Journal of Plant Diseases and Protection (2022) 129:37–44
https://doi.org/10.1007/s41348-021-00553-9

ORIGINAL ARTICLE

Enhancing septoria leaf blotch forecasts in winter wheat I: the effect of temperature on the temporal distance between critical rainfall periods and the breaking of the control threshold

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Received: 27 May 2021 / Accepted: 16 November 2021 / Published online: 29 November 2021

Abstract

In integrated pest management (IPM), pests are controlled when the costs of control correspond with the damage caused by a pest on a monetary scale, implying that low pest levels are left uncontrolled. Several forecast models have been developed in plant pathology to warn farmers before an epidemic occurs to allow timely control. Most of these models do not predict a control threshold (pest level at which action needs to be taken to prevent economic losses at the farm level) directly making an application in precision agriculture where pesticides and other inputs shall be used precisely where and when they are needed, difficult. Here, we quantified the temporal distance between critical rainfall periods and the breaking of the control threshold of *Z. tritici* on winter wheat, as affected by temperature based on data from 52 field experiments carried out in Luxembourg between 2005 and 2016. The highest frequency of hours with rain (≥ 0.1 mm/h) was observed approximately at 300 h before epidemic outbreaks at about 13 °C, at 350 h at 11.5 °C and at about 475 h at about 7.5 °C. A Q10 value of 2.8 was estimated. The knowledge generated here will be used to construct a model that directly forecasts the time at which the control threshold will be reached and thus, when fungicide use is needed according to the standards of IPM with direct applicability in precision agriculture.

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

Introduction

Zymoseptoria tritici (Desm.) Quaedvlieg and Crous, 2011 (formerly *Septoria tritici* Rob. ex Desm.) is the most damaging fungal wheat pathogen in Western Europe. The teleomorph of *Z. tritici* is called *Mycosphaerella graminicola*. Total annual losses caused by the pathogen in France, Germany and the United Kingdom were estimated to range from 800 to 2400 million euros (Fones and Gurr 2015).

Laboratory experiments established that the fungus depends on water for essential developmental steps, such as spore germination (Guo and Verreet 2008). Chaloner et al. (2019) recently presented two mechanistic models for predicting septoria leaf blotch using data on germination as affected by wetness as well as experimental data on growth and death of the causal agent. They found several shortcomings of the mechanistic models 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. However, they noted the importance of the temperature dependency of relevant processes. The latent period of *Z. tritici* is affected by temperature (Shaw 1990) and was estimated to be approximately 20 days under the humid conditions of Northern Germany during the critical growth stages 31–65 (Henze et al. 2007). The latent period is defined as the time between infection and sporulation (Xu 1999). This period is an important parameter for understanding the epidemiology of the fungus on wheat, but decision-making at the

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farm level must consider economic parameters. Therefore, the concept of control thresholds (= disease incidence that causes monetary losses approximately equivalent to the costs of one control action) was introduced into integrated pest management (Zadocks 1985; Beer 2005).

Previous studies (Magarey et al. 2005; El Jarroudi et al. 2017; El Jarroudi et al. 2009; El Jarroudi et al. 2014a,b; Lalancette et al. 1988; Giroux et al. 2016; Walter et al. 2016; Zhao et al. 2017; Molitor et al. 2016; te Beest et al. 2009) focused on identifying weather conditions with epidemiological relevance rather than with direct applicability in Integrated Pest Management (IPM). In IPM, control thresholds are used for deciding on the best timing of crop protection actions, including pesticide application from the farm level's economic point of view. The present manuscript describes, to the best of our knowledge, the first attempt to identify the temporal distance of critical rainfall events from the breaking of the control threshold of *Z. tritici* in winter wheat as it is affected by temperature. This knowledge is needed to develop disease forecast models with direct applicability in IPM and precision farming.

