Journal of Plant Protection Research ISSN 1427-4345

ORIGINAL ARTICLE

Predicting wheat stripe rust epidemics according to influential climatic variables

Bita Naseri[1]*, Farhad Sharifi[2]

[1] Plant Protection Research Department, Kermanshah Agricultural & Natural Resources Research & Education Center, Kermanshah, Iran

[2] Plant Protection Office, Agriculture Organization, Kermanshah, Iran

Vol. 59, No. 4: 519–528, 2019

DOI: 10.24425/jppr.2019.131260

Received: April 9, 2019
Accepted: June 18, 2019

*Corresponding address:
bitanaseri@yahoo.com

Abstract

From 2009 to 2018, a total of 80 wheat crops were studied at plot and regional scales to predict stripe rust epidemics based on influential climatic indicators in Kermanshah province, Iran. Disease onset time and epidemic intensity varied spatially and temporarily. The disease epidemic variable was classified as having experienced nonepidemic, moderate or severe epidemics to be used for statistical analysis. Principal component analysis (PCA) was used to identify climatic variables associated with occurrence and intensity of stripe rust epidemics. Two principal factors accounting for 70% of the total variance indicated association of stripe rust epidemic occurrence with the number of icy days with minimum temperatures below 0°C (for subtropical regions) and below −10°C (for cool temperate and semi-arid regions). Disease epidemic intensity was linked to the number of rainy days, the number of days with minimum temperatures within the range of 7–8°C and relative humidity (RH) above 60%, and the number of periods involving consecutive days with minimum temperature within the range of 6–9°C and RH% > 60% during a 240-day period, from September 23 to May 21. Among mean monthly minimum temperatures and maximum relative humidity examined, mean maximum relative humidity for Aban (from October 23 to November 21) and mean minimum temperature for Esfand (from February 20 to March 20) indicated higher contributions to stripe rust epidemic development. Confirming PCA results, a multivariate logit ordinal model was developed to predict severe disease epidemics. The findings of this study improved our understanding of the combined interactions between air temperature, relative humidity, rainfall, and wheat stripe rust development over a three-season period of autumn-winter-spring.

Keywords: cereals, climate, epidemiology, yellow rust

Introduction

Crop production in major wheat growing areas of Iran is severely curtailed by *Puccinia striiformis* f. sp. *tritici* (Afzal *et al.* 2007). This pathogen can cause severe stripe rust disease in a susceptible host under appropriate environmental conditions, especially in cool climates. Furthermore, in North America and Europe, temperatures warmer than 18°C suppressed stripe rust under wheat field conditions (Coakley *et al.* 1988; van den Berg and van den Bosch 2007; Te Beest *et al.* 2008). Milus *et al.* (2009) found evidence that wheat rust pathogens can adapt to inappropriate warmer temperatures. Our preliminary studies on stripe rust epidemics were carried out in main wheat growing areas and disease hotspots of Kermanshah province, Iran. We found significant links between disease development and cool, wet climates in late winter and early spring. In Kansas, USA, regional occurrences of wheat stripe rust corresponded to soil moisture during fall and winter (Grabow *et al.* 2016). In addition, the development of severe epidemics in Kansas winter wheat was associated with optimal temperatures, 7–12°C. The relationship of air temperature and moisture during fall and winter months with the intensity of wheat stripe rust has been reported previously (van den Berg and van den Bosch 2007; Te Beest *et al.* 2008). For instance, temperatures in fall (October to November) and winter (December and January) and spring (April) precipitation were linked to stripe rust severity in the U.S. Pacific Northwest (Coakley *et al.* 1988). Elsewhere, temperature and rainfall during autumn (April and May) were strongly linked to stripe rust epidemics in Australian wheat crops (Park 1990). It is believed that comparative epidemiology of plant diseases assists with improving the development of more efficient disease management programs (Jeger 2004). For sustainable productivity, it appears crucial to identify influential climatic indicators of epidemic development to predict and reduce crop losses with carefully optimized timing of fungicide applications. Furthermore, wisely developed control strategies can decrease wheat growers' costs of managing the disease. Moreover, more effective management of stripe rust may lower disease pressure on resistant cultivars and presumably improve the durability of genetic resistance in wheat crops. Most previous attempts were made to predict stripe rust epidemics based on plot-scale dataminr, large scale disease epidemics occur under highly heterogeneous environmental conditions. Therefore, it is necessary to determine relationships between the development of wheat stripe rust epidemics and highly variable environmental conditions on a regional basis. Although a few studies have looked at the development of stripe rust epidemics on a regional basis (Newlands 2018), their predictions are dependent on inoculum monitoring which is difficult for local experts and farmers to conduct without the necessary equipment. Therefore, a regional attempt was made to explore: (i) how much of spatial and temporal variability in stripe rust epidemics can be explained by climatic variables, (ii) which climatic variables correspond to epidemic variability, (iii) how strongly these climatic descriptors interact with the rust-wheat pathosystem under prevailing environmental conditions in Kermanshah province in order to develop a predicting model.

