



Prediction of leaf Bloch disease risk in Norwegian spring wheat based on weather factors and host phenology

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Abstract Leaf blotch diseases (LBD), such as *Septoria nodorum* blotch (*Parastagonospora nodorum*), *Septoria tritici* blotch (*Zymoseptoria tritici*) and Tan spot (*Pyrenophora tritici-repentis*) can cause severe yield losses (up to 50%) in Norwegian spring wheat (*Triticum aestivum*) and are mainly controlled by fungicide applications. A forecasting model to predict disease risk can be an important tool to optimize disease control. The association between specific weather variables and the development of LBD differs between wheat growth stages. In this study, a mathematical model to estimate phenological development of spring wheat was derived based on sowing date, air temperature and photoperiod. Weather factors associated with LBD severity were then identified for selected phenological growth stages by a correlation study of LBD severity data (17 years). Although information regarding host resistance and previous crop were added to the identified weather factors, two purely weather-based risk prediction models (CART, classification and regression tree algorithm) and one black box model (KNN, based on K nearest neighbor algorithm) were most accurate to predict moderate to high LBD severity (>5% infection). The predictive accuracy of these models (76–83%) was compared to that of two existing

models used in Norway and Denmark (60 and 61% accuracy, respectively). The newly developed models performed better than the existing models, but still had the tendency to overestimate disease risk. Specificity of the new models varied between 49 and 74% compared to 40 and 37% for the existing models. These new models are promising decision tools to improve integrated LBD management of spring wheat in Norway.

Keywords Phenological development in wheat · Cereals · *Parastagonospora nodorum* · *Septoria tritici* · *Zymoseptoria tritici* · *Pyrenophora tritici-repentis* · Disease risk models

Introduction

Parastagonospora nodorum (also known as *Septoria nodorum*, *Phaeosphaeria nodorum*, or *Stagonospora nodorum*) causal agent of Glume blotch and *Septoria nodorum* blotch (SNB), *Zymoseptoria tritici* (also known as *Septoria tritici* or *Mycosphaerella graminicola*) causing *Septoria tritici* blotch (STB) and *Pyrenophora tritici-repentis* (also known as *Drechlera tritici-repentis*), causing Tan spot or Yellow spot (DTR) are major necrotrophic leaf pathogens in wheat (Bergstrom 2010; Shaner 2010; McMullen 2010). These pathogens cause similar symptoms on wheat leaves, e.g. light brown oval to elongated lesions or blotches with yellow margins. As they can co-occur in the same field and on the same leaf, the three leaf diseases are difficult to distinguish with the unaided

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eye and are considered together as the leaf blotch disease (LBD) complex in this study. In Norway, *P. nodorum* is the dominating pathogen in spring wheat, but *Z. tritici* and *P. tritici-repentis* also occur regularly (Ficke et al. 2018a) and need to be considered for effective disease management. The potential for *P. nodorum* to cause significant grain yield and quality losses has been discussed recently (Ficke et al. 2018b). In fungicide trials in Norway, an average yield loss has been found to range from 13% in a moderately resistant cultivar to 25% in a susceptible cultivar (Ficke et al. 2016a).

The photosynthetic active tissue area of the flag leaf is considered an important factor in determining grain yield (Simpson 1968; Lupton 1972). King et al. (1983) found a strong relationship between LBD severity on the flag (first) and second leaf at growth stage (GS) 75 (medium milk (Zadoks et al. 1974)) and yield reduction. Assessment of LBD on the last upper two to three leaves at GS 70–77 (water ripe to late milk) have become a standard GS in many countries to evaluate disease severity (Bhathal et al. 2003; King et al. 1983). The reduction of the yield determining area and consequently yield loss from LBD pathogens can vary considerably between years, varieties and locations, making the use of a general management threshold unfeasible. Control of LBD pathogens is based on the use of healthy or fungicide treated seed (for SNB and DTR), tillage and crop rotation, varietal host resistance when available, and fungicide applications (Shipton et al. 1971; Jørgensen and Olsen 2007; Jørgensen et al. 2008). Fungicide applications are only profitable when their application is aligned with the actual need to control a disease and justified by a certain level of expected yield loss. Wiik and Rosenqvist (2010) showed that the mean net return for fungicide use in Swedish winter wheat fields was negative in 10 out of 25 years, and it was less than 12 € per ha on average during the period. Routine application of fungicide appears little profitable and should be replaced by reliable disease risk models to guide the farmers decisions and implement integrated pest management (IPM) principles.

Weather conditions in the growing season, tillage, crop rotation and host resistance influence the development of LBD and yield loss. All three LBD pathogens can survive on wheat stubble between growth seasons. *Parastagonospora nodorum* and *Z. tritici* produce splash dispersed conidia in pycnidia or ascospores in pseudothecia on wheat debris (Faulkner and Colhoun 1976; Shaw and Royle 1993; Suffert et al. 2011), while

P. tritici-repentis produces wind-dispersed conidia or ascospores from pseudothecia that can infect the young wheat plants (Wright and Sutton 1990). Once infection is established, these polycyclic diseases infect upper layers of the growing wheat plants via conidia. Conditions considered favorable for infections include continuous precipitation or high levels of humidity (> 90%) for several hours (> 4 h) (Jeger et al. 1981; Hess and Shaner 1987; Francl 1998). Temperature also plays an important role in LBD development. Severity of DTR was positively correlated with temperature, with an optimum between 18 to 28 °C depending on the variety used (Da Luz and Bergstrom 1986). Highest STB inoculum production on wheat seedlings has been reported between 18 and 22 °C during the day (Chungu et al. 2001), and for SNB the latent period was shortest at 23 °C (Shearer and Zadoks 1972). Wiik and Ewaldz (2009) showed that air temperature and precipitation as monthly means explained more than 50% of the variation in yield increase due to fungicides and variation in diseases, including LBD on winter wheat in Sweden. Prediction models to estimate risk based on weather factors influencing disease development would be very useful to determine the need for chemical control and the optimal timing of these control measures to avoid redundant use of resources.

