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Validation of risk models for control of leaf blotch diseases in wheat in the Nordic and Baltic countries

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Abstract Risk models for decisions on fungicide use based on weather data, disease monitoring, and control thresholds are used as important elements in a sustainable cropping system. The need for control of leaf blotch diseases in wheat (caused by *Zymoseptoria tritici, Parastagonospora nodorum* and *Pyrenophora tritici-repentis)* vary significantly across years and locations. Disease development is mainly driven by humidity events during stem elongation and heading. Two risk models were tested in field trials in order to identify situations favourable for the development of leaf blotch diseases in Lithuania, Norway, Sweden, Finland and Denmark. The Crop Protection Online (CPO) model uses days with precipitation (>1 mm), while the humidity model (HM) uses 20 continuous hours with relative humidity (RH) ≥ 85% as criteria for the need of a fungicide application. Forty-seven field trials were carried out during two seasons to validate these two risk-models against reference fungicide treatments. The season 2018 was dry and 2019 had an average precipitation profile. The two risk models with few exceptions provided acceptable disease control. In 2018, very few treatments were recommended by the models, saving 85–98% of treatments compared to the reference treatments, while in the wetter season 2019, 31% fewer applications were recommended. Based on specific criteria including fungicide input and net yield responses the models gave correct recommendations in 95% of the trials in 2018 and in 54–58% of the trials in 2019 compared with reference treatments dominated by 2–3 sprays. In comparison with single spray references, the models gave correct recommendations in 54–69% of the situations.

Keywords Humidity model · Crop protection online · Septoria tritici blotch · Tan spot · Stagonospora nodorum blotch

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Introduction

One of the most important foliar diseases of wheat (*Triticum aestivum* L.) is septoria tritici blotch (STB) caused by the ascomycete *Zymoseptoria tritici*. Based on estimates from several surveys, STB is considered as the most prevalent and yield reducing disease in western Europe, typically resulting in yield reductions within the range of 5-20 dt/ha (Eyal et al. 1987; Jørgensen et al. 2014; Fones and Gurr 2015). In the wheat producing areas of the Nordic and Baltic countries, tan spot (TS) caused by *Pyrenophora tritici-repentis* and stagonospora nodorum blotch (SNB) caused by *Parastagonospora nodorum* are also regarded as serious leaf blotch diseases in addition to STB. The yield reducing potential of leaf blotch diseases, and particularly STB, results in intensive use of fungicides in major parts of Europe. This puts a strain on farmers' net return from wheat production, fungicide resistance management, and the environmental load from pesticides. Due to the large variations in net return from fungicide treatments, (Djurle and Bommarco 2014; Jørgensen et al. 2017a; Wiik and Rosenqvist 2010), it is difficult to make specific decisions on the need of fungicide application in individual fields. An analysis of a historical dataset collected across the Nordic and Baltic region (Jalli et al. 2020) showed a significant variation in disease intensity and yield response between countries and years. This study emphasised the need for decision tools to better align fungicide treatment with the actual need in the field based on disease risk and potential economic return.

For foliar diseases of cereals, injury (Nutter et al. 1993) means some measurable degree of symptoms in the crop canopy, and damage means a resulting reduction in quantity or quality of crop yield. A damage threshold (the economic injury level) is defined as the level of injury at which the financial benefit of control just exceeds its cost. By the time the damage threshold is reached, it is likely too late for control to be effective, so an earlier action threshold is commonly defined to trigger fungicide treatment (Zadoks 1985). In this project, the aim has been to develop an action threshold based on a risk model, as the basis for action.

With the aim of managing STB various action thresholds have been developed, mainly based on precipitation events (Tyldesley and Thomsen 1980; Hansen et al. 1994; Wiik and Ewaldz 2009; te Beest et al. 2009) or on disease incidence (Verreet et al. 2000). Several weather-based systems, particularly for the management of STB, have been tested and validated over the years and compared for their ability to optimise fungicide input. Often, these systems provide quite comparable outputs. In Denmark a comparison between several systems were made in several field trials, and the best net return was provided by low input systems like Crop protection Online, which typically recommended 33-66 % of standard fungicide rates (Jørgensen and Hagelskjær 2003). In Ireland, the simple septoria timer provided the best solution (Burke and Dunne 2008).

Based on trial data from 1994 and 1995, Paveley et al. (1997) suggested that traditional action thresholds based on observed disease intensities may be unreliable as predictors of the need to apply fungicides. Specifically, a poor correlation between early disease assessments of STB (GS 31 to 39 BBCH) (Lancashire et al. 1991) and future damage to the crop has been found (Jalli et al. 2020; Thomas et al. 1989).

Despite this, risk models based on weather data, disease monitoring and a fixed action thresholds for decision on fungicide use are traditionally highlighted as important IPM elements in sustainable cropping systems (Anononymous 2009). Development and validation of plant disease management models requires a lot of resources. This is also the case when disease risk models are applied in other regions than where they were originally developed and validated. Validation of models is typically carried out comparing the recommendations from the risk models with untreated plots and a few reference treatments representing local control practises. In order to convince farmers and advisors on the value of a risk model the validations must show a reliable outcome from testing, including both sufficient disease control and net yields in line with or better in comparison with references using similar or lower pesticide input.

The Danish STB humidity model (HM) has been tested with different settings under various historical weather conditions from different locations as well as in validation trials (Bligaard et al. 2017; Jørgensen et al. 2017b, 2018). The model is based on hourly values for percent relative humidity (% RH), leaf wetness or rain events. Thresholds for treatment recommendations are based on a continuum of a fixed number of hours with humid conditions. The pathogen causing STB is known to require humidity for developing and spreading spores and for infection (Ponomarenko et al. 2011). Various limit values for high RH levels and hours have been used in the scenarios, whereas leaf wetness only counts if more than 30 minutes of an hour was wet, or if rain was more than 0.2 mm/hour. Another well-established model from Crop Protection Online (CPO) uses the number of days with precipitation as an indicator for infection risk (Hansen et al. 1994). This model integrates control on all cereal leaf diseases in wheat including powdery mildew and rust diseases (Secher et al. 1995; Henriksen et al. 2000). Specifically for control of STB, the model recommends treatments after either 4 or 5 days with rain (>1 mm rain/day).

