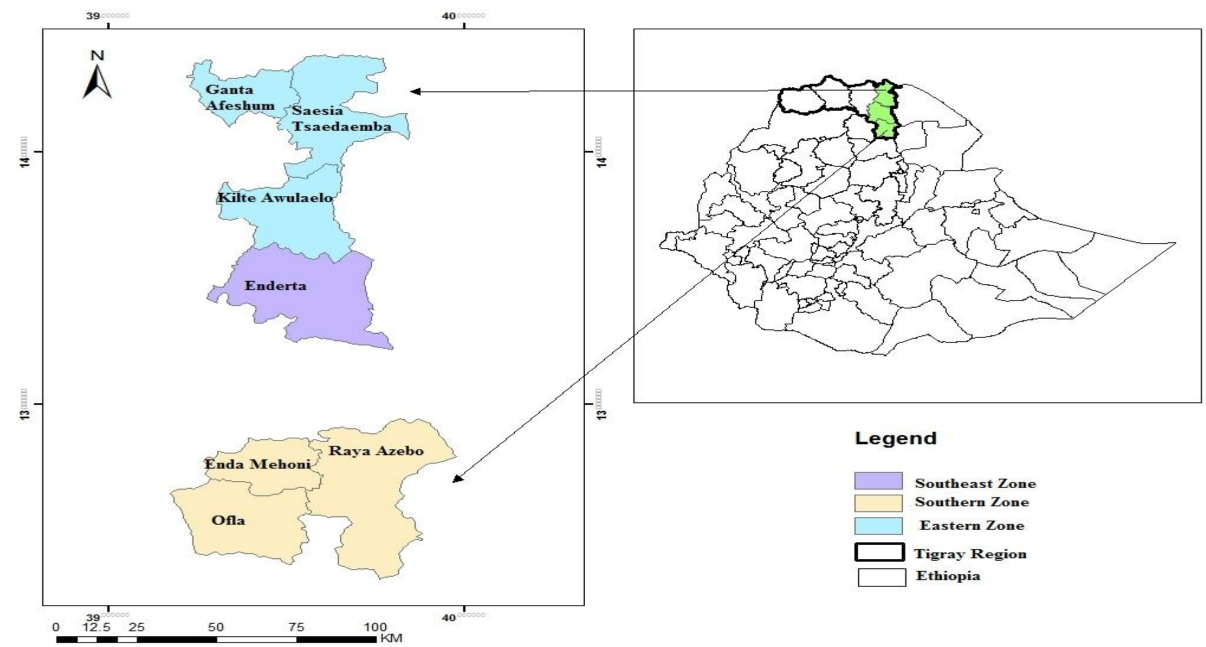


Fig.2 Stem rust distribution across the different zones of Tigray region in 2017 main cropping season