Materials and Methods

Epidemiological study

Stripe rust disease occurrence and epidemic levels from 2009 to 2013 were derived from plant disease monitoring reports collected by the Kermanshah Plant Protection Office. From 2013 to 2018, disease onset time and epidemic development were assessed in commercial winter wheat fields across Sarpolzohab, Gilangharb, Islamabad, and Mahidasht districts, and non-fungicide-treated experimental plots at the Islamabad Research Station (latitude 34°7´N, longitude 46°28´E). These districts involved main stripe rust hotspots in tropical (Sarpolzohab and Gilangharb) and temperate (Islamabad) regions of Kermanshah province (Fig. 1; Table 1). Only irrigated wheat crops were considered in the districts studied. All quality-controlled climatic data provided by the weather stations (one station per region) was accessed directly from the Kermanshah Met office (http://www.kermanshahmet.ir/)

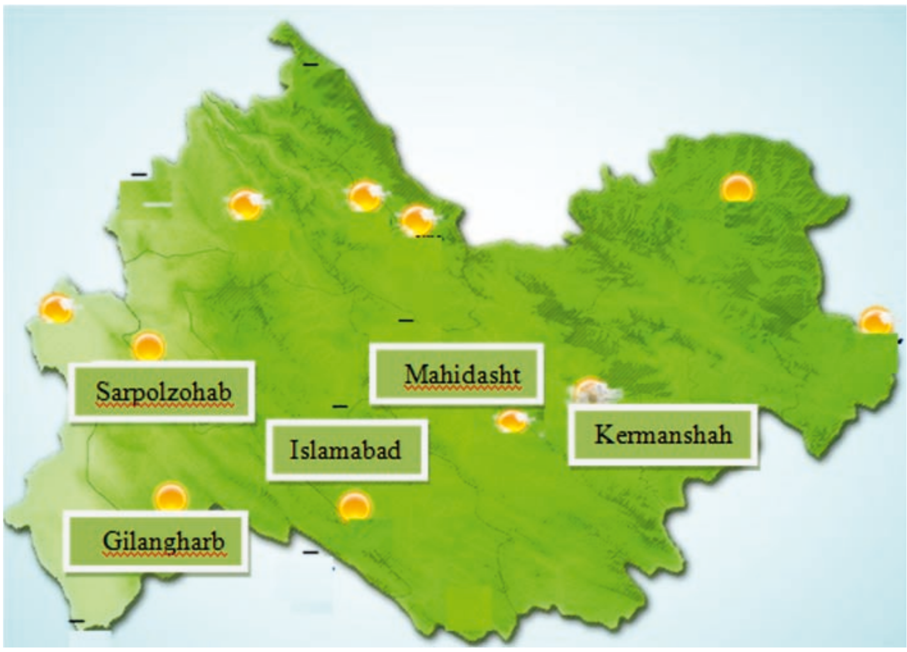

Fig. 1. Location of climate stations and regions studied from 2009 to 2018 in Kermanshah province, Iran

Table 1. Climatic characteristics for Kermanshah districts studied in this research

Name of districts	Climates	Annual mean rainfall [mm]	Annual mean temperature [°C]
Islamabad	cool temperate	479.8	13.7
Gilangharb	subtropical	429.0	20.3
Mahidasht	cool semi-arid	335.1	14.1
Sarpolzohab	subtropical	421.3	19.9

maintained by the Iran Meteorological Organization (Fig. 1). Study fields or plots were located up to 20 km from the weather stations. Cultivars were selected as representative genotypes currently grown in temperate and tropical regions of Iran. The date of planting wheat crops in the study area ranged from Mehr (the first Iranian month of autumn, from September 23 to October 22) to Dey (the first Iranian month of winter, from December 22 to January 20). The harvest time ranged from Ordibehesht (the second Iranian month of spring, from April 21 to May 21) in tropical regions to Tir (the first Iranian month of summer, from June 22 to July 22) in temperate regions. The disease onset was detected when the first stripe rust pustule was evident on the leaves in each study field or plot. Disease epidemic levels were described as follows: 0 = no stripe rust pustules developed on leaves, 1 = low disease levels and sparse distribution, 2 = high and epidemic disease levels across wheat fields. Each study year was characterized according to this disease epidemic classification for statistical analysis.

