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Disease threshold-based fungicide applications: potential of multi-disease resistance in winter wheat cultivars in Germany

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Abstract The presence of foliar pathogens often leads to yield losses in winter wheat (*Triticum aestivum* L.), the most important crop in Germany. In this study the efficacy of different host resistance levels of eight wheat cultivars and three fungicide strategies on fungal disease control was studied in terms of yield and net return in field trials at five sites over three crop years. Fungicide treatments included a situation-related strategy in which cultivars were treated individually based on disease control thresholds, a practice-related strategy in which all cultivars were treated after disease thresholds had been exceeded in one cultivar, and an untreated control. Disease severity and incidence differed between cultivars and were reduced by fungicide treatments compared to the untreated control. On average over all locations and years, the Fungicide Treatment Frequency Index (TFI) of all cultivars treated with the situation-related strategy was significantly lower than those treated with the practice-related strategy, except the highly susceptible cultivar JB Asano. A reduction of the TFI by up to 82% was possible in the situation-related strategy. Despite slightly increased yields in the practice-related strategy compared to the situation-related strategy, these could not compensate for the higher fungicide costs in

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most cases and led to lower net returns. The cultivars with multi-disease resistance showed clear advantages. Their potential benefits are not only demonstrated by the attainment of high yields, but also in fungicide savings without reducing net returns, provided that their disease resistance characteristics are taken into account.

Keywords Winter wheat · Fungal diseases · IPM · Treatment frequency index · Disease threshold · Multi-disease resistance · Net return

Introduction

Winter wheat is the most important cereal crop in Germany. In 2020, the wheat cultivation area was 2.8 million hectares or 48% of the total cereal area (BMEL, 2020). Winter wheat can be attacked by a number of important wheat pathogens, primarily Septoria leaf blotch (*Zymoseptoria tritici*), yellow rust (*Puccinia striiformis* f. sp. *tritici*), leaf rust (*Puccinia triticina*), powdery mildew (*Blumeria graminis* f. sp. *tritici*) and Fusarium head blight (*Fusarium graminearum*, *F. oxysporum*), which can severely reduce yields and quality depending on the infestation level (Hovmøller et al., 2011; Jahn et al., 2012; Serfling et al., 2017). Savary et al. (2019) documented yield losses in winter wheat of 22% caused by different pathogens and pests. The most common method of controlling the above mentioned fungal pathogens is the application of fungicides (Lopez et al., 2015; Thompson et al., 2014). Fungicides are widely used to control fungal diseases and could reduce yield losses by 12% based on German data (von Witzke & Noleppa, 2011). However, the use of plant protection products may lead to negative effects on the environment and on human health (Geiger et al., 2010; Mahmood et al., 2016).

Directive 128/2009/EC on the sustainable use of pesticides provided the first comprehensive regulation on the use of plant protection products in Europe. Integrated pest management (IPM) was implemented as the main plant protection strategy and is mandatory in EU member states since January 2014 (Anonymous, 2009). The principles of IPM assume that plant protection products are only used when all other practicable options, such as preventive and non-chemical measures to prevent and control harmful organisms, have been exhausted and that concerns of consumer and environmental protection as well as human health have been sufficiently taken into account. IPM, its implementation and the best possible solutions have been the focus of many researchers (Barzman & Dachbrodt-Saaydeh, 2011; Bottrell & Schoenly, 2018; Dara, 2019; Matyjaszczyk, 2019).

Cultivar resistance is an important tool in IPM to prevent pest infestation and is considered a cost-effective and environmentally friendly approach to controlling fungal diseases. Yield losses and benefits strongly depend on the level of cultivar resistance (Carmona et al., 2020; Mercer & Ruddock, 2005; Zhang et al., 2007). In German winter wheat cultivars, progress in increasing cultivar yields can largely be attributed to advances in breeding for pathogen resistance (Laidig et al., 2021; Zetsche et al., 2020). So far, more than 60 resistance genes could be integrated into winter wheat cultivars to control for powdery mildew, and more than 80 for yellow and leaf rust (Gessese et al., 2019; Sapkota et al., 2019; Zhang et al., 2018). More than 50% of German winter wheat cultivars have effective genes for resistance to powdery mildew and yellow rust and 24% for leaf rust (Bundessortenamt, 2020). However, it is not known in detail which genes were introgressed into each individual cultivar.

The disease control threshold, i.e. the infestation level where a treatment is required to avoid economic losses, also plays a major role in IPM. German disease thresholds have been developed for a series of fungal wheat diseases (Beer, 1991; Beer et al., 1996). These are based on the frequency of infestation at a specific stage of development. In Germany, the plant protection services of the federal states describe disease control thresholds for the five wheat diseases powdery mildew, yellow rust, leaf rust, tan spot and Septoria leaf blotch (Pflanzenschutzdienste der Länder Berlin, Brandenburg, Sachsen, Sachsen-Anhalt und Thüringen, 2016, 2017, 2018). By combining disease thresholds with cultivars with good pathogen resistance, it is possible to save fungicide applications (Hovmøller & Henriksen, 2008; Jahn et al., 2010; Jørgensen et al., 2017). In addition to disease control thresholds, the use of forecasting models is recommended by the plant protection services. In Germany, the models SEPTRI and SIMCERC are available in winter wheat for a field-specific forecast of Septoria leaf blotch and eyespot (Erven, 2011; Weinert et al., 2004).

The most common cultivars grown in Germany have high yields and high grain quality in terms of the protein content, have effective resistance to a few pathogens that cause the above mentioned diseases, but have no effective resistance to all locally occurring diseases (Bundessortenamt, 2020). Lack of resistance is usually compensated by targeted fungicide applications. In years with severe infection pressure, high susceptibility to only one disease may lead to high yield losses despite intensive fungicide application, due to poor timing of fungicide applications (Jahn et al., 2012; Joshi et al., 2017). The choice of cultivar must therefore be made anew every year, considering the disease pressure of the previous years and the location, and taking into account economic and ecological criteria. Since there are now approved cultivars in Germany that have high protein content, respectable yields and effective resistance to several fungal diseases, these cultivars should be given preference in the future (Bundessortenamt, 2020). Until now, there has been a lack of knowledge about the economic benefit of applying disease control thresholds in combination with cultivar resistance. The effort of intensive, regular, and time-consuming monitoring must also be considered from an economical point of view. The objective of the present study was to evaluate the potential of multi-disease resistant cultivars to reduce the number of fungicide applications when their resistance to the major fungal pathogens is used effectively by utilizing disease control thresholds. The study wanted to answer the following questions: (i) Does the use of disease thresholds affect the fungicide application intensity, (ii) can cultivars with multi-disease resistance reduce the fungicide application intensity and (iii) are yields and net returns from such cultivars comparable to those from cultivars lacking these resistance genes?

Materials and methods

Description of the field sites

Field experiments were conducted over 3 years at five field sites in Germany with different pedo-climatic properties (Table 1).

Experimental design, cultivars and treatments

Fifteen experiments including eight cultivars and three fungicide strategies were conducted. The experimental design was a two-factorial randomized block design with four replicates and finally 96 plots per site. Each plot had a minimum size of 10 m^2. Eight winter wheat cultivars with different susceptibilities to diseases present at the five locations were used (Table 2).

Four of the selected cultivars (Apertus, JB Asano, Julius and Patras) were widely cultivated in Germany at the start of the field trials. The other four cultivars (Attraktion, Dichter, Capone and Spontan) demonstrated a high resistance level with scores from 1 to 3 against at least four of the five diseases (Table 2) and are further designated as cultivars with multi-disease resistance according to Miedaner and Juroszek (2021). The German wheat classification system grades cultivars according to their baking quality as part of the approval process (Bundessortenamt, 2020). Class E wheat (elite) has the highest quality, followed by A wheat (quality), B wheat (breadmaking) and C wheat (not suitable for baking). Assignment to a specific quality group depends on individual quality characteristics such as protein content, loaf volume, falling number, sedimentation value, water absorption and milling efficiency, as well as a comparison with a defined reference cultivar. All cultivars used for the field experiments belong to wheat quality level A of the German wheat quality classification.

Sowing took place in all years between September 24 and October 19. The sowing rate was identical at each location for the individual cultivars and varied between 250 and 360 seeds m^{-2}. The additional cropping decisions such as fertilization, use of growth regulators, herbicides and insecticides were made in accordance with local conditions.