In theory, the identification of critical precipitation events should be possible by simply comparing epidemic and non-epidemic cases. Critical precipitation events should be found in all epidemic cases but should be absent in all non-epidemic cases. However, in humid regions where epidemics occur virtually every year, non-epidemic cases can be too scarce for proper statistical analyses. Furthermore, a meaningful time tag in a sense of a temporal starting point for analyses is hard to define for non-epidemic studies. For epidemic studies, the time of an epidemic outbreak can be defined unambiguously, but for non-epidemic cases, a counterpart is missing. Hence, a way of identifying critical precipitation events must be found without the help of non-epidemic cases.

The identification of critical precipitation events is further complicated by the fact that biological processes such as fungal spore germination and mycelial development respond to temperature (Guo and Verreet 2008). The temporal distance between an epidemic outbreak and the precipitation event that caused it must be expected to be smaller at a high physiological temperature than at a low physiological temperature. Temperature-response relationships may be estimated from in vitro experiments, but such experiments usually mimic natural temperature and humidity fluctuations as well as effects of natural rain splash poorly, if at all, resulting in uncertainty as to whether relationships derived from in vitro experiments can be transferred 1:1 into field situations (see for instance Calisi and Bentley 2009). It is therefore desirable to estimate relationships for plant disease forecast models from field observations and field measurements.

The objectives of the present study were (1) to find a method for identifying critical precipitation events without the help of non-epidemic cases and (2) 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 from field data. The weather scenarios identified can be used as predictors for disease forecast models with better adoption in agriculture than previous approaches.

Materials and methods

Acquisition of disease data

Forty plants were marked in fungicide-untreated winter wheat plots at the beginning of each season and monitored repeatedly as previously described in Dam et al. (2020). The development of leaf necroses caused by *Z. tritici* was monitored by visual assessment in 52 environments over the period 2005–2016. Before the visual assessments, employees were trained 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 control threshold for leaf blotch on winter wheat was reached when 30% or 10% of the plants expressed symptoms on the upper 4 leaves during growth stages 32–37 and 39–61, respectively. The date on which the control threshold was reached will be subsequently referred to as the date of the epidemic outbreak and this date was kept for further analysis (Table 1). Selected agronomic information such as sowing dates, previous crops and nitrogen fertilization was published previously (Dam et al. 2020, supplementary Table 1).

Acquisition of weather data

The hourly temperature (measured 2 m above the ground) and precipitation data were downloaded from the weather station closest to the respective experimental field (Fig. 1, Table 1) up to 1200 h before epidemic outbreaks. Weather data can be accessed via the website agrimeteo.lu. The distance between the fields where the plant disease was assessed and the closest weather station averaged 3.7 ± 1.2 km (Fig. 1). Weather data were checked for gaps before further use.

Data presentation and analysis

Temperature time courses before epidemic outbreaks were plotted and hours without precipitation were marked green, hours with 0.1 mm rain yellow and hours with > 0.1 mm rain were marked red (Fig. 1). Subsequently, hours with rain

Table 1 Case study identification number (ID), year, winter wheat cultivar, cultivar susceptibility toward wheat leaf blotch, location, nearest weather station (agrimeteo.lu) and dates of epidemic outbreak

