Wheat disease forecasting using weather radar observations

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1. Introduction

Septoria leaf blotch (SLB) is an important foliar disease of wheat which can cause considerable yield loss. The difficulty of SLB risk assessment for farmers has resulted in prophylactic fungicide applications at two or three growth stages, although trials often demonstrate cost effectiveness for only one or even no fungicide application. Environmental concerns and changes in the cost/price ratio in wheat production have increased the demand for site-specific SLB risk assessment and fungicide application decision-support systems.

Since the early 1990s, various forecasting models have been used to support decisions for plant disease management by simulating the relationship between meteorological data and SLB infection periods. One of them, PROCULTURE, applied mainly in Belgium and Luxembourg, is an interactive Web-based, field-specific, decision-support system based on the mechanistic modelling of the infection development. The meteorological input data are temperature, relative humidity, and rainfall measurements provided by a network of automatic weather stations.

Due to its high spatial variability precipitation field cannot be fully captured by a network of rain gauges which limits the performance of the disease forecasting system. In this paper we briefly present a research on the use of radar-derived rainfall information to improve the forecasting and management of SLB. This research is extensively described in Mahtour et al. (2011).

2. Material and methods

2.1 Disease prediction model

PROCULTURE is a decision-support system based on the mechanistic modeling of the development of the last five leaf layers of the crop and of SLB development on these layers (El Jarroudi et al., 2009; Moreau and Maraite, 2009). The input data are (i) temperature, relative humidity, and rainfall data provided by a network of automatic weather stations; (ii) field-specific data such as location, sowing date, and cultivar susceptibility; and (iii) one adjustment around the first node of the actual growth stage and of SLB incidence on one particular leaf layer specified by the model. The model considers infection to have occurred when, during a 2-h rainfall event, precipitation for the first hour is at least 0.1 mm, to allow for the swelling of pycnidia, followed by a second hour with at least 0.5 mm of precipitation, leading to the release and splash dispersal of the conidia. In addition, after rainfall, relative humidity should be higher than 60% during the following 16 h and the temperature should remain above 4°C for 24 h for germination and infection. The assessment of the PROCULTURE model at several sites in Belgium and Luxembourg showed that the model can explain disease progression in the canopy and can be used to advise farmers when to apply fungicides during stem elongation, when the three upper leaves emerge. Overall, the assessment of the infection periods achieved an accuracy of 85%. Overestimation or underestimation of the risk could often be traced back to differences in rain events captured by the tipping-bucket rain gauges at the weather station compared with the rainfall to which a particular field was actually exposed. Rainfall data could be interpolated between weather stations but precipitation between fields is characterized by high spatial and temporal variability, making the interpolation unreliable.

2.2 Disease assessment

Replicated field experiments were established in three villages in Luxembourg (Reuler, Burmerange, Useldange) and in one village in Belgium (Humain) during the growing seasons in 2003, 2004, and 2005. Experimental fields were typically sown in approximately mid-October. The sowing and harvest methods and crop practices used reflected the usual wheat production practices in Belgium and Luxembourg. Disease development and severity were monitored weekly from April to July.

2.3 Radar and gauge rainfall data

Radar observations are provided by a C-band weather radar located in Wideumont (Belgium) and operated by the Royal Meteorological Institute of Belgium. The raw radar data are produced by a 5-elevation scan performed every 5 minutes. Measurements are collected up to 240 km with a resolution of 250 m in range and 1 degree in azimuth. A time-domain Doppler filtering is applied for ground clutter removal. An additional treatment, based on a static clutter map, is applied to eliminate residual permanent ground clutter. A two-dimensional radar product is then extracted from the three-dimensional polar data on a Cartesian grid with a resolution of 600×600 m2 (Goudenhoofdt and Delobbe, 2009). Reflectivity values are then converted into precipitation rates using the Marshall-Palmer relation $Z=aR^b$ with a=200 and b=1.6. Hourly rainfall amounts are produced by summing 5-min rainfall maps.

