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Spatiotemporal hotspot patterns of wheat rust incidence and severity in Ethiopia

Abu Tolcha 1*, Olika Dessalegn 2, Almaz Nigussie 1 and Degefie Tibebe 3

1Kulumsa Research Center, Ethiopian Institute of Agricultural Research, Ethiopia.
2Melkassa Research Center, Ethiopian Institute of Agricultural Research, Ethiopia.
3Head Quarter, Ethiopian Institute of Agricultural Research, Ethiopia

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Wheat rusts, stem rust, leaf rust, and stripe or yellow rust are the major biotic constraints in all wheat-growing regions of Ethiopia. Therefore, the main objective of this study is to identify the temporal-spatial hot spot pattern of wheat rust incidence and severity in Ethiopia. A GIS-based hotspot analysis tool was employed to identify the spatial distribution of hot spot patterns and temporal trends using survey data collected by the International Maize and Wheat Improvement Center and the Ethiopian Institute of Agricultural Research from the fields of smallholder farmers in Ethiopia. The analysis identified seven hot spot pattern categories; no trend detected, new hot spot, consecutive hot spot, diminishing hot spot, oscillating hot spot, persistent hot spot and a sporadic hot spot for yellow and stem rusts distributed in different parts of the country. For instance, the persistent hot spot is observed in west Arsi and Bale zones, which are the potential wheat-growing areas of the country while new hot spots are emerging in central and northern parts of the country. Generally, areas where these two hot spot patterns occurred, are requiring special attention to minimize yield loss due to rust and tackle food insecurity.

Key words: Emerging hotspot, stem rust, yellow rust, leaf rust.

INTRODUCTION

Wheat is cultivated on over 1.6 million hectares of land, with an annual production of 4.64 million tons, contributing about 15.17% of the total grain production in Ethiopia (CSA, 2017). The area under wheat has increased from 0.77 million ha in 1997 to 1.69 million ha in 2017 during the last 20 years (CSA, 1998, 2017). It ranked fourth after tef (Eragrostis tef), maize (Zea mays L) and Sorghum (Sorghum bicolor L) in land-coverage and total production (CSA, 2017). Following maize, wheat ranks second in terms of productivity with the average yield of 2.73 t/ha at the national level.

Despite the large area coverage of wheat in Ethiopia, the national average yield is 2.7 t/ha (CSA, 2017), which is much lower than the average of African and world yield productivity. There are several factors including biotic (diseases, insect pest, and weeds) and abiotic (moisture,
soil fertility, etc.), and adoption of new agricultural technologies contributed to this low productivity (Zegeye et al., 2001; DRRW, 2010; Nelson, 2013).

The major biotic constraints in all wheat-growing regions of Ethiopia are wheat rusts, stem rust (*Puccinia graminis* Pers. f.sp. triticci), leaf rust (*Puccinia triticina* Eriks) and stripe rust (*Puccinia striformis* Westend. f. sp. triticici). Among these, wheat stem rust has been the most devastating disease of all wheat rusts in Ethiopia causing up to the total damage of wheat crops over wide areas during the epidemic years. It is widespread in the wheat-growing regions, particularly in Central, South-East and North-West Ethiopia (Admasu and Fikadu, 2005; Admasu et al., 2010).

Leaf or stripe (yellow) rust can cause up to 60% of yield loss and 61 to 100% loss for stem rust (Admasu et al., 2009; Park, 2007). The specific characteristics of the rust fungi make rusts persistently significant disease in wheat. These characteristics include the ability to change genetically, thus producing new races that can overcome previously resistant wheat cultivars and a capacity to produce a large number of spores that can be wind-disseminated over wide areas and infect wheat under favorable environmental conditions.

Because of emerging and re-emerging of virulent races that break previous resistance of cultivars, several epidemics have been reported at different times. Therefore, to give a clear picture of the distribution and importance of wheat rusts, it is usually suggested that continuous and exhaustive surveys need to be carried out. Disease monitoring and surveillance are very important for sustainable wheat production and assure food security. The measurement and quantification of plant diseases are therefore of essential importance in the study and analysis of plant disease epidemics. Therefore, the main objective of this study is to identify the spatial-temporal hot spot pattern of wheat stem, leaf, and stripe (yellow) rust incidence and severity in Ethiopia to give an insight to decision-makers and end-users for better livelihood.

MATERIALS

Eleven years (2007-2017) wheat rust incidence and severity data from a panel survey conducted on smallholder farmers’ field in Ethiopia were used. The data was collected annually by the International Maize and Wheat Improvement Center (CIMMYT) and the Ethiopian Institute of Agricultural Research (EIAR) from the known wheat-growing areas of the country using a random sampling method for the development of early warning system. The rust severity was computed using the “Modified Cobb scale” method.

