Enhancing septoria leaf blotch forecasts in winter wheat II: model architecture and validation results

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Abstract

In precision agriculture, pesticides and other inputs shall be used precisely when (and where) they are needed. European Directive 2009/128/EC calls for respecting the principles of integrated pest management (IPM) in the member states. To clarify the question, when, for instance, fungicide use is needed, the well-established economic principle of IPM may be used. This principle says that pests shall be controlled when the costs of control correspond with the damage the pests will cause. Disease levels corresponding with the costs of control are referred to as control thresholds in IPM. Several models have been developed in plant pathology to predict when epidemics will occur, but hardly any of these models predicts a control threshold directly limiting their usefulness for answering the question when pest control is needed according to the principles of IPM. Previously, we quantified the temporal distance between critical rainfall periods and the breaking of the control threshold of *Zymoseptoria tritici* on winter wheat as being affected by temperature, based on data from 52 field experiments carried out in Luxembourg from 2005 to 2016. This knowledge was used to construct the ShIFT (Septoria Forecast, <https://shift.list.lu/>) model, which has been validated using external data recorded between 2017 and 2019. Within the efficacy period of a systemic fungicide, the model allowed correct predictions in 84.6% of the cases, while 15.4% of the cases were predicted falsely. The average deviation between the observed and predicted dates of epidemic outbreaks was 0.62 ± 2.4 days with a maximum deviation of 19 days. The observed and predicted dates were closely correlated ($r=0.92$, $P<0.0001$). Apart from outliers, the forecast model tested here was reliable within the period of efficacy of current commercial fungicides.

Keywords Crop protection · Integrated pest management · Leaf blotch · Model · Pest control · Precision agriculture

Introduction

The fungal wheat pathogen *Zymoseptoria tritici* (Desm.) Quaedvlieg and Crous, 2011 (formerly *Septoria tritici* Rob. ex Desm.) causes total annual losses of between 800 and 2,400 million euros in France, Germany and the UK (Fones and Gurr 2015). Agronomic practices such as tillage, crop rotation and late sowing dates contribute only marginally

to the control of the disease (Thomas et al. 1989; Gladders et al. 2001), while growing resistant cultivars is an important factor (Karisto et al. 2018). Preventing losses caused by *Z. tritici* therefore strongly depends on fungicide use. Contact fungicides protect a winter wheat crop for approximately 16 days, while systemic fungicides protect the crop for approximately 22 days (Greiner et al. 2019). With contact fungicides versus leaf blotch recently banned, systemic fungicides remain available to the farmers in the region studied here. Since fungicide use is the last resort of farmers to prevent losses, these periods represent the minimum requirement for the accuracy of leaf blotch forecast models. The timing of fungicide spraying remains a challenge for farmers because (1) spraying before the disease occurs implies the risk of spraying in vain if the disease should not reach a damaging level, (2) spraying too late cannot reverse the damage that the disease has already inflicted and (3) *Z. tritici* has a long latent period during which the pathogen

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spreads without exhibiting visible symptoms that could be the trigger for countermeasures.

In integrated pest management (IPM), minor disease incidences are left untreated since they do not justify the costs of pest control. The control threshold is the disease incidence for which the loss caused by the disease at the farm level is approximately equivalent to the costs of disease control (Zadocks 1985; Beer 2005). Control thresholds are used to determine the best timing for crop protection actions, including pesticide application from an economic point of view at the farm level. In precision agriculture, actions are taken precisely where and when they are needed. Previous studies focused on forecasting events with epidemiological relevance (Magarey et al. 2005; El Jarroudi et al. 2017; Lalancette et al. 1988; Giroux et al. 2016; Walter et al. 2016; Zhao et al. 2018; Molitor et al. 2016), but with often unclear relevance for precision agriculture. A predictive model for early warning of septoria leaf blotch on winter wheat was developed by te Beest et al. (2009) based on data from the UK. While te Beest et al. (2009) predicted if 5% disease severity will be reached on the upper three-leaf layers within a cropping season using the window pane approach (Coakley and Line 1982; Kriss et al. 2010), the model presented here directly predicts when a spray is due according to the criterion developed by Beer (2005). Chaloner et al. (2019) presented two new mechanistic models for predicting septoria leaf blotch considering experimental data on wetness-dependent germination, growth and death of the causal agent and found several shortcomings including failure to predict the observed annual disease and a cumulative overestimation of the disease over the course of a growing season with one of the two models. We previously used field data to quantify the temperature dependency of the temporal distance between critical rain events and the breaking of the control threshold of *Z. tritici* on winter wheat in order to achieve direct applicability in IPM and precision farming (Beyer et al. 2022).