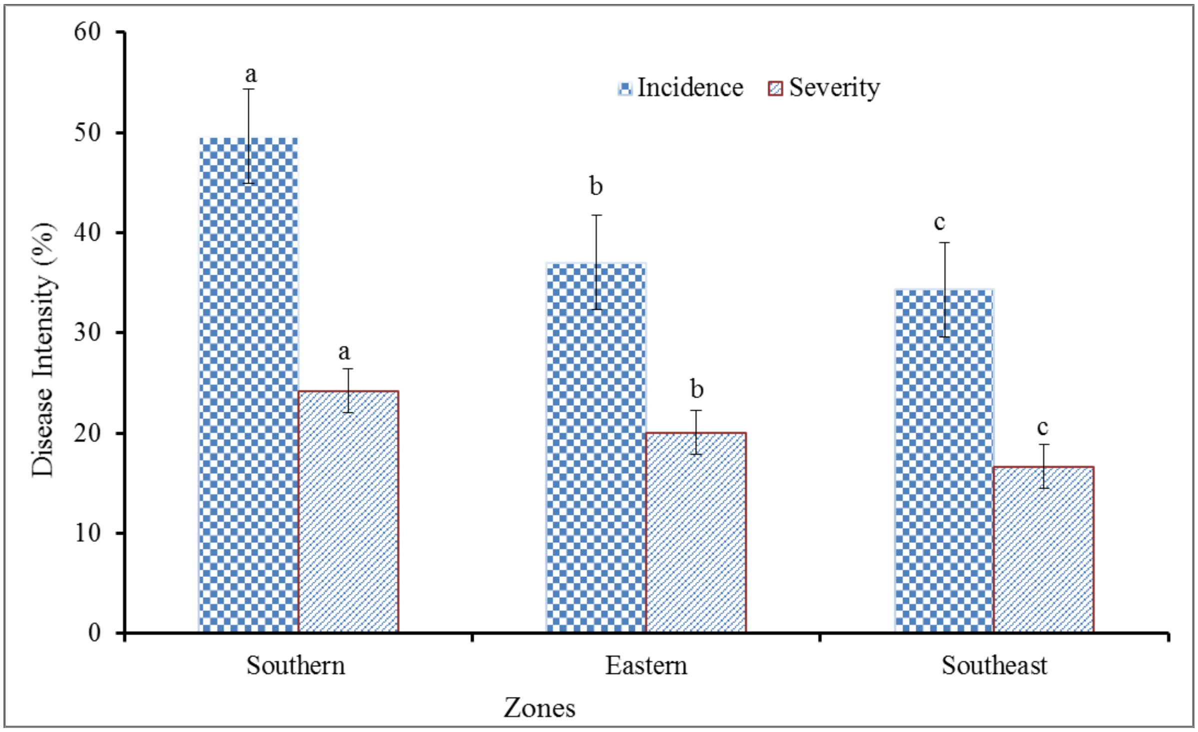


Fig.3 Disease prevalence across varieties in the zones of Tigray region during 2017 cropping season