The quality of radar data was assessed through a comparison with 77 tipping-bucket rain gauges from the Hydrological Service of the Walloon Region of Belgium (SETHY). Data quality control was ensured by both RMI and SETHY. The comparison between radar- and gauge-derived data was made from March to July over 3 years (2003, 2004, and 2005). This period was chosen because it corresponded to the most important part of the crop growing season and the life cycle of the pathogen. For this comparison, an analysis of rainfall amounts and occurrences was conducted for each station by comparing hourly rainfall events estimated by the RMI radar with precipitation measured by the rain gauges. With regard to the radar's ability to determine the presence or absence of precipitation, a dichotomous categorical verification was performed to quantify the proportion of hourly events correctly estimated by the weather radar. Various scores were used for the comparison, including the probability of detection (POD), false alarm ratio (FAR), and critical success index (CSI). These statistical scores were calculated using the following formulae:

$$POD = a/(a + c); FAR = b/(a + b); CSI = a/(a + b + c)$$

where a = precipitation, measured by a rain gauge and detected by radar; b = precipitation detected by radar but not measured by a rain gauge; and c = precipitation measured by a rain gauge but not detected by radar. In order to overcome the problem of extremely low rainfall amounts (≤0.1 mm) caused by the detection limits of both instruments, adjusted POD, FAR, and CSI (POD′, FAR′, and CSI′, respectively) were also calculated. In this case, rainfall occurrence was assumed when both radar- and gauge-derived rainfall exceed 0.1 mm.

2.4 Impact of radar-derived rainfall data on the accuracy of SLB forecasting.

The incidence of infection estimated by the PROCULTURE model, with two rainfall input datasets (i.e., 14 rain-gauge measurements and the RMI weather-radar estimates) were assessed. The 14 rain-gauge stations belonged to four individual networks. Three of these stations were part of the RMI network, seven were from the Promotion of Agrometeorology in Southeastern Belgium network, three were Administration des Services Techniques de l'Agriculture stations, and one was a CRP-Gabriel Lippmann station in Luxembourg (Fig. 1). These meteorological stations were included because they provided hourly data on relative humidity, temperature, and rainfall that were necessary for PROCULTURE.

The effect of rainfall data source, from either rain gauges or radar, was also assessed by a comparison between field observations of SLB severity (the reference) and model results including both rainfall estimates in four selected weather stations near the four field trials. The identification of infection events was based on the development of symptom severity over time. An infection event was considered to have occurred when disease severity increased significantly between two successive observations.

For the comparison between radar and rain-gauge data in the simulated infection periods with PROCULTURE, the three classes in the contingency table —a, b, and c—were called a_s, b_s, and c_s; therefore, the simulated POD, FAR, and CSI (POD_s, FAR_s, and CSI_s, respectively) were expressed as:

$$POD_s = a_s /(a_s + c_s); FAR_s = b_s/(a_s + b_s); CSI_s = a_s /(a_s + b_s + c_s)$$

where a_s = infection occurrences simulated using both radar and rain-gauges, b_s = infection occurrences simulated using radar but not simulated using rain gauges, and c_s = infection occurrences not simulated using radar but simulated when using rain gauges.