The aim of the current study was to compare the efficacy and yield responses from fungicide treatments in wheat applied according to the HM and CPO models with untreated and reference treatments. The models were validated in field trials during two growing seasons across the Nordic-Baltic region in order to investigate if they could provide economical recommendations and limit the fungicide input. Another aim was to investigate if the models could be used in different wheat growing conditions outside of Denmark from where they originated.

Method and materials

In total, 47 field trials were conducted during two seasons with 22 trials in 2018 and 25 trials in 2019 in Denmark, Finland, Lithuania, Norway and Sweden. Due to lodging, one trial was not harvested and was excluded from the yield analysis. The trials were sown according to local standard practices with commonly grown wheat cultivars in the five countries. The cultivars ranged from moderately susceptible to very susceptible to leaf blotch diseases. In Sweden, Denmark and Lithuania winter wheat was included in the validation. In Finland, the models were tested in spring wheat, while spring- as well as winter wheat was used in Norway. The trials were located as shown in Fig. 1 and listed in Table S1. They had four replicates (Norway only three) and a randomised design with plot sizes between 10-25 m^2.

The trials included a range of different reference fungicide treatments with varying doses and number of applications (Table 1). The table represents input from 2019 since very few treatments were recommended in 2018. For average number of treatments by country and year see Table 3. The exact treatment dates and GSs are given in a supplementary table. The treatments were done with active ingredients that represented the three major modes of action: demethylation inhibitors (DMIs), succinate dehydrogenase inhibitors (SDHIs) and quinone outside inhibitors (QoIs). The three actives are systemic target site fungicides providing both preventative and some degree of curative control (Table 2). The treatments were applied using plot sprayers with flat fan nozzles and a water volume of 150-200 l/ha. Additional plant protection products and fertilizers were applied according to local standard practices. If necessary, early onset of powdery mildew and rust diseases was controlled with a cover treatment using products such as proquinazid (Talius) and pyraclostrobin (Comet Pro). These cover treatments were not included in the net-yield calculations, as only trials with low severities of powdery mildew and rust diseases during the grain filling phase were evaluated.

Testing of models in the field trials

Two models for optimising leaf blotch control were selected for the project. The Humidity model (HM) used the limit of 85 % RH, 30 minutes of leaf wetness, or more than 0.2 mm rain as a humidity hour. If just one of these criteria was fulfilled, it counted as a humidity hour. A threshold of 20 humid hours was tested in the trials, and fungicide treatments were recommended when that condition was met. When investigating the HM, the season started at GS 31, but treatments would generally not be recommended before GS 32, which is regarded as the critical time for starting control of STB. The Crop Protection Online (CPO) model (Henriksen et al. 2000) counts the number of days with precipitation above 1 mm. In susceptible cultivars, four days with more than 1 mm of rain registered between GS 32 and 71 was used as a threshold. For more resistant cultivars, five days with more than 1 mm rain from GS 37 to 71 was required. For both models, the crop was regarded as protected for 10 days after a fungicide application, and then the accumulation of humidity hours or rain days started again. The two selected models, HM and CPO were accessed by all countries from the VIPS platform or from the Danish Platform (https://plantevaernonline.dlbr.dk/cp/menu/menu.asp?id=djf&subjectid=1). Weather data from weather stations close to the field sites, as needed by the models was also available through the VIPS platform.

Assessments and harvest

The field trials were visually assessed from stem elongation to end of grain filling for percentage of leaf area with STB and other leaf blotch diseases. In this paper we focused on assessments carried out during the grain

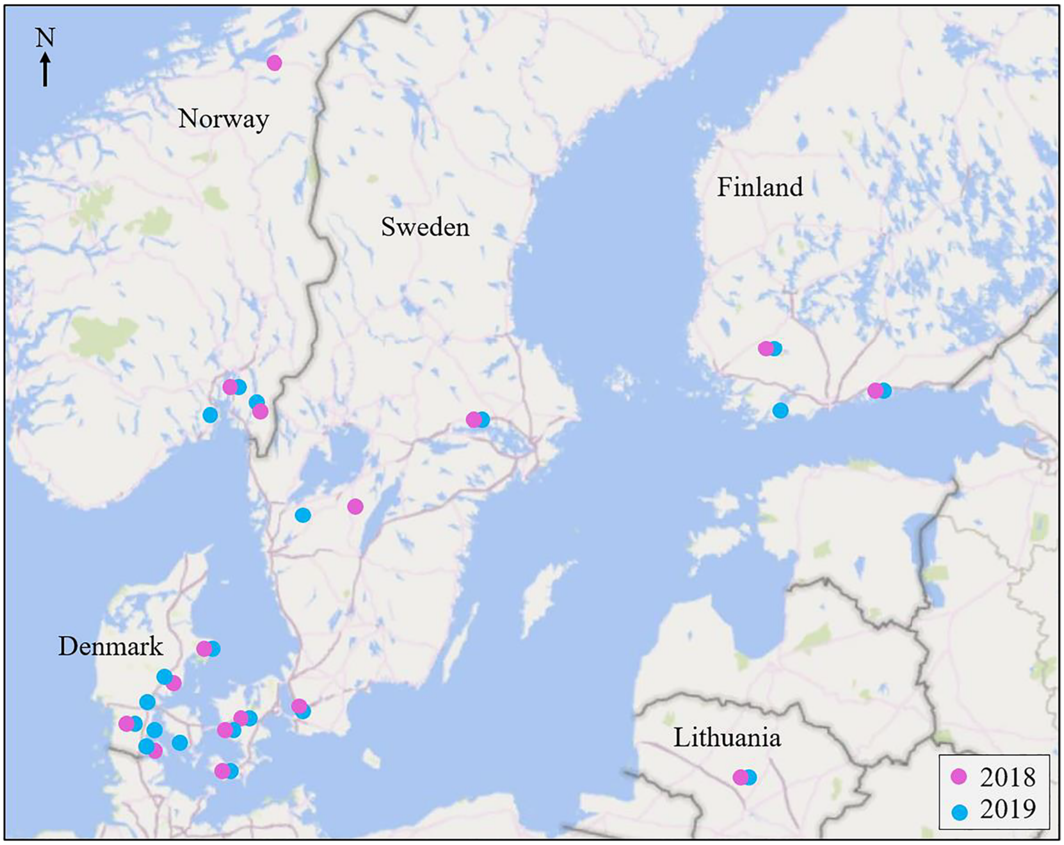


Fig. 1 Wheat trials from 2018 and 2019 were placed as shown on the map

filling period and disease severity was assessed on the flag leaf (F), leaf two (F-1) or as a score on all green parts at GS 73-77 BBCH. With one exception the trials were carried through to harvest. Grain yields were measured plot wise and adjusted to 85 % dry matter. For all trials, the net yield from all treatments was calculated deducting the cost of fungicides and cost of applying fungicides from the gross yield.