Three different fungicide strategies were tested: (1) untreated control, (2) situation-related strategy and (3) practice-related strategy (Table 3). No fungicide treatment was applied in the untreated control. In the situation-related strategy, the resistance level of each respective cultivar was considered, and a fungicide application in one cultivar was only applied after the respective disease control threshold was exceeded in this cultivar. In the practice-related strategy, the resistance of a cultivar was not considered and all cultivars were treated equally if a threshold was exceeded in one cultivar.

After exceeding the disease threshold an adequate fungicide for the main indication was selected and applied. In addition, forecasting models were used to predict the occurrence of eyespot and Septoria leaf blotch infections (Erven, 2011; Weinert et al., 2004). Strobilurins and carboxamides were used only once per season and azoles were changed as recommended for

Table 1 GPS-Coordinates and soil characteristics of the five locations of the experimental sites

Site	Abbrev.	GPS-Coordinates	State	Soil characteristics
Bingen	BIN	50.577518 N 7.229924 E	Rhineland Palatinate	sandy loamy
Dahnsdorf	DAH	52.108494 N 12.636338 E	Brandenburg	sandy silt
Groß Lüsewitz	GL	54.071600 N 12.336659 E	Mecklenburg Western Pomerania	sandy loamy
Söllingen	SOL	52.091594 N 10.926326 E	Lower Saxony	loamy
Thyrow	THY	52.251630 N 13.251703 E	Brandenburg	sand to loamy sand

Table 2 Resistance classification of the eight winter wheat cultivars according to the descriptive cultivar list of the Federal plant cultivar office and their year of release (Bundessortenamt, 2016)

Cultivar	Year of release	Powdery mildew	Septoria leaf blotch	Yellow rust	Leaf rust	Fusarium head blight
JB Asano	2008	3	7	8	5	6
Julius	2008	4	4	2	4	5
Patras	2012	3	5	3	5	4
Apertus	2013	4	4	3	5	4
Attraktion	2014	1	3	2	3	6
Capone	2012	2	3	3	2	5
Dichter	2014	3	2	2	2	4
Spontan	2014	3	3	1	4	3

1 = completely resistant, 9 = highly susceptible

fungicide resistance management. Further treatment was only applied after the reoccurrence of active spores or lesions on the three upper leaves. The application rates of the fungicides used were at least 70%. All fungicides were sprayed with a water content of 200 to 320 l ha^{-1}. As fungicide resistances were also investigated in another subproject, an attempt was made to use identical fungicides in the 3 years of testing if possible.

Field assessments

In order to decide on the necessary fungicide applications, disease infestation was evaluated in all years starting from growth stage (GS) 31 by mostly weekly control assessments up to the first treatment date. In order to determine the effectiveness of the fungicides, additional assessments were carried out 14 to 21 days after application. The disease incidence (number of infested plants) and severity (percentage of leaf area affected) of all fungal pathogens on the upper three or four leaves was recorded every 1 to 2 weeks. Ten plants were assessed per plot. Treatment with a fungicide approved for the observed diseases (Tables 4 and 5) was carried out after exceeding the disease control threshold for each disease (Table 6). A treatment against Fusarium head blight was applied depending on the resistance level, previous crop, tillage and weather conditions during flowering according to Brandfaß and

Table 3 Fungicide strategies for the eight cultivars

Fungicide strategy	Cultivar disease resistance	Fungicide treatment
untreated control		none
situation-related	considered	each cultivar treated individually (application rate; spraying date) once disease threshold is exceeded in the specific cultivar
practice-related	partly ignored	same treatment for all cultivars once disease threshold is exceeded in any one of them

Table 4 Treated diseases and fungicides used, application rates and growth stages (GS) at the time of fungicide application in the situation-related (sit) and practice-related (prac) strategy at the five field sites in the years 2016–2018

Year	Site	Treated diseases	GS	Strategy (cultivars sprayed)	Trade name - Fungicide	Application dose [l ha^{-1}]
2016	BIN	YR	31	prac (all)	Pronto Plus	1.5
		SLB	39/43	prac (all)	Aviator Xpro / Fandango	0.75/0.75
		FHB	63/65	prac (all)	Osiris	2.5
		YR	31	sit (JB Asano)	Pronto Plus	1.5
		YR	39/43	sit (Apertus, Attraktion, Capone, JB Asano, Patras)	Ceriax	2
		FHB	63/65	sit (Attraktion, JB Asano)	Input Classic	1.25
		LR	59/63	sit (Dichter, Julius, Spontan)	Ceriax	2
	DAH	YR	31	prac (all)	Pronto Plus	1.5
		YR	43/51	prac (all)	Aviator Xpro / Fandango	0.75/0.75
		YR	31	sit (JB Asano, Apertus, Attraktion)	Pronto Plus	1.5
		YR	43/51	sit (Capone, Patras)	Ceriax	2
		YR	59/61	sit (JB Asano, Julius)	Ceriax	2
	SOL	YR	31	prac (all)	Input Classic	1.25
		YR	39/43	prac (all)	Adexar	1.6
		FHB	63/65	prac (all)	Prosaro	1
		YR	31	sit (JB Asano, Apertus, Attraktion)	Input Classic	1.25
		YR	39/43	sit (JB Asano, Capone, Patras)	Ceriax	2
		FHB	63/65	sit (Attraktion, JB Asano)	Prosaro	1
	THY	PM	31	prac (all)	Capalo	2
		YR	49/51	prac (all)	Aviator Xpro / Fandango	0.75/0.75
		YR	31	sit (JB Asano)	Pronto Plus	1.5
		YR	49/51	sit (JB Asano)	Ceriax	2
2017	BIN	YR	37/39	prac (all)	Ceriax	2
		YR	37/39	sit (JB Asano)	Ceriax	2
	DAH	SLB	31/32	prac (all)	Input Classic	1.25
		YR	59/61	prac (all)	Ceriax	2
		SLB	31/32	sit (all)	Input Classic	1.25
		YR	59/61	sit (Apertus, JB Asano, Julius)	Ceriax	2
		LR	69	sit (Patras, Spontan)	Ceriax	2
	GL	SLB/YR	31/32	prac (all)	Input Classic	1.25
		SLB/YR	31/32	sit (JB Asano)	Input Classic	1.25
		SLB	32	sit (Julius, Patras, Apertus)	Input Classic	1.25
	SOL	SLB	32	prac (all)	Input Classic	1.25
		LR	67/69	prac (all)	Ceriax	2
		SLB	32	sit (all)	Input Classic	1.25
		LR	67/69	sit (JB Asano, Julius, Patras, Spontan)	Ceriax	2
	THY	SLB	31	prac (all)	Input Classic	1.25
		SLB	31	sit (JB Asano, Julius)	Input Classic	1.25
2018	BIN	YR	35/37	prac (all)	Ceriax	2
		FHB	61/65	prac (all)	Prosaro	1
		LR	35/37	sit (Apertus, Julius)	Ceriax	2
		YR	35/37	sit (JB Asano)	Ceriax	2

Table 4 (continued)

Year	Site	Treated diseases	GS	Strategy (cultivars sprayed)	Trade name - Fungicide	Application dose [l ha^{-1}]
		LR	49/55	sit (Attraktion, Patras, Spontan)	Ceriax	2
		FHB	61/65	sit (Attraktion, JB Asano)	Prosaro	1
		LR	61/65	sit (Capone, Dichter)	Prosaro	1
	DAH	YR	31	prac (all)	Pronto Plus	1.5
		LR	49/55	prac (all)	Ceriax	2
		YR	31	sit (JB Asano)	Pronto Plus	1.5
		LR	49/55	sit (Apertus, JB Asano, Julius, Patras, Spontan)	Ceriax	2
	GL	YR	33/36	prac (all)	Pronto Plus	1.5
		YR	33/35	sit (JB Asano)	Pronto Plus	1.5
	SOL	YR	32	prac (all)	Input Classic	1.25
		LR	59/61	prac (all)	Ceriax	2
		YR	32	sit (JB Asano)	Input Classic	1.25
		LR	59/61	sit (all except Capone)	Ceriax	2
	THY	YR	55	prac (all)	Ceriax	2
		YR	55	sit (JB Asano)	Ceriax	2

YR Yellow rust, *LR* Leaf rust, *SLB* Septoria leaf blotch, *FHB* Fusarium head blight, PM = Powdery mildew

Weinert (2009). A particularly high risk of infection is only present if sufficient precipitation occurs during flowering, together with high average daily temperatures above 17 °C.