Data analysis

To ease interpretation of results, principal component analysis (PCA) based on a correlation matrix was used to estimate the principal component loadings for climatic and disease variables. The highest loading values were considered for interpretation. An eigenvalue, which demonstrates the proportion of total variance explained by each principal component (Sharma 1996), was used for interpretation if it was >1.0. A preliminary examination of disease and climatic data indicated notable associations of the development of stripe rust epidemics with the following climatic variables: the 30-day average minimum temperature and maximum relative humidity (RH%) for autumn, winter and spring, the number of days with minimum temperatures equal to or below zero, −5°C and −10°C, the number of days with minimum temperatures within a 5–12°C range, and the number of rainy days within the 240-day period, from September 23 to May 21. Besides these climatic variables, a number of indicators were defined to involve both temperature and RH% recorded within the 240-day period as follows: the number of days with a daily minimum temperature within the range of 7–8°C and RH% > 60% (Naseri and Marefat 2019), the number of consecutive days with minimum temperatures within the range of 6–9°C and RH% > 60%, and the greatest number of such consecutive days. These temperature ranges were used as appropriate temperatures for disease development according to the findings of de Vallavieille-Pope *et al.* (1995) and Grabow *et al.* (2016). The 240-day period was considered for assessing climatic conditions to cover the development of stripe rust epidemics over the growing season (Naseri and Marefat 2019). Thus, PCA was performed to examine interrelationships among the climatic indicators of stripe rust epidemic variability across wheat crops. In the next step, univariate and multivariate ordinal logit regressions were used to evaluate climatic descriptors as independent variables for predicting stripe rust disease epidemics as dependent variables. Predictions of a severe disease epidemic level using ordinal regression models were based on fitted and observed values. All statistical analyses were performed using GENSTAT (VSN International, Oxford, UK).

Results

A total of 80 commercial, irrigated wheat crops was studied to describe associations of climatic variables with stripe rust epidemics in Kermanshah province. Climatic data for Sarpolzohab and Islamabad are presented in Tables 2 and 3, respectively. In Sarpolzohab district, based on low mean monthly minimum temperatures, cold winters were detected in Dey (2.8°C) and Bahman (2.8°C) for 2010–2011, in Azar (1.0°C) and Dey (2.7°C) for 2011–2012, in Dey (2.9°C) for 2012–2013, in Dey (3.1°C) for 2013–2014, in Dey (2.5°C) for 2014–2015, and in Dey (3.1°C) and Bahman (1.8°C) for 2016–2017 growing seasons. In the same district, dry autumns in terms of the low mean maximum relative humidity in the month of Aban were recorded in 2010–2011 with 66%, in 2016–2017 with 65%, and in 2017–2018 with 64% values. Similar

Table 2. Climatic data for Sarpolzohab district of Kermanshah studied between 2009–2018

Years	Mehr	Aban	Azar	Dey	Bahman	Esfand	Farvardin	Ordibehesht
	Sep. 23–Oct. 22	Oct. 23–Nov. 21	Nov. 22–Dec. 21	Dec. 22–Jan. 20	Jan. 21–Feb. 19	Feb. 20–Mar. 20	Mar. 21–Apr. 20	Apr. 21–May 21
2009–2010	12.9°C[a] 59%[b]	11.5°C 84%	5.8°C 94%	6.9°C 89%	5.0°C 91%	9.4°C 85%	9.7°C 91%	15.1°C 80%
2010–2011	16.4°C 60%	10.7°C 66%	5.0°C 70%	2.8°C 90%	2.8°C 90%	6.1°C 82%	9.3°C 79%	14.7°C 81%
2011–2012	14.4°C 58%	8.4°C 83%	1.0°C 83%	2.7°C 87%	3.4°C 85%	3.6°C 80%	10.0°C 80%	14.8°C 66%
2012–2013	16.3°C 52%	12.4°C 84%	6.5°C 95%	2.9°C 87%	5.7°C 91%	7.0°C 85%	9.7°C 77%	13.6°C 80%
2013–2014	12.8°C 83%	10.0°C 93%	5.8°C 93%	3.1°C 88%	3.4°C 90%	7.5°C 90%	8.3°C 85%	15.2°C 68%
2014–2015	15.7°C 67%	8.9°C 82%	7.3°C 93%	2.5°C 93%	4.7°C 89%	5.3°C 84%	9.1°C 83%	14.1°C 59%
2015–2016	17.4°C 54%	10.8°C 92%	4.9°C 92%	4.2°C 95%	3.5°C 91%	8.7°C 89%	8.8°C 89%	14.9°C 79%
2016–2017	14.5°C 53%	10.5°C 65%	3.7°C 74%	3.1°C 91%	1.8°C 93%	4.8°C 85%	10.0°C 90%	13.9°C 74%
2017–2018	14.1°C 55%	13.2°C 64%	5.7°C 83%	5.8°C 78%	5.4°C 84%	8.7°C 85%	12.0°C 78%	15.1°C 81%