By systemizing our knowledge on the effect of these weather factors, a prediction model to estimate risk of disease outbreaks can be constructed. EPISSET, a SNB simulation model was developed by Rapilly and Jolivet in 1976 to understand better each stage of pathogen development in relation to precipitation, humidity and temperature (Rapilly and Jolivet 1976). Several disease prediction models exist for *Z. tritici* and/or *P. nodorum* development in winter wheat, based on precipitation (Tyldesley and Thompson 1980; Hansen et al. 1994), and for *Z. tritici* based on precipitation and air temperature (Coakley et al. 1985; Te Beest et al. 2009), precipitation and relative humidity or precipitation, air temperature and wind speed (Pietravalle et al. 2003). Some of these models additionally require information about when the plant reach stem elongation (Hansen et al. 1994; Te Beest et al. 2009; Pietravalle et al. 2003). De Wolf and Francl (1998) evaluated an empirical *P. tritici-repentis* infection period model for its use in a DTR forecasting system based on temperature, relative humidity, wind speed, wind direction, solar radiation, precipitation, and flat-plate type wetness sensor resistance. Djurle and Yuen (1991) developed a simulation model for *P. nodorum* that was connected to a winter wheat growth model to demonstrate that

weather conditions were the most important factors for an SNB epidemic in a particular year. However, only a few models are widely used by the farmers and models to predict the risk of all three LBD diseases in spring wheat are absent in the peer reviewed literature.

Hansen et al. (1994) developed a forecasting model to estimate the risk of Septoria development (including SNB and STB) in winter wheat under Danish conditions based on 10 years of field data. The model starts at the beginning of stem elongation (GS 32) and considers sowing date, air temperature and precipitation as inputs to give an estimate of infection risk as output. In this model, a threshold value of 5% disease severity of total green leaf area at medium milk to soft dough (GS 75–85) was used to distinguish between low and high risk. High risk of the Septoria diseases was predicted when the number of days with precipitation above or equal to 1 mm, calculated during a period of 30 days, was above 8 for susceptible and above 9 for resistant winter wheat varieties. However, a spraying threshold of 7 to 8 days with precipitation above or equal to 1 mm during the last 30 days was recommended, because the resulting yield gain from two fungicide sprays justified the fungicide costs under these conditions. This ‘Hansen model’ has been adjusted and implemented in the Danish decision support system Crop Protection Online (CPO) to optimize fungicide inputs in winter wheat (Hagelskjær and Jørgensen 2003).

Based on the ‘Hansen model’ developed for winter wheat, a Norwegian LBD prediction model was developed to estimate the level of LBD severity and assess the need for fungicide treatment in spring wheat using Norwegian field observations (Elen 2007). The starting value for disease development in this model is corrected for by host resistance, tillage and crop rotation. The main factors driving the model are the number of days with precipitation above 1 mm and the total amount of precipitation over a certain time. The model estimates the level of LBD severity and the need for fungicide treatment over time. To increase the accuracy of the recommended spraying time, the model was adjusted on a yearly basis according to spring wheat trial observations in Norway. This model was included in the Norwegian decision support system VIPS (www.vips-landbruk.no) in 2001 and is currently available to farmers and agricultural extension services. VIPS is a Norwegian open source information platform that implements IPM tools, by making pest and disease forecast risk models for agricultural and horticultural crops available. Testing of this ‘VIPS 2001’ model for

LBD in wheat with Norwegian field data from 2010 to 2017 showed that it had the tendency to overestimate the need for fungicide applications (Ficke et al. 2019).

It is known that host susceptibility and disease development of stripe rust changes with the developmental stage of the wheat plant (Farber and Mundt 2017). Resistance mechanisms in durum wheat to DTR were shown to differ between plant organs and to be under different genetic control depending on the host phenological growth stage (Fernandez et al. 1994). Jones and Odeunmi (1971) showed that later inoculations of spring wheat variety ‘Opal’ with *P. nodorum* lead to larger reduction in grain size and numbers than earlier inoculations. The greater SNB development at later growth stages was also confirmed by Wainshilbaum and Lipps (1991). No such effect was observed for *Z. tritici* in the same study (Wainshilbaum and Lipps 1991). The dynamic host-pathogen interactions over different phenological stages lead us to hypothesize that different weather variables can have a different effect on LBD development at different growth stages in the spring wheat development as well.

The objective of this study was to develop a new prediction model for LBD risk in spring wheat during the milk development stage (GS 70–79), based on host resistance, previous crop and weather factors during different phenological growth stages. The study was performed in three different steps: (1) a model was developed to predict spring wheat phenological development, (2) the associations between LBD severity and weather conditions during different phenological growth stages was determined in a correlation study, and (3) three models to predict the risk of LBD (classified at a 5% severity threshold, as used by Hansen et al. 1994) were developed and further compared with two existing models (‘VIPS 2001’ and the ‘Hansen-model’). Our goal was to develop a disease prediction tool with high accuracy and sensitivity that could be included in the integrated management of LBD in spring wheat.

Material and methods

Part 1: Phenological model to predict spring wheat development

Phenological growth stage data from field trials

Data on phenological growth stages of spring wheat were obtained from field trials conducted by NIBIO

and the Norwegian extension service. A total of 153 observations of average phenological growth stage were recorded in different field trials between 2009 and 2016, with most data collected in 2015 (24%) and 2016 (19%). All observations were from South Eastern Norway, representing the main production area (> 95%) for wheat in Norway. The phenological growth stages (GS) of the spring wheat plants were observed between GS 12 (seedling growth, two leavers unfolded) and GS 90 (ripening). For all observations, field location and sowing date was recorded in addition to the phenological growth stage of the plants at a specific date.

Weather records connected to the growth stage observations

Mean daily records of air temperature (T ; °C), minimum daily air temperature (T_{\min} ; °C) and maximum daily air temperature (T_{\max} ; °C) were provided by the nearest weather station owned by Agrometeorology Norway (2020) and downloaded via the national agricultural meteorological services (<https://lmt.nibio.no/>). Additionally, the environmental variable photoperiod (Ph , h day⁻¹), which is the number of daylight hours, was calculated based on the latitude of the nearest weather station and the day of the year according to Olseth and Skartveit (1985). All weather stations were within a distance between 0 and 22 km from the field trials we recorded the phenological growth stages from.

Development of a model to predict phenological growth stages of spring wheat

Mathematical models were constructed to predict phenological growth stages of spring wheat (see e-Xtra Table S1). Nineteen different models were proposed based on the Gompertz function (Batschelet 1976). The models depended on air temperature alone or in combination with photoperiod, which are the two main environmental variables affecting crop growth (Shaykewich 1995).