The objective of the present study was to test whether the previously found empirical relationship (Beyer et al. 2022) allows a prediction of when the control threshold of *Z. tritici* as defined by Beer (2005) will be reached.

Materials and methods

Acquisition of disease data

Forty plants were marked in winter wheat plots untreated with fungicide at the beginning of each season and were monitored repeatedly. The development of leaf necroses caused by *Z. tritici* was monitored by visual assessment in 13 environments over the 2017–2019 period at the same locations described previously (Aslanov et al. 2019, Beyer

et al. 2022). Staff were trained before the visual assessments using the online tool provided by the Julius-Kühn Institute (<http://prozentualer-befall.julius-kuehn.de/schadbilder.php?show=5>). According to Beer (2005), the point of time when winter wheat needs to be sprayed versus leaf blotch is reached when 30% or 10% of the plants express symptoms on the upper four leaves during growth stages 32–37 and 39–61, respectively. The date on which the control threshold was reached will subsequently be referred to as the date of epidemic outbreak and was used for further data analysis (Table 1).

Input variables

We studied the period comprising growth stages 31–65, because during this period, fungicide use is allowed. Some fungicides are currently registered for use until growth stage 69. To determine whether the plants are in a susceptible growth stage, in which fungicide use can be recommended, the user must state either the date of sowing or the plant growth stage. If no plant growth stage is available, this will be estimated from the date of sowing using the relationship previously published by Beyer et al. (2012). However, entering observations on the plant growth stage is the preferred and recommended method.

The susceptibility rank (given, for instance, in national cultivar assessment lists such as BSA (2017)) of the winter wheat cultivar grown must be specified by the users. Previous experimental evidence demonstrated that septoria leaf blotch epidemics occur about 5.4 days earlier per susceptibility rank (Beyer et al. 2022). The cultivar susceptibility scale ranges from 1 (resistant) to 9 (susceptible). Varieties that were tested and are recommended for cultivation in Luxembourg (<https://www.sortenversuche.lu/>) can be selected in a drop-down menu of the software with their susceptibility rank given in brackets.

The weather input variables that are required for running the model are the hourly temperature (measured 2 m above the ground as standard weather stations do) and the hourly precipitation data between 1 March and 30 June. Hours with precipitation, but temperatures below 6.5 °C were discarded, because no epidemic was observed below that temperature (Henze et al. 2007).

The date on which the last fungicide spray was applied to the crop under consideration must be given. The efficacy of a modern systemic fungicide expires after 22 days (Greiner et al. 2019). During this post-spraying period, no alerts will be displayed, even if weather conditions were favorable for disease progress.

Table 1 Validation with external data. Observed days when the control threshold for *Z. tritici* was reached in winter wheat and predicted days when the control threshold was reached are given for 13 case studies that were not used for model construction. The case studies are identified according to the location of the field where the observations took place, the wheat cultivar, its susceptibility rank (SR) con-

cerning leaf blotch, the observation year and the plant growth stage (BBCH code) at which the control threshold was reached. Predictions were accepted as “correct,” if they fell into the efficacy period of common commercial fungicides (Greiner et al. 2019), and as “false,” if epidemic outbreaks were forecasted outside of this time frame. For details, please see “materials and methods”