ID	Year	Cultivar	CSR*	Location of field	Location of weather station	Date of epidemic outbreak
1	2006	Akteur	6	Everlange	Useldange	08/04/2006
2	2016	Desamo	4	Everlange	Useldange	15/04/2016
3	2016	Kerubino	5	Burmerange	Remich	18/04/2016
4	2013	Cubus	6	Christnach	Christnach	13/05/2013
5	2016	Kerubino	5	Bettendorf	Bettendorf	02/05/2016
6	2016	Achat	5	Bettendorf	Bettendorf	02/05/2016
7	2013	Cubus	6	Everlange	Useldange	27/05/2013
8	2012	Achat	5	Everlange	Useldange	30/04/2012
9	2013	Kerubino	5	Burmerange	Remich	13/05/2013
10	2014	Privileg	4	Everlange	Useldange	22/04/2014
11	2014	Achat	5	Bettendorf	Fouhren	14/04/2014
12	2010	Privileg	4	Everlange	Useldange	03/05/2010
13	2012	Arktis	6	Reuler	Reuler	14/05/2012
14	2006	Achat	5	Everlange	Useldange	08/05/2006
15	2015	Asano	7	Burmerange	Remich	27/04/2015
16	2012	Akteur	6	Christnach	Christnach	30/04/2012
17	2014	Asano	7	Burmerange	Remich	14/04/2014
18	2007	Tommi		Christnach	Godbrange	30/04/2007
19	2015	Kerubino	5	Reuler	Reuler	18/05/2015
20	2011	Achat	5	Everlange	Useldange	26/04/2011
21	2009	Boomer		Christnach	Christnach	04/05/2009
22	2008	Tommi		Everlange	Useldange	13/05/2008
23	2012	Cubus	6	Everlange	Useldange	14/05/2012
24	2014	Kerubino	5	Bettendorf	Bettendorf	28/04/2014
25	2014	Kerubino	5	Reuler	Reuler	12/05/2014
26	2009	Achat	5	Everlange	Useldange	04/05/2009
27	2011	Akteur	6	Reuler	Reuler	02/05/2011
28	2008	Cubus	6	Burmerange	Remich	13/05/2008
29	2005	Rosario	5	Christnach	Godbrange	23/05/2005
30	2008	Schamane	4	Reuler	Reuler	26/05/2008
31	2010	Cubus	6	Christnach	Christnach	31/05/2010
32	2012	Cubus	6	Burmerange	Remich	14/05/2012
33	2015	Achat	5	Bettendorf	Fouhren	11/05/2015
34	2015	Kerubino	5	Bettendorf	Fouhren	11/05/2015
35	2015	Desamo	4	Everlange	Useldange	11/05/2015
36	2013	Kerubino	5	Reuler	Reuler	10/06/2013
37	2005	Flair	4	Reuler	Reuler	30/05/2005
38	2011	Cubus	6	Burmerange	Remich	02/05/2011
39	2007	Akteur	6	Everlange	Useldange	07/05/2007
40	2007	Flair	4	Everlange	Useldange	07/05/2007
41	2005	Akteur	6	Everlange	Useldange	30/05/2005
42	2009	Schamane	4	Reuler	Reuler	25/05/2009
43	2009	Cubus	6	Burmerange	Remich	11/05/2009
44	2006	Flair	4	Christnach	Godbrange	06/06/2006
45	2016	Kerubino	5	Reuler	Reuler	13/06/2016
46	2010	Manager	4	Reuler	Reuler	14/06/2010
47	2006	Cubus	6	Burmerange	Remich	29/05/2006
48	2009	Privileg	4	Everlange	Useldange	25/05/2009
49	2008	Flair	4	Christnach	Christnach	02/06/2008

Table 1 (continued)

ID	Year	Cultivar	CSR*	Location of field	Location of weather station	Date of epidemic outbreak
50	2006	Dekan	4	Reuler	Reuler	26/06/2006
51	2005	Cubus	6	Burmerange	Remich	13/06/2005
52	2007	Achat	5	Everlange	Useldange	04/06/2007

*Cultivar Susceptibility Rank according to BSA (2017)

