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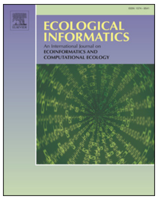

Spatial prediction of wheat septoria leaf blotch (*Septoria tritici*) disease severity in Central Ethiopia

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ABSTRACT

A number of studies have reported the presence of wheat septoria leaf blotch (*Septoria tritici*; SLB) disease in Ethiopia. However, the environmental factors associated with SLB disease, and areas under risk of SLB disease, have not been studied. Here, we tested the hypothesis that environmental variables can adequately explain observed SLB disease severity levels in West Shewa, Central Ethiopia. Specifically, we identified 50 environmental variables and assessed their relationships with SLB disease severity. Geographically referenced disease severity data were obtained from the field, and linear regression and Boosted Regression Trees (BRT) modeling approaches were used for developing spatial models. Moderate-resolution imaging spectroradiometer (MODIS) derived vegetation indices and land surface temperature (LST) variables highly influenced SLB model predictions. Soil and topographic variables did not sufficiently explain observed SLB disease severity variation in this study. Our results show that wheat growing areas in Central Ethiopia, including highly productive districts, are at risk of SLB disease. The study demonstrates the integration of field data with modeling approaches such as BRT for predicting the spatial patterns of severity of a pathogenic wheat disease in Central Ethiopia. Our results can aid Ethiopia's wheat disease monitoring efforts, while our methods can be replicated for testing related hypotheses elsewhere.

1. Introduction

Wheat is the third most widely produced cereal crop in the world and the fourth most important staple crop in Ethiopia. As the human population rises and moves into the urban centers, wheat demand in Ethiopia is expected to increase sharply (Macauley, 2015). Over the past decade wheat productivity in Ethiopia has moderately increased (Dercon and Hill, 2009; Taffesse et al., 2012). However, in order to achieve food self-sufficiency and food security, Ethiopia needs to increase its wheat productivity at a higher rate, while minimizing yield loss from diseases and pests. Our goal was to identify wheat growing areas in West Shewa (Ethiopia) that are vulnerable to attacks from the pathogenic fungal species called *Zymoseptoria tritici* (Desm).

In Ethiopia, wheat is mainly grown in the highlands during the main crop season (locally called *meher*). Depending on the availability of the rains and the crop varieties used, seed sowing occurs in the *meher* season from June to July, while harvesting takes place from October to January. A minor, less reliable and unpredictable crop season named *belg* also occurs from March to May. More than 90% of the crop yield in Ethiopia is produced during the *meher* season (CSA, 2015); thus, the focus of this study is the *meher* season. Rain-fed farming in Ethiopia is vulnerable to natural drought, particularly during the El Niño and La Niña years (Broad and Agrawala, 2000; Lyon, 2014; WFP, 2015). Fungal diseases are another threat that poses substantial risk to Ethiopian wheat production, often causing up to 50% yield loss on susceptible varieties (Abebe et al., 2015; Ponomarenko et al., 2011; Takele et al., 2015a). World-wide annual wheat yield loss from only two pathogenic genera, *Septoria* and *Stagonospora*, are estimated in the billions of dollars (Eyal, 1999; Fones and Gurr, 2015; Ponomarenko et al., 2011).

Zymoseptoria tritici (synonym *Mycosphaerella graminicola* or *Septoria tritici*) is the fungal pathogen that causes the wheat disease, referred to as *Septoria triciti* blotch (STB) or septoria leaf blotch (SLB).[1] *Mycosphaerella graminicola* was rated as one of the top 10 economically important fungal pathogens in the world (Dean et al., 2012). A number of studies have

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[1] The disease causing pathogen *Mycosphaerella graminicola* was recently named *Zymoseptoria tritici*. Others have used *Septoria triciti* blotch (STB) to refer to septoria leaf blotch (SLB). Most published works from Ethiopia use the term SLB. Here, we use SLB to refer to the disease, and *M. graminicola* to refer to the disease causing pathogen.

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reported the occurrence of *M. graminicola* and SLB in Ethiopian wheat farms (Arraiano and Brown, 2006; Beyene et al., 1990; Takele et al., 2015b; Tanner and Hulluka, 1991). *M. graminicola* is primarily disseminated through airborne ascospores, and pycnidiospores that linger on crop residues. Spores grow on leaves and inoculate the host via stomatal openings. The life cycle of *M. graminicola* has been described using distinct stages and phases (O'Driscoll et al., 2014; Ponomarenko et al., 2011). These include hyphal growth on leaf surface, host penetration via stomata, intercellular hyphal growth, necrotrophic growth, and formation of asexual (conidia, pycnidia) and sexual (pseudothecia) fruiting bodies (Dean et al., 2012; Eyal, 1999; Ponomarenko et al., 2011). The necrotrophic stage is characterized by the formation of lesions on infected leaves and stems. Conidia spreads upward on the same plant and to nearby plants, with rain-splash aiding the secondary infection and dissemination processes. Under the right environmental conditions, spread via conidia may occur several times and the infection may quickly reach epidemic levels.