Weather data including mean temperature (°C) and total precipitation (mm) for all sites and years was provided by the German weather service (DWD) and in Dahnsdorf from the operational weather station.

Intensity of plant protection and economic efficiency

To evaluate the intensity of fungicide applications the fungicide treatment frequency was determined as the number of fungicide applications performed and the treatment frequency index (TFI). The TFI is calculated as the quotient of the real application rate and the maximum possible application rate multiplied by the quotient of treated area and total area (Kudsk & Jensen, 2014). An application on the entire area with the full application rate results in a TFI of 1. If the application rate is reduced by 50%, the TFI is halved to a value of 0.5.

The grain prices valid in the respective years of 14.42 € dt^{-1}, 15.38€ dt^{-1} and 15.13€ dt^{-1} (AMI Marktbilanz, 2016, 2017, 2018) and fungicide prices as well as application costs were used for the calculation of the net

Table 5 Trade name, active ingredients and maximum individual dose of the used fungicides

Trade name fungicide	Active ingredients [g l^{-1}]	Maximum individual dose [l ha^{-1}]
Adexar	62.5 Epoxiconazol, 62.5 Fluxapyroxad	2.5
Aviator Xpro	150 Prothioconazol, 75 Bixafen	1.25
Capalo	62.5 Epoxiconazol, 200 Fenpropimorph, 75 Metrafenone	2
Ceriax	41.6 Epoxiconazol, 66.6 Pyraclostrobin, 41.6 Fluxapyroxad	3
Fandango	100 Prothioconazol, 100 Fluoxastrobin	1.5
Input Classic	160 Prothioconazol, 300 Spiroxamine	1.25
Pronto Plus	250 Spiroxamine, 133 Tebuconazol	1.5
Prosaro	125 Tebuconazol, 125 Prothioconazol	1
Osiris	37.5 Epoxiconazol, 27.5 Metconazol	3

Table 6 Disease control threshold for fungal diseases in winter wheat as well as object and growth stage (GS)

Disease	Object	GS	Disease control threshold (Incidence)
Powdery mildew	3 upper leaves	32–61	60%
Septoria ssp.*	4 upper leaves	32–37	30%
		39–61	10%
Yellow rust	3 upper leaves	31–61	first nests (susceptible cultivars)
			30% (resistant cultivars)
Leaf rust	3 upper leaves	37–61/69	30%
Eyespot**			

* = additional use of decision support system SEPTRI, ** = decision support system SIMCERC

return. The net return is the product of the yield and the product price minus the fungicide costs (fungicide price and application costs). Labour and machine costs of fungicide sprayings are calculated as the mean of common field sizes ranging from 1 to 20 ha and farm-field distances from 1 to 30 km (KTBL, 2016–2018). Labour and diesel costs are included. The respective labour costs range between 4.03 and 4.90 € ha^{-1}, the machine costs between 8.68 and 9.67 € ha^{-1}. In total, the application costs vary between 12.71 and 14.57 € ha^{-1}. Under these assumptions, the average application costs amount to 12.48 € ha^{-1}. Other direct and fixed costs were not considered in this study.

Data analyses

The effects of different fungicide strategies and cultivars on dependent variables were analysed with linear mixed models (Moll & Piepho, 2001) using the PROC GLIMMIX procedure of SAS 9.4. Due to the large differences between sites and years in terms of disease pressure and yields, statistical studies were conducted both across years and sites, but also within years and sites. Wheat grain yield, disease severity, TFI and net return were the dependent variables and strategies, cultivars, field sites and their interactions were treated as fixed effects. Years and blocks were considered random effects. Least squares mean for grain yields, treatment frequency index and disease severity were estimated by using the LS means option and a 0.05 probability level. These squares were then compared for differences in the different strategies and cultivars with Simulate or Tukey HSD adjustment tests. The data on disease severities were calculated with a chi-square statistic. In the model, the percentages were transformed with the link function logit. The variance function was defined with the variable $variance = \mu^2(1-\mu)^2$ (Munzert, 2015).

Results

Weather conditions during the growing season for all sites and years

The mean air temperature and the total precipitation in the individual months of the trial years are shown in Table 7.

The five sites differed in terms of temperature and precipitation (Table 7). The lowest rainfall over the years was recorded in Thyrow. The average annual temperature was highest in all years in Bingen with 11.6 to 12.8 °C. In contrast, Groß Lüsewitz had the lowest mean annual temperatures of 9.2 to 9.9 °C but the highest precipitation over the years. The year 2018 was characterized by severe drought in many parts of Germany. This is reflected in the low precipitation, lowest at Dahnsdorf (275 mm) and highest in Bingen (465 mm). In 2016 large parts of the eight cultivated cultivars showed severe damage in Groß Lüsewitz because of outwintering. Thus, the trial was abandoned and broken up. In 2016, only results from the other four locations are available.

Table 7 Total precipitation and mean air temperature at the five field sites in the years 2016 to 2018

Site	Mean air temperature (°C)			Total precipitation (mm)		
	2016	2017	2018	2016	2017	2018
Bingen	11.5	11.7	12.7	555	519	465
Dahnsdorf	9.7	9.7	10.6	614	622	275
Groß Lüsewitz	9.4	9.2	9.9	490	845	469
Söllingen	10.5	10.5	11.2	443	736	366
Thyrow	10.1	10.0	11.0	482	702	324

Disease severity data

The incidence of the diseases varied strongly during the 3 years of investigation and at the different sites (Fig. 1). In 2016, the main disease at the sites in Bingen, Dahnsdorf and Söllingen was early developing yellow rust. Treatments were already required at these three sites at GS 31 (Table 4). While all cultivars were treated in the practice-related strategy, only the cultivars on which the disease threshold was exceeded were treated in the situation-related strategy. The cultivar JB Asano was most severely affected due to its high susceptibility. In Bingen, the leaves of JB Asano were already absent at the last assessment date due to the high infestation with