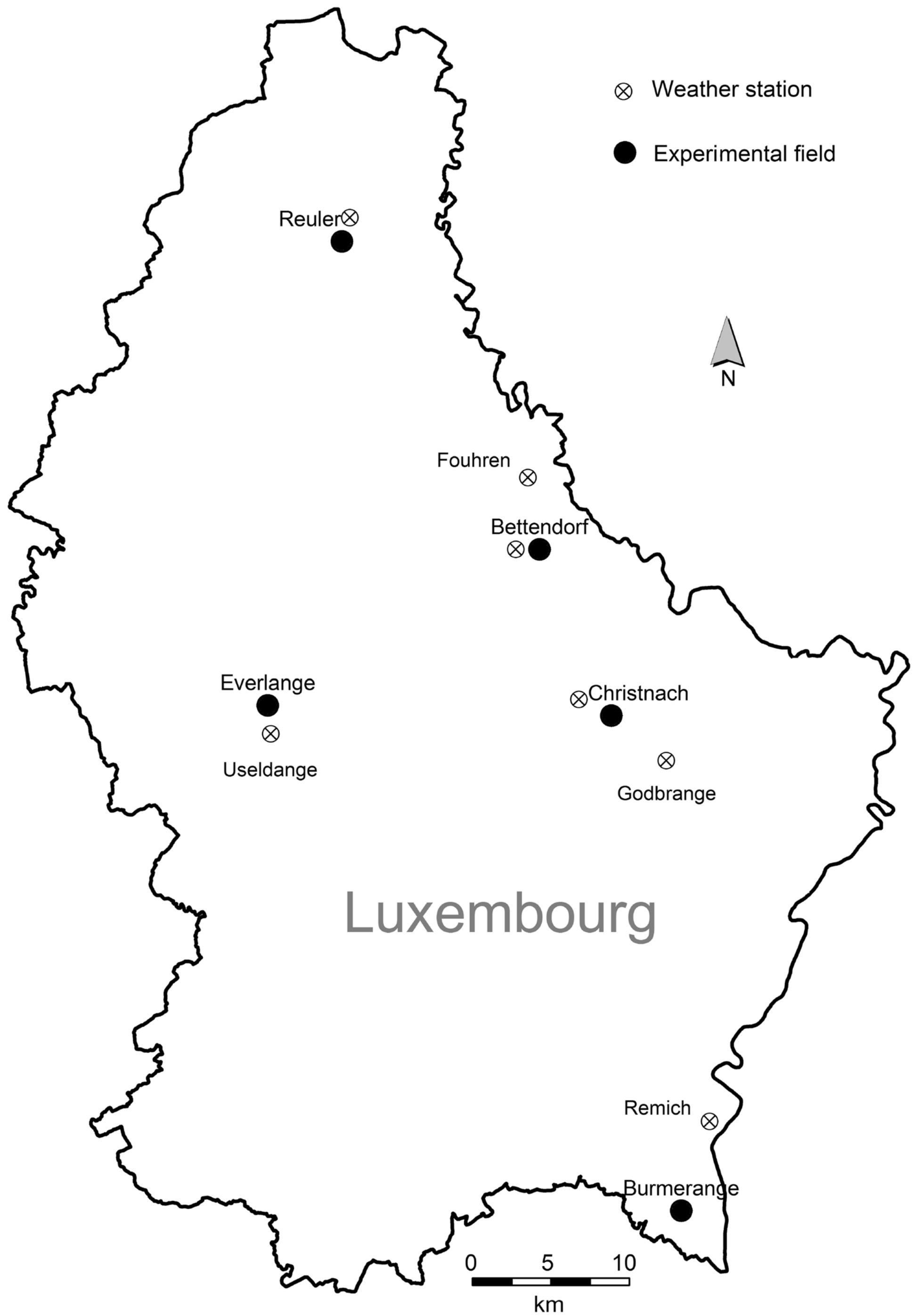

Fig. 1 Location of experimental fields and weather stations

were coded with “1” in the entire data set and hours without precipitation were coded with “0.” From these data, the frequency of hours with precipitation as related to temperature was plotted starting at the epidemic outbreak and ending 1200 h before the outbreak (Fig. 2). Data were smoothed before plotting using the Loess method in the software package Sigmaplot version 13.0 (Systat Software GmbH, Erkrath, Germany) with a sampling proportion of 0.1 and a polynomial degree of 1. The relationship between times of rain before epidemic outbreaks and temperature and the effect of cultivar susceptibility on the day of the year on which the control threshold was reached were estimated by linear regression. Effects were considered significant if the slope of a regression line was different from 0 at $P < 0.05$.