A correct decision from the tested models was assessed relative to reference treatments based on the three criteria below. The recommendations from the models were considered to be correct if there was: a) a reduced number of treatments with no or positive effect on net yield, b) an increased net yield relative to reference treatments, and c) a higher application frequency increased net yield by more than 0.5 dt/ha (50 kg) relative to the references (estimated as farmers acceptance level). The different trials had different references using either one, two or three treatments with reduced dose rates (Table 1 and S1). The Danish trials carried out by the Danish advisory service, SEGES had a dominance of references with only three treatments, while other trials had the option of comparing models with references using either one or two treatments. Comparisons of models to references were carried out using references with 2-3 treatments and also with one single treatment, the latter applied at flag leaf development. Sweden was the exception to this as some trials only had references with one treatment, which was then included in both comparisons. In two cases where net yields were better from three treatments compared with two sprays, three treatments was chosen as the reference. This was only the case for the Danish AU-trials in 2019.

Statistical analysis

Statistical analyses were carried out using RStudio version 1.2.5019 (RStudio Team 2019) with α=0.05 for all tests. It was not possible to obtain normal distribution and homogeneous variation of the data. Therefore, the non-parametric Kruskal-Wallis test with post-hoc

Table 1 Fungicide products and dosage (l/ha) applied as reference solutions or following the models at different timings in the reported trials listing 1st, 2nd, 3rd and 4th treatments

Location	Trt.	1st trt. GS 31-61	2nd trt. GS 33-71	3rd trt. GS 41-70	4th trt. GS 65-70	1 trt. GS 37-59
SE, SLU	Ref.	0.5-0.75 Ascra Xpro	0.6 Prosaro			0.5-0.75 Ascra Xpro
	CPO	0.4 Proline	0.5 Ascra Xpro			
	HM	0.4 Proline	0.5 Armure			
DK, SEGES	Ref.	0.3 Prosaro/ 0.3 Proline Xpert/ 0.55 Viverda+ 0.55 Ultimate S	0.5 Propulse+0.2 Folicur Xpert/0.55 Viverda+ 0.55 Ultimate S/ 0.375 Propulse/ 0.2 Prosaro+0.3 Bell	0.4 Prosaro/ 0.375 Propulse		
	CPO	0.44-0.56 Prosaro/ 0.49-0.6 Propulse+ 0.2 Folicur Xpert/ 0.45-0.86 Viverda+ 0.45-0.66 Ultimate S/ 0.43 Bell/ 0.64 Propulse	0.5 Propulse+ 0.2 Folicur Xpert/ 0.73-0.78 Viverda+ 0.73-0.78 Ultimate S/ 0.4-0.66 Prosaro	0.6 Propulse+ 0.2 Folicur Xpert/ 0.58 Prosaro		
	HM	0.35 Propulse+ 0.2 Folicur Xpert/ 0.3 Prosaro/ 0.55 Viverda+ 0.55 Ultimate S	0.3-0.4 Prosaro/ 0.35 Propulse+ 0.2 Folicur Xpert/ 0.55 Viverda+ 0.55 Ultimate S	0.3-0.4 Prosaro/ 0.55 Viverda+ 0.55 Ultimate S	0.4 Prosaro	
DK, AU	Ref.	0.5 Ascra Xpro	0.5 Prosaro			0.5 Ascra Xpro
	CPO	0.5 Viverda+ 0.5 Ultimate S/ 0.45 Prosaro/ 0.75 Ascra Xpro	0.6 Viverda+ 0.6 Ultimate S			
	HM	0.5 Ascra Xpro	0.5 Ascra Xpro			
NO, NIBIO	Ref.	0.5 Ascra Xpro	0.5 Prosaro/0.4 Armure			0.5 Ascra Xpro
	CPO	0.5 Ascra Xpro/ 0.5 Prosaro	0.5 Ascra Xpro	0.5 Prosaro (GS:80)		
	HM	0.5 Prosaro				
FI, Luke and NSL	Ref.	0.5 Prosaro	0.5 Ascra Xpro			0.5 Ascra Xpro
	CPO	0.5 Ascra Xpro				
	HM	0.5 Ascra Xpro	0.5 Ascra Xpro			
LT, LAMMC	Ref.	0.7-1.0 Ascra Xpro	0.7-1.0 Ascra Xpro			0.7-1.0 Ascra Xpro
	CPO	1.0 Ascra Xpro				
	HM	1.0 Ascra Xpro				

The growth stage (GS BBCH) span is large for each group and indicates that e.g. 2nd treatments have been carried out in the interval given. The span covers several trials, which have been treated either 1, 2, 3 or 4 times. In most cases the trials were treated twice, the exception to this was the SEGES trials – which had three timings in the reference. In one case, the HM tested at SEGES recommended four treatments. To the right the timing and products included when just applying one treatment in the interval between GS 37 and 59 as reference

Table 2 Products used in the field trials in wheat

Product name	Active ingredient (a.i.)	a.i. (g/L)	max. dose (L/ha)
Armure, Syngenta Nordics A/S	Difenoconazole + propiconazole	150 + 150	0.8
Ascra Xpro EC 260, Bayer A/S	Prothioconazole + bixafen + fluopyram	130 + 65 + 65	1.5
Bell, BASF A/S	Epoxiconazole + boscalid	67 + 233	1.5
Folicur Xpert, Bayer A/S	Tebuconazol + prothioconazole	160 + 80	0.5–1.0
Proline EC 250, Bayer A/S	Prothioconazole	250	0.8
Proline Xpert, Bayer A/S	Tebuconazol + prothioconazole	80 + 160	0.75–1.0
Propulse SE 250, Bayer A/S	Prothioconazole + fluopyram	125 + 125	1.0
Prosaro EC 250, Bayer A/S	Tebuconazole + prothioconazole	125 + 125	1.0
Viverda, BASF A/S	Epoxiconazole + pyraclostrobin + boscalid	50 + 60 + 140	2.5

Dunn's Test of the FSA R package were used for distinguishing significant differences between levels of the factors year and treatment (R Core Team 2017).