[a] mean monthly minimum air temperature
[b] mean monthly maximum relative humidity

Table 3. Climatic data for Islamabad district of Kermanshah studied between 2009–2018

Years	Mehr	Aban	Aza	Dey	Bahman	Esfand	Farvardin	Ordibehesht
	Sep. 23–Oct. 22	Oct. 23–Nov. 21	Nov. 22–Dec. 21	Dec. 22–Jan. 20	Jan. 21–Feb. 19	Feb. 20–Mar. 20	Mar. 21–Apr. 20	Apr. 21–May 21
2009–2010	5.2°C[a] 63%[b]	4.6°C 93%	0.0°C 94%	−0.3°C 90%	−1.8°C 89%	2.5°C 86%	3.5°C 87%	7.5°C 89%
2010–2011	8.7°C 60%	3.2°C 79%	−2.1°C 73%	−3.7°C 92%	−4.4°C 95%	−1.4°C 88%	3.1°C 84%	7.9°C 91%
2011–2012	6.5°C 57%	2.8°C 92%	−5.3°C 91%	−4.0°C 89%	−3.7°C 92%	−3.8°C 85%	2.5°C 84%	7.5°C 72%
2012–2013	8.7°C 53%	5.8°C 86%	0.4°C 95%	−4.3°C 91%	−0.8°C 91%	0.1°C 83%	2.8°C 77%	6.8°C 85%
2013–2014	4.8°C 58%	4.2°C 85%	−0.2°C 92%	−4.4°C 89%	−3.9°C 90%	0.8°C 88%	2.5°C 85%	7.8°C 77%
2014–2015	8.2°C 72%	1.9°C 88%	1.1°C 92%	−3.7°C 92%	−1.3°C 87%	−1.1°C 85%	2.6°C 86%	6.5°C 68%
2015–2016	9.6°C 59%	5.0°C 91%	−1.8°C 91%	−2.0°C 92%	−2.8°C 90%	2.5°C 89%	3.3°C 87%	8.1°C 87%
2016–2017	6.3°C 63%	3.2°C 68%	−3.7°C 81%	−2.9°C 90%	−6.3°C 92%	−2.4°C 89%	4.2°C 89%	7.3°C 80%
2017–2018	6.3°C 58%	4.8°C 78%	−2.6°C 88%	−2.0°C 89%	−1.3°C 89%	1.8°C 87%	4.3°C 82%	7.8°C 90%

[a] mean monthly minimum air temperature
[b] mean monthly maximum relative humidity

Table 4. Stripe rust disease characteristics for Kermanshah districts studied in this research

Years	Disease onset				Epidemic level[a]			
	Mahidasht	Islamabad	Gilangharb	Sarpolzohab	Mahidasht	Islamabad	Gilangharb	Sarpolzohab
2009–2010	March 2	March 2	na[b]	na	2	2	2	2
2010–2011	April 28	April 28	na	na	1	1	1	1
2011–2012	–	–	–	–	0	0	0	0
2012–2013	March 7	March 7	na	na	1	1	1	1
2013–2014	March 29	March 29	May 5	–	1	1	1	0
2014–2015	March 15	March 15	May 22	–	1	1	1	0
2015–2016	March 23	March 23	April 17	May 10	2	2	2	2
2016–2017	–	–	May 6	–	0	0	1	0
2017–2018	–	–	–	–	0	0	0	0

[a]epidemic levels: 0 = no stripe rust pustules developed on leaves, 1 = low disease levels and sparse distribution, 2 = high and epidemic disease levels across wheat fields
[b]na = not assessed

trends of cold winters and dry autumns were detected in Islamabad (Table 3), Gilangharb and Mahidasht districts (climatic data not shown).

From 2009 to 2018, there was a distinct variability in the disease onset time and epidemic development studied in wheat fields across Sarpolzohab, Gilangharb, Islamabad, and Mahidasht districts (Table 4). No disease symptoms were observed in the 2011–2012 and 2017–2018 growing seasons across all the districts studied. Severe stripe rust epidemics occurred in 2009–2010 and 2015–2016. A common mild disease development was seen in the other study years. Stripe rust disease occurred sooner in subtropical regions, Sarpolzohab and Gilangharb, with warmer winters and ended earlier than in Islamabad and Mahidasht districts (Table 4).

From PCA, two principal factors accounting for 70% of the total variance characterized the disease onset time and occurrence of stripe rust epidemics occurring from 2009 to 2018 across highly diverse wheat cropping systems in Kermanshah province. The first PC accounted for 51% of the variance in climate-disease data (Fig. 2). PC1 showed the highest loading for the negative contribution of icy day descriptors, or the number of days with minimum temperatures equal to or lower than 0°C. The second PC, which accounted for 19% of the data variance, identified the significance of mean maximum RH in Aban and the number of days with minimum temperatures within the range of 7–8°C and RH above 60% to predict the development of stripe rust epidemics over the wheat growing season.