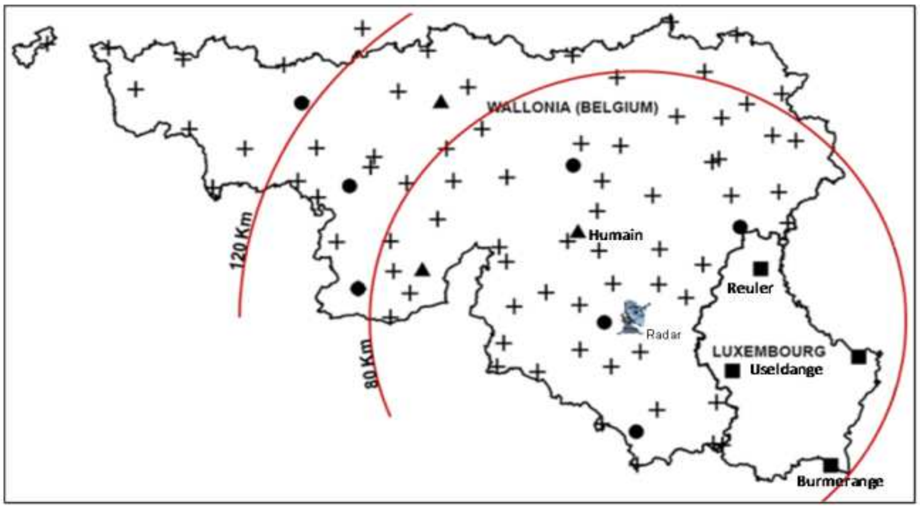

Fig. 1. *Location of the weather radar of the Royal Meteorological Institute (RMI) of Belgium, the 77 automatic stations of the Hydrological Service of the Walloon Region of Belgium (+), the seven agrometeorological stations of the Promotion of Agrometeorology in southeastern Belgium (●, the four automatic stations in Luxembourg (■), and the three automatic stations of the RMI (▲). The circles represent the range of the weather radar*.

The same contingency table was used to compare radar- and gauge-derived simulated infections with infections assessed from observed leaf spot. However, here the simulation-observed POD, FAR, and CSI (POD_{so}, FAR_{so}, and CSI_{so}, respectively) were expressed as:

$PODso = a_{so} /(a_{so} + c_{so})$; $FAR_{so} = b_{so} /(a_{so} + b_{so})$; $CSI_{so} = a_{so} /(a_{so} + b_{so} + c_{so})$

where a_{so} = infections both observed and simulated, b_{so} = infections simulated but not observed, and c_{so} = infections observed but not simulated.

3. Results

3.1 Comparison of rainfall occurrence derived from radar and rain gauge data

Rainfall occurrence was assessed using both hourly weather-radar and rain-gauge data from weather stations (Fig.2). The POD values of rainfall events varied from 0.44 to 0.80 throughout the study (average = 0.71 ± 0.09). This acceptable POD, however, was accompanied by a high FAR (0.21 to 0.44), which may be explained by the low rainfall that was close to the limit of detectability by the rain gauges. This was clearly expressed in the hourly precipitation contingency table showing the relationship between gauge- and radar-derived hourly rainfall estimates (not shown). The largest discrepancies between the two sets of measurements were observed for very weak intensity rainfall (0 to 0.1 mm). When the hourly rainfall threshold indicating a rainfall event was increased (i.e., a rainfall event was considered when >0.1 mm), the FAR scores were reduced from 0.32 ± 0.06 to 0.13 ± 0.04. This improvement was also observed for the POD (from 0.71 ± 0.09 to 0.87 ± 0.08 on average) and CSI (from 0.53 ± 0.08 to 0.76 ± 0.08, on average).

3.2 Evaluation of radar- and gauge-derived infection simulations against observed leaf spot symptoms

Field monitoring of the visually estimated leaf area covered by disease lesions on the five upper leaves at four sites from 2003 to 2005 revealed significant differences among years, and a significant interaction between years and sites. Analysis of the changes in disease severity identified 148 new infection events on the upper three leaves. Overall, the duration of periods with a high probability of infection calculated by PROCULTURE on the basis of radar rainfall data for these trials was similar to that based on gauge measurements (Table 1; Fig. 3). At Humain, out of 42 infection events over the three cropping seasons, 90% were correctly predicted by PROCULTURE using the weather-radar data, while only 84% were correctly anticipated using rain gauges. Only 4% of infection events predicted by PROCULTURE using radar estimates as input data were not confirmed by visual observations of symptoms. For the three other sites (Useldange, Burmerange, and Reuler), for 48, 37 and 21 infection events, respectively, the radar was always more accurate than the rain gauges in simulating infection risks.