Location	Cultivar	Year	BBCH	Observed		Predicted		Peak height ^a	Prediction
				Date	DOY	Date	DOY		
Bettendorf	Kerubino	2017	39	21/05/2017	141	22/05/2017	142	30	Correct
Burmerange	Kerubino	2017	39	17/05/2017	137	22/05/2017	142	21	Correct
Everlange	Kerubino	2017	32	15/05/2017	135	22/05/2017	142	36	Correct
Reuler	Kerubino	2017	49	31/05/2017	151	27/05/2017	148	25	Correct
Bettendorf	Kerubino	2018	39	14/05/2018	133	17/05/2018	137	15	Correct
Everlange	Genius	2018	31	16/04/2018	106	21/04/2018	111	20	Correct
Burmerange	Reform	2018	63	28/05/2018	147	08/06/2018	158	25	Correct
Reuler	Kerubino	2018	67	04/06/2018	154	03/06/2018	153	22	Correct
Bicherhaff	Kerubino	2019	31	15/04/2019	105	11/04/2019	101	19	Correct
Koerich	Kerubino	2019	31	29/04/2019	119	03/05/2019	123	15	Correct
Bettendorf	Kerubino	2019	32	23/04/2019	113	05/04/2019	95	13	False
Bettendorf	Desamo	2019	33	29/04/2019	119	10/04/2019	100	13	False
Weiswampach	Kerubino	2019	31	06/05/2019	126	06/05/2019	126	15	Correct

^aClosest peak to observed

Estimating the risk of reaching critical disease levels / the control threshold

Dry hours are excluded as potential predictors, because septoria needs water to infect crops. The time between rainfall and reaching the control threshold is then calculated for all wet hours according to the previously established empirical relationship (Beyer et al. 2022, Eq. 1):

$$\text{Time shift (h)} = 713.144 - 31.701 \times \text{current temperature (°C) during rainfall event.} \quad (1)$$

For each wet hour warmer than 6.58 °C, the time shift is added to the actual day of the year of the precipitation event. A frequency distribution (histogram) of the resulting data is plotted, reflecting the points of time at which epidemic outbreaks are expected based on the studies used for the construction of the model described here.

Outputs

The resulting frequency distribution usually displays several peaks. Each peak represents a period of time before which favorable weather conditions for reaching the control threshold

occurred frequently. The higher the peak, the higher the risk. The default output is generated for cultivars with susceptibility rank 5. For each susceptibility rank, the bars are shifted by one bar width. Bar width was chosen to match the temporal shift caused by one susceptibility rank (approx. 5 days, Beyer et al. 2022). The graph for a cultivar with susceptibility rank 4 is shifted to a later date by one bar width, while the graph for a cultivar with susceptibility rank 7 is shifted to an earlier date by 2 bar widths.

Validation

To validate the approach outlined above, new data were recorded (that were not used for the construction of the model) in the 2017–2019 period in the same region as above (Beyer et al. 2022). Risk graphs were plotted and the point of time at which the control threshold according to Beer (2005) was reached in the experimental fields was determined by visual observation on 30–40 plants per location and assessment date. The actual day of the year on which the control threshold was reached was compared with the predicted day. The peaks with the highest predictive power in the risk graphs were identified (for details, see below). The relationship between predicted and

Fig. 1 Graphical model output. The time shift between hours with temperature $> 6.5^{\circ}\text{C}$ and rain (**B**) and the point of time at which the control threshold was reached was estimated based on the empirical relationship depicted in Eq. (1). The graphical output (**A**) is a histogram of the time points with suitable infection conditions after the temperature-dependent time shift between rain and exceeding the control threshold was considered. High bars indicate that the control threshold will be reached and that a fungicide with efficacy against *Z. tritici* should be sprayed to prevent economic losses at the farm level. The bar width in (**A**) is 125 h and corresponds to the effect of one rank in the cultivar susceptibility ranks published by the BSA (2017). A histogram of the height of the peaks closest to the observed epidemics showed a clear maximum of 15 (Fig. 3). Therefore, bars exceeding “15” on the “Urgency to spray” axis are marked red. The yellow area indicates the period between plant growth stages 31 and 65, when fungicide use is allowed

observed values was visualized using a Deming regression that takes, unlike conventional regression, errors in the x - and y -directions into account (Linnet 1993).