According to the cross-year validation technique (Landschoot et al. 2012), the data were grouped by year, and for each subset with observations from a specific year, the model was fitted to the remaining dataset (without using the observations of the subset under consideration). Thereafter, the observations in the subset were used to evaluate the predictive performance of the model. The Bayesian calibration framework (Robert

and Casella 1999) was used to best fit the model to observed data, while the root mean square error of validation (RMSEV) was included for model evaluation and to select the best model to predict spring wheat development.

Part 2: Associations between leaf blotch disease severity and weather conditions during different phenological growth stages in spring wheat

Field data of leaf blotch disease severity

Observations of LBD severity were obtained from field trials conducted by NIBIO and the Norwegian extension service (not the same dataset as described in Part 1). This dataset was collected in the same area and during the same time period than the one for determining phenological growth stages. Not all trials that contained data on phenological stages contained the data on LBD severity, so the two datasets contain a different selection of field trials. The LBD severity was recorded as the average percentage of the leaf area with LBD symptoms on the upper two to three leaves per plant of a total of 25 plants per plot. LBD severity was then averaged over two or three replicates (one plot per replicate) per experimental field. For each observation, registration date, sowing date, previous crop (wheat or not wheat), host resistance level and field location were recorded in addition to LBD severity. Most of the observations (99%) were from field trials located in South Eastern Norway (Viken – 63%, Innlandet – 19% and Vestfold and Telemark – 17%) and the remaining 1% from Middle Norway (Trøndelag). Only observations conducted during milk development stage (GS 70–79) were included in the dataset. Moreover, observations with missing values or poor quality of weather data (especially relative humidity records) were discarded. The remaining data set contained 283 observations of LBD severity and were collected between 2002 and 2018 (no suitable data was available for 2004 and 2006). More than 97% of the fields were ploughed, making the data unsuitable for testing the effect of tillage on LBD severity. Almost 20% of the fields had wheat as previous crop, and the resistance factor of the host to LBD varied between three and seven (Russenes et al. 2019), where one is most susceptible and 10 least susceptible.

The observed severity of LBD varied between 0% and 100% infection and the mean severity across all field trials was 15% with a median value of 6%. A total

of 177 observations (63%) were recorded with LBD severity above or equal to 5%, 120 observations (42%) with LBD severity above or equal to 10%, and 71 observations (25%) with LBD above or equal to 20%. The 283 observations of LBD severity were divided randomly into a training dataset of 189 observations (67%) and a test dataset of 94 observations (33%).

Weather records connected to the leaf blotch disease severity observations

Hourly air temperature (T; °C), precipitation (P; mm) and relative humidity (RH; %) were obtained from 14 different weather stations of the Agrometeorology Norway (<https://lmt.nibio.no/>). Additionally, vapor pressure deficit (vpd; kPa) was estimated. Saturated vapor pressure was estimated from measured air temperatures according to Goff and Gratch (1946), while the actual vapor pressure deficit was derived from the estimated saturated vapor pressure and the measured relative humidity (Perry and Green 1997).

Data analysis

The associations between LBD severity in spring wheat during milk development stages and weather conditions during different phenological growth stages were assessed in a correlation study based on the methodology introduced by Coakley et al. (1982), later called ‘window-pane’. For each observation of LBD severity, growth stages were estimated daily between sowing and end of flowering by the phenological model developed in this study (SWM1, presented in the results below). Flowering (GS 65) is usually the last stage at which fungicides can be applied in Norway, as there must be a 5-week period between the last application of fungicides and the time of harvest. These estimated phenological growth stages were further separated into six groups (phenological windows), reflecting the different plant developmental stages that correspond to germination/ seedling growth, tillering, stem elongation, booting, heading, and flowering (Table 1). Additionally, a seventh group was constructed by combining the tillering and stem elongation windows, as the number of observations of growth stage data from these two periods were limited in the dataset used to develop SWM1. Based on our understanding of LBD epidemiology, 139 different

weather summarisations (air temperature, precipitation, relative humidity and vapor pressure deficit) were defined (see e-Xtra Table S2) and calculated within each phenological window for the training data of LBD severity. Possible associations between LBD severity during the milk development stage and the estimated weather summarisations were calculated using the Pearson (assesses the linear relationship between two continuous variables) and the Spearman correlation coefficients (assesses the ranked values for each variable). The training data were randomly split into two different datasets, and the correlation study repeated for both datasets separately to ensure robustness. Weather summarisations with a significant (5% level) correlation (Pearson or Spearman) to LBD severity, for both datasets, were retained as important weather conditions for LBD development and included as possible factors in the LBD risk model. Several of these summarisations were highly intercorrelated, and for the weather summarisations that were highly correlated (>0.9), only the summarisations with highest correlation to LBD were retained for developing the LBD risk model.

Part 3: Prediction model to classify risk of leaf blotch disease severity

Development of a prediction model to classify risk of leaf blotch disease severity

In order to develop a classification model to predict the risk of moderate to high LBD severity ($\geq 5\%$), weather summarizations, host resistance and previous crop were included as variables. Two different algorithms were tested: (1) Classification and Regression Trees (CART), and (2) K-Nearest Neighbors (KNN). The algorithms are respectively (1) a tree-like structure with its root node at the top, and with a set of if-else statements used to classify (Breiman et al. 1984), and (2) a nonparametric memory-based algorithm that requires training data at run time (Altman 2012).