Results

The number of fungicide treatments from the two seasons of field trials are summarised and listed by year in Table 3. Since the rain events and humid days were very few in 2018, only a few treatment warnings were released, which meant that only 1 and 7 treatments were recommended using HM and CPO respectively in all the 22 trials (Table 3) during that season, whereas in 2019 the HM recommended 0, 1, 2 or 3 treatments per trial and CPO either 1 or 2 treatments per trial. The reference treatment included 1-3 treatments depending on locality in both seasons, but, overall, the reference treatment included fewer treatments in 2018 compared to 2019. Compared to reference treatments the use of the models reduced the number of applications in 2018 by 85 and 98 % using the CPO and HM respectively. In 2019, the reductions were 31 % for both models.

The disease intensity in 2019 was significantly higher than in 2018 (Fig. 2). In 2019, the reference treatments and the two tested models provided comparable levels of disease control (Fig. 2; Table 5), the better of the two varied between sites. In 2018, where disease levels were very low, the models provided inferior disease control compared to the references due to few treatments (Table 4). The comparisons were made using the reference treatments dominated by 2-3 spray strategies or a single spray strategy. The trial data included assessments on all present diseases, SEPTTR = septoria tritici

Table 3 The number of trials and average number of treatments applied according to the references, and the two risk models Crop Protection Online (CPO) and Humidity model (HM)

Country	Number of trials		Reference		CPO		HM	
	2018	2019	2018	2019	2018	2019	2018	2019
Denmark	11	12	2.4	3.0	0.5	2.0	0.1	2.5
Sweden	2	2	1.0	1.5	0.0	2.0	0.0	1.5
Norway	3	4	2.0	2.0	0.3	1.8	0.0	0.5
Finland	3	3	2.0	2.0	0.3	1.0	0.0	1.0
Lithuania	3	3	2.0	2.0	0.0	1.0	0.0	1.0
All trials	22	24	2.1	2.5	0.3	1.7	0.0	1.7
Total number of treatments			46	59	7	41	1	41
Reduction in the number of applications (%)					85	31	98	31

For specific trials, the numbers varied from 0 to 3 times. The exact treatment dates and growth stages are given in a supplementary table

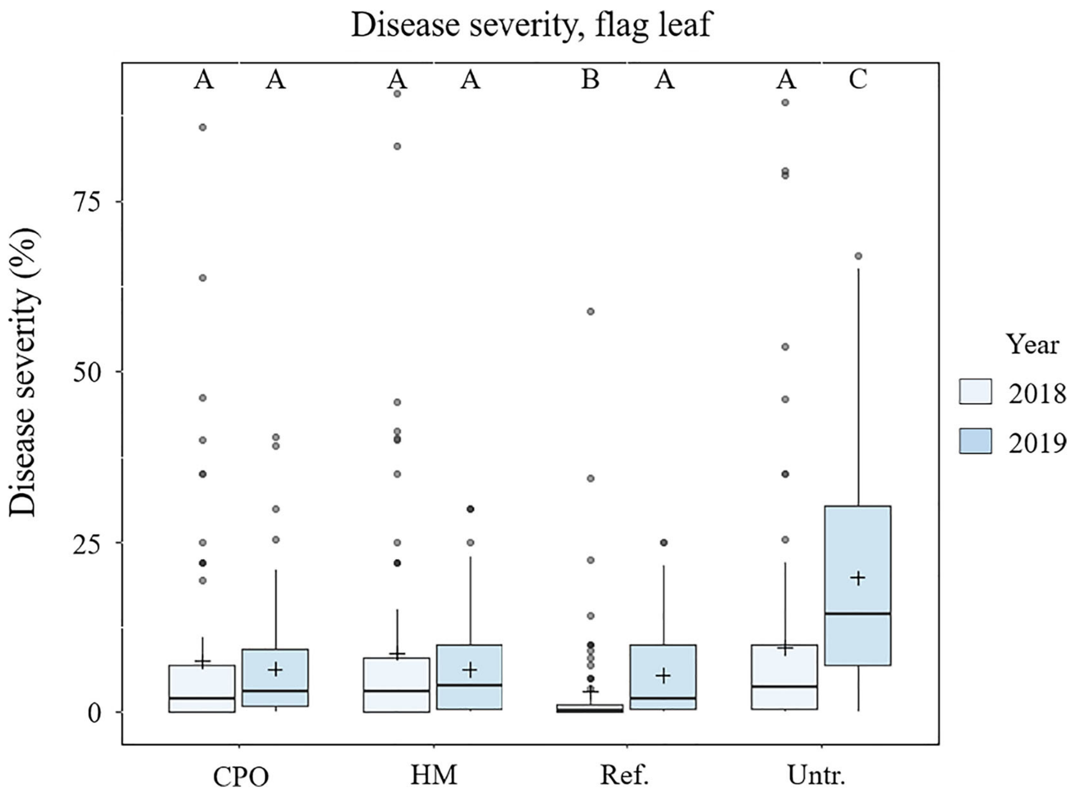


Fig. 2 Boxplot illustrating the disease control effect of leaf blotch diseases in plots treated according to the risk models CPO = Crop Protection Online and HM = Humidity model as well as the reference treatment (Ref.). Untreated (Untr.) is included for comparison. Different letters represent statistically significant differences between treatments and years (α = 0.05)

blotch; ERYSGR = powdery mildew; PUCCST = yellow rust; PUCCRT = brown rust; LEPTNO = stagonospora nodorum blotch; PYRNTR=tan spot. The specific data for disease control per country showed low disease severities in Lithuania and Norway and more severe disease in Denmark and Sweden. High severities of tan spot were observed in Finland in both seasons, while this disease was nearly absent in the other countries (Tables 4 and 5). Specifically, for Norway LEPTNO dominated in 2019. The disease control from using the two models varied between countries in 2019. In Denmark, the two models provided equal disease control. In Sweden and Norway, the efficacy from the HM was inferior to reference treatments and in Finland this was the case for the CPO-model.

The yield responses from fungicide treatments in 2018 were very low and not significantly different from untreated, while the models as well as the reference treatments led to significant yield increases in 2019 (Table 6, Fig. 3). This yield increase from treatments in 2019 was particularly high in the Danish trials but less so for trials in Finland and Lithuania. Use of the models generally provided superior net yields compared with reference treatments. However, this was not the case for the Swedish and Norwegian trials in 2019 (Table 7). In 2019, the benefits from applying fungicides in general were low in Finland and Lithuania with less than 1 dt/ha in net yield.