Results and discussion

Model architecture

Hourly precipitation (sum) and temperature (average) data were plotted starting 1 March and ending 15 June (Fig. 1). This period corresponds roughly with plant growth stages 29–69 in winter wheat in the area of observation. We decided to start before growth stage 31 is reached, because of the time lag between infection and symptom expression/reaching of the control threshold. Then, the time shift between each wet hour and the point of time at which the control threshold was observed over the period 2015–2016 was estimated using the empirical relationship published in the first paper of the present series (Beyer et al. 2022). A histogram was then generated from the time points at

Fig. 2 Histogram of the peak heights displayed by the ShIFT model outputs (Fig. 1A) based on weather and cultivar susceptibility data from eight years and four locations. The closest peaks to each observed *Z. tritici* epidemic between the growth stages 31 and flowering were considered

which the reaching of the control threshold was forecasted (Fig. 1A). A graph of the type in Fig. 1A will subsequently be referred to as a risk profile. The more wet hours are emphasized by the respective temperature conditions on the same time slice, the higher the bars of the histogram become. The bar width of the histogram was adjusted to 125 h, corresponding to the effect of one rank in the winter wheat cultivar susceptibility ranks regularly published by BSA (2017 ff.). For instance, in the period 2005–2016, a cultivar with susceptibility rank 4 reached the control threshold on average 125 h later than a cultivar with susceptibility rank 5 (Beyer et al. 2022). The default setting of the model estimates the risk profile (Fig. 1A) for cultivars with susceptibility rank 5 (the most frequent rank of the cultivars grown in the region of observation). For cultivars with other susceptibility ranks, the risk profile is shifted, with the size of the shift corresponding to the susceptibility rank of the cultivar grown. For instance, for a cultivar with susceptibility rank 4 (lower than average), the default histogram is shifted to later dates by one bar width (= 125 h).

The period in which fungicide use is allowed (between the growth stages 31 and 65–69, depending on fungicide) is estimated from the sowing date according to Beyer et al. (2012). Therefore, users of the forecast model need to give the sowing date of the winter wheat. The precision of the estimates can be enhanced by manually entering the current growth stage of the crop, thus requiring it to be determined in (each) field concerned. Users can decide whether

they want to enter the sowing date or the growth stage of the winter wheat, although the growth stage is preferred due to better precision. During the period when fungicide use is permitted, spraying is recommended, before a red bar is reached (Fig. 1).

Validation

A typical risk profile (Fig. 1A) contains several peaks. Each peak represents a period of time, during which it is highly likely that the control threshold for *Z. tritici* will be reached. No warning is displayed for peaks that occur before or after fungicide spraying is allowed (for an example, see Fig. 1A). A histogram was generated, showing the peak heights from the period in which fungicide use was allowed (Fig. 2). A clear maximum was observed at 15 (Fig. 2). Hence, we assume that a peak height of 15 or higher indicates the reaching of the control threshold and thus the need to apply a fungicide spray. Among the six peaks that were smaller than 15 but associated with a breaking of the control threshold (Beer 2005), four were observed in the year 2014 (Fig. 2).

The pattern used to construct the model was detected in data acquired in field experiments during the period 2005–2016 (Beyer et al. 2022). Data from 2017–2019 were used for external validation. If a predicted point of time was within ± 11 days (being equivalent to 50% of the efficacy duration of a systemic fungicide (Greiner et al. 2019)) of the observed point of time, the prediction was accepted as correct, splitting the risk of applying either too early or too late. If predicted times were outside of the period specified above, the predictions were categorized as false. Of 13 cases, 2 were identified as false with external data (Table 1). This corresponds to 84.6% correct predictions. Predicted and observed dates were closely related ($r=0.92$, $P<0.0001$, Fig. 3).

Fig. 3 Day of the year (DOY) on which it was observed that the control threshold of leaf blotch on winter wheat had been reached versus the predicted DOY for reaching the control threshold. The solid line represents a Deming regression; the dotted lines represent the 95% confidence interval

Critical evaluation of model performance

In contrast to previous models, ShIFT forecasts the time for which a fungicide spray is needed directly. Users do not need to interpret epidemiological outputs to identify a suitable time frame for a fungicide spray based on the control threshold concept of integrated pest management.

The winter wheat crop is particularly sensitive toward septoria leaf blotch between plant growth stages 31 and 65. Therefore, peaks occurring before GS31 or after GS65 indicate favorable weather conditions for epidemics but do not indicate a need for fungicide use. Note that in many countries, including EU countries, fungicide spray application outside of the mentioned time frame is illegal due to the registration conditions of the products.