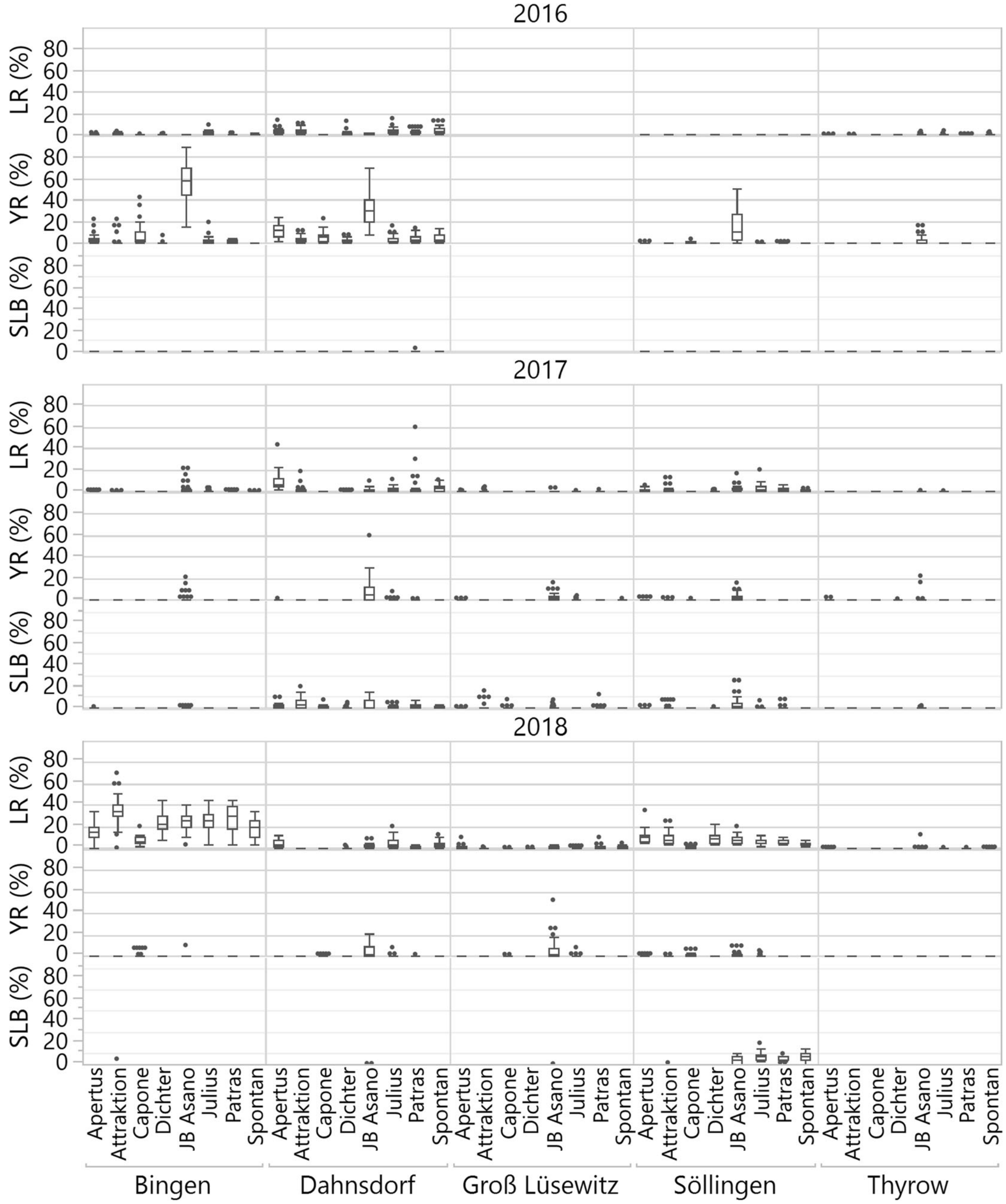

Fig. 1 Box plots of disease severities for leaf rust (LR), yellow rust (YR) and Septoria leaf blotch (SLB) in the untreated control assessed on the eight cultivars at the five field sites in the 3 years of investigation averaged over the two upper leaves (GS 59–85)

yellow rust. Thus a previous date (GS 59) was selected to quantify the disease severity. Also, the cultivars classified as resistant (Table 2) showed yellow rust infestation. Due to optimal weather conditions for Fusarium head blight, treatments were required in Bingen and Dahnsdorf. Powdery mildew only occurred in Thyrow and had to be treated due to the high frequency of infestation of more than 60% of the plants. Later, leaf rust led to further treatments in some cultivars in Bingen.

In 2017, the control threshold for Septoria leaf blotch was exceeded early in Dahnsdorf and Söllingen and the decision support system SEPTRI (Erven, 2011) also indicated infection events. This resulted in fungicide applications in both fungicide strategies (Table 4). In addition, treatments were conducted against yellow rust in Dahnsdorf and against late occurring leaf rust in Söllingen. In Groß Lüsewitz, Thyrow and Bingen, the disease severity and incidence was very low in 2017. As a result, fungicide treatments were only necessary for a few cultivars in the situation-related strategy at these locations, and this was also evident in the practice-related strategy.

Due to severe drought throughout Germany in 2018, Septoria leaf blotch did not exceed the control threshold at any of the locations as the necessary moisture was lacking and in some locations senescence of the leaves began early. Treatments against yellow rust in the susceptible cultivar JB Asano were carried out early at all sites except in Thyrow. Late treatments against leaf rust were carried out in Söllingen, Dahnsdorf and Bingen. Disease incidence in the cultivars Dichter and Capone exceeded the action thresholds for leaf rust despite their classification as strongly resistant based on the information of the German Federal Plant Variety Office (Table 2), resulting in a treatment (Table 4). The lowest levels of disease severities for leaf rust were recorded in the cultivar Capone at the end of the growing season (Fig. 1). In Groß Lüsewitz and Thyrow the infestation level was also very low in 2018. As a result, fungicide treatments in the situation-related strategy were only necessary in a few cultivars at these sites.

Effects of fungicide strategies and host resistance on disease severity

In all 3 years, the treatments in the situation-related and practice-related strategies led to low levels of disease severities (Fig. 2). This was particularly obvious at the sites in Bingen, Dahnsdorf and Söllingen with somewhat high initial severities. Disease severities of the highly susceptible cultivar JB Asano were significantly reduced by fungicide applications at all sites. In 2016, the cultivars Spontan, Dichter and Attraktion showed only low disease severities for yellow rust. The cultivar Dichter showed moderately high levels of disease infestation in 2018, which was significantly controlled by both fungicide strategies (Fig. 2). In Thyrow, there were less significant differences between strategies due to the low disease incidence on the two upper leaves.

Effects of fungicide strategies and host resistance on fungicide intensity

Table 8 shows the fungicide TFIs of the situation-related and practice-related strategies for the five sites in the years 2016 to 2018. Here, the differences between the sites and years in terms of fungicide treatments are clearly visible. At the Dahnsdorf (1.8), Bingen (1.9) and Söllingen (2.1) sites the TFI was significantly higher over the years and cultivars in the practice-related strategy than in Groß Lüsewitz (1.0) and in Thyrow (1.3). The average TFI over all years and locations was 1.7 in the practice-related strategy (Table 8). In contrast, the situation-based strategy only showed an average TFI of 0.7. The cultivars Dichter (0.3), Capone (0.4) and Spontan (0.4) were treated much less frequently and accordingly showed a significantly different average TFI compared to the practice-related strategy. These three cultivars remained untreated in Thyrow and Groß Lüsewitz in all of the 3 years, as the control thresholds were not exceeded at any time. However, no significant differences could be found between these three cultivars and the more resistant cultivars (Dichter, Capone and Spontan). The highly susceptible cultivar JB Asano showed the highest TFI of 1.6 in the situation-based strategy, which did not differ significantly from the TFI in the practice-based strategy of 1.7. The high yellow rust susceptibility of this cultivar required several fungicide applications in 2016, as there was no leeway to prevent reduced yields. Between years, there were differences in TFI due to the varying disease pressure of each fungal pathogen (Fig. 2). The early and strong appearance of yellow rust in 2016 resulted in early and sometimes additional fungicide treatments, while leaf rust usually appeared late in Germany and therefore required only a single treatment (Table 4).