Based on the three listed criteria, it was investigated if correct decisions from the tested models were made compared with the outcome from the reference treatments. The results from this analysis showed that the number of correct treatments in both seasons were higher for the HM and CPO models compared to the references. In 2018, 95 % of the trials were correct for both the HM and CPO models. In 2019, the corresponding figures were 54 % and 58 % for the HM and CPO models respectively (Table 8). As an alternative to comparing model treatments with the reference treatments using two or three treatments, it was possible to make a comparison with another reference treatment using a single spray strategy in 27 trials (Table 9). In this comparison, the success rate for the CPO model was 69 and 57 % in 2018 and 2019 respectively.

Table 4 Severity of diseases in trials during 2018, by country

				Comparison with 1–3 treatments reference					Comparison with 1 treatment reference	
Country	Disease	GS	Part rated	Trials (N)	Untr.	ref.	CPO	HM	1 trt.	Trials (N)
Denmark	SEPTTR	73–81	Plant	11	5.5	2.3	5.2	5.5	–	–
	SEPTTR	75	FL-1	2	19.9	2.9	5.3	16.8	3.6	2
	ERYSGR	73–81	Plant	11	2.1	0.0	1.9	0.0	–	–
	PUCCRT	73–81	Plant	11	0.1	0.0	0.1	0.1		
Sweden	SEPTTR	75–85	FL-1	2	0.3	0.0	0.3	0.3	0.0	2
Norway	SEPTTR	75–77	FL	3	5.9	0.3	0.9	2.1	0.3	3
Finland	PYRNTR	75–83	FL	3	31.3	11.9	20.9	26.8	10.1	3
Lithuania	SEPTTR	73–75	FL	3	3.4	0.1	3.6	3.4	0.1	3
	PYRNTR	73–75	FL	3	1.0	0.2	1.0	1.0	0.2	3
All trials	SEPTTR	73–77	FL/plant	19	3.8	0.9	3.2	3.7	0.2	6
	SEPTTR	73–75	FL-1	4	10.1	1.4	2.8	8.5	1.8	2
	PYRNTR	73–83	FL	6	16.2	6.1	11.0	13.9	5.1	6.0

Diseases were assessed either on all green parts (Plant), flag leaf (FL) or leaf below flag leaf (FL-1). Assessments were carried out in untreated (Untr.), reference treatment (ref.) with 1-3 treatments; HM = humidity model; CPO = Crop Protection Online. To the right comparisons are made with a reference treatment using only one treatment

Table 5 Severity of diseases in trials during 2019, divided by country

				Comparison with 1–3 treatments reference					Comparison with 1 treatment reference	
Country	Disease	GS	part rated	Trials (N)	Untr.	ref.	CPO	HM	1 trt.	Trials (N)
Denmark	SEPTTR	61–77	FL/plant	12	21.5	7.4	7.8	8.3	2.9	2
	SEPTTR	69–75	FL-1	2	41.9	5.4	17.5	3.0	16.6	2
	PUCCST	61–77	Plant	12	3.9	0.4	0.5	0.5	–	–
	PUCCRT	61–77	Plant	12	2.0	0.0	0.0	0.0	–	–
	ERYSGR	61–77	Plant	12	2.5	0.6	0.4	0.4	–	–
Sweden	SEPTTR	65–83	FL	2	4.4	0.2	0.4	0.5	0.4	2
	SEPTTR	75–83	FL-1	2	48.8	2.8	13.5	22.4	3.9	2
Norway	LEPTNO	65–83	FL	4	5.9	1.6	1.4	3.0	2.3	4
Finland	PYRNTR	73–77	FL	3	11.8	4.5	8.7	3.7	8.2	3
	PUCCRT	73–77	FL	3	4.7	1.7	2.6	1.1	3.5	3
Lithuania	SEPTTR	75	FL	3	5.4	0.4	0.6	1.7	1.0	3
	PYRNTR	75	FL	3	3.3	1.2	1.3	2.0	1.4	3
All trials	SEPTTR	61–83	FL/plant	17	10.5	2.7	2.9	3.5	1.4	7
	SEPTTR	69–83	FL-1	4	45.3	4.1	15.5	12.7	10.2	4
	PUCCRT	61–77	FL/plant	15	3.4	0.8	1.3	0.6	–	–
	PYRNTR	73–77	FL	6	7.5	2.9	5.0	2.9	4.8	6
	LEPTNO	65–83	FL	4	5.9	1.6	1.4	3.0	2.3	4

Diseases are assessed either on all green parts (Plant), flag leaf (FL) or leaf below flag leaf (FL-1). Assessments are carried out in untreated (Untr.), reference treatment (ref.); HM = humidity model; CPO = Crop Protection Online. To the right comparisons are made with a reference treatment using only one treatment

Table 6 Yield and yield increases (dt/ha) in wheat trials comparing the reference using 1–3 applications, with the two risk models, CPO = Crop Protection Online and HM = Humidity model

Year	Country	Trials N	Yield (Untr.) and yield increases (dt/ha)					Trials, N
			Untr.	Ref. 1–3 tr.	CPO	HM	Ref.. 1 trt	
2018	Denmark	11	83.5 ns	2.5 ns	0.9 ns	0.0 ns	3.3	2
	Sweden	2	65.5 b	1.2 a	0.5 ab	1.5 ab	1.2	2
	Norway	3	39.3 ns	−0.7 ns	0.8 ns	1.0 ns	4.1	3
	Finland	3	45.8 ns	1.6 ns	0.5 ns	−0.8 ns	1.7	3
	Lithuania	3	81.2 ns	5.4 ns	−0.6 ns	0.3 ns	3.1	3
2019	Denmark	12	83.6 b	13.5 a	13.1 a	14.0 a	16.1	2
	Sweden	2	107.7 b	12.4 a	7.4 ab	6.5 ab	8.4	2
	Norway	4	54.8 ns	10.4 ns	7.8 ns	2.3 ns	7.0	4
	Finland	3	59.8 ns	4.4 ns	3.0 ns	2.5 ns	2.1	3
	Lithuania	3	70.0 ns	3.9 ns	4.3 ns	4.2 ns	3.2	3

To the right the comparison from 1 treatment reference is shown for the trials where this was possible. For each country, it is indicated with letters, if the yield responses from the different treatments are significantly different from untreated