Both algorithms were fitted to the training dataset according to the 5-fold cross validation technique, where the data were divided between five groups, and for each subset with observations from a specific group, the model was fitted to the remaining dataset (without using the observations of the subset under consideration). Thereafter, the observations in the subset were used to evaluate the predictive performance of the

Table 1 Growth stages with estimated degree days adjusted with photoperiod from sowing to end of flowering stage and mean number of days with standard deviation for each growth stage for Norwegian spring wheat based on observations in field trials in the years 2009 to 2016

Growth stage (GS)	Phenological growth stage windows	Degree days adjusted with photoperiod from sowing to end of GS window	Number of days in the GS window, as mean and standard deviation
[0 20)*	Germination/seedling growth	255	33.5 (6.1)
[20 30)	Tillering	354	9.5 (1.3)
[30 40)	Stem elongation	448	8.8 (0.9)
[40 50)	Booting	545	8.1 (1.0)
[50 60)	Heading	654	9.1 (0.9)
[60 65)	Flowering	715	5.4 (0.8)

* The bracket [indicates that the following number is included in the interval while) indicates that the previous number is not included

model. Contingency tables were developed and summary statistics of accuracy, sensitivity (percentage of predictions correctly classified as moderate to high presence of LBD ($\geq 5\%$)) and specificity (percentage of predictions correctly classified as low presence of LBD ($< 5\%$)) calculated. Further, model selection was based on the accuracy, but also simplicity, biological relevance, sensitivity and the values of the false positives (falsely classified as low presence of LBD).

Model testing and comparison

The best models to predict risk of LBD in spring wheat, developed in this study were tested on the separate test dataset that was not included in model development. Additionally, the ‘VIPS 2001’ model and the ‘Hansen model’ were tested with the same test data. The Hansen model was developed to predict development of *Septoria* spp. in winter wheat under Danish weather conditions and requires the host growth stage as input. Before testing this model, the growth stages of the spring wheat fields included in our dataset were calculated by using the phenological model developed in our study (SWM1, presented in the results below). Contingency tables were created, and model accuracy, sensitivity and specificity calculated and used to assess if the new models would outperform the two older LBD forecasting models.

Software

MATLAB R2019a was used for the data mining and for the model development.

Results

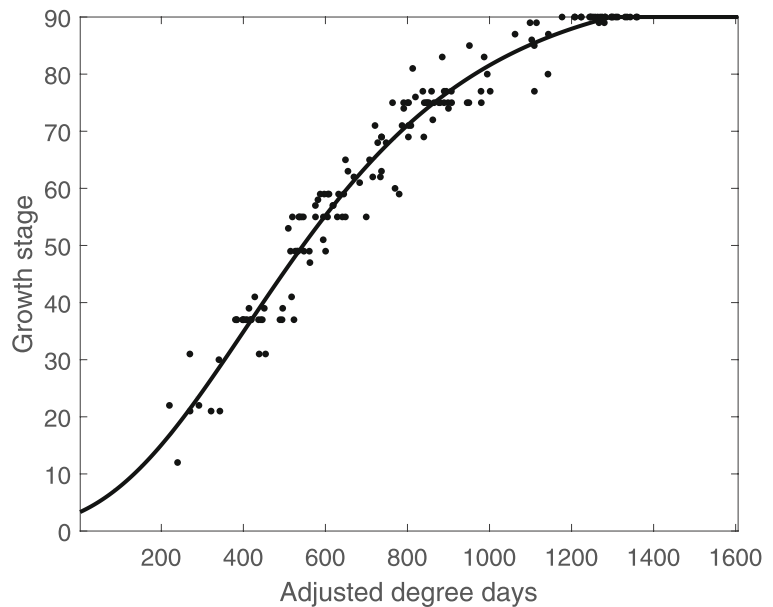
Phenological model to predict spring wheat development

Nineteen different mathematical models to estimate phenological growth stages of Norwegian spring wheat were developed based on air temperature alone or in combination with photoperiod (see *e-Xtra* Table S1). The predictive performance was estimated for each proposed model, and the one with lowest error term (root mean square error of validation, RMSEV) was selected as the best model to predict spring wheat development under Norwegian conditions (hereby referred to as SWM1). The model is described in Eq. 1.

$$GS_i = \min\left(96.4 \cdot e^{-3.388 \cdot e^{-0.003 \cdot DD_i}}, 90\right) \quad (1)$$

The model predicts daily growth stages (GS_i) and is driven by the adjusted degree day (DD_i) which is described in Model 6 in the *e-Xtra* (Table S1). Specifically, the adjusted degree day is here defined as the accumulated air temperature from sowing to day i , using a lower boundary base air temperature of 0 °C and with an additional weighing function by photoperiod (the relative number of day light hours). The output from the SWM1 model is plotted together with field observations in Fig. 1. Table 1 shows the adjusted degree days and the number of days for the previously defined phenological growth stage windows until flowering (GS 65), estimated for Norwegian spring wheat based on the SWM1 model. From the model, end of flowering (GS 65) was estimated at 715 adjusted degree days from sowing (Table 1), while mature grain (GS 90) was

Fig. 1 Estimated phenological development of Norwegian spring wheat from the SWM1 model (curve) together with observed data (dots)



estimated at 1298 adjusted degree days from sowing. From the observed data, the average time between sowing and end of flowering was 74 days (Table 1), and 138 days from sowing to estimated ripening (GS 90). The number of days between sowing and GS 87 (hard dough) of spring wheat is in this paper referred to as the growth period, and the duration of this period was estimated to be 117 days using this dataset, with a variation between 102 and 138 days depending on location and sowing day.

Associations between leaf blotch disease severity in spring wheat and weather conditions at different phenological growth stage windows

The SWM1 model was used to predict the starting date of each of the seven defined phenological growth stage windows (germination and seedling growth, tillering, stem elongation, booting, heading, flowering and the combined tillering and stem elongation window) for all the observations of LBD severity in the training dataset. The 139 weather summarisations defined (*e*-Xtra Table S2) were estimated within each of the seven phenological windows and then correlated with LBD severity during the milk development stage. This was done separately for two splits of the LBD datasets. The weather summarisations with significant ($p < 0.05$) correlation (Pearson or Spearman) to LBD severity for both splits of the data, were retained as important weather conditions for LBD development and

listed in the *e*-Xtra (Table S3 and Table S4). To reflect some major findings in the association between LBD severity in spring wheat and weather conditions during different phenological windows, three important weather summarisations are visualized in Fig. 2.

Figure 2a shows the Pearson correlation between LBD severity and rainy periods (occurrence of ≥ 8 consecutive hours with precipitation > 0.2 mm) for each of the six defined growth stage windows. LBD severity was positively and significantly ($p < 0.05$) correlated with rainy conditions during stem elongation. During the other phenological windows, this weather summarisation was not significantly associated with LBD severity.

Figure 2b shows the Pearson correlation between LBD severity and moist conditions (relative humidity $> 80\%$) for each of the six defined growth stage windows. A positive significant ($p < 0.05$) correlation was identified between LBD severity and moist conditions from stem elongation to heading, with highest association during booting.