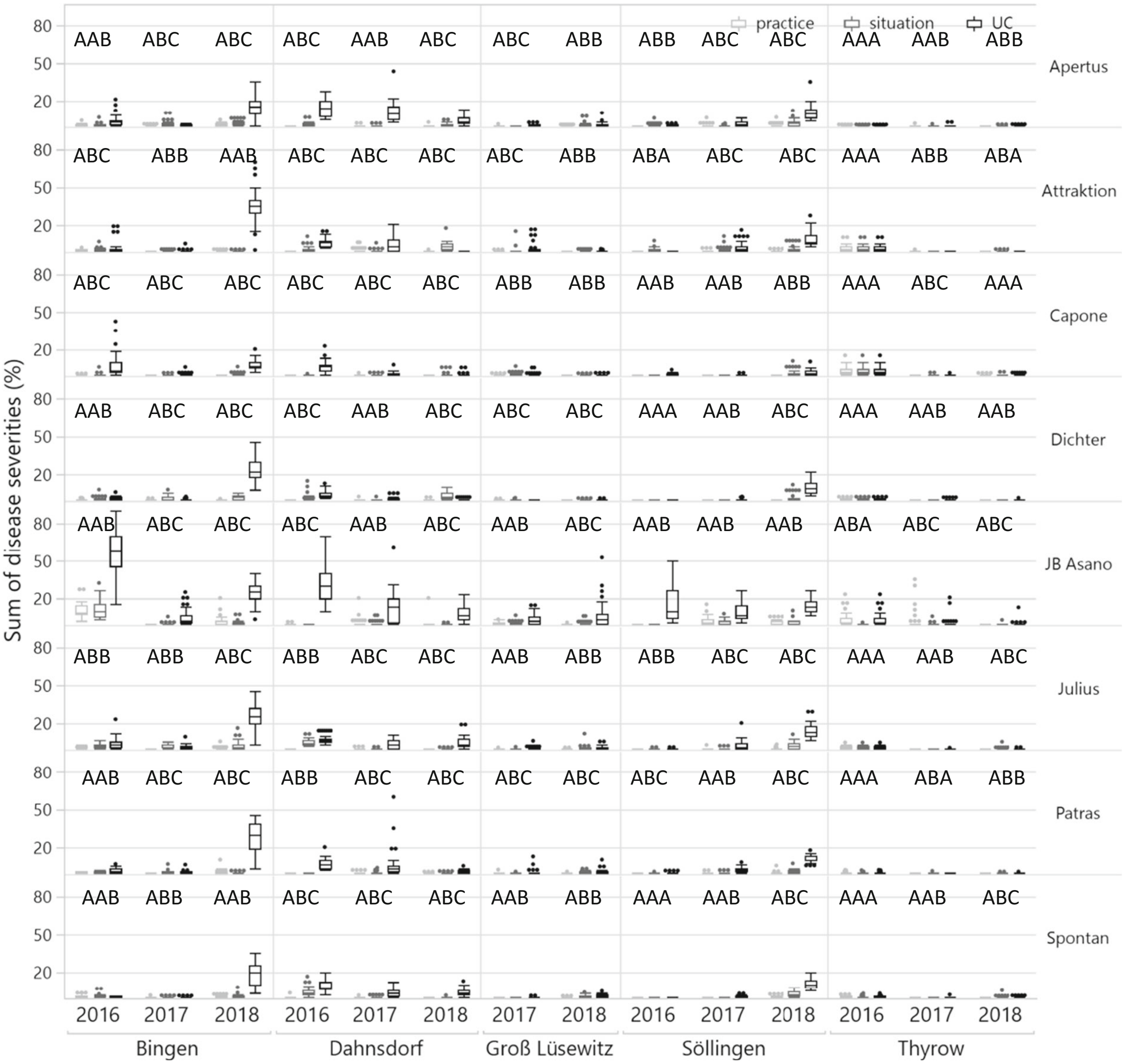

Fig. 2 Box plots for the sum of all disease severities (yellow rust, powdery mildew, leaf rust, Septoria leaf blotch) averaged over the two upper leaves (GS 59–85) and assessed on the eight cultivars in the different strategies (untreated, situation-related and practice-related) at the five field sites in the years 2016–2018 (same letters within the site and year are not significantly different according to Tukey adjustment test at the 0.05 probability level)

On average over all years and sites, a reduction of the TFI by up to 82% was possible in the cultivar Dichter. For the highly susceptible cultivar JB Asano this value was reduced by only 7%. A total of 25 treatments per cultivar were carried out in the practice-related strategy over all years and sites (Table 4). In the situation-related strategy, the cultivars Dichter and Capone were treated only 5 and 6 times respectively, while the highly susceptible cultivar JB Asano was treated 25 times, the same frequency as in the practice-related strategy.

Effects of fungicide strategies and host resistance on grain yield

The variability of yields between the five locations and years was very high (Fig. 3a). In Thyrow, with its slightly silty sandy soil, a marginal site for wheat cultivation, the average yield of the years and cultivars was 35 dt ha^{-1} (practice-related strategy), whereas in Söllingen, a breeder's site with high organic matter content and loamy topsoil, it was 109 dt ha^{-1}

Table 8 TFI for the situation- and practice-related fungicide strategy in the eight cultivars at the five field sites during the 3 years of investigation

Strategy	Cultivar	Bingen				Dahnsdorf				Groß Lüsewitz				Söllingen				Thyrow				All			
		‘16	‘17	‘18	Ø	‘16	‘17	‘18	Ø	‘16	‘17	‘18	Ø	‘16	‘17	‘18	Ø	‘16	‘17	‘18	Ø	‘16	‘17	‘18	Ø
practice	all cultivars	2.9	0.7	1.7	1.8^{a}	2.1	1.7	1.7	1.8^{a}	–	1	1	1^{a}	2.8	1.7	1.7	2.1^{a}	2.1	1	0.7	1.3^{a}	2.5^{a}	1.2^{a}	1.4^{a}	1.7^{a}
situation	Apertus	0.7	0	0.7	0.5	1	1.7	0.7	1.1	–	1	1	1	1	1	1.7	1.2	0	0	0.7	0.2	0.7	0.7	1.0	0.8^{bc}
situation	Attraktion	1.7	0	1.7	1.1	1	1	0	0.7	–	0	0	0	2	1	0.7	1.2	0	0	0	0	1.2	0.4	0.5	0.7^{c}
situation	Capone	0.7	0	1	0.6	0.7	1	0	0.6	–	0	0	0	0.7	1	0	0.6	0	0	0	0	0.5	0.4	0.2	0.4^{c}
situation	Dichter	0.7	0	1	0.6	0	1	0	0.3	–	0	0	0	0	1	0.7	0.6	0	0	0	0	0.2	0.4	0.3	0.3^{c}
situation	JB Asano	2.7	0.7	1.7	1.7	1.7	1.7	1.7	1.7	–	1	1	1	2.7	1.7	1.7	2	1.7	1	0.7	1.1	2.2	1.2	1.4	1.6^{ab}
situation	Julius	0.7	0	0.7	0.5	0.7	1.7	0.7	1	–	1	0	0.5	0	1.7	0.7	0.8	0	1	0	0.3	0.4	1.1	0.4	0.6^{c}
situation	Patras	0.7	0	0.7	0.5	0.7	1.7	0.7	1	–	1	0	0.5	0.7	1.7	0.7	1	0	0	0	0	0.5	0.9	0.4	0.6^{c}
situation	Spontan	0.7	0	0.7	0.5	0	1.7	0.7	0.8	–	0	0	0	0	1.7	0.7	0.8	0	0	0	0	0.2	0.7	0.4	0.4^{c}
situation	mean	1.1	0.1	1	0.7^{b}	0.7	1.4	0.6	0.9^{b}	–	0.5	0.3	0.4^{b}	0.9	1.4	0.9	1^{b}	0.2	0.3	0.2	0.2^{b}	0.7^{b}	0.7^{b}	0.6^{b}	0.7^{b}

- = indicates no data due to outwintering; within columns, means followed by the same letter are not significantly different according to t-test and Tukey’s honestly significant difference test at the 0.05 probability level, letters of situation mean refers only to the comparison with practice all cultivars

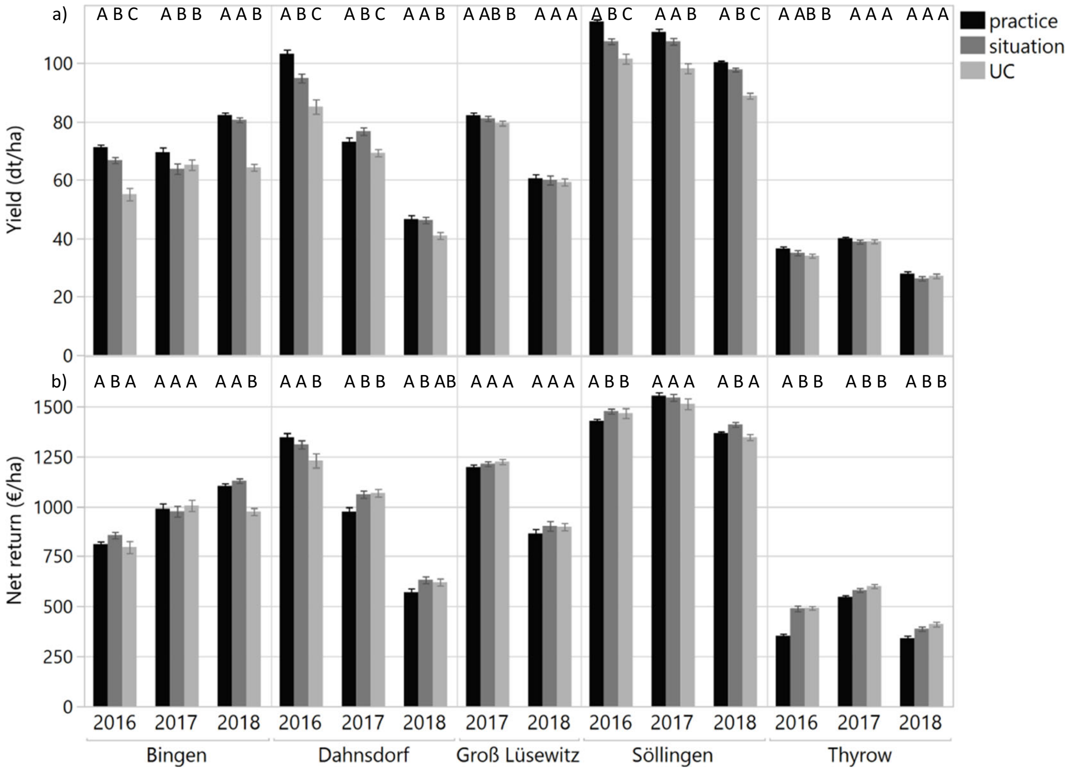

Fig. 3 Yield (**a**), net return (**b**) and standard error of winter wheat for the situation-related strategy, practice-related strategy and untreated control (UC) at the five field sites for the 3 years averaged for the eight cultivars (same letters within the site and year are not significantly different according to Simulate adjustment test at the 0.05 probability level)

(practice-related strategy). Compared to the other years, the drought in 2018 led to lower yields at all sites with the exception of the site in Bingen. In all years, Söllingen showed a significant difference between the treated strategies and the untreated control (Fig. 3a). The same applied to the sites in Bingen and Dahnsdorf in the years 2016 and 2018. In Thyrow only in 2016 and Groß Lüsewitz in 2017 a significant additional yield could be observed for the practice-related strategy compared to the untreated control. Compared to the situation-related strategy, the practice-related strategy showed a higher yield in 2016 in Bingen, Dahnsdorf and Söllingen. There was also a difference in Bingen in 2017, in Söllingen in 2018.