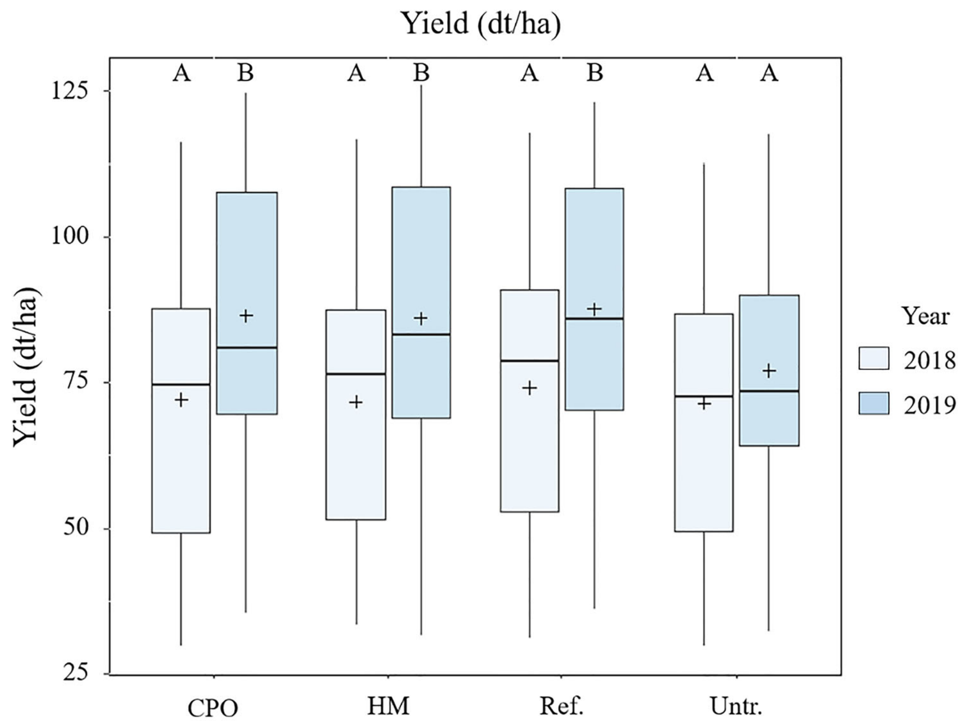
For the HM model the success rate was 54 and 64% in 2018 and 2019 respectively.

Discussion

The occurrence and severity of leaf blotch diseases in wheat varies significantly between seasons and regions in the Nordic - Baltic zone (Djurle and Bommarco 2014; Jørgensen et al. 2017a, b; Wiik and Rosenqvist 2010). While septoria tritici blotch is the most important leaf blotch disease in Denmark and southern Sweden, stagonospora nodorum blotch and tan spot are more common problems in Norway, Finland and Lithuania (Ronis et al. 2009; Ficke et al. 2018; Jalli et al. 2020). The results from the presented field trials during the two seasons confirmed this distribution of diseases in the Nordic-Baltic region, and also that there are major differences in the required number of treatments between seasons and regions. The year 2018 represented a very dry season with no or almost no need for control of leaf blotch diseases, while 2019 represented a more normal season with several humidity events stimulating the development of humidity driven leaf blotch diseases. Overall, the tested models supported the IPM concept that major savings in fungicides can be obtained by using such tools. The results also highlighted that the benefits from using such models vary across the regions. This will govern the model preference and the degree of local adjustments required in the model settings for each region.

The CPO model for prediction of STB, using either four or five days with precipitation as the basis for its recommendation (Henriksen et al. 2000), has previously been tested and compared with other models in various projects (Jørgensen and Hagelskjær 2003). The CPO model has generally provided slightly lower disease control levels compared to fixed two or three treatment strategies. However, when it comes to net yield, CPO has generally provided comparable results with a lower input of fungicides (Jørgensen et al. 2017b, 2019). The HM model has not been validated to the same extent as CPO, but Danish field trials from 2016-2017 have shown, that the HM model performs well compared with the reference treatments, and in line with the CPO model (Jørgensen et al. 2018). This is further confirmed by the results from the trials presented in this paper.

Ideally, farmers should be able to make predictions about disease development and its possible effect on yield based on disease severity at the time of decision making, which is normally between GS 32-55. However, it has been shown that the correlation between disease severities of STB at GS 39-51 and yield loss is weak (Jalli et al. 2020). This is supported by Bhathal et al. (2003), who showed that it is not possible to estimate the wheat yield impact from early season



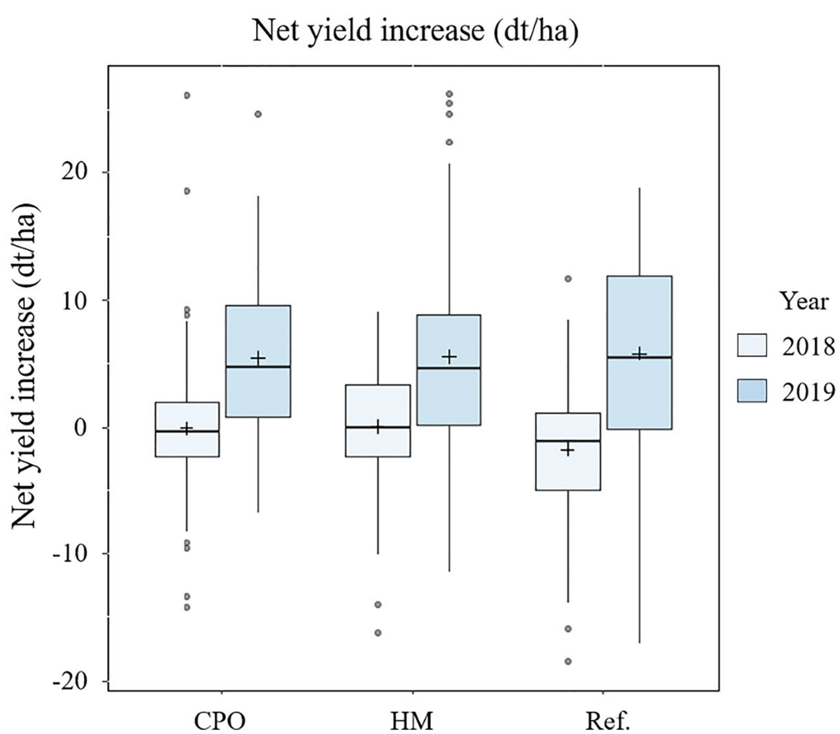


Fig. 3 Boxplots illustrating the gross yield increase (top) and net yield increase (bottom) (dt/ha) following disease control in plots treated according to the risk models CPO = Crop Protection Online and HM = Humidity model as well as the reference treatment (Ref.). Different letters represent statistically significant differences between treatments and years (α = 0.05)