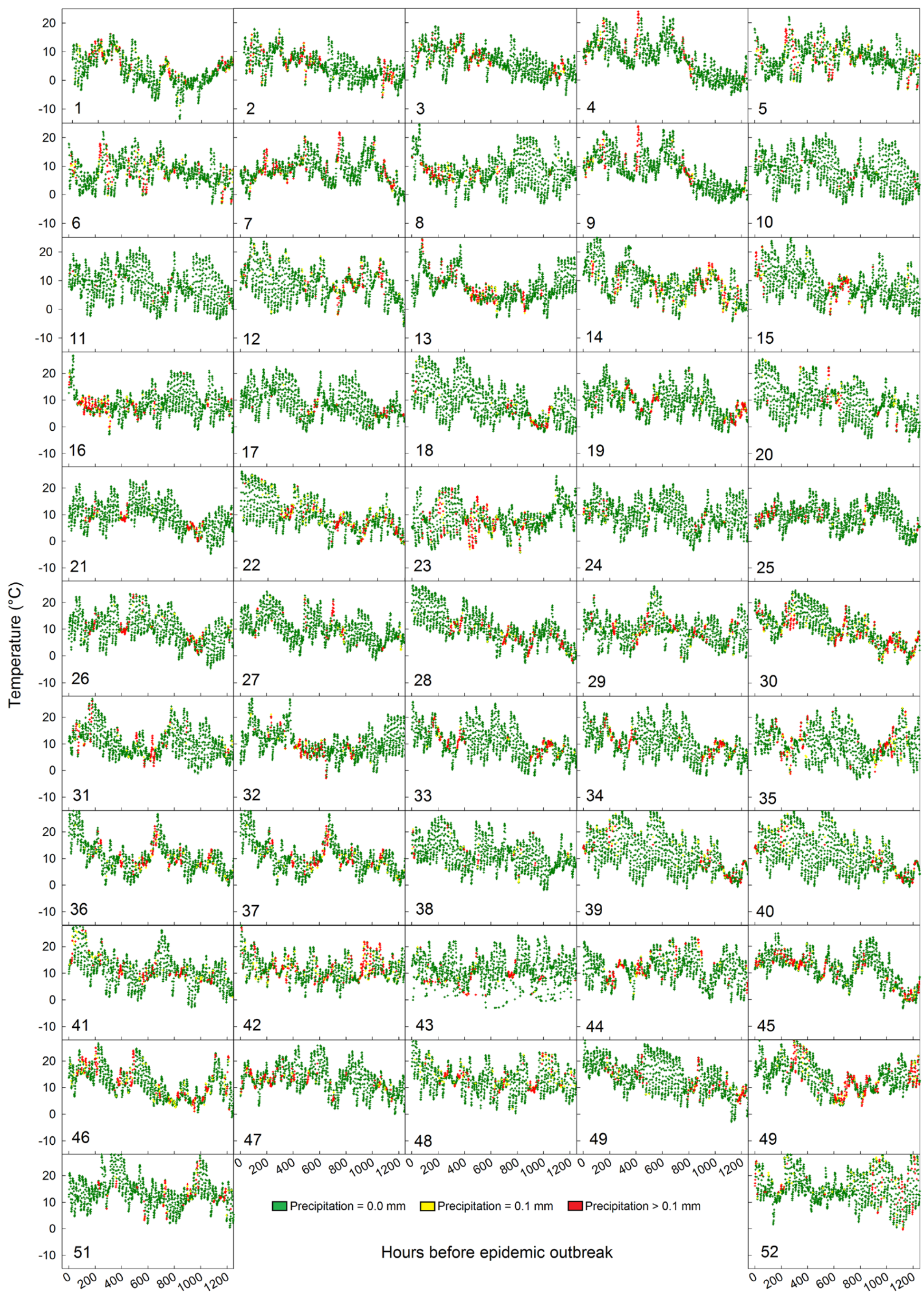

Fig. 2 Temperature time courses that preceded epidemic outbreaks of *Zymoseptoria tritici* on winter wheat. Hours with precipitation > 0.1 mm are marked red, hours with precipitation of = 0.1 mm are marked yellow and hours without precipitation are marked green. Outbreaks are considered epidemic when the control threshold defined in Beer et al. (2005) is reached. The numbers in the graphs represent the case study ID that is also given in Table 1. Case studies are sorted according to their average temperature, beginning with the lowest average temperature and ending with the highest average temperature

Results

The average temperatures before epidemic outbreaks varied greatly (Fig. 2) and ranged from 3.40 to 14.74 °C. The distribution of precipitation periods before epidemic outbreaks was also highly variable (Fig. 2) with no obvious pattern upon visual inspection. To visualize how often hours with precipitation occurred before epidemic outbreaks in relation to temperature, a contour plot based on all data from the years 2005–2016 was produced (Fig. 3).

At about 13 °C, the highest frequency of hours with rain was observed approximately at 300 h before epidemic outbreaks, while at about 11.5 °C, the highest frequency of hours with rain was observed approximately at 350 h before epidemic outbreaks and at about 7.5 °C, the highest frequency of hours with rain was observed at about 475 h before epidemic outbreaks (Fig. 3, solid line). The frequency of hours with rain before epidemic outbreaks quickly declined below 6.58 °C (Fig. 3, dashed line).

Cultivar resistance rankings ranged from 4 to 7 on a scale of 1 (resistant) to 9 (susceptible) (Table 1). On average, susceptible cultivars reached control thresholds earlier than resistant cultivars (regression equation: DOY when the control threshold was reached = 162.9–5.4 × cultivar susceptibility rank), but the effect was slightly non-significant at $P = 0.07$.

Discussion