According to the loadings obtained for both of PC1 and PC2 (Fig. 2), the strong contributions of climatic indicators to the development of stripe rust epidemics studied over nine growing seasons on a regional basis were summarized as follows: the number of rainy days, the number of days with minimum temperatures within the range of 7–8°C and RH above 60%, and the number of periods involving consecutive days with minimum temperature within the range of 6–9°C and RH% > 60% during a 240-day period, from September 23 to May 21.

In addition, PCA demonstrated a close association of disease-onset time with the number of icy days with minimum temperatures below –10°C within the 240-day period. Since such low temperatures commonly happen during winter months in the cool temperate and semi-arid regions studied, the number of icy days with minimum temperatures below –10°C was defined as the climatic descriptor of the disease onset in these regions (Islamabad and Mahidasht districts). Due to the close contribution of region into the disease-onset-time descriptor, the number of icy days with minimum temperatures below 0°C during the 240-day period was considered to predict stripe rust onset for the two subtropical regions studied, Gilangharb and Sarpolzohab. During the eight months examined from 2009 to 2018 in four representative districts of Kermanshah province, the mean maximum relative humidity for Aban (from October 23 to November 21) and mean minimum temperature for Esfand (from February 20 to March 20) indicated their very significant contribution to the development of severe stripe rust epidemics (Fig. 2).

Univariate ordinal logit regressions demonstrated that there were significant linkages between stripe rust disease epidemics (dependent variable) and climatic variables (independent variable, Table 5). As expected, none of the climatic descriptors, individually, could estimate successfully the level of disease epidemics occurring between 2009 and 2018. For this reason, multivariate ordinal logit regressions were used to examine

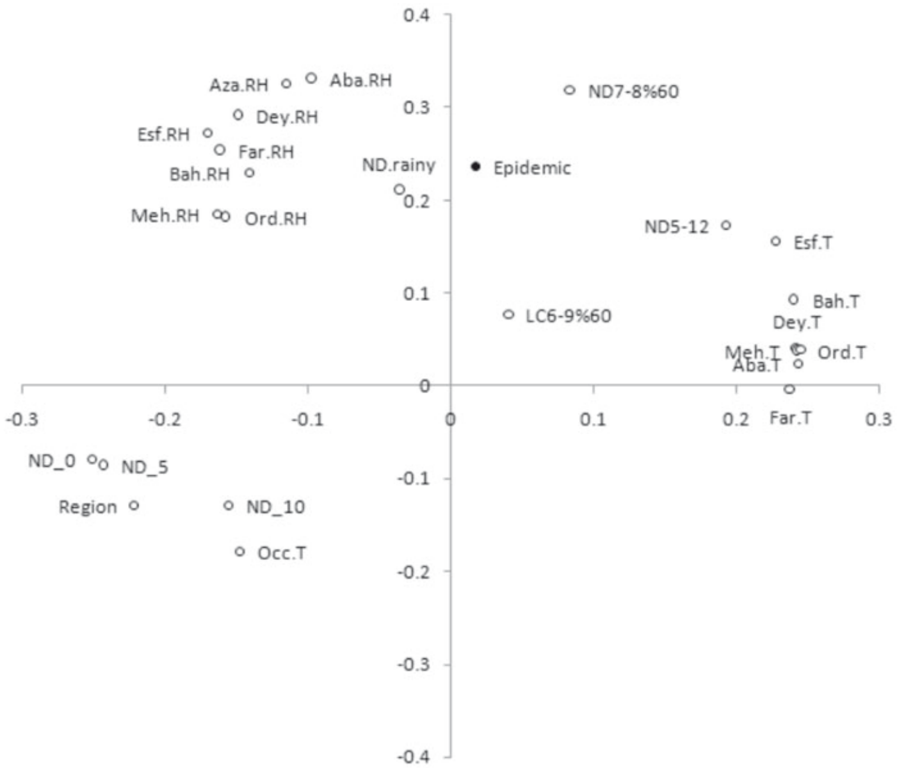

Fig. 2. Principal component (PC) analysis of climatic and disease data collected from 2009 to 2018 to predict stripe rust epidemics in Kermanshah (ND-10 = number of days with minimum temperature below –10°C; ND5-12 = number of days with minimum temperature within 5–12°C; ND7-8%60 = number of days with minimum temperature within 7–8°C and maximum relative humidity >60%; NC6-9%60 = number of periods involving consecutive days with minimum temperature within 6–9°C and maximum relative humidity >60%; LC6-9%60 = longest period of consecutive days with the above criteria; Occ.T = disease onset time; RH = monthly mean maximum relative humidity; T = monthly mean minimum temperature)