Table 7 Average net yield increase (dt/ha) in wheat after deducting the cost of fungicide and cost of application

		Average yield (untr.) and net yield increases (dt/ha)						
Year	Country	Trials, N	Untr.	Ref.	CPO	HM	1 Trt.	Trials, N
2018	Denmark	11	83.5	−1.7	0.0	−0.2	1.1	2
	Sweden	2	65.5	−1.0	0.5	1.5	−1.0	2
	Norway	3	39.3	−4.5	0.1	1.0	1.9	3
	Finland	3	45.8	−2.2	−0.3	−0.8	−0.5	3
	Lithuania	3	81.2	−0.3	−0.6	0.3	0.2	3
2019	Denmark	12	83.6	8.9	8.5	9.5	13.9	2
	Sweden	2	107.7	8.4	3.8	3.8	5.8	2
	Norway	4	54.8	6.6	4.2	1.5	2.9	4
	Finland	3	59.8	0.6	0.8	0.3	−0.1	3
	Lithuania	3	70.0	−3.8	0.5	0.4	−0.6	3

The data compare input in trials testing two risk models. The net yields for the risk models, CPO = Crop Protection Online and HM = Humidity model, are compared with "ref." (reference with 1–3 applications). In the far right column, the comparison from 1 treatment reference is included for the trials where this was possible

assessments of leaf blotch disease development. The main reason for the uncertain correlation between yield and the disease intensities is that yield loss is highly unpredictable and highly influenced by particularly weather conditions. The epidemic rates can be highly variable affecting the disease development from one week to the next and the impact on yield is also affected by many other factors than the specific disease (te Beest et al. 2013). Examples of such interfering factors can be other diseases, abundance of weeds and lodging or draught during grain filling. The uncertainty of the outcome of prediction models will likewise be affected by these interfering factors.

Based on specific criteria including fungicide input and net yield responses the models gave correct recommendations in 95 % of the trials in 2018 and in 54-58 % of the trials in 2019 compared with reference treatments dominated by 2-3 treatments. Correct recommendations were ranging from 54 - 69% for the two models, if compared with only one treatment strategies. Apart from a comparable net yield following the use of the models

Table 8 The number of trials with correct recommendations listed for both reference treatment (1–3 reference treatments) and treatments applied according to risk models based on listed criteria

Country	Trials, N		CPO vs. Ref.		HM vs. Ref.	
	2018	2019	2018	2019	2018	2019
Denmark	11	12	11	7	11	7
Sweden	2	2	2	1	2	0
Norway	3	4	3	1	3	1
Finland	3	3	3	1	3	2
Lithuania	3	3	2	3	2	3
All trials	22	24	21	14	21	13
% correct recommendations			95	58	95	54

From left to right: Number of trials conducted, followed by number of correct recommendations by models CPO = Crop Protection Online and HM = Humidity model compared with references in 2018 and 2019 respectively

Table 9 The number of trials with correct recommendations listed for both reference treatment (one application treatment exclusively = 1 Trt.) and treatments applied according to risk models based on listed criteria

Country	Trials, N (1 Trt.)		CPO vs. 1 Trt.		HM vs. 1 Trt.	
	2018	2019	2018	2019	2018	2019
Denmark	2	2	1	0	0	2
Sweden	2	2	2	1	2	0
Norway	3	4	2	2	1	3
Finland	3	3	2	2	2	2
Lithuania	3	3	2	3	2	2
All trials	13	14	9	8	7	9
% correct recommendations			69	57	54	64

From left to right: Number of trials conducted, followed by number of correct recommendations by models CPO = Crop Protection Online and HM = Humidity model compared with references, in 2018 and 2019 respectively the main achievement from using the models were the major saving of fungicides particularly in the dry season 2018. The big variation between the reduction potential from the models in the two years is caused by the very different weather conditions in the two seasons. The season was very dry in 2018 while the weather was more normal in 2019. In seasons with more normal weather conditions, the reduction potential is less compared with standard treatments using one or two applications.

The results presented in this paper should be seen in the following light: The two models tested in this project were developed and previously validated for control of STB in winter wheat in Denmark. In this project, the use has been extended to other Nordic and Baltic countries and to cover also spring wheat and more diseases. Several agronomic factors are different in the region and can explain the lower net yields from using the models outside of Denmark as seen from the results in this project. The dominating diseases in some of these countries are stagonospora nodorum blotch and tan spot (Jalli et al. 2020), which might require different models than the STB models developed in Denmark. The proportion of winter wheat fields in Denmark, southern Sweden and Lithuania is higher than for the other countries, which might lead to a high density of STB inoculum, which again could lead to more severe attack. In addition, the yield levels in several parts of the region are significantly lower than the Danish yield levels (Jalli et al. 2020). This might provide a different yield loss profile from a given disease intensity. A third factor, which might influence the model performance, could be linked to spring wheat being more commonly grown particularly in Norway and Finland. This might give a different yield response pattern compared to winter wheat. In summary, these circumstances might put some constraints on a successful use of the Danish models in other countries. An analysis based on historical data from the expanded region could show to what extent adaptation of the models would be needed.