Wet and cool environmental conditions are known to favor *M. graminicola* infection and spread. Wet conditions lasting longer than 12 h and temperatures ranging from 7 °C to 22 °C generally create suitable conditions for *M. graminicola* invasion (Magboul et al., 1992; Te Beest et al., 2009). Soil conditions such as high soil clay content and application of nitrogen fertilizer may also influence SLB occurrence (Simón et al., 2013; Te Beest et al., 2009). Using environmental variables and different modeling approaches researchers have successfully predicted areas that are vulnerable to invasion from problematic species (Kumar et al., 2014, 2015; Macdonald et al., 2003; Schurich et al., 2014) including pathogens (Flory et al., 2012; Murray et al., 2011). More recently, Kumar (2014) predicted the occurrence of leaf rust in India using climatic variables, disease severity data, and multiple regression techniques. Despite the existence of highly reliable predictive techniques and the availability of global scale climatic, environmental, and topographic data, areas at risk of SLB disease have not been identified in Ethiopia. Likewise, the environmental conditions that favor high SLB disease severity levels have not been adequately evaluated. Here, we used disease severity data; linear regression and Boosted Regression Trees (BRT) modeling techniques; and suites of bioclimatic, remotely sensed, topographic, and soil variables to quantify the risk of SLB disease in Central Ethiopia. Our objectives were to: a) map and predict SLB disease severity patterns in West Shewa, Central Ethiopia; and b) identify the environmental variables associated with different levels of SLB disease severity. Our results can aid SLB disease monitoring and prevention efforts in Ethiopia including the identification and prioritization of vulnerable areas.

2. Materials and methods

2.1. Study area

The West Shewa administrative zone is located in the central parts of Ethiopia within the Oromia regional state. It shares boundaries with Addis Ababa City, Amhara regional state, Southern Nations regional state, and four other Oromia administrative zones (i.e., East Shewa, East Welega, North Shewa, and Jimma; Fig. 1). Elevation in West Shewa ranges from 650 m to 3600 m above sea level. The three dominant soil types in the study site are Nitosols, Vertisols, and Cambisols (Batjes, 2012). Agricultural crops are mainly produced by subsistent farmers or by 'small holding farmers' for house hold consumption purposes. The top five cereal crops produced in the area include *teff*, barely, wheat, corn, and sorghum (CSA, 2011). In the study site, wheat is the third most important cereal crop, both in terms of area cultivated and quantity produced (Chamberlin and Schmidt, 2013; CSA, 2011). The projected Total Human Population (THP) of West Shewa in 2016 is about 1.4 million, while the projected THP of Ethiopia for the same period ranges from 101 to 104 million (CSA, 2013). Securing food for the growing THP in Ethiopia requires increasing wheat productivity and minimizing yield loss.

2.2. Disease severity and environmental data

Geographically referenced SLB disease severity data were collected in 2014 from 64 different *kebeles* or 'peasant associations' (Takele et al., 2015b). The 64 *kebeles* were located in 11 *weredas* (districts) of the West Shewa administrative zone. The districts include Ambo, Ameya, Becho, Cheliya, Dawo, Dendi, Ejere, Kokir, Tikur Inchini, Weliso/Goro, and Wenchi. The data were randomly collected at an interval of 5–10 km; thus, they fairly represent the environmental conditions of the study area (Fig. 1). Disease severity was recorded using the double digit standardized scoring system (Eyal, 1999; Saari and Prescott, 1975; Zhu et al., 2014). The first digit (D1) indicates the vertical advancement of the disease, while the second digit (D2) indicates disease symptoms in terms of damaged leaf area; the scale range for both D1 and D2 is 0–9. Percent disease severity was then calculated using the following equation:

$$\%Severity = (D1/9) * (D2/9) * 100$$

We selected a suite of remote sensing, bioclimatic, topographic, and soil variables to model SLB distribution in West Shewa (Appendix A). We considered MODIS normalized difference vegetation index (NDVI) for the *meher* growing season (i.e., June to December 2014) to represent chlorophyll content, greenness and crop health. We chose the year 2014 because it represents our field data collection period (i.e., 2014). We considered monthly NDVI values, *meher* season average NDVI values, and their corresponding standard deviations. June, July, and August represent the environmental conditions of the wet season, which are crucial for the development of wheat crop and *M. graminicola*, while October and November represent the cool and dry season that favor SLB disease progress (Takele et al., 2015b).

Moisture- and temperature-related variables are known to influence the distribution of *M. graminicola* (Beyer et al., 2012; Pietravalle et al., 2003; Te Beest et al., 2009). Thus, we considered MODIS land surface temperature (LST), and the widely known 19 bioclimatic variables (Hijmans et al., 2005; http://www.worldclim.org/) for modeling *M. graminicola* in West Shewa (Appendix A). We normalized the MODIS LST products by subtracting LST values from their corresponding monthly maximum temperature values. We performed the normalization process to reduce elevation-induced variations from the LST products. Monthly maximum temperature values used in the normalization process were obtained from the WorldClim website (Hijmans et al., 2005).

All MODIS layers were obtained from National Aeronautics Space Agency (NASA) Land Processes Distributed Active Archive Center (LPDAAC) (Wan, 2013). We downloaded the data using the MODIS Reprojection Tool Web Interface (MRTWeb), and performed additional spatial analyses using ArcGIS software Version 10.3.1 (Esri, 2014). The MODIS NDVI layers had a spatial resolution of 232 m × 232 m, while the MODIS LST products had a spatial resolution of 1000 m × 1000 m. Elevation and Compound Topographic Index (CTI) were included to represent topographic heterogeneity. The topographic variables were derived from the Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) at 90 m spatial resolution. Clay mass, water holding capacity, and total nitrogen content at the top 20 cm horizon were considered as soil variables (Appendix A). We obtained all soil layers from the ISRIC-WISE database at 5 × 5 arc-minute spatial resolution (Batjes, 2012). We performed spatial joining in ArcGIS 10.3.1 (Esri, 2014), and linked the soil layers with the remote sensing and topo-climatic variables. A total of 50 predictor layers were prepared for modeling SLB disease severity in the study site (Appendix A). All spatial analyses were performed at the MODIS NDVI spatial resolution (i.e., 232 m × 232 m).

2.3. Disease risk modeling

We conducted multicollinearity tests among predictor variables in R statistical software using the 'Hmisc' package (R Development Core Team, R., 2011). We found most of the 50 variables to be highly