Table 5. Univariate ordinal logit regression between stripe rust disease epidemics (dependent variable) and climatic conditions (independent variable)

Climatic variables	Parameter estimate	*Chi* probability	Climatic variables	Parameter estimate	*Chi* probability
Mehr Max RH	–0.02	0.180	Mehr Min T	0.09	0.024
Aban Max RH	0.06	0.001	Aban Min T	0.08	0.120
Azar Max RH	0.04	0.022	Azar Min T	0.03	0.567
Dey Max RH	0.05	0.070	Dey Min T	0.10	0.084
Bahman Max RH	0.04	0.098	Bahman Min T	0.05	0.379
Esfand Max RH	0.04	0.143	Esfand Min T	0.21	0.001
Farvardin Max RH	0.03	0.127	Farvardin Min T	–0.01	0.891
Ordibehesht Max RH	0.04	0.028	Ordibehesht Min T	0.09	0.119
LC Min 6–9°C, RH > 60%	0.16	0.145	ND Min < 0	–0.01	0.139
NC Min 6–9°C, RH > 60%	0.36	0.001	ND Min ≤ 5	–0.02	0.206
ND Min 7–8°C, RH > 60%	0.12	0.023	ND Min ≤ 10	–0.08	0.307
ND Min 5–12°C	0.04	0.002	Region	–0.12	0.327
ND rainy	0.13	0.001			

LC Min 6–9°C, RH (relative humidity) > 60% = longest period involving consecutive days with minimum temperatures of 6–9°C and maximum relative humidity >60%; NC Min 6–9°C, RH > 60% = number of periods involving consecutive days with minimum temperatures of 6–9°C and maximum relative humidity >60%; ND Min ≤ 10 = number of days with minimum temperature below –10°C; ND Min 7–8°C, RH > 60% = number of days with minimum temperatures of 7–8°C and maximum relative humidity > 60%; Min = minimum; Max = maximum; T = temperature

Table 6. Ordinal logit regression model to predict stripe rust disease epidemics (dependent variable) according to climatic variables (independent variable)

Climatic variables	Parameter estimate	*Chi* probability
Intercept 1	9.95	0.001
Intercept 2	13.85	0.001
Aban mean maximum relative humidity	0.06	0.006
Esfand mean minimum temperature	0.29	0.001
NC Min 6–9°C, RH > 60%	0.35	0.014
ND Min 7–8°C, RH > 60%	–0.23	0.015
Number of rainy days	0.12	0.001

NC Min 6–9°C, RH (relative humidity) > 60% = number of periods involving consecutive days with minimum temperatures of 6–9°C and maximum relative humidity > 60%; ND Min 7–8°C, RH > 60% = number of days with minimum temperatures of 7–8°C and maximum relative humidity > 60%

predictive models for wheat stripe rust epidemics. Then, the best discriminant variables were selected based on significant univariate ordinal logit regressions. The resultant predictions were then compared with observed epidemics. When the variables for the number of rainy days, the number of days with minimum temperatures within the range of 7–8°C and RH above 60%, the number of periods involving consecutive days with minimum temperature within the range of 6–9°C and RH% > 60% during a 240-day period, the mean maximum relative humidity for Aban, and the mean minimum temperature for Esfand were included in the regression model (Table 6), the epidemic level for all the study years was correctly estimated. A comparison of the observed and fitted data showed that all (100%) of the observed stripe rust epidemics occurring across the regions studied from 2009 to 2018 were estimated to be severe epidemics according to the fitted values estimated by the ordinal logit regression developed. Based on simple linear regression results, the time of stripe rust epidemic occurrence was linked to the number of icy days with minimum temperatures below 0°C ($R^2 = 0.35$; F probability < 0.001), below −5°C ($R^2 = 0.26$; F probability < 0.001), and −10°C ($R^2 = 0.10$; F probability = 0.005) during the 240-day period. Thus, our PCA and regression analyses indicated that the occurrence and development of stripe rust epidemics occurring in wheat crops was dependent mainly on six climatic indicators depending on the region. The actual values of these effective climatic predictors were presented for all study years and districts (Table 7).