At the cultivar level, six of the eight cultivars showed a significantly higher yield in the practice-related strategy compared to the untreated control over the years in Söllingen (Table 9). At all other sites there were few significant differences and no differences were found in Groß Lüsewitz. In addition, there were no significant differences for the multi-resistant cultivars Capone and Spontan at any site.

Within the strategies averaged over all years, differences between the cultivars could only be detected at the sites Bingen and Söllingen, mainly in the untreated control compared to the susceptible cultivar JB Asano which always showed lower yields here. Compared to the cultivar Dichter, the cultivar JB Asano showed a significantly higher yield in the situation-related strategy (Table 10).

Effects of fungicide strategies and host resistance on net return

Similar to the yields, the variability of the net returns between the five sites and years was very high (Fig. 3b). The lowest net returns were achieved in Thyrow, the highest in Söllingen. In contrast to the yields, which tended to be always highest in the practice-related strategy, the net returns are often lower than in the situation-related strategy and sometimes even lower than in the untreated control. In eight environments, the net return of the situation-related strategy is significantly higher than in the practice-related strategy. In Thyrow, the

Table 9 Significant differences for the pairwise comparison of yields (dt ha^{-1}) between the strategies practice-related, situation-related and untreated control for the eight winter wheat cultivars at the five field sites averaged over all years (Simulate adjustment test at the 0.05 probability level, non-significant results were not shown)

Site	Cultivar	Strategy	Strategy	Estimate	P value
BIN	Dichter	practice	untreated control	15.7912	0.0237
DAH	Apertus	practice	untreated control	11.6630	0.0277
DAH	Apertus	situation	untreated control	10.1425	0.0440
DAH	Julius	situation	untreated control	12.1825	0.0446
SOL	Apertus	practice	untreated control	14.1495	0.0125
SOL	Attraktion	practice	untreated control	9.9787	0.0213
SOL	Dichter	practice	untreated control	14.8833	0.0274
SOL	JB Asano	practice	untreated control	21.6524	0.0210
SOL	JB Asano	situation	untreated control	21.1853	0.0222
SOL	Julius	practice	untreated control	13.4162	0.0331
SOL	Patras	practice	untreated control	14.7172	0.0019
SOL	Patras	situation	untreated control	10.5986	0.0071
THY	Attraktion	practice	untreated control	3.7044	0.0190

practice-related strategy resulted in significantly lower net return from the different cultivars than the situation-related strategy and even the untreated control treatment.

At the cultivar level, the untreated control and the situation-related strategy showed a significant increase in net return compared to the practice-related strategy for the cultivar Capone (Fig. 4a). With the exception of the cultivar JB Asano, the net returns for all other cultivars tended to be lower in the practice-related strategy. The application costs were always higher in the practice-related strategy with 130 € ha^{-1} than in the situation-related strategy (Fig. 4b). Cultivar Dichter had the lowest fungicide and application costs in the situation-related strategy, JB Asano the highest.

Table 10 Significant differences for the pairwise comparison of yields (dt ha^{-1}) between the eight winter wheat cultivars for three fungicide strategies at the five field sites over all years (Simulate adjustment test at the 0.05 probability level, non-significant results were not shown)

Site	Strategy	Cultivar	Cultivar	Estimate	P value
BIN	untreated	Apertus	JB Asano	12.6647	0.0456
BIN	untreated	Attraktion	JB Asano	15.5402	0.0052
BIN	untreated	Capone	JB Asano	14.3004	0.0129
BIN	untreated	JB Asano	Spontan	−15.0273	0.0074
SOL	situation	Dichter	JB Asano	−9.9967	0.0079
SOL	untreated	Capone	Dichter	11.9319	0.0401
SOL	untreated	Capone	JB Asano	17.5126	0.0002
SOL	untreated	JB Asano	Spontan	−11.6175	0.0489

When comparing the cultivars within the strategies over the years, significant differences in net returns were only found at the sites in Söllingen and Bingen (Table 11). The cultivar Capone with multi-disease resistance often showed significantly higher returns here and cultivar JB Asano significantly lower returns.

Discussion

The results of this study demonstrate that consistent use of disease thresholds may significantly reduce the intensity of fungicide use without reducing the net return. The level of reducing fungicide application was strongly dependent on the type and level of resistance of the cultivars to the diseases occurring at the field site. The cultivars with multi-disease resistance were shown to be comparable to the other cultivars in terms of yield and net return.

The dominant diseases in the years under investigation were yellow rust and leaf rust. In the years 2014 to 2016 a yellow rust calamity was observed in Germany, caused by the spread of the newly emerged Warrior races (Flath et al., 2014). Prior to this, yellow rust appeared rather sporadically in Germany, but its occurrence resulted in high yield losses or increased fungicide

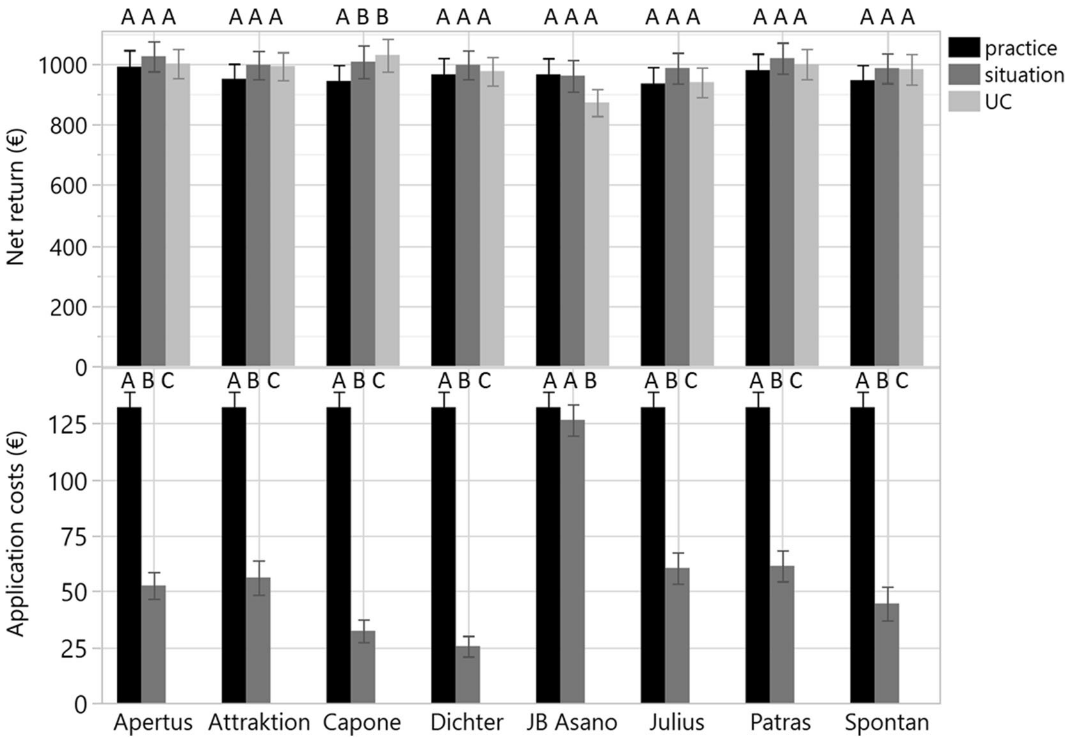

Fig. 4 Net return (**a**), application costs (**b**) and standard error for the eight winter wheat cultivars for the situation-related strategy, practice-related strategy and untreated control (UC) averaged for the 3 years and sites (same letters within the cultivar are not significantly different according to Simulate adjustment test at the 0.05 probability level)

treatments. The outbreak of yellow rust, as a result of the new races, was not only observed in Germany, but also in many other European countries in all years (Hovmøller et al., 2015). Many of the previously resistant cultivars now proved to be susceptible (Flath & Miedaner, 2014). At that time, the cultivar JB Asano was most frequently grown in Germany, with a share of 10.2% in 2014 and 8.3% in 2015 (BMEL, 2015), and it showed high susceptibility to Septoria leaf blotch and yellow rust. The cultivar JB Asano was also one of the cultivars examined within this study and its susceptibility inevitably led to high disease levels that required fungicide treatments to avoid high yield losses. All other cultivars showed effective resistance to yellow rust, but even some cultivars with effective resistance had sufficient disease to exceed the disease threshold, resulting in a subsequent treatment. However, the disease severities were much lower than in the highly susceptible cultivar JB Asano.

