Crop Protection 74 (2015) 150–157

Contents lists available at ScienceDirect

Crop Protection

journal homepage: www.elsevier.com/locate/cropro

Temporal and spatial dynamics of wheat powdery mildew in Sichuan Province, China

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A R T I C L E I N F O

Article history:
Received 25 August 2014
Received in revised form
1 May 2015
Accepted 2 May 2015
Available online 16 May 2015

Keywords:
Blumeria graminis f. sp. *tritici*
Effective dispersal
Epidemic dynamics
Meteorological factors

A B S T R A C T

Wheat powdery mildew, which is caused by *Blumeria graminis* f. sp. *tritici*, is an important and destructive wheat disease that can cause a considerable reduction in grain yield. The temporal dynamics of wheat powdery mildew examined over a five-year period (2007–2012) indicated that disease incidence and index fitted an “S”-shaped curve. The initial stage of wheat powdery mildew occurred mainly in late November, and the logistic stage in 2010–2011 was the longest in all experiments. The 2010 and 2011 experiments exhibited the highest disease index across the five years. The logistic curve best fit disease development during the five years and provided a good prediction of powdery mildew with an accuracy of 85%. Meteorological factors in March and April were highly correlated with disease index. To better understand powdery mildew epidemics, effective dispersal of the fungus was studied in 2011 and 2012. The results showed that the pathogen can spread more than 500 cm in one infection cycle. The rate of disease spread was relatively fast between late March and mid-April in 2012 and reached 175 cm/d. Curve fitting of the disease spread distance in eight directions identified the exponential and quadratic functions as the best fitting curves. Information on the temporal dynamics and effective spread distance of wheat powdery mildew and the relationship between disease epidemics and weather conditions provides the insight needed for future disease forecasting and management.

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1. Introduction

Wheat powdery mildew caused by *Blumeria graminis* (DC.) Speer 1975 f. sp. *tritici* emend. É. J. Marchal can result in a considerable reduction in grain yield and is one of the most devastating diseases of wheat in China (Chen et al., 2009; Hunger and Edwards, 2012; Ji et al., 2008; Kranz, 2003; Machado et al., 2002). Wheat powdery mildew was first detected in China in 1927 (Dai, 1927) with occasional reports between the 1920s and 1970s, followed by serious outbreaks since the late 1970s. Wheat powdery mildew had become an important disease by the 1980s and causes significant losses in wheat grain yield under favorable climatic conditions (He et al., 1998; Liu and Xiao, 2004). In southwest China, powdery mildew is likely the most damaging disease and is considered more serious than stripe rust, especially in irrigated areas or those with high inputs of nitrogen fertilizer (Luo et al., 2009).

The fungal pathogen is biotrophic (Both and Spanu, 2004; Brown and Hovmøller, 2002; Green et al., 2002) and colonizes the host epidermal cells by penetrating through the cell wall to form haustoria inside cells to obtain the nutrients required for survival (Bruggmann et al., 2005; Viljanen-Rollinson et al., 2007). This fungus can infect all aerial parts of a plant but is mainly found on the upper surface of leaves (Rossi and Giosuè, 2003).

Monitoring the epidemic dynamics of a disease is critical for disease management (Madden, 2006; Savary and Cooke, 2006). Fried et al. (1979) reported that the basic structure of the logistic model can accurately describe disease progression in various fields of study. Van der Plank (1960) used exponential, monomolecular and logistic models to describe the development of disease epidemics. A study on the development and epidemics of wheat powdery mildew in Henan Province indicated that the exponential model can best fit the curve of disease progression ($R^2 = 0.86$) (Tan, 1991). Powdery mildew exhibits an extended logistic period in extremely susceptible plant varieties (Wang and Zhang, 1998) and

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http://dx.doi.org/10.1016/j.cropro.2015.05.001
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the occurrence and severity of this disease are determined by weather factors (Te Beest et al., 2008). The spatial epidemiology of wheat powdery mildew was affected mainly by wind and airflow, and the temporal dynamics were affected primarily by temperature and humidity (Bruggmann et al., 2005; Chen et al., 2007; Johnson et al., 1994; Last, 1953; Moschini and Pérez, 1999; Schepers et al., 1996; Te Beest et al., 2008). The relationship between weather and disease epidemics was examined by Johnson et al. (1994) using linear discriminant and logistic regression analyses. Te Beest et al. (2008) showed that disease severity of powdery mildew in the UK was closely related to temperature, humidity and rainfall from April to June. In addition, Cao et al. (1994) indicated that disease index had a significant positive correlation with mean temperatures.

Many plant pathogens can spread over distances (Burt et al., 1997; Carlier et al., 2000; Nagarajan and Singh, 1990; Wang et al., 2010; Zeng and Luo, 2006). The invasive potential of a pathogen can be largely predicted by its ability to spread rapidly into new areas (Isard et al., 2005). Powdery mildew is a wind-dispersed disease that infects volunteer wheat after harvest as well as autumn-sown crops (Brown and Hovmøller, 2002; Liu et al., 2012; Te Beest et al., 2008). It is difficult to microscopically detect the fungal spores at the initial stage of a disease epidemic. Therefore, the local appearance of disease is used as the main criterion for the prior arrival of the pathogen and to monitor the spread of the pathogen over a particular distance. Thus, the "effective dispersal" of a pathogen is used to measure the spread of a disease, where the first appearance of a disease at a new site is used as evidence of the physical movement of a pathogen (Aylor, 2003). Weather conditions such as wind direction, airflow and rainfall are the major forces that affect pathogen dispersal (Aylor, 2003).