The data was transformed into a Network Common Data Form (NetCDF) data cube structure before running the statistical analysis. The GIS-based “create space-time cube” tool was used to transform data by aggregating rust disease points in each location into space-time ‘bins’ with a spatial resolution of 10 km and a one-year time-step interval based on the available survey data and survey design. The NetCDF structure stores space as latitude and longitude coordinates (x, y) and time (t) (that is, the year the disease was observed) as another dimension (Figure 1). Each bin represents a fixed position in space (x, y) and in time (t) that collectively create a three-dimensional cube (Figure 1). The value of each bin was assigned as the count of rust incidence and severity in the bin for a given year. The ESRI ArcGIS Emerging Hot Spot Analysis geoprocessing tool was used for statistical analysis and ArcGIS software was used for map symbolization.

METHODS

A GIS-based hotspot analysis tool was employed to identify the temporal trends and spatial distribution of hot spot patterns of wheat rust incidence and severity. Different hot or cold spot trends such as new, consecutive, intensifying, persistent, diminishing, sporadic, oscillating and historical can be detected by this tool. This tool uses a space-time implementation of the Getis-Ord-Gi* statistic to measure the intensity of feature clustering which considers the value for each bin within the context of the values for neighboring bins. Emerging Hot Spot Analysis tool evaluates the spatiotemporal patterns in rust incidence and severity in the country using a combination of two statistical measures: the Getis-Ord Gi statistic (Ord and Getis, 1995) to identify the location and degree of spatial clustering of the disease, and Mann-Kendall non-parametric trend test (Mann, 1945; Kendall and Gibbons, 1990) to evaluate temporal trends of the time series.

First, the Getis-Ord Gi* statistic measures the intensity of clustering of high or low values (that is counts of rust incidence and severity) in a bin relative to its neighboring bins in the data cube. The sum for a bin and its neighbors is compared proportionally to the sum of all bins. The Getis-Ord Gi* statistic generates z-scores (standard deviations) and P values (statistical probabilities) for each bin. This value indicates whether rust incidence and severity in a given bin is statistically clustered compared to incidence and severity in neighboring bins, as well as incidence and severity across the entire analysis domain. A z-score above 1.96 or below -1.96 means that there is a statistically significant hot spot or a statistically significant cold spot of the disease incidence and severity at a significance level of P <0.05. The larger a bin’s z-score, the more intense the clustering of values (hot spot). The Getis-Ord Gi* local statistic is given as:

\[
G^*_i = \frac{\sum_{j=1}^{n} w_{ij} x_j - \bar{X} \sum_{j=1}^{n} w_i}{\sqrt{n \sum_{j=1}^{n} w_j^2 - (\sum_{j=1}^{n} w_i \bar{X})^2}}
\]

where \(G^*_i\) is the local G statistic for a feature (i), \(W_i\) represents the spatial weight for the target-neighbor \(i\) and \(j\) pair (Peeters et al., 2015). \(X_j\) is the attribute value for feature \(j\), \(n\) is the total number of features and:

\[
\bar{X} = \frac{\sum_{j=1}^{n} x_j}{n}
\]

\[
S = \sqrt{\frac{\sum_{j=1}^{n} x_j^2}{n} - \left(\bar{X}\right)^2}
\]

The \(G^*_i\) statistic is a z-score so no further calculations are required. The output of the \(G^*_i\) statistic is a map indicating the location of the spatial clusters in the study area. The degree of clustering and its statistical significance is evaluated based on a confidence level and
the output z-scores. If z-score is positive and significant, it shows that one location and its neighboring locations have a relatively high frequency of rust incidence and severity, that is, is a spatial cluster of high data values (hotspot); while conversely, if z-score is negative and significant, it points to a cold spot (spatial cluster of low data values).

Second, the Emerging Hot Spot Analysis tool uses the Mann-Kendall statistic (Mann, 1945; Kendall and Gibbons, 1990) to test whether a statistically significant temporal trend exists through each bin's 11-year time series of z-scores resulting from the Getis-Ord Gi*

Figure 1. Space-time cube. Source: Modified from http://desktop.arcgis.com/en/arcmap/10.3/tools/space-time-pattern-mining-toolbox/emerginghotspots.htm.
Figure 2. Space-time hot spot patterns of yellow (stripe) rust incidence in wheat-growing areas of Ethiopia during 2007-2017.

RESULTS AND DISCUSSION

Wheat rust incidence

The map in Figures 2 to 4 presents the emerging hot spots of wheat yellow rust, stem rust and leaf rust incidence, respectively. The analysis identified eight hot spot pattern categories: no trend detected, new hot spot, consecutive hot spot, diminishing hot spot, oscillating hot spot, persistent hot spot, historical hotspot and sporadic hotspot for all rust types.