In the year 2014 (that was part of the data set used to detect the pattern used for the model), a massive yellow rust epidemic was observed in Luxembourg for the first time (Dam et al. 2020), probably due to the spread of more aggressive strains throughout Europe at that time (Aslanov et al. 2019). The poor performance of the model in that year, as indicated in Fig. 2, suggests that other diseases can seriously interfere with the percentage of correct model outputs at high disease levels. Thus, the model described here should not be used in other regions without locally validating model outputs with field observations, particularly if fungal plant pathogens other than *Z. tritici* are dominant.

The model allowed correct predictions in 84.6% of cases, while 15.4% of the cases were predicted falsely. The average deviation between the observed and predicted dates of relevant epidemic outbreaks was 0.62 ± 2.4 days with a maximum deviation of 19 days. Observed and predicted dates were closely correlated ($r=0.92$, $P<0.0001$). The model demonstrated considerable prognostic power when being tested with independent new data, and however, the possibility of outliers being falsely classified cannot be denied.

Considerations on fungicide efficacy

Greiner et al. (2019) determined the period of fungicide efficacy for Bravo 500 (a representative of contact fungicides containing chlorothalonil as active ingredient), Epoxion (a representative of systemic azole fungicides containing epoxiconazole as active ingredient) and Imbrex (a representative of systemic succinate dehydrogenase inhibitors containing fluxapyroxad as active ingredient) at full dose rates. The effective period of the fungicides ranged from 16 days for the contact fungicide Bravo to 22 days for the systemic fungicide Imbrex. Due to the ban of chlorothalonil and epoxiconazole, the situation in Luxembourg was greatly simplified, such that only products from the group with an effective period of approximately 22 days remained on the market and were therefore considered in the ShIFT model.

Fig. 4 The plot symbols represent the number of sprays recommended by ShIFT. Error bars represent the standard error of the mean from four locations. The dashed line indicates the average number of sprays recommended by ShIFT

Considerations on the number of sprays recommended–potential for pesticide savings

Under weather conditions that continuously allow for infections and disease development, three sprays may be applied for the best protection of the upper three-leaf layers that are largely responsible for grain filling, namely one spray after the formation of each of the leaf layer. Under weather conditions that do not allow for infections and disease development continuously, the number of sprays and thereby costs may be reduced without giving rise to an epidemic. ShIFT recommended on average 1.4 sprays on winter wheat per season against *Zymoseptoria tritici* (Fig. 4). In a survey with 108 participants, Luxembourgish farmers responded that they believed that on average, 1.6 fungicide applications are needed per season in winter wheat (Beyer et al. 2019). In neighboring Germany, 2.3 sprays are applied on average per season (<https://papa.julius-kuehn.de/index.php?menuid=46>). The difference between the 1.4 sprays per season recommended by ShIFT, the 1.6 sprays mentioned by Luxembourgish farmers and the 2.3 sprays applied on German farms can probably be attributed to the need for controlling other diseases besides leaf blotch. However, most commercial fungicides show efficacy against several fungal pathogens, and therefore, an additional spray is needed only if the temporal distance between the occurrences of the diseases is larger than the period of efficacy of the fungicide. Besides leaf blotch, yellow rust has also often been observed since 2014 in Luxembourg (Aslanov et al. 2019). In the 2005–2017 period, leaf blotch and yellow rust reached their respective control thresholds in 17 of 62 cases. The breaking of the control threshold for both diseases was within the

period of a systemic fungicide in 14 cases. In 3 of 62 cases (= 5%), the temporal distance between the occurrence of the two diseases was too large to control both diseases with the same spray. In approximately one out of five years, weather conditions for *Fusarium head blight* were favorable enough to allow for at least local mycotoxin contamination (Pallez et al. 2021). The 1.4 sprays per season recommended by ShIFT against leaf blotch in winter wheat seem to be roughly realistic with regard to farmers' opinions and factual use, leaving little room to further reduce fungicide use in winter wheat without accepting avoidable losses.

Availability of the model

ShIFT is freely available in the year 2022 for a test period in English, French, German and Luxembourgish at <https://shift.list.lu/> (Identifier: JPDP, Password: DPG_2022).

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

Human and animal rights This article does not contain any studies undertaken on human or animal subjects by any of the authors.

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