Figure 2c shows the Pearson correlation between LBD severity and air temperatures between 15 and 30 °C combined with and no rain ($P \leq 0.2$ mm) for each of the six defined growth stage windows. This shows a negative significant ($p < 0.05$) correlation between LBD severity and the daily number of hours with the combination of high air temperatures (15–30 °C) combined with no rain during tillering.

Development of a prediction model to classify risk of leaf blotch disease severity

Two binary CART models to classify moderate to high risk ($\geq 5\%$) of LBD severity during milk development stage were selected based on accuracy and sensitivity to predict LBD severity, referred to as CART1 and CART2. Both models turned out to be purely weather based.

The CART1 model (Fig. 3) predicted risk of moderate to high LBD severity when the average daily number of hours with air temperature between 15 and 30 °C combined with precipitation ≤ 0.2 mm during tillering was below 16.3 h and the daily temperature fluctuation (difference between the daily maximum and minimum air temperature) during booting was below 9.1 °C. Additionally, the model predicted risk of moderate to high LBD severity when the average daily number of hours with air temperature between 15 and 30 °C combined with precipitation ≤ 0.2 mm during tillering was below 16.3 h, the daily temperature fluctuation (difference

between the daily maximum and minimum air temperature) during booting was above 9.1 °C, and the average daily number of hours with air temperature between 15 and 20 °C combined with relative humidity $>70\%$ during booting was above 1.7. Based on cross validation, CART1 had an accuracy of 80% with a sensitivity of 94% (predictions correctly classified with moderate to high severity of LBD) and a specificity of 52% (predictions correctly classified with low severity of LBD). This gave a low percentage of false negative (6%) and a high percentage of false positive (48%).

The CART2 model (Fig. 4) predicted risk of moderate to high LBD severity when the average daily number of hours with air temperature between 15 and 30 °C and precipitation ≤ 0.2 mm during tillering was below 16.3 h and the daily number of hours with relative humidity $>80\%$ during booting was more than 3.7 h. From the cross validation, an accuracy of 80% was calculated with a sensitivity of 98% (predictions correctly classified with moderate to high severity of LBD) and a specificity of 46% (predictions correctly classified with

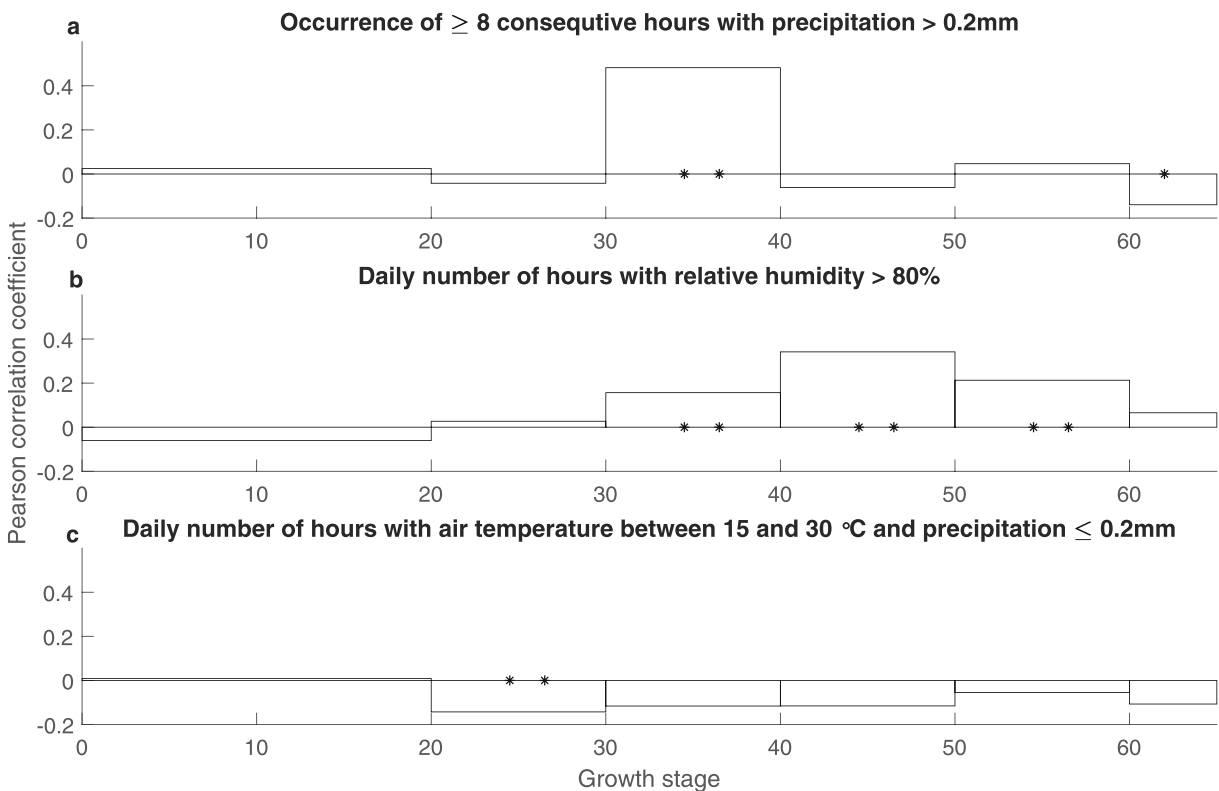


Fig. 2 The Pearson correlation coefficient calculated between LBD severity (% infection) at the milk development stage in Norwegian spring wheat and different weather factors, during

estimated growth stage windows (GS). Asterisks indicate that the correlation is significant at the 10% level (*) or at the 5% level (**)