Out of the detected hot spot pattern categories, the areas where persistent hot spot, consecutive hot spot and new hot spot were identified are of particular interest to pathologists as they indicate areas where require special attention. Sporadic hot spots and oscillating hot spots are relatively less significant and difficult to manage since they are irregular and variable. These detected hot spot pattern categories occurred in different parts of Ethiopia. Persistent hot spot is identified in west Arsi and Bale zones for yellow and stem rusts and in the West Arsi zone for leaf rust. Consecutive hot spot pattern is identified in Hadiya zone of Southern Nation Nationalities and Peoples Region (SNNPR) and west Shewa, west Wellega, southwest Shewa, and HoroGuduru zones of Oromia regional state for all the three rust types and expanded to west Arsi zone for yellow and leaf rusts (Figures 2 to 4). Vast areas of new hot spot are present in Gurage, Selti, east Shewa, west Shewa, southwest Shewa, west Wellega, HoroGuduru, north Shewa of Amhara region, south Wollo, North Wollo, and eastern Tigray zones of the country for all rust types during the
last eleven years (2007-2017) (Figure 2 to 4). This indicates that they are expanded to the areas that are less affected before. The sporadic hot spot widely occurs in Arsi, West Arsi, Bale, HoroGuduru, West, and southwest Shewa zones of Oromia region and North Shewa and north Wollo zones of Amhara region for all rusts (Figures 2 to 4).

Overall, the detected hot spot pattern categories occurred in different parts of the surveyed areas and similarly distributed for all rust types. Meaning that the same hot spot pattern has appeared in similar parts of the country for all rust types. For instance, the persistent hot spot is observed in southeastern highlands (Arsi, West Arsi, and Bale) for all the three rust types (Figures 2 to 4). This might be due to the weather condition of the area as favorable environmental condition is required for wheat rust to occur. Changes in atmospheric composition and the physical climate including temperature, rainfall and humidity will no doubt affect the economic importance, geographical distribution, and management of rusts of wheat ultimately affecting wheat production and food security (Chakraborty et al., 2011). For example, a change in weather too warm and humid may lead to more rapid development of a plant disease, a loss in yield of a crop, and consequent financial adversity for individual farmers and for the people of the region. The existing environmental conditions will favour stem rust infection in most wheat-growing regions of the world which leads to epidemic buildup (Singh et al., 2011). The situation is worsened by the fact that a large proportion of current breeding materials are susceptible to wheat rust races and susceptible wheat varieties are distributed to large areas.

Wheat rust severity

Like the incidence, different hot spot pattern categories are identified for the severity of wheat yellow (stripe), stem and leaf rusts in Ethiopia (Figures 5 to 7). Consecutive hot spot is observed in Arsi, West Arsi, Hadiya, West Shewa, South-west Shewa, and Horo-Guduru Wellega zones of the country for all rust types and expanded to Gurage and Selti zones for stem rust. It covers wide areas of west and southwest Shewa zones for leaf rust. Persistent severity hot spot is identified in
Figure 4. Space-time hot spot patterns of leaf rust incidence in wheat-growing areas of Ethiopia during 2007-2017.

Figure 5. Space-time hot spot patterns of yellow (stripe) rust severity in Wheat-growing areas of Ethiopia during 2007-2017.
west Arsi and Bale zones for yellow and stem rusts and in the West Arsi zone for leaf rust during the last ten years (Figures 5 to 7). This could result in high wheat yield reduction which in turn can affect the wheat supply of the country as these zones are the major wheat-growing areas in the country. New hot spots have emerged in different parts of the country such as Gurage, Selti, West Shewa, Horo Guduru, West Wellega, North Shewa of Amhara region, South Wollo, North Wollo, and Eastern Tigray zones for all rust types (Figures 5 to 7). Overall, new severity is observed in the northern and western parts of wheat-growing areas of the country for all rust types. Meaning that they become sever over the areas where they were not or fewer sever before. Moreover, sporadic hot spots have occurred in Bale, West Arsi, southwest Shewa and West Shewa zones of Oromia region for all the three rust types while expanded to North Shewa and South Wollo of Amhara region for yellow and stem rusts (Figures 5 to 7).

Conclusions

Wheat rusts, stem rust, leaf rust, and stripe or yellow rust are the major biotic constraints in all wheat-growing regions of Ethiopia. It is usually suggested that continuous and exhaustive surveys need to be carried out to give a clear picture of the distribution and importance of wheat rusts. Therefore, the emerging hot spot analysis tool was applied to show the spatial distribution and temporal trends of wheat rust incidence and severity in wheat-growing areas of the country using wheat rust survey data. Thus, the space-time analysis revealed that similar hot spot patterns of wheat rust incidence and severity occurred in different parts of the country for all rust types. For instance, persistent hot spot occurs in Bale and West Arsi zones while new hot spot emerges in the northern and western parts of the country for all the three rust types. Similarly, persistent and new severity hot spots are observed in the northern and
western parts of wheat-growing areas of the country for all rust types. Both of these hot spot pattern categories require special attention.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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