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Improved integrated management of Cercospora leaf spot (*Cercospora beticola*) with a new-type resistant sugar beet (*Beta vulgaris* L.) variety

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Abstract Plant breeding has continued to improve the resistance of sugar beet to Cercospora leaf spot (CLS) caused by the fungus *Cercospora beticola.* A new, highly resistant variety type has recently been introduced, which we tested in a three-year field trial series in a wide range of environmental conditions across Germany and Austria. Compared with a standard variety, the epidemic progression of CLS was significantly reduced. In the standard variety, CLS incidence reached the threshold for fungicide application in all 25 field trials and 1–4 fungicide applications were necessary. In the highly resistant variety, CLS never reached the treatment threshold in twelve trials. In the other 13 trials, 1–2 fungicide applications were made according to the threshold system. A close linear relationship was found between CLS severity at harvest and white sugar yield loss. Depending on the disease pressure of CLS, yield loss without fungicide reached up to 30% for the standard variety and up to 12% for the highly resistant variety. Our study shows that highly resistant varieties improve the integrated management of CLS by reducing the use of fungicides without sacrificing yield. However, a balance must be struck between the aim to reduce fungicide use and preventing the development of resistance-breaking strains of the fungus. It is therefore recommended that new-type resistant varieties are treated with fungicides according to approved integrated management programmes to prevent severe disease progression.

Keywords Integrated disease management · Variety resistance · Fungicide application · Application threshold · Yield loss

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10658-025-03036-x.

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Introduction

Sugar beet (*Beta vulgaris* L.) can be attacked by several pathogenic fungi, the most common and destructive being *Cercospora beticola* Sacc., the causal agent of Cercospora leaf spot (CLS). Infested leaves show circular lesions that increase in size and later coalesce to form larger necrotic areas. Cell death is caused by phytotoxins such as cercosporin and beticolin produced by the fungus (Rangel et al., 2020). Due to the reduction in photosynthetic leaf area and leaf regrowth, CLS causes sugar yield losses of up to 50% (Gouda et al., 2022; Skaracis et al., 2010).

Integrated management strategies combining cultural techniques, variety choice, and fungicide

application are used to control the disease. In Europe, this has become increasingly difficult in recent years. Climate change is causing earlier and more severe CLS epidemics (Kremer et al., 2016; Richerzhagen et al., 2011), the efficacy of fungicides has been compromised by the emergence of resistant strains of the fungus (Rangel et al., 2020), and the availability of highly effective fungicides is limited. As a result, varieties with low susceptibility are becoming increasingly important for CLS management.

Breeding for CLS resistance began more than 100 years ago in Italy, where the disease supposedly originated (Munerati, 1920). For decades, resistant varieties showed a yield penalty in the absence of the disease. Therefore, they lacked acceptance in commercial farming under Central European conditions, when CLS epidemics were less severe than today and effective fungicides were available (Gummert et al., 2015). In the 2010s, resistant varieties caught up with the susceptible varieties in terms of yield, and their economic performance could be even better (Vogel et al., 2018). Further breeding progress led to the introduction of a new resistance gene into existing sugar beet hybrids carrying quantitative background resistance, resulting in a variety type with significantly improved CLS resistance (Törjék et al., 2023). In Germany, these new type varieties have been available for commercial cultivation since 2021 (Bundessortenamt, 2021).

Integrated management of CLS includes the use of fungicides. In Germany, forecasting models are applied to provide field-specific predictions of epidemic development and recommendations for fungicide use based on disease monitoring programmes and weather data (e.g. Racca & Jörg, 2007). It was found that a certain level of disease development can be tolerated depending on the stage of the growing season, and treatment thresholds were set accordingly (5, 15 and 45% of affected leaves at different times from the onset of disease to mid-September) (*ibid.*). In countries where CLS pressure has long been higher than in Germany, e.g. Italy or Austria, prediction models are also used, but fungicide application starts earlier, i.e. when the first leaf spots occur or 1% of the leaves are affected, respectively (Cioni et al., 2014a, 2014b). In line with European legislation on the sustainable use of pesticides, which aims to reduce pesticide use to the minimum necessary (European Union, 2009), sugar beet growers must apply fungicides in accordance with these programmes, which are usually provided by official advisory services. Nevertheless, depending on the disease pressure, repeated fungicide applications are usually required for an effective management of CLS. Resistant varieties can help reduce the use of fungicides, thereby also helping to slow the emergence of fungicide resistance, which occurs more rapidly the more often fungicides are used (Corkley et al., 2022). For sugar beet growers, however, it is crucial that new varieties yield as well as established varieties. This needs to be assessed in field trials under varying disease pressure of CLS, which will also facilitate adjusted recommendations for the integrated disease management in agricultural practice.

The objectives of the present study are to I) analyse the development of CLS epidemics in a new-type sugar beet variety with high resistance compared to a standard variety, II) quantify yield effects of CLS depending on variety type and fungicide treatment, and III) assess options for integrated management of CLS with new resistant sugar beet varieties.