The frequency of hours with rain quickly declined below 6.58 °C (Fig. 3, dashed line). This temperature was previously described as the minimum required for leaf blotch epidemics (Henze et al. 2007). Even though Henze et al. (2007) used the formation of pycnidia as the endpoint of their study, results can be compared at the epidemic development level (yes/no), since neither leaf necroses (used here) nor pycnidia can form without prior infection and disease development.

Q10 values indicate how much the pace of a process changes when the temperature increases by 10 °C (Nobel 1991). At 7 °C, it would take about 491 h until an epidemic outbreak occurred after a rain event that allowed infection (Fig. 3). At 17 °C (relationship in Fig. 3 extrapolated), the same process would take approximately 174 h resulting in a Q10 value of 2.8. Q10 values > 2 are considered to be indicative for the involvement of metabolism (Nobel 1991), which seems to be a reasonable result for a process that included fungal development and plant-pathogen interaction at the metabolic level.

Even though previous models did not predict the IPM control threshold directly, some of them demonstrated considerable economic advantages over standard spraying schemes (for instance El Jarroudi et al. 2015).

The susceptibility ranks of the cultivars grown by the farmers who provided fields for the present study ranged from 4 to 7 on a scale of 1–9 (Table 1). Thus, all cultivars included in the present study were moderately resistant. The control threshold was reached on average 5.4 days earlier per susceptibility rank (Table 1) for sensitive cultivars compared with resistant cultivars. With a P value of 0.07, this effect was non-significant at the 5% level, but would be considered significant at the 10% level. For deriving a forecast model that is used to consult farmers, it would be advantageous to include cultivars with susceptibility ranks < 4 and > 7 to clarify whether the consideration of a cultivar effect would be justified or not. However, strongly resistant cultivars with susceptibility ranks < 4 are scarce and susceptible cultivars with rankings > 7 are usually (1) not recommended by