Certain studies have demonstrated the temporal development of plant diseases and presented temporally optimized management strategies (Parker et al., 1997; Pethybridge et al., 2005; Shah et al., 2001). However, reports on epidemiological studies that include both the temporal and spatial dynamics of wheat powdery mildew are scarce. Approximately 1,770,000 ha of wheat are planted annually in Sichuan Province. Recently, powdery mildew has been identified in 16% of this cultivated area, resulting in annual wheat losses of approximately 23,000 tons, which accounts for 15% of the total losses caused by pests and diseases (Liu et al., 2012; Tu et al., 1999). In the current study, the temporal dynamics and the effective spread distance of wheat powdery mildew were monitored, and correlations between disease epidemics and weather factors throughout the seasons were examined. Models were developed for predicting powdery mildew disease development. The results will provide a scientific foundation for future disease control through an improved disease management strategy.

2. Materials and methods

2.1. Temporal dynamics of wheat powdery mildew

A field experiment was conducted at the experimental farm of Sichuan Agricultural University in Ya'an from 2007 to 2012. Two susceptible wheat varieties, i.e., *Triticum aestivum* L. cv. Chuanyu 20 (CY20) and Chuannong 26 (CN26), were used as hosts. These varieties were planted in one-acre fields using hill plots with 10 cm between hills and 25 cm between rows. Conventional management was carried out without the application of herbicides or fungicides during the growing period. The presence of wheat powdery mildew was checked periodically, and disease notes were taken from 2007 to 2012; each year was considered as a replicate. In each field, five sites containing 100 seedlings each were selected using the five-point method (Chen and Xu, 2001) with some modifications. Disease notes were taken every 10 d before the jointing stage, and every 5–7 d after the jointing stage until the end of the milk-ripe stage. Disease incidence, severity and index were calculated following Chen and Xu (2001): Disease incidence (%) = (number of diseased leaves/total number of leaves examined) × 100%; Average disease severity = $\sum$ (severity × number of diseased leaves at this severity/number of leaves examined; Disease index = incidence × severity × 100). The disease severities were estimated as: 0, 1%, 5%, 10%, 20%, 40%, 60%, 80% or 100%.

Statistical analyses were performed using the SAS/STAT® statistical package. Analyses of variance were conducted using the General Linear Models (GLM) procedure (Goodnight et al., 1982). Curve fitting was performed using SPSS software 19.0 (SPSS, 2010) based on the phenotypic data collected from 2007 to 2012. Model selection was based on the R^2-value of the fitted models. Model validation was performed by computing the percentage prediction accuracy and chi-square using the 2013 phenotypic data and by regressing the actual and predicted disease values derived for the selected models.

Correlation between the five-year meteorological data and disease index was examined. Meteorological data used in this study were provided by the Ya'an and Chengdu Meteorological Administration.

2.2. Effective dispersal distance of wheat powdery mildew in the field

The effective dispersal distance of wheat powdery mildew was determined in 2011 and 2012. A susceptible wheat variety, *T. aestivum* L. cv. Chuanyu 20 (CY20), was selected as the host. Two fields where wheat had not previously been grown were selected in Xiali (Ya'an, Sichuan Province, China) and Qingpuyuan (Chengdu, Sichuan Province, China). The size of each field was 5 acres. The planting method used was the same as that described above. Wheat was planted in Xiali and Qingpuyuan in early December of 2010 and 2011, and 40 wheat plants that were heavily infected with powdery mildew in the laboratory were transplanted in the center of each field on the 25th of January 2011 and 17th of January 2012 to serve as the initial infection sites.

Spread distance survey was initiated after one incubation period (approximately 25–30 days under natural inoculation conditions). The survey was performed every 2 d in eight directions from the initial infection site, i.e., east, north, south, west, northeast, southeast, southwest and northwest. The minimum effective infection of powdery mildew was determined by the identification of one conidium within a distance of one meter. An equidistance survey along the spread direction of the disease was used to measure the gradient of disease spread. Here, plants in every other row from the initial infection site were selected for the survey and all the leaves of the selected plants were carefully checked for disease. Curve fitting was performed using SPSS software 19.0 (SPSS, 2010).

3. Results

3.1. Temporal dynamics of wheat powdery mildew

3.1.1. Field monitoring

Wheat is typically sown in late October or early November and harvested in May of the following year in Sichuan Province. In this 5-year study, the initial incidence of wheat powdery mildew occurred mainly in late November (Table 1). After the initial infection, the disease exhibited an exponential growth phase (incidence < 5%). The disease index and average severity increased slowly during this stage (Fig. 1), and the apparent infection rate was low. The logistic period of the disease (incidence between 5% and

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