Discussion

Although there has been substantial work on predicting wheat stripe rust epidemics, epidemiological studies on climate-disease relationships in middle eastern Asian regions including Iran deserve further attention. Such information on stripe rust epidemics developed on wheat crops sown in different geographical areas in the context of regional disease measurements improves our understanding of climatic determinants of the disease. There is no stripe rust predicting model for Iranian irrigated wheat crops. Thus, attempts were made in the current regional study to identify the best predictors of stripe rust epidemics over a nine-year period in the western part of Iran, Kermanshah province. To the best of our knowledge, this is the first joint analysis of minimum temperature, maximum relative humidity, icy and rainy days in interaction with stripe rust epidemics examined across commercial and experimental wheat crops cultivated from 2009–2018 in the area studied. The appropriate temperature ranges for stripe rust development, 7–8°C and 5–12°C, were considered in the present study were based on earlier reports (Coakley *et al.* 1988; de Vallavieille-Pope *et al.* 1995; Grabow *et al*. 2016) and preliminary examination of our climate-disease datasets. Due to the importance of weather conditions during the night when more durable wetness periods coincide with lower temperatures favoring pathogen infection (Stubbs 1985; El Jarroudi *et al.* 2017), daily and monthly minimum temperature and maximum relative humidity were used in this study. Furthermore, our previous plot-scale findings (Naseri and Marefat 2019) indicated that the number of days with minimum temperatures within the range of 7–8°C and RH above 60% as the climatic indicator could be used to predict the development of stripe rust epidemics in wheat crops.

There are several earlier reports about the relationship between temperature and moisture during fall and winter months and wheat stripe rust development (van den Berg and van den Bosch 2007; Te Beest *et al*. 2008). In the USA, monthly temperatures in autumn and winter were suggested as the best indicators of stripe rust epidemics. For instance, there was a significant relationship between disease intensity and minimum temperatures during October–November

Table 7. Climatic descriptors used to predict stripe rust epidemics for representative districts of Kermanshah province

Years	Districts	Rainy days	Icy days	ND Min ≤ 10	ND Min 7–8°C RH > 60%	NC Min 6–9°C RH > 60%	Esfand Mean min temperature	Aban Mean max RH%
2009–2010	Sarpolzohab	61	4	0	16	10	9.4°C	84
	Gilangharb	71	5	0	16	8	9.2°C	69
2010–2011	Sarpolzohab	55	15	0	16	11	6.1°C	66
	Gilangharb	52	10	0	15	8	6.4°C	39
2011–2012	Sarpolzohab	49	31	0	10	8	3.6°C	83
	Gilangharb	48	14	0	10	7	3.6°C	68
2012–2013	Sarpolzohab	69	7	0	20	9	7.0°C	84
	Gilangharb	57	6	0	11	6	7.0°C	65
2013–2014	Sarpolzohab	53	18	0	19	9	7.5°C	93
	Gilangharb	39	13	0	13	5	7.6°C	69
	Islamabad	53	85	2	14	9	0.8°C	85
2014–2015	Sarpolzohab	60	8	0	25	13	5.3°C	82
	Gilangharb	54	5	0	16	10	6.0°C	59
	Islamabad	62	97	0	13	6	−1.1°C	88
	Mahidasht	61	112	2	4	3	−2.7°C	78
2015–2016	Sarpolzohab	74	8	0	16	7	8.7°C	92
	Gilangharb	50	9	0	15	11	9.2°C	77
	Islamabad	78	87	1	16	13	2.5°C	91
	Mahidasht	71	90	0	11	8	0.9°C	86
2016–2017	Sarpolzohab	59	30	0	15	7	4.8°C	65
	Gilangharb	47	15	1	16	7	6.1°C	44
	Islamabad	59	109	8	11	4	−2.4°C	68
	Mahidasht	44	110	6	13	5	−1.5°C	73
2017–2018	Sarpolzohab	66	7	0	21	7	8.7°C	64
	Gilangharb	62	2	0	13	7	8.5°C	54
	Islamabad	66	81	0	13	8	1.8°C	78
	Mahidasht	50	90	0	14	9	1.6°C	80

ND Min ≤ 10 = number of days with minimum temperature below −10°C; ND Min 7–8°C, RH > 60% = number of days with minimum temperatures of 7–8°C and maximum relative humidity > 60%; NC Min 6–9°C, RH (relative humidity) > 60% = number of periods involving consecutive days with minimum temperatures of 6–9°C and maximum relative humidity >60%; min = minimum; max = maximum