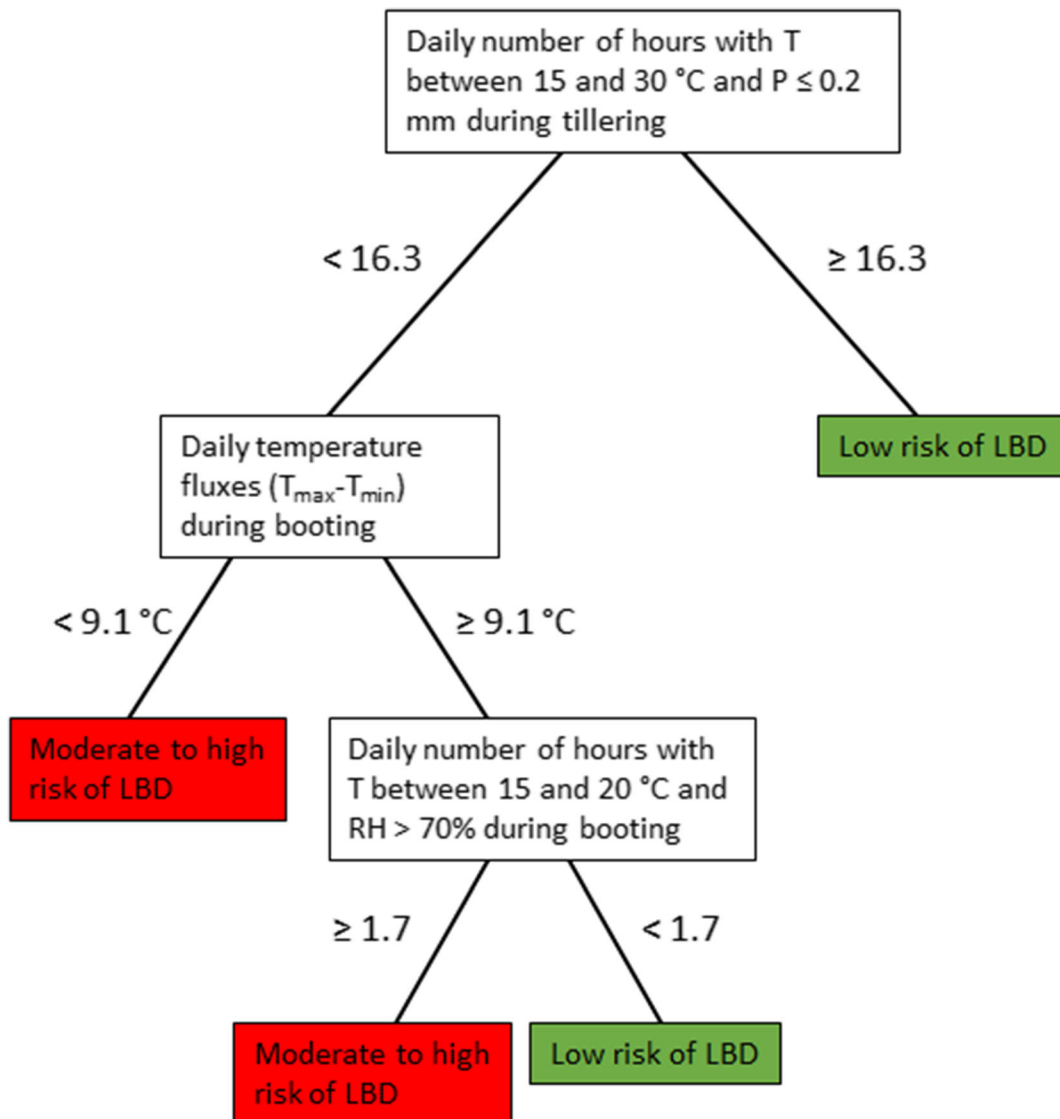


Fig. 3 The CART1 model, a binary classification and regression tree to predict the risk for moderate to high LBD severity ($\geq 5\%$ infection) based on weather conditions (mean air temperature T,

minimum air temperature T_{min} , maximum air temperature T_{max} , precipitation P and relative humidity RH) during different phenological windows in Norwegian spring wheat

low severity of LBD). This led to a low percentage of false negatives (2%) and a high percentage of false positive (54%).

One KNN model was selected based on accurate classification of LBD severity (KNN1). Using the validation data, the model had an accuracy of 85%, with a sensitivity of 90% (predictions correctly classified with moderate to high severity of LBD) and a specificity of 73% (predictions correctly classified with low severity of LBD). This led to a low percentage of false negative (10%) and a moderate percentage of false positive (27%).

Model comparison and predictive accuracy

The predictive performance of the three models developed and selected in this study were calculated with the test data set consisting of 94 observations of LBD severity (Table 2). The two CART models performed in the same range as with cross validation based on the training test data set, with a predictive accuracy of 78% and 76% respectively for CART1 and CART2. Both models had a high sensitivity of 100% and 98% respectively, with correspondingly few false negatives