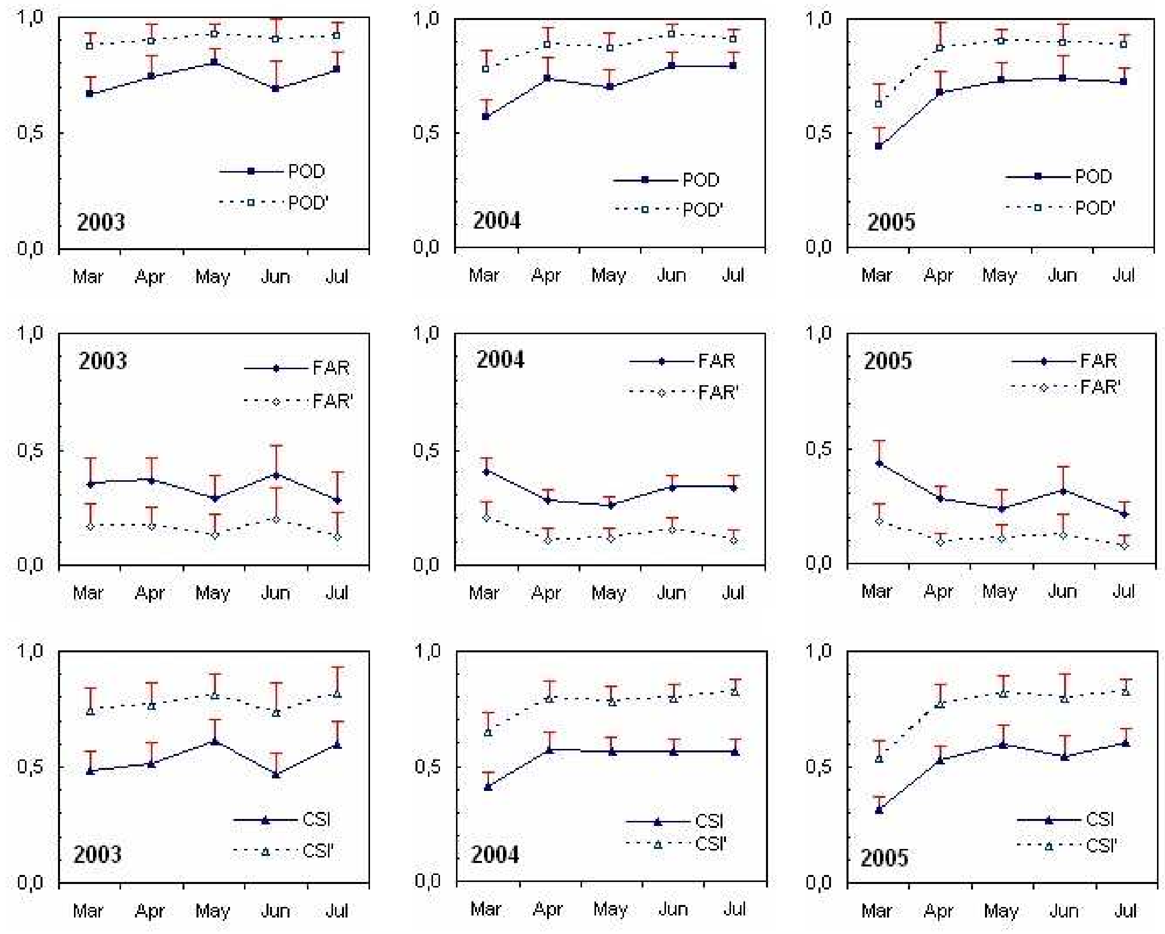

Fig. 2. Adjusted verification scores. POD′, FAR′, and CSI′ are the adjusted probability of detection (POD), false alarm ratio (FAR), and critical success index (CSI) values, respectively, obtained when raising the minimum rainfall threshold. Values of POD′, FAR′, and CSI′ were calculated by considering only those hours when the weather-radar rainfall estimates and rain-gauge precipitation measurements both exceeded 0.1 mm.