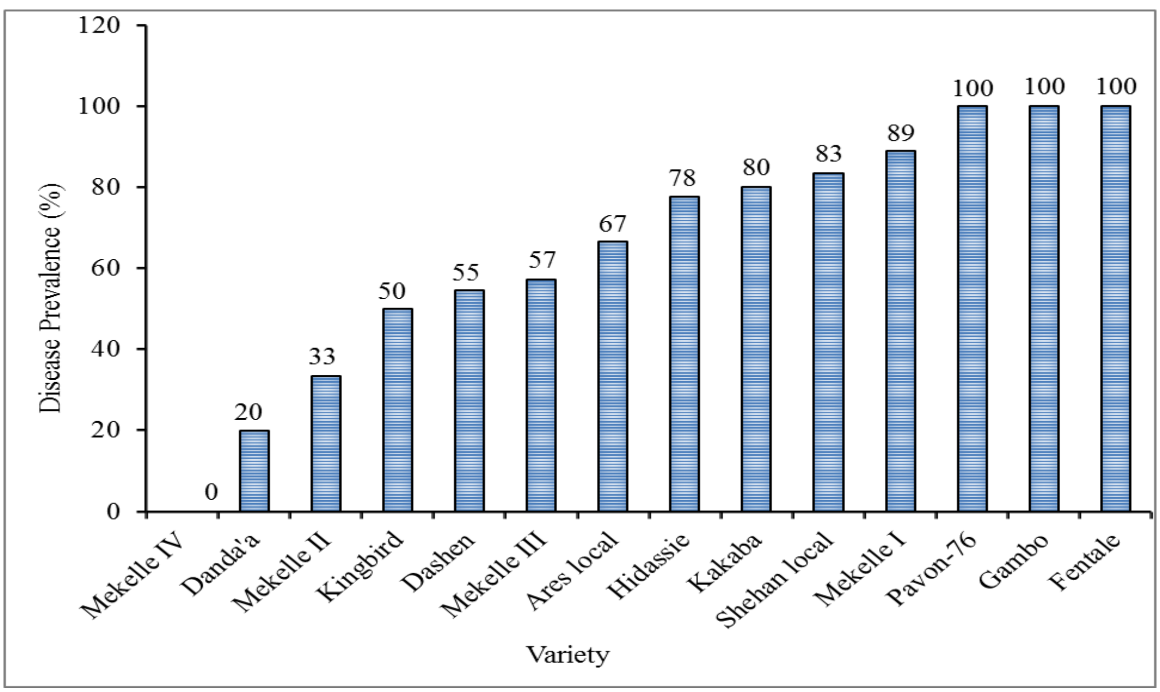


Fig.4 Typical symptoms of stem rust during survey in the zones of Tigray region from; Eastern zone, Kilte Awulaelo (C) and Southern Zone, Raya Azebo districts (A and B)

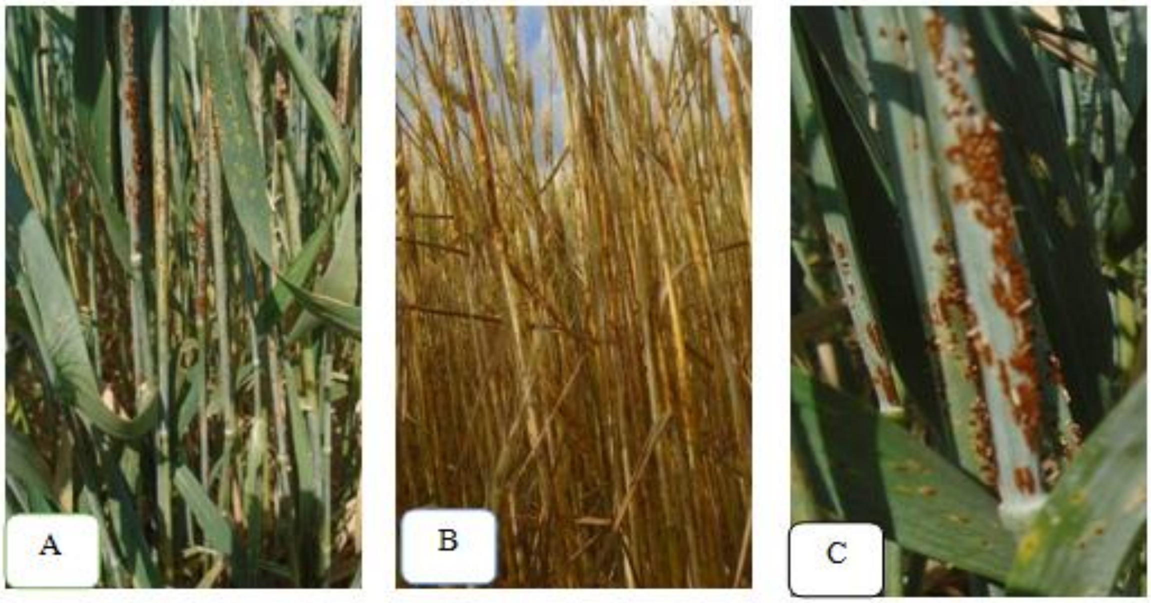
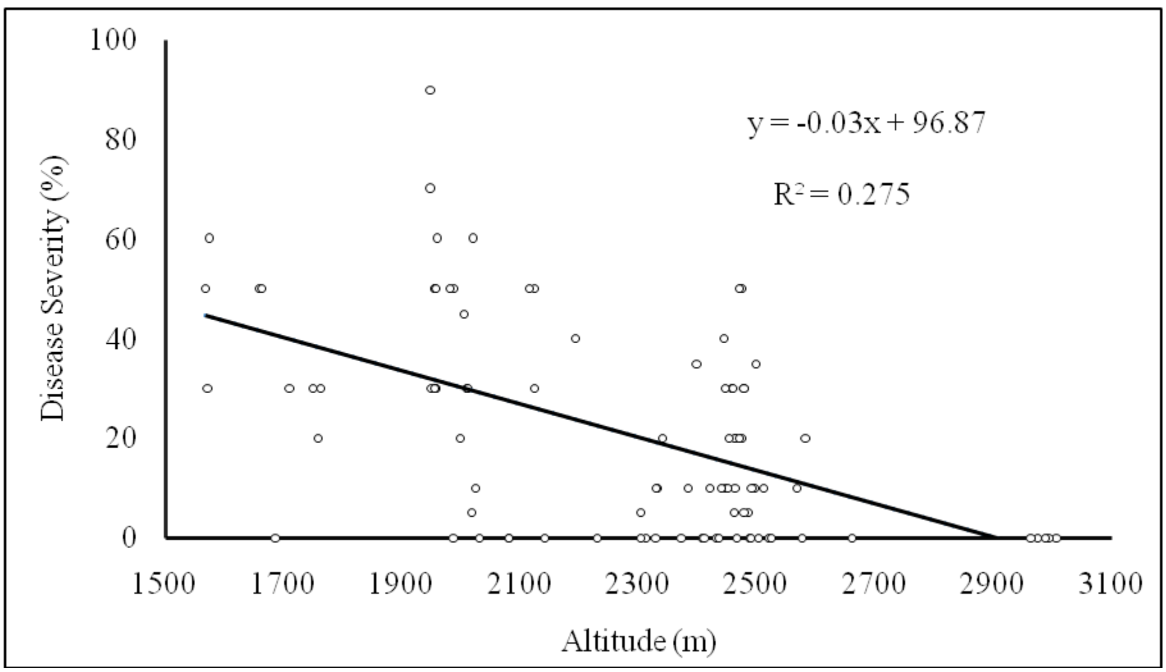