Materials & Methods

Field trials

A series of 25 field trials were conducted from 2020 to 2022 in German and Austrian regions with regular CLS epidemics (Supporting Information 1). All trials were set up in a complete randomised block design with six-row plots in four replicates. They were run by regional working units for sugar beet growing in Germany, AGRANA Research & Innovation Center in Austria and by KWS Einbeck and Seligenstadt. Beets were sown between mid-March and the end of April. After field emergence, the plots were manually thinned to 80,000–90,000 plants ha^{-1} to avoid unintended variance in plant density. Fertiliser, insecticides and herbicides were applied in accordance with best local practices. Irrigation was applied in five trials.

Sugar beet varieties and fungicide programmes

Two sugar beet varieties were grown, one with medium susceptibility to CLS (BSA identifier 2301), hereafter referred to as “standard” and a new-type

variety with very low susceptibility (BSA identifier 3706), referred to as "resistant" (Bundessortenamt, 2021) (Table 1). Both varieties were tested without fungicides (treatments 1 and 3) and treated according to the summary threshold system (treatments 2 and 4) with fungicides being applied when the treatment threshold of 5% disease incidence (DI) was reached by 31 July, 15% DI from 1–15 August and 45% DI from 16 August onward (Racca & Jörg, 2007). Additionally, the resistant variety was treated with fungicides at the same time as the standard variety (treatment 5). The summary threshold refers to the sum of all fungal leaf diseases occurring.

The fungicide programmes were designed to provide the most effective control of CLS based on products that were available in Germany and Austria (Supporting Information 2). As the registration situation changed over the years and was slightly different in the two countries, the fungicide programmes had to be adjusted each year. In 2020 and 2021, different products with epoxiconazole, difenoconazole and tetraconazole were used for the first three applications. They were combined with additional contact fungicides to improve resistance management and reflect the situation in farming practice (Laufer et al., 2020). Mancozeb was used at all sites in 2020 and copper only in Austria in 2021. In 2022, tetraconazole and difenoconazole were used alternately, because the use of epoxiconazole was banned (European Union, 2024). These applications were made in combination with copper-based contact fungicides.

Disease ratings

CLS incidence (DI, % infested plants) and severity (DS, % infested leaf area) were rated every 7–14 days from mid-June/mid-July, depending on the onset of infestation. One leaf from the central leaf apparatus of 25 randomly selected plants per plot (100 leaves per treatment) was assessed. If other leaf diseases were found, these were also rated. CLS was the dominant leaf disease and usually the first to occur in the season. Powdery mildew (caused by *Erysiphe betae*) and beet rust (caused by *Uromyces betae*) were found occasionally (data not shown), but not considered relevant to sugar beet yield, except in the Hankensbüttel 2020 trial with heavy infestation of beet rust (see below).

To create disease progression curves for multiple trials, the CLS ratings were aggregated by calendar weeks across sites and years. For DI, all trials and for DS, 17 trials with at least four ratings were aggregated (except Hankensbüttel and Trübensee 2021 and 2022, Zwingendorf 2021 and Frankenwinheim, Herxheim and Immendorf 2022). DS at harvest ($DS_{harvest}$) was assessed in 20 of the 25 trials, with the exception of the trials in Austria in 2021 and 2022 and at Frankenwinheim in 2022. Based on the DS ratings, the area under disease progress curve (AUDPC) was calculated according to Shaner and Finney (1977) for the 17 aforementioned trials with at least four DS ratings (including a final one at harvest).

Yield and quality assessments

The beets were harvested between mid-September and mid-November (Supporting Information 1) with on-site available machinery. In all six-row plots, three of the four central rows (6.3–10.0 m^2) were harvested. Beets were washed, weighed and brei samples were prepared. The brei was analysed for polarimetric sugar content, potassium, sodium and amino-N according to standard procedures (ICUMSA, 1994) using automatic beet laboratory systems (Anton Paar OptoTec GmbH, Seelze, DE, or Venema Installations, Eemshaven, NL) in the local sugar factories or at KWS. White sugar yield (WSY) was calculated from root yield and quality parameters (Märländer et al., 2003). Yield data from four trials were discarded because of a patchy crop after

Table 1 Sugar beet varieties (BSA, 2021) and fungicide programmes in the field trials 2020–2022
[a] summary threshold system: fungicide application at 5/15/45% disease incidence (Racca & Jörg, 2007)

Treatment	Variety	Variety type	Fungicide programme
1	BSA 2301	standard	untreated
2	BSA 2301		according to summary threshold system[a]
3	BSA 3706	CLS resistant	untreated
4	BSA 3706		according to summary threshold system[a]
5	BSA 3706		treated simultaneously with no. 2

poor field emergence or because of interactions due to unexpected occurrences of pests or diseases (Supporting Information 1).

Statistical analysis

Statistical analysis was