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		Infection hours*		POD		FAR		CSI	
Stations	Year	Gauge	Radar	Gauge	Radar	Gauge	Radar	Gauge	Radar
	2003	60	62	0.93	0.83	0	0	0.93	0.83
	2004	46	40	0.73	0.87	0	0	0.73	0.87
	2005	24	27	0.86	1.00	0	0.12	0.85	0.87
HUMAIN		**128**	**129**	**0.84**	**0.90**	**0**	**0.04**	**0.84**	**0.86**
	2003	56	44	0.87	0.80	0	0	0.87	0.80
	2004	48	48	0.72	0.78	0	0	0.72	0.78
	2005	33	32	0.71	0.86	0.09	0.07	0.67	0.81
USELDANGE		**137**	**124**	**0.77**	**0.81**	**0.03**	**0.02**	**0.75**	**0.80**
	2003	30	22	0.70	0.70	0	0	0.70	0.70
	2004	43	55	0.73	0.93	0	0	0.73	0.93
	2005	24	28	0.91	0.83	0	0	0.91	0.83
BURMERANGE		**97**	**105**	**0.78**	**0.82**	**0**	**0**	**0.78**	**0.82**
	2003	-	-	-	-	-	-	-	-
	2004	45	32	0.70	0.70	0	0	0.70	0.70
	2005	24	23	0.82	1.00	0	0	0.82	1.00
REULER		**69**	**55**	**0.76**	**0.85**	**0**	**0**	**0.76**	**0.85**
ALL		**433**	**413**	**0.79**	**0.84**	**0.01**	**0.02**	**0.77**	**0.83**

***Table 1**. Number of hours with high probability of S. tritici infection in four sites and during the period mid-April to mid June for three cropping seasons (2003, 2004 and 2005). Score indices (POD, FAR and CSI) show the qualitative comparison between infection periods (on the last three leaves) determined by visual observations and simulated by the PROCULTURE model using four rain gauges and weather radar estimates.*