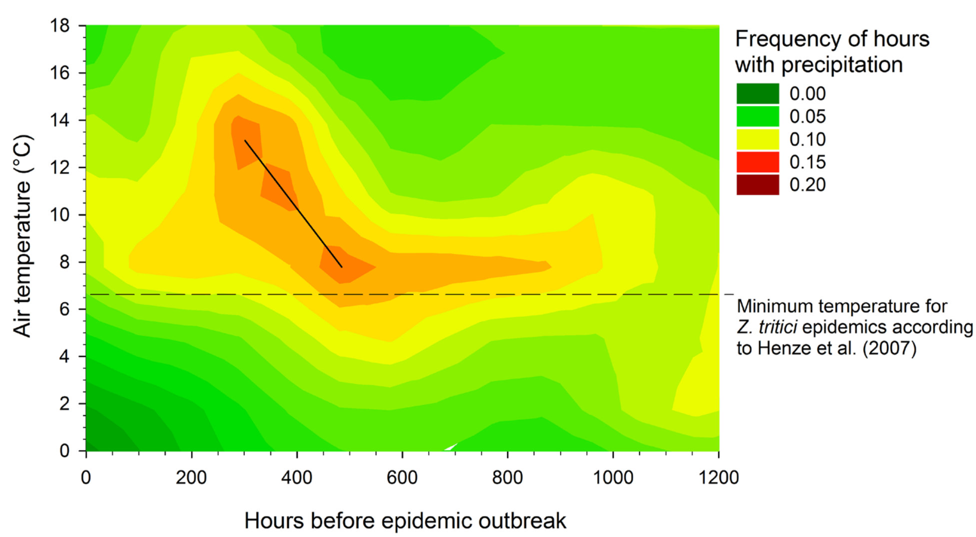

Fig. 3 Contour plot of the frequency of hours with precipitation before epidemic outbreaks of *Zymoseptoria tritici* on winter wheat as related to air temperature. Outbreaks are considered epidemic when the control threshold defined in Beer et al. (2005) is reached. Orange regions indicate high frequencies of hours with rainfall, green regions indicate low frequency of hours with rainfall. The number of case studies that was used to generate the plot was $n = 52$. The individual case studies are shown in Fig. 2

consultants and (2) not preferred by farmers due to the high risk of damage by the pathogen studied here.

Agronomic practices such as tillage, crop rotation and late sowing dates contribute marginally to the control of the disease (Thomas et al. 1989; Gladders et al. 2001), while some previous publications suggest that growing resistant cultivars is an important factor (e.g., Karisto et al. 2018). Furthermore, European strains of *Z. tritici* become increasingly resistant toward fungicides of the QoI class (Fraaije et al. 2003; Beyer et al. 2011), limiting the options of chemical control. Therefore, control of *Z. tritici* relies strongly on demethylase inhibitors, succinate dehydrogenase inhibitors (Dubos et al. 2013) and multisite inhibitors. With the knowledge generated here, the timing of the application of these compounds can be enhanced to further minimize losses caused by *Z. tritici* in winter wheat as well as to limit the number of fungicide applications.

The maximum frequencies with wet hours before epidemic outbreaks depicted in Fig. 3 for any individual point may seem rather low, but it has to be kept in mind that the line with relevant wetness-temperature combinations depicted in Fig. 3 may be crossed several times in each case study.

Acknowledgements We thank Rufat Aslanov, Tiphaine Dubos, Frédéric Giraud, Mélanie Gollier, Friderike Pogoda, Louis Kouadio, Christophe Mackels, Jasmin Mahboubi, Abdeslam Mahtour, Benedek Marozsák, Bertrand Martin, Aura Montemayor, Michel Noel, Matias Pasquali, Farid Traoré, Virginie Schyns and Carine Vrancken for excellent technical assistance, Lindsey Auguin for language editing and the Luxembourg Administration des Services Techniques de l'Agriculture for its financial support of the Sentinelle project.

Declarations

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

Human or animal rights This article does not contain any studies with human or animal subjects performed by any of the authors.

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