In our validation trials, reduced rates of effective fungicides were applied in reference treatments and treatments according to the models once the respective threshold was reached. In the trials presented here between 33 and 66 % of the approved dose rates were typically applied. The models were tested with the assumption, that a reduced input of an effective fungicide will provide sufficient control and a reasonable chance of obtaining an economical benefit. This assumption is based on many years of experience supported by trial work verifying that the best economic output is obtained from an adjusted dose rate, normally in the range of 33-75 % of standard rates. It is today common practice to apply reduced fungicide rates in many countries (Jørgensen et al. 2017a, b). The level of disease control achieved from the inputs provided by the models have been in line with the reference treatments (>75 % control), which indicates that the recommended reduced fungicide doses have provided acceptable control. The Swedish trials in 2019 represent an exception. The main reason for the low efficacy in the Swedish trials in 2019 is linked to the choice of product, where prothioconazole (Proline) was one of the fungicides in the HM and CPO treatments. Fungicide resistance to prothioconazole has reduced the field performance of this substance, especially in southern Sweden (Heick et al. 2020). In the same trial, the more effective Ascra Xpro (prothiconazole + bixafen + fluopyram) was used as the reference treatment providing better control and yields generating an unfair comparison. Previous investigations of historical Swedish trial data found that five factors are important for prediction of positive marginal returns. These factors include; rain days in April/May and three weeks before ear emergence, disease severity at ear emergence, soil type and previous crop (Djurle et al. 2018). With respect to these identified factors, rain events seem to be a major factor, which is also included in the tested models presented in this paper. Other Swedish investigations have shown low net returns from the use of fungicides. The mean net return from fungicide use was no more than 12 € ha-1 over a period of 25 years, and the mean net return was negative in 10 out of 25 years (Wiik and Rosenqvist 2010). The Norwegian data showed a poor and non-significant yield response from the HM model in 2019, which also to some extent was reflected in poorer disease control (Tables 5 and 6). Given the low disease severity in Norway also in 2019, it is uncertain how big the impact of the present disease on yield was in the conducted trials

When evaluating the benefit of using risk models, untreated and reference treatments are always required. The fungicide input in the reference treatment can always be discussed and should ideally be adjusted locally. In Denmark and southern Sweden, 2-3 fungicide treatments are common, while strategies with only one treatment are more common in central Sweden, Finland, Norway and Lithuania. When comparing the success rate of the forecasting models with 2-3 application strategies, the models proved more successful than when comparing with a one-treatment strategy, particularly in the dry season (Tables 8 and 9).

With the increasing concern from the public regarding use of pesticides and the EU directive on the sustainable use of pesticides (Anononymous 2009), there is an ambition to limit the use of pesticides according to the actual need. It is important for the farmers to minimise costs, and to ensure a net return from the investments in control measures. Minimising the use of input should also be seen as an important strategy to reduce the risk of substantial problems with fungicide resistance (van den Bosch et al. 2014) and negative effects on human health and the environment. It has previously been stated by Zadoks (1985) that forecasting systems, although seen as a cornerstone in IPM, are known to have their limitations. Several of the assumptions for disease risk models might not be fulfilled, for example the assumption of a similar predictable epidemic growth rate across different sites and seasons. Most models also assume that the damage function or the relationship between disease and yield loss is consistent across sites and seasons, whereas, in practice, many genetic and environmental factors affect the relationship between injury and damage (Gaunt 1995). In addition, the calculation of the damage threshold assumes that the efficacy of a treatment is constant and the value of yield quantity and quality is known in advance. This is not realistic in practice since several factors influence the yield parameters and the net result (Djurle et al. 2018).

In the current study, the main benefit of using risk models was achieved in the dry season 2018, when almost no treatments were recommended, and the disease levels were low. In that season, 85-98 % of the treatments were saved when the recommendations from the models were applied. In the more normal season (2019), with several rain events during stem elongation and heading, the differences in percent control and obtained yields between reference treatments and the treatments applied according to the models were less pronounced. The savings in the number of fungicide applications were similarly 30 %, for both models. In the UK, the potential for saving fungicide input by using risk models for the control of early occurrence of STB has been investigated and compared with application programmes not using forecasts (te Beest et al. 2013). The saving of fungicides was approximately 25 % on wheat cultivars with partial resistance to STB, but there was little or no fungicide saving when the forecast was applied to STB-susceptible cultivars. As many different cultivars were included in the current study, it was not possible to determine if the level of resistance in the cultivars had an impact on the potential savings from using the two models. The CPO model does, however, take genetic resistance into account as previously described, by including a later starting time and a higher number of days with rain (Henriksen et al. 2000). This difference in threshold for the two levels of resistance will in most seasons ensure fewer treatments in cultivars with partial resistance (Jørgensen et al. 2003).

Besides the challenges to develop and validate a reliable model to guide the farmers regarding decision on input and timing of fungicide applications, sociological studies both as part of this current project, but also experienced by previous studies, show that there are major barriers to overcome in order to increase farmers' use of risk models in decision support systems (DSS). A Danish study showed that farmers cannot be generalised in how they receive guidance on crop protection issues and that they have different requirements for support. It was observed that farmers prefer direct input from their local advisors instead of relying on output from a DSS (Jørgensen et al. 2008). Currently, many advisory services create farming production systems, which integrate all information needed for taking actions in arable crops, which ideally also include data from the farmers own weather stations. Although a major uncertainty exists, the decision making regarding treatments at the farm level is often a function of disease symptoms, cultivar resistance, weather conditions, as well as farmer’s expertise, experiences and yield expectations. The decision making is also related to how risk adverse the specific farmer is, where many farmers prefer a certain element of insurance, which can lead to the use of higher doses or extra fungicide application (Hardwick et al. 2001; te Beest et al. 2013). The presented study highlights that good guidance and support for farm-based decisions can be provided by disease risk models such as the ones tested in this project.

Conclusion

Two risk models, Crop Protection Online and the Humidity Model, which are based on humidity parameters were tested as decision support systems for applying fungicides for control of leaf blotch diseases in wheat during two seasons in the Nordic and Baltic region. The two models have provided sufficient disease control and reliable yield responses in line with reference treatments in most cases. The two models have in both seasons helped to save the input of fungicides and reduce unnecessary treatments. Compared to using a reference standard treatment with dominance of 2-3 treatments per season, 85 to 98 % reduction in treatments were gained in the dry season 2018 and 30 % in the more normal humid season 2019. Based on net-yield evaluation and the model's ability to reduce input, it was found that the risk models gave correct recommendations in 54-96 % of the trials. Compared to references using only one treatment per season the risk models gave correct recommendations in 54-69% of the trials. Only minor differences were seen between the performances of the two models. The benefits of the models varied across the region indicating that local adjustments of the models might optimise their performances.

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Author contribution LNJ designed the study and coordinated the activity. NM organised the collected data and performed the statistical analysis. BA, AF, GCN, AR and MJ were responsible for the national testing. LNJ, NM, AD, AF, BA, GCN, AR and MJ participated in writing the manuscript.

Compliance with ethical standards

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

Informed consent All authors consent to this submission and bear all ethical responsibilities of this manuscript.

Ethical statement The manuscript has not been submitted to other journals and data has not been published previously (partly or in full).

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