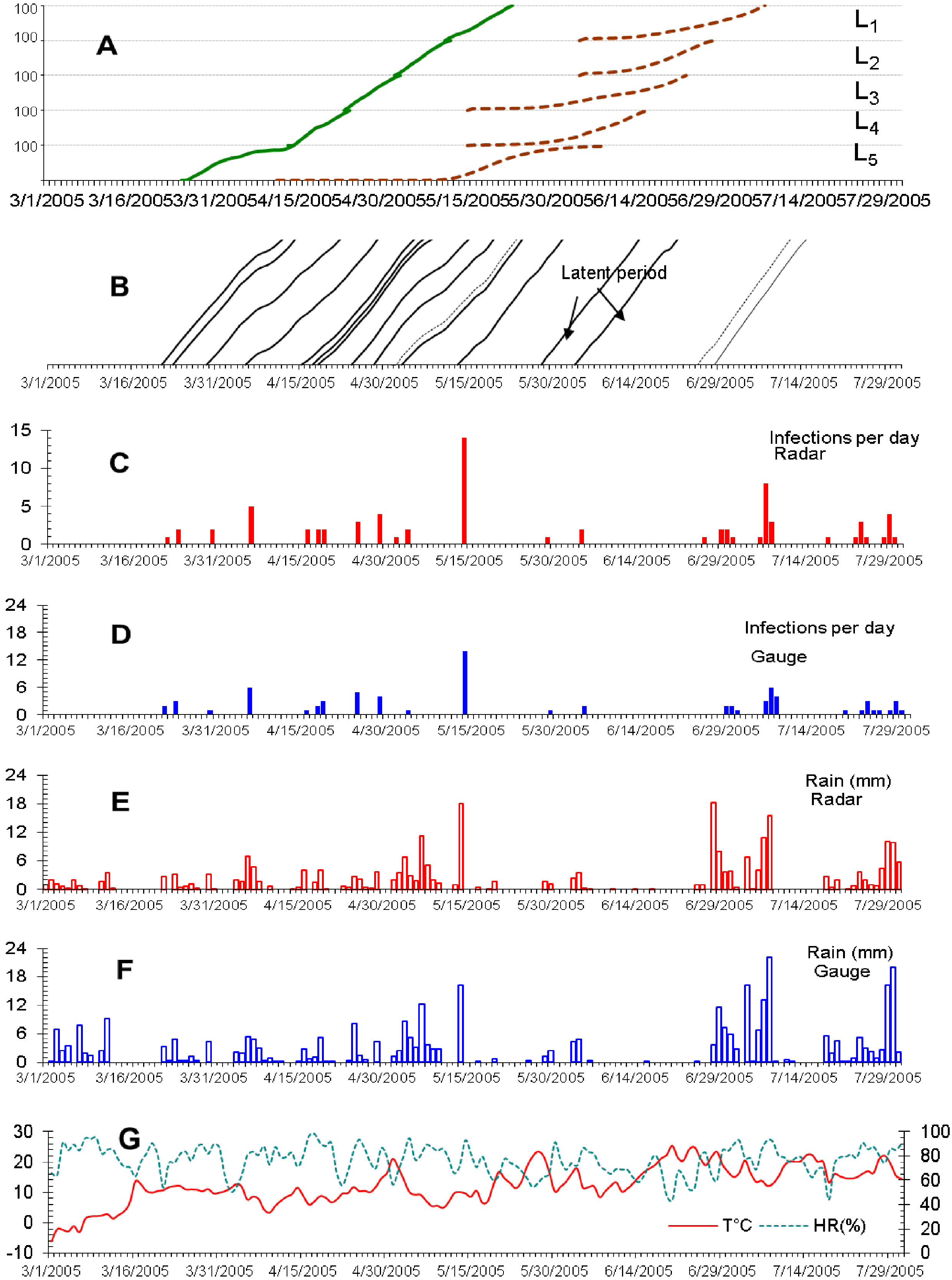

*Fig. 3. Example of inputs and outputs of the Septoria leaf blotch (SLB) risk assessment model PROCULTURE in winter wheat fields at the Humain site in 2005. **A,** Greenlines represent the percentage of leaf area development for leaves L5 to L1. Pink lines represent SLB severity (%) on L5 to L1. **B,** Latent period and duration (dashed lineindicates the latent period caused only by radar rainfall data). **C,** Number of hours per day with a high probability of infection determined by using radar rainfall estimate data.**D,** Number of hours per day with a high probability of infection determined by using rain-gauge precipitation data. **E,** Royal Meteorological Institute of Belgium radar daily rainfall estimates from the Humain weather station. **F,** Daily rain-gauge precipitation (mm) measured at the Humain weather station. **G,** Average daily air temperature (°C) andrelative humidity (%).*

The FAR_{so} index was 0 for all stations, except for the radar data at Humain in 2005 and for both the gauge and radar data at Useldange in 2005. Although the POD_{so} was, on average, 0.84 for all stations when using the radar estimates as input data for the PROCULTURE model, the POD_{so} fell to 0.79 when using the rain gauge data. There was no significant difference ($P > 0.05$) in the number of infection events of simulations using rainfall data derived from either radar assessments or rain-gauge measurements.

4. Conclusion

The assessment of the PROCULTURE model at several sites in Belgium and Luxembourg over several years has shown that it can explain disease progression in the canopy. The PROCULTURE model is being used in early warning systems in Belgium and Luxembourg to define, in real time, the risk of SLB on the upper leaves of winter wheat during stem elongation. Setting up an operational network, however, for recommending the optimal time for fungicide application in Belgium and Luxembourg requires representative rainfall measurements network throughout the territory. Due to the high spatial variability of rainfall, particularly for convective events during the growing season in Belgium and Luxembourg, data from the existing rain-gauge network may miss rain events in some localities and be inadequate for delivering rapid advice to farmers whose fields are not located near a gauge.

Rain gauge measurements are generally considered as more accurate than radar-derived precipitation estimates. However, the present study suggests that at relatively short range weather radars are as performant as on-site rain gauges for the estimation of the occurrence of precipitation. This is probably due to the limitations of rain gauges in measuring very small rainfall amounts. As a result weather radar observations can provide predictions of infection event occurences comparable with those obtained with rain gauges. Since the radar is able to provide observations over a large geographical area, its use can be very beneficial for operational site-specific SLB risk assessment

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