in autumn and December–January in winter (Coakley *et al.* 1988). In Kansas, regional occurrence of wheat stripe rust corresponded to soil moisture during fall and winter (Grabow *et al.* 2016). In Australia, Park (1990) reported a significant association of stripe rust epidemics with temperature and rainfall during autumn (April and May). In the present nine-year research, the mean minimum temperature in Aban (the second month of autumn in Iran, from October 23 to November 21) and mean maximum relative humidity in Esfand (the third month of winter in Iran, from February 20 to March 20) were recognized as the key indicators of severe stripe rust epidemics in irrigated wheat crops. In addition, the number of icy days with minimum temperatures below 0°C, −5°C and −10°C during autumn and winter months corresponded strongly to the disease onset across different geographical regions. Previous documents (Gladders *et al.* 2007) and our preliminary examination demonstrated that stripe rust epidemics rarely follow cold winters. Although frost can kill sporulating hyphae of the stripe rust pathogen (Zadoks 1961), nonsporulating mycelium is able to tolerate up to −10°C temperatures (Rapilly 1979). Since the pathogen survival over winter is a key determinant of stripe rust epidemics and crop losses (Gladders *et al.* 2007; Sharma-Poudyal and Chen 2011), this study involved the number of icy days and mean monthly minimum temperatures during autumn and winter to predict spring epidemics of stripe rust in Kermanshah province. Furthermore, the involvement of a region variable in our analysis indicated a strong association between with the disease onset time and the number of icy days over the autumn–winter period. This suggested that the number of days with a minimum temperature below 0°C and −10°C could assist with predicting the disease occurrence in spring for subtropical and cold regions, respectively. Therefore, stripe rust predicting models for areas with heterogeneous geographical and climatic characteristics may benefit from considering region descriptors in order to examine relevant autumn and winter conditions. Such large-scale findings demonstrate the remarkable impact of climatic differences between regions that should be considered in the development of more accurate predicting models.

Although rainfalls in spring have been found to have strong associations with stripe rust epidemics according to the literature, autumn and winter rainfalls or moisture also have significant influence on disease outbreaks. For instance, Sharma-Poudyal and Chen (2011) found a correlation of the number of winter rainy days with yield loss due to stripe rust epidemics in the USA. Park (1990) found that rainfalls in April and May (autumn) were strongly associated with the development of stripe rust epidemics in Australian wheat. Even Grabow *et al.* (2016) reported a significant association of soil moisture during autumn-winter with wheat stripe rust epidemics. Based on such evidence, we examined all the daily and monthly climatic variables such as maximum relative humidity and the number of rainy days during an eight-month period from the beginning of autumn to the end of the second month of spring in Iran. This period involves the presence of wheat crops, rainfalls, and appropriate temperatures (5–12°C) in the regions studied. For this reason, like the two above-mentioned moisture predictors, the number of appropriate days with minimum temperatures (7–8°C) and RH > 60%, and the number of periods involving consecutive days with minimum temperatures of 6–9°C and RH > 60% were tested during the same 240-day period, from September 23 to May 21. Consistent with the prevailing opinion, combined temperature-moisture variables allow for more accurate prediction of stripe rust epidemics according to the present PCA and ordinal regression results. The current research also extended our understanding of noticeable temperature-humidity-rust-wheat interactions over time periods longer than individual autumn, winter or spring seasons.

In conclusion, this is the first evidence of the combined effects of air temperature, icy and rainy days, relative humidity and region over an autumn-winter-spring period on stripe rust epidemics and disease onset. Furthermore, the present findings provide an easy to use and cost-effective basis for predicting the development of disease epidemics according to climatic indicators, not only in hotspot regions but also in later-detected-disease regions. Such a wise application of fungicides based on this predicting model may minimize environmental and human hazards, pathogen resistance to fungicides and farmers' costs particularly in hotspot and early-detected regions. Therefore, future stripe-rust-predicting models could involve region and whole-season disease and climate interactions to improve the predictive accuracy. According to the actual values for the best climatic predictors recorded in the present study, the following conclusions were derived for easy use purposes. Cold winters in subtropical districts (involving stripe rust hotspots) of Kermanshah with more than 15 daily minimum temperatures below 0°C can suppress disease epidemics, irrespective of frequent, heavy rainfalls. This also leads to sparse and low disease pressure in temperate and semi-arid regions. A severe epidemic can occur if all of the following climatic criteria in subtropical regions are met: (1) <8 icy days with minimum temperatures below 0°C, (2) >60 rainy days from the beginning of Mehr to the end of Esfand, (3) >15 days with minimum temperatures (7–8°C) and maximum relative humidity above 60%, (4) >7 periods of consecutive days with minimum temperatures (6–9°C) and maximum relative humidity above 60%, (5) mean monthly maximum relative humidity above 85% in Aban, and (6) mean monthly minimum temperature around 8.5°C in Esfand. Following the prediction of disease epidemics in subtropical regions, it is possible to predict epidemic development using the climatic conditions as follows: (1) <85 icy days with minimum temperatures below 0°C, (2) >65 rainy days over Mehr-Esfand, (3) >15 days with minimum temperatures of 7–8°C and maximum relative humidity above 60%, (4) >10 periods of consecutive days with minimum temperatures of 6–9°C and maximum relative humidity above 60%, (5) mean monthly maximum relative humidity above 85% in Aban, and (6) mean monthly minimum temperature around 2.5°C in Esfand.

Acknowledgements

This research was financially supported by the Iranian Agricultural Research, Education & Extension Organization, project no. 4-55-16-92197. The authors acknowledge all wheat growers who were involved in this study.

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