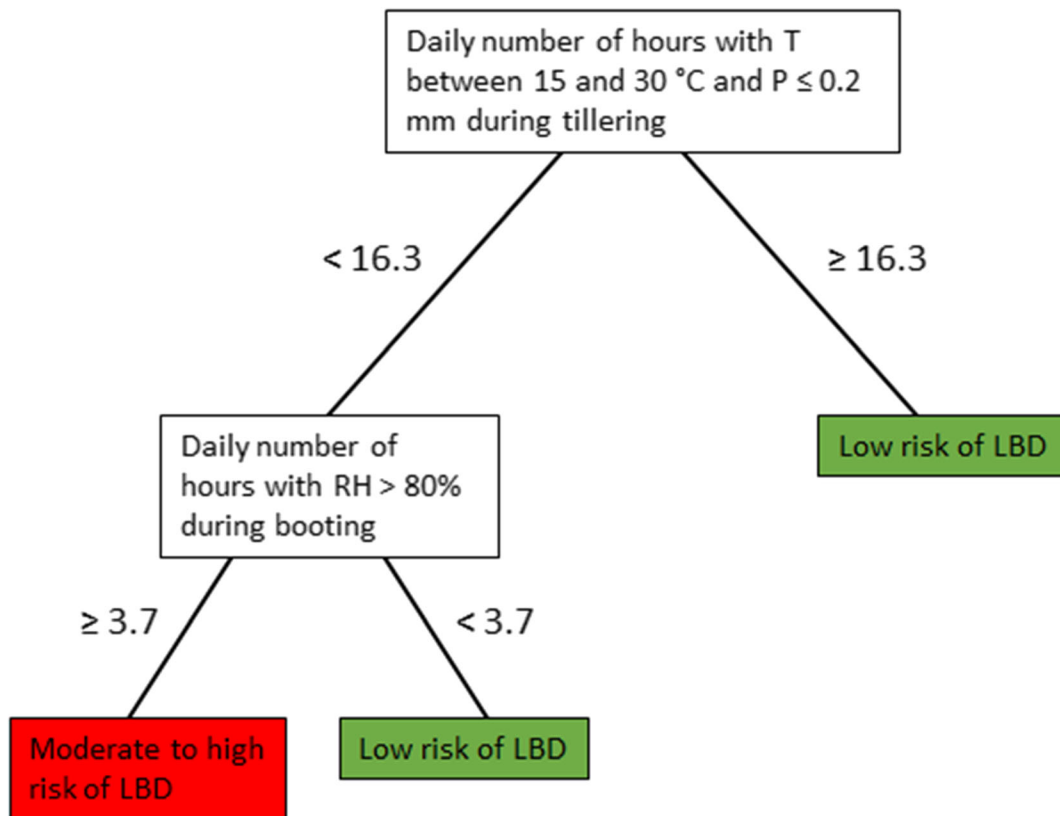


Fig. 4 The CART2 model, a binary classification and regression tree to predict the risk for moderate to high LBD severity (> 5% infection) based on weather conditions (mean air temperature T,

precipitation P and relative humidity RH) during different phenological windows in Norwegian spring wheat

(Table 2). Only one observation of 15% LBD severity was misclassified with low risk. Despite the high sensitivity, the CART models performed with specificities of 51% (CART1) and 49% (CART2). The KNN1 model performed with a higher accuracy (83%) than both CART models. The sensitivity was slightly lower (90%), but the highest observed value of the 10% false

negatives was only 12% LBD severity. In addition, the KNN1 model had a much higher specificity (74%) than CART1 models as it misclassified fewer observations with moderate to high LBD severity.

Both the ‘VIPS 2001’ and the ‘Hansen model’ were tested on the same test set as the newly developed models in this study. Based on the test data set, we

Table 2 The performance (accuracy, sensitivity and specificity) of the three models developed in this study (CART1, CART2 and KNN1), an on-line forecasting model (‘VIPS 2001’) and the

‘Hansen model’ to predict the risk of LBD severity (> 5% infection) in Norwegian spring wheat based on the test data set

Model	Accuracy (%)	Sensitivity ¹ (%)	Specificity ² (%)
CART1	78	100	51
CART2	76	98	49
KNN1	83	90	74
‘VIPS 2001’	60	76	40
‘Hansen model’	61	80	37

¹ percentage of predictions correctly classified as moderate to high presence of LBD ($\geq 5\%$ disease severity)

² percentage of predictions correctly classified as low presence of LBD (< 5% disease severity)

estimated the predictive accuracy of the models to be 60% and 61% for the ‘VIPS 2001’ model and the ‘Hansen model’, respectively. Also, for these models, the sensitivity was higher than the specificity, 76% and 40% for the ‘VIPS 2001’ model and 80% and 37% for the ‘Hansen model’. Among the false negatives, the highest LBD severity misclassified with low risk was respectively 75% and 42% for these two models.

Discussion

The goal of our work was to develop a prediction model for LBD risk in spring wheat under Norwegian conditions that would perform better than the model currently used in the Norwegian decision support platform VIPS. VIPS is an important tool for the Norwegian farmers in the integrated management of diseases and pest in several crops. For development and validation of a LBD risk model, data from field observations of LBD in spring wheat were collected between 2002 and 2018 from the main cereal growing areas of Norway, and weather data were collected from the nearest weather stations. Several models were designed using both the CART and KNN algorithms to identify factors (host resistance, previous crop, and weather summarizations during different phenological windows) associated with development of LBD in Norwegian spring wheat. The performance of the prediction models based on CART was not improved by including information on host resistance and previous crop. Thus, the selected CART models are purely weather based. The KNN approach is on the other hand based on a non-parametric evaluation of similarity. The algorithm stores all the available data and classifies the new data points to the class most common among its nearest neighbors. Hence, all factors (host resistance, previous crop and weather summarizations during different phenological windows) contribute in the classification, but with different weight.

As disease development and the associated need for fungicide application is closely related to weather conditions during plant development, we tested the association between LBD severity and weather conditions at defined plant growth stages. The data set we had available for developing our disease risk model did rarely include information on observed growth stages. Therefore, so as to obtain weather data related to a specific growth stage period, a mathematical model (SWM1) was developed to calculate the starting dates and

duration of different growth stage periods for each spring wheat field included in this study. For the various stages of plant development, weather factors highly associated with risk of LBD, could then be identified.

Among the 19 simple models derived in this study to estimate phenological development of spring wheat in Norway, the model named SWM1 was selected as the best model because of the lowest error term. All proposed models followed the Gompertz growth function of degree-days, in line with Shaykewich (1995), who concluded that developmental rate of cereal crops was a sigmoid function of degree-days. As other studies agree, air temperature and photoperiod are the two most important factors for spring wheat development (Davidson and Campbell 1983; Olesen et al. 2012; Yan and Wallace 1998; Saarikko and Carter 1996), and only these environmental variables were evaluated in this study and combined in SWM1. Other factors, such as N fertility, soil moisture or water stress appeared to have no direct effect on spring wheat development in other studies (Davidson and Campbell 1983; Penning de Vries et al. 1989) and were therefore not considered here. The base temperature is the threshold temperature, at which no plant growth takes place. A base temperature of both 0 °C (Wang and Engel 1998; Dofing and Knight 1992) and 5 °C (Olesen et al. 2012; Saarikko and Carter 1996) are common to use and a base temperature of 0 °C turned out to fit the Norwegian spring wheat data best. From the SWM1 model, the growth period from sowing to GS 87 was estimated to be 117 days on average, varying between 102 and 138 in our data set. However, the growth period (the number of days between sowing and GS 87) is observed to vary between 120 and 127 days for the most common spring wheat varieties grown in Norway (Russenes et al. 2019). Hence, on average the phenological model slightly underestimated the number of days between sowing and hard dough (sowing - GS 87) but gave a high variation in estimated number of days. This large variation in the estimated growth period might be due to the extended sowing period for spring wheat in Norway, which can vary strongly between sites and years due to differences in soil temperature along the cereal growing area (it varied between 16th April and 6th June in our data set). Nonetheless, the predicted number of days between sowing and flowering (sowing – GS 65), when disease risk classification is most relevant, was within a reasonable estimate.