Table 11 Significant differences for the pairwise comparison of net returns (€ ha^{-1}) between the eight winter wheat cultivars for the three strategies at the five field sites over the years (Simulate adjustment test at the 0.05 probability level, non-significant differences were not shown)

Site	Strategy	Cultivar	Cultivar	Estimate	P value
BIN	UC	Attraktion	JB Asano	226.3488	0.0192
BIN	UC	Capone	JB Asano	210.2275	0.0394
BIN	UC	JB Asano	Spontan	−219.394	0.0259
SOL	UC	Capone	Dichter	178.7927	0.0267
SOL	UC	Capone	JB Asano	259.9901	0.0002
SOL	UC	Capone	Julius	168.426	0.0486
SOL	UC	JB Asano	Spontan	−170.364	0.0439
SOL	sit	Attraktion	Capone	−132.081	0.0135

In addition to yellow rust, leaf rust also occurred in all years at the end of the vegetation period, in some cases exceeding the action threshold, which also resulted in treatments.

Other diseases included Fusarium head blight and Septoria leaf blotch. Cultivars had to be treated due to their susceptibility to Fusarium head blight, as the weather was highly conducive to this disease. Early Septoria leaf blotch infections did not always develop further, because rain splash and moisture were insufficient to spread the infection to the next leaf layer. However, at the sites in Söllingen and Dahnsdorf, clear infections appeared at the end of the growing season in 2017 and 2018. Septoria leaf blotch is one of the most important diseases in Europe, as it is in Germany, and lack of control can lead to high yield losses (Jahn et al., 2012; Willocquet et al., 2021). The severe yellow rust epidemic masked the Septoria leaf blotch symptoms on the leaves to some extent in the years studied and at the same time the weather conditions were not always optimal for further Septoria infections. During these years, yellow rust had an advantage due to its wind-borne spread, which resulted in high disease severities in some areas.

The practice-related strategy was selected in our study because farmers often treat different cultivars with fungicides at the same time, regardless of their resistance level and disease thresholds (Klocke & Dachbrodt-Saaydeh, 2018). The situation-related strategy is the strategy that would be implemented by the farmers according to the principles of IPM. The fungicide treatments in our field trials were effective and led to many significant reductions in disease severities. This was particularly evident at the sites in Bingen, Söllingen and Dahnsdorf, where disease severities were in some cases high. Due to the effective resistance of some cultivars, additional savings of fungicides were possible in the situation-related strategy. Consequently, the use of the disease thresholds allowed a reduction in fungicide use. In 2016, the high yellow rust infestation led to the appearance of active yellow rust spores on the upper three leaves in the cultivars that were supposedly resistant like Attraktion, Capone, Apertus and Patras with a level of 2 (Attraktion) and 3 (Bundessortenamt, 2016). This resulted in unnecessary fungicide applications because disease severities for these cultivars were very low at the end of the growing season in the untreated controls. However, this was not apparent at the time of treatment because the disease threshold was exceeded and confidence in the cultivar's resistance was low due to the unexpected high disease pressure early in the season. Nevertheless, it demonstrated that cultivar resistance, if it can be classified as stable, would allow additional fungicide savings. The previous German disease threshold for yellow rust, which is already exceeded when the first patches with infected plants appear, does not necessarily seem to be valid for resistant cultivars. This is particularly true for adult plant resistance, where seedlings are susceptible, but older plants display strong adult plant resistance. An adjustment for resistant cultivars would be desirable. Due to the race-specific resistance background of many cultivars, overcoming resistance must still always be considered a risk. Pathogen populations are able to change and adapt over time (Poole & Arnaudin, 2014). This was clearly demonstrated with the spread of virulent pathotypes of yellow rust in the last two decades which at that time led to high susceptibilities in the cultivars grown (Bayles et al., 2000; Hovmøller et al., 2008; Hovmøller et al., 2015; Milus et al., 2009). This shows the difficulty farmers are facing when decisions on fungicide applications must be made. The plant protection services of the German federal states have a special function here, as they are supposed to provide updated information to farmers on cultivar resistance levels and the current races and their virulences dominating the German pathogen populations.

In the practice-related strategy described, when the disease threshold was exceeded and all cultivars were treated, no further control of the plots was initially necessary. In the situation-related strategy this was different, as all cultivars were considered individually. The effort of this monitoring was greater as ratings had to be carried out more frequently in order to detect exceeded disease thresholds in the individual cultivars at an early stage. The monitoring efforts should also be taken into account from an economic point of view. The mandatory practice of IPM, however, prescribes situation-based pest management instead of preventive pesticide applications (Anonymous, 2009). In order to reduce the use of fungicides to the necessary minimum, cultivar resistance and disease thresholds are well-suited tools (Jørgensen, Nielsen, et al., 2008a; Klocke et al., 2020) and should be used by farmers. Moreover, they do not necessarily lead to low yields and qualities compared to control treatments that ignore disease thresholds (Das et al., 2007).

At present, it appears that control thresholds are not sufficiently used in practice. The reasons for the low acceptance are certainly diverse. Farmers' decision making is not always the same (Jørgensen, Noe, et al., 2008b). This is partly due to the size of the farms, which does not always allow decisions to be made for each field individually. In addition, farmers believe that not applying fungicides carries risks that can affect yield and cause additional work. A risk-averse farmer is more difficult to convince to use disease thresholds. The use of preventive measures for pest control faces obstacles related to profitability and lack of farmer knowledge (Matyjaszczyk, 2019). Plant protection services should be the link here between science and farmers to effectively communicate the risks and benefits of implementing different IPM strategies.

The potential for reducing pesticide applications when growing a resistant cultivar when using disease thresholds becomes obvious in the situation-related strategy. The TFIs of the resistant cultivars are significantly reduced within this strategy for all cultivars except cultivar JB Asano. The cultivars Capone and Dichter showed the lowest TFI across all years and locations which could reduce the use of fungicides by more than 80% compared to the practice-related strategy. On average, across all cultivars using the situation-related strategy, this reduction was still 59% with a TFI of 0.7. However, a reduction of only 7% was possible in the susceptible cultivar JB Asano. There is not much tolerance for reduction of pesticide applications in highly susceptible cultivars where rapid treatment is required to avoid high infestation levels and therewith reduced yields (Chen, 2014). This conclusion was also drawn by Viljanen-Rollinson et al. (2010) who observed low efficacy of fungicides against yellow rust if the fungicide application was done after the occurrence of the disease in a susceptible wheat cultivar. In contrast, the resistant cultivars could be effectively protected when treated after disease emergence. Using susceptible cultivars makes implementation of IPM more difficult because acute fungicide applications need to be applied almost before symptom development, and a long time before it is known whether an epidemic would have an impact on yield. Since treatment should only take place after the disease threshold has been exceeded the choice of a resistant cultivar should always be recommended.

Compared to the studies by Dachbrodt-Saaydeh et al. (2021), who found TFIs in German arable farms in winter wheat of 2.6 and 2.5 for the years 2016–2017 and 2.0 for 2018 (personal communication), the TFIs achieved in our study can nevertheless be described as lower in the practice-related strategy. In Groß Lüsewitz, only one treatment was carried out in the practice-related strategy over both trial years. Also, at the high-yield site Söllingen, the cultivars Capone, Dichter, Julius and Spontan were not treated in the situation-related strategy in some years. Compared to common practice, this is rather unusual in German winter wheat, but due to the use of the disease thresholds, also in the practice-related strategy, no further treatment was necessary in the results shown. Ear treatments, which are mainly applied against Fusarium head blight to avoid the formation of mycotoxins, cannot be prevented in years with optimal infection conditions at flowering (Wegulo et al., 2015). In this study, treatments against Fusarium were also carried out in cultivars that showed increased susceptibility. By optimising crop rotation and selecting moderately resistant cultivars, it is nevertheless possible to manage infections by IPM means (Blandino et al., 2012).