Fig.5 Regression relationship between disease severity (%) against altitude (meter)



Generally, some varieties released recently in the country were succumbed to stem rust disease shortly after their introduction. The high susceptibility of the wheat varieties to stem rust might be due to the climatic change especially, warmer temperature and adaptation of the pathogen to the wider environmental conditions. In most cases, the failures have been due to the virulence present in the pathogen population and deployment of the qualitative type of resistance in a wide array of wheat varieties (Hei *et al.*, 2017). However, Mekelle IV variety was free from stem rust disease during the survey time and cultivated at higher altitudes (>2900 m.a.s.l). This could be due to the fact that the varieties became resistant to stem rust as rainfall decreased or the existence of weather conditions and higher elevation which was not conducive for the development of the pathogen.

In agreement with this result, Mideksa *et al.,* (2018) reported that cultivars might be become resistant to disease as the amount of rainfall decreased or the prevailing weather conditions were not conducive for the development of stem rust epidemics. According to Jain *et al.,* (2009), the differences in disease incidence and severity within the similar agro-ecological area when a similar variety grown are an indication of pathogen virulence variability. The typical symptom of wheat tem rust in the zones of the region was illustrated below (Figure 4).

Occurrence of wheat stem rust by wheat growth stages

Whenever disease assessments are made, the growth stage of plants is essential for meaningful comparisons between varieties, locations and years. During the assessments, the crop growth sages ranged from milk to hard dough or GS73-GS87, according to Zadoks (1974) cereal growth stages guideline. Out of 95 fields inspected, 10 (10.5%), 45 (47.4%), 25 (26.3%) and 15 (15.8%) were at milk, early dough, soft dough and hard dough, respectively. In the same order, stem rust was observed on 2 (20%), 36 (80%), 15 (60%) and 14 (93.30%) of 10, 45, 25 and 15 wheat fields inspected in the mentioned growth stages (Table 6).

The results revealed that the intensity of stem rust varied significantly among the growth stages of the wheat crop. The highest disease incidence (66.33%) was observed in the hard dough growth stage followed by early dough stage (47.89%) which was not significantly different. The highest disease severity was recorded from the hard dough stage (34%) followed by early dough stage (23.56%). The lowest disease intensity was recorded from milk growth stage which was 5% disease incidence and 2% disease severity. The variation in the levels of wheat stem rust infections depended on the growth stages.

In the study area, wheat was grown in different agro-ecological zones that have different planting dates. This staggered planting date provides a green crop most part of the season allowing stem rust spores to move by wind from one growth stage to another and that way spreads to different farms nearby. According to Fetch *et al.,* (2011) planting as early as possible and planting early maturing cultivars would help to reduce the time of exposure of the crop to the pathogen, reduces the time frame for establishment of urediniospores and ultimately limits the growth period of the fungus. Singh *et al.,* (2008) also reported that stem rust is more important late in the growing season, on late-sown and late maturing wheat cultivars. The highest disease incidence and severity in hard dough growth stage could be due to the fact that the pathogen is more important in the late growth stage.

The importance of wheat stem rust was increasing with mounting in the growth stage of the crop and therefore, the prevalence and intensity of the disease were highest during hard dough development growth stage. Roelfs *et al.,* (1992) mentioned that the late growth stage of the crop is the most important period to reach stem rust disease of wheat at its maximum severity level. The same results were also reported by Mandefro (2000). Bhavani *et al.,* (2011) indicated that disease severity was as high as 80-100% at soft dough to hard dough growth stages.

Association between stem rust intensity with altitude, weed infestation levels and growth stages

The study showed that disease severity was linearly correlated with disease incidence, which means for higher disease incidence higher disease severity was recorded. There was highly significant ($p < 0.001$) and negative correlation between altitude and incidence ($r = -0.44$) and severity ($r = -0.50$) of wheat stem rust disease. The negative relationship between altitude and level of wheat stem rust is also reported by Abebe *et al.,* (2012) and Hailu *et al.,* (2015) who found that stem rust was more important at mid altitudes than at high altitude (Table 7). Similarly, there was significant ($p < 0.05$) and positive correlation between wheat growth stages and disease incidence ($r = 0.26$) and severity ($r = 0.27$). The positive relationship between wheat growth stages and intensity of wheat stem rust reflected that as the wheat growth stages increase the development of the pathogen become more severe (Mandefro, 2000). In this study, there was also highly significant ($p < 0.001$) and strong positive correlation between weed infestation levels and disease incidence ($r = 0.74$) and severity ($r = 0.66$). This implies that the disease became more intense in the weedy farm (Joseph *et al.,* 2007).

The regression analysis between altitude and severity revealed that a negative relationship was observed among them. This demonstrates that elevation increment in meter, stem rust disease severity decreased by about 0.03% (Figure 5). The negative relationship between altitude and disease severity implied that the pathogen was more important at lower and mid altitudes resulting in decreased intensity at higher altitudes (Badebo *et al.*, 2008).

Wheat (*Triticum* spp.) is a stable food crop for billions of peoples worldwide. It is excellent sources of nutrition and the most important cereal crop cultivated in Ethiopia. However, wheat stem rust pathogen has hindered and seriously threatening the production since the domestication of the crop. Its susceptibility to this pathogen poses a constant threat to sustainable production and hence food security in the study area. During the assessment, wheat stem rust was prevalent in all assessed zones of the region at variable levels and its intensity varied from slight to complete infection in wheat fields. The mean prevalence of the pathogen was 85.55% in Southern, 62.22% in Eastern and 53.33% in Southeast zones. The overall mean prevalence of stem rust was 70.53% across all assessed zones of Tigray region. The highest rates of disease incidence 78.67, 66.5 and 47% were recorded in Kilte Awulaelo, Raya Azebo and Ofla districts, respectively with the corresponding severity of 43.67, 35, and 20.67%.

The overall mean incidence and severity of stem rust was 41.88 and 21.36%, respectively. The results indicated that the present distribution of the disease is remarkably on increasing trend, possibly associated with the evolution of new pathogen races, extensive cultivation of the susceptible varieties and the current climate change (warmer temperature and humid conditions). Moreover, the study confirmed that stem rust is a shifty, changing and constantly evolving enemy which remains a major challenge to wheat production in the region due to the variability of virulence pattern in the pathogen population, the evolution of new races and an exponential reproduction capacity of the pathogen. In conclusion, there is a need to develop a coordinated network on the assessment of wheat stem rust research program along with a regular evaluation of commercial wheat varieties.

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