Weather conditions during the phenological windows stem elongation and booting were identified as most

decisive for LBD severity in the correlation analysis. Both CART models showed a negative correlation between moderate to high LBD severity and a dry period ($P < 0.2$ mm) with temperature between 15 and 30 °C during tillering. This is not surprising, as the primary inoculum is most likely coming from infected plant material at the soil surface, and/or from infected untreated seeds. Extended dry and warm periods during tillering will stop the splash dispersal of the LBD pathogen *P. nodorum* and prevent infection of the young leaves, delaying the start of the epidemic considerably. Once the stem elongation period starts (GS 30), the splash dispersed spores from the soil or lowest leaf level might not reach the upper leaves to colonize successfully the third, second and first leaf which were assessed for LBD severity in our study. Royle et al. (1986) mentioned that the risk of dispersal for *Septoria* species is highest during stem elongation of wheat. If there is no efficient vertical dispersal during stem elongation, the risk for infection of the upper leaves and the head is reduced (Royle et al. 1986). Ascospores might still be able to infect the upper leaf layers but could be arriving too late in the season and in too low numbers to cause significant damage in Norway (Ficke et al. 2016b). Number of hours with high humidity (RH > 70–80%), daily temperatures between 15 and 20 °C and/or large temperature fluctuations ($T_{\max} - T_{\min}$) during booting were positively correlated with the risk of high LBD severity. Humidity is a major prerequisite for sporulation and spread of LBD across the leaf surface. At the booting stage, the upper two leaves including the flag leaf might already be infected by splash dispersed conidia and the high humidity will then lead to optimal sporulation conditions and high LBD severity on these leaf layers. It is peculiar that high temperature fluctuations were correlated with severe LBD infections. However, during cool, clear nights and warm days, when temperature fluctuations are rather large, Norway can experience extended dew periods, which could explain the positive correlation between increased infection risk and those temperature conditions.

Both CART models can be interpreted by using knowledge of the biology of pathogens causing LBD and the host plant, as they show the important effect of weather during different phenological windows on the LBD severity. Beside the weather factors, host resistance level and previous crop were included in the model development and then discarded, as only weather factors appeared significantly correlated with LBD severity based on our data set. However, the agronomic factors,

such as previous crop, tillage and host resistance are highly relevant for LBD disease development in general and should be considered when interpreting the results from the weather-based LBD risk classification.

In contrast to the CART models, the KNN model classifies based on similarity to other data. Specifically, each data to be classified by KNN1 was assigned to the class most common among its ten nearest neighbors, in the space spanned by all factors (weather factors, host resistance level and previous crop). As it is a non-parametric memory-based algorithm, no further biological interpretation of the model is possible.

The three new models were compared to two ‘older’ regression models, ‘VIPS 2001’ (Elen 2007) used by the Norwegian extension service, and with the ‘Hansen model’ (Hansen et al. 1994) based on their accuracy, sensitivity and specificity. The ‘VIPS 2001’ model and the ‘Hansen model’ consider precipitation as the most important parameter for LBD risk prediction and do not include humidity. Also, the ‘Hansen model’ was developed for winter wheat, but adapted for spring wheat, based on the SWM1 phenological model in our comparison. Both models showed an overall accuracy of about 60% and specificity of about 40%, indicating that they both overestimated LBD risk for the Norwegian data. All three new models developed here performed better than the ‘older’ models for these characteristics. The KNN model had the overall highest accuracy (83%) and specificity (74%). Sensitivity on the other hand was highest for the two CART models, but these models also had a tendency to overestimate LBD infection, and predicted risk of moderate to high LBD severity when the risk was actually low in ca 50% of the tested cases (model specificity). However, based on feedback obtained from extension specialists, overestimation of risk is preferable to underestimation of the risk (model sensitivity). A user will quickly lose trust and interest in using decision support tools if the use of these tools leads to ‘missing’ fungicide applications that were actually needed. In addition, a prediction of ‘high risk’ will not necessarily lead to a fungicide spray, as it only indicates to the user that the weather conditions were favorable for infection. The final decision on the actual need for action, will depend also on other agronomic factors, such as previous crop, tillage, crop density, grain prices, yield expectations and host resistance level.

Every model is only a simplification of the actual situation in the field and is based on several assumptions that might not be fully met in the field. Our models

include an estimation of growth stages of wheat based on a given sowing date and temperature for the actual field. Furthermore, the humidity and precipitation data came from weather stations in the area, not from in-field weather stations, which could lead to incorrect weather input for LBD risk prediction. In Denmark, farmers have stopped using local weather stations for predicting disease risk and are now using interpolated weather data from the Danish Meteorological Institute (Bligaard et al. 2016). These additional uncertainties regarding growth stage estimates and weather data input constitute important sources of error that can contribute to the relatively low specificity. An additional source of uncertainty is the composition of the LBD complex which is currently dominated by SNB in Norway. Future changes in the climate and/or agricultural practices can lead to a shift in this complex towards STB and/or DTR, which might lead to poorer performance of the developed model.

With these considerations in mind, we have designed three risk models that capture the most relevant factors for leaf blotch development on spring wheat in Norway. These models can be used as forecasting models to guide farmers decisions under the current Norwegian growing conditions. Even though the new models appear to have a higher accuracy than the two older models, we are aware that their performance might change under future weather conditions and possible alterations in the composition of the LBD complex.

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Authors' contributions Anne-Grete Roer Hjelkrem and Andrea Ficke designed the study. Andrea Ficke and Unni Abrahamsen compiled the data. Andrea Ficke, Guro Brodal and Anne-Grete Roer Hjelkrem selected the data while Anne-Grete Roer Hjelkrem analyzed the data and derived the models with support from Andrea Ficke, Ingerd Skow Hofgaard and Guro Brodal. The first draft of the manuscript was written by Anne-Grete Roer Hjelkrem and Andrea Ficke with considerable input from Guro Brodal. All authors commented on the following

versions of the manuscript. All authors read and approved the final manuscript.

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Declarations

Ethical approval This study does not contain any studies with human participants or animals performed by any of the authors.

Consent for publication All authors consent to this submission.

Conflict of interest There is no conflict of interest related to this research.

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