Therefore, the situation-related strategy shows a clear advantage compared to the practice-related strategy in terms of saving fungicides. The additional fungicide applications in the practice-related strategy did not lead to significantly higher yield in any of the eight cultivars, even though yield tended to be higher and highest in the susceptible cultivar JB Asano. On average over all cultivars, there were some significant differences between the three strategies. This is particularly obvious for the years 2016 and 2018, with high disease pressure for yellow and leaf rust. However, even when comparing the practice-related strategy and the untreated control, significant differences were not found at all sites. The multi-resistant cultivars Capone and Dichter showed no differences between the treated and untreated strategies at all sites, averaged over the years. Thus, treatment of these cultivars would not have been necessary at all and this emphasized the importance of resistance in disease management.

Other studies on fungicide applications in wheat revealed clearer differences between untreated controls and treated plants (Chen, 2014; Lollato et al., 2019; Thompson et al., 2014; Wegulo et al., 2011; Wiik & Rosenqvist, 2010). The good efficacy of fungicides with regard to the protection of the upper three leaves especially in susceptible cultivars under high disease pressure is often described. Seven of the eight cultivars used here showed effective resistance characteristics at all sites in all 3 years. As a result, disease thresholds were not reached thus saving fungicide applications. The combination of cultivar resistance and disease thresholds can lead to a more efficient management of fungal diseases (Jørgensen, Nielsen, et al., 2008a), which is supported by this study.

Since Septoria leaf blotch did not lead to significant disease severities in any of the years, unfortunately no statements can be made about how this would have affected yields. Septoria leaf blotch is one of the most important diseases in Germany with high yield losses and the higher susceptibility of the cultivars on the market inevitably leads to necessary fungicide measures (Jahn et al., 2010; Jahn et al., 2012; Savary et al., 2019). In the 3 years under investigation, however, this disease did not play a major role at any of the sites, shown by the low disease severities in the untreated controls. Due to the high susceptibility of the cultivars JB Asano, Patras, Julius and Apertus, the situation-related strategy could have shown a completely different application pattern if Septoria leaf blotch had also been present. The cultivars with multi-disease resistance could then have been able to show their potential even better.

Yield, disease resistance and quality are important breeding goals, and focusing on one goal can lead to negative consequences for the other (Dahl et al., 2004). So far, disease resistance is still not the top priority, because yield is the most important factor for the performance of a variety (Brown, 2002). Loyce et al. (2008) could not show (high) disadvantages in yields of cultivars with multi-disease resistance compared to cultivars that had effective resistance against fewer of the important fungal diseases. Similarly here, the multi-disease resistant cultivars Attraktion, Capone, Dichter, and Spontan maintained the yields of the other cultivars. At the same time, they also showed their clear advantage within the situation-related strategy due to their great potential for fungicide savings. While Loyce et al. (2012) suggest cultivars with multi-disease resistance in low input systems, we suggest that these cultivars should also be preferred in high input cropping systems.

The economic benefits of the situation-related strategy with significantly lower fungicide input become apparent when considering the net returns. In all cultivars, with the exception of the cultivar JB Asano, the lowest net return was achieved in the practice-related strategy averaged over all years and locations. The high application costs (fungicide and passage costs) were not compensated by higher yields. A treatment did not lead to significant differences in any cultivar after consideration of the returns, so treatments would not have been necessary. These results cannot be expected in future years since yields and also net returns are highly variable between years (Wiik & Rosenqvist, 2010). If cultivar susceptibility and disease pressure is high, fungicide treatments are often economically advantageous (Ransom & McMullen, 2008; Thompson et al., 2014; Wegulo et al., 2011). Here, this is attributable to the application costs of 130 € ha^{-1} and also dependent on German market wheat prices, which in the 3 years were 14.42 € dt^{-1}, 15.38€ dt^{-1} and 15.13€ dt^{-1} respectively. Due to the high application costs, a treatment was therefore only worthwhile if at least about 8.5 dt ha^{-1} additional yield per cultivar could be achieved in the practice-related strategy. One approach taken by other countries is to greatly reduce the dose rate. As a result, in studies on yellow rust, it was not the dose that was decisive, but the optimal time of treatment (Jørgensen & Nielsen, 1994). In Germany, these strong reductions are not recommended by the plant protection services of the federal states. Costs have to be balanced with increased yields and wheat prices to evaluate the economic efficiency of a fungicide treatment to control fungal wheat diseases (Wegulo et al., 2011).

The five locations should be distributed over different regions of Germany to improve the overall comparability of the results. The heterogeneity of these selected locations in terms of yield potential was very high. While high yields were generated in Söllingen, with the best soil for growing wheat, these were extremely low at the site in Thyrow with its sandy soil (Table 1). Dahnsdorf, Groß Lüsewitz and Bingen showed moderate, but in some cases also very heterogeneous yields, e.g. in Dahnsdorf. These large annual differences at the sites are due to the drought in 2018, which led to lower yields at all sites except Bingen. The choice of location plays an additional role here. At all sites, the net return averaged over all cultivars was significantly higher in the situation-based strategy or there was no significant difference from the practice-based strategy. In no case was the practice-based strategy more advantageous in terms of net returns. At sites with low yield potential, such as Thyrow, regular treatments were only necessary in the highly susceptible cultivar JB Asano. In five cultivars, no treatment was carried out in the situation-related strategy. Here, the use of resistant cultivars would be advisable and thus fungicides could be completely dispensed with. Additionally at all other sites, cases existed where cultivars were not treated at all in the situation-related strategy. The low incidence of diseases in Groß Lüsewitz was also surprising, as higher infestation pressure was expected due to the close location to the coast.

For farmers, it is not always easy to trust the resistance of a cultivar if there is a risk of a possible yield loss and weather conditions are not predictable. Race specific resistances are often used in breeding resistant cultivars but are known to not be durable since there is always a risk that resistance is overcome because of the emergence of new virulent races (Pink, 2002). It is therefore necessary to constantly update the ranking of cultivars, which is carried out regularly by the Federal Plant Variety Office. Some of the cultivars used in this study are now classified with higher susceptibility scores for some diseases (Bundessortenamt, 2021). The cultivar Julius, for example, can no longer be classified as resistant to yellow rust and the same applies to the cultivar Dichter for powdery mildew. Both cultivars are now classified with a score of 5 in contrast to the previous classification of 3 (Dichter) and 2 (Julius) in 2016. Even in the cultivars classified as resistant, it is therefore always necessary to carry out consistent monitoring during the season in order to detect when a threshold is exceeded at an early stage. Since there is no disease threshold for fusarium head blight, a decision on fungicide application is based on weather conditions, cultivar resistance and tillage.

Conclusion

After considering the diseases, the TFI, the yield and the net return in this study, it becomes clear that situation-related crop protection is an integrated concept which can significantly reduce fungicide applications without economic loss. The higher yields of the more susceptible, high-yielding cultivar JB Asano, although cultivated over a large area at the time of this study, could not compensate for the increase in fungicide costs from the required additional fungicide applications. The IPM goal of reducing fungicide measures to the necessary minimum is achieved through the consistent use of disease control thresholds in combination with effective cultivar disease resistance. The consistent use of disease thresholds led to a significant reduction of the TFI in the situation-related strategy. By integrating cultivars with multi-disease resistance into crop rotations, it is possible to avoid fungicide applications thus practising sustainable crop protection and IPM. Moreover, in the light of decreasing availability of fungicidal substances and in the context of resistance management, this is a promising alternative with high potential for farmers.

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Author contribution BK designed the study with the support of HK, JS, MB, FE, AJ and JP, prepared the figures and wrote large parts of the paper. NS, CW and JS organised the collected data and performed the statistical analysis. NS and BK coordinated the field activity. JS, MB, FE, AJ, KM, JP and PW were responsible for the field trial management. NS, HK, JP, JS, PW and SR participated in writing the manuscript.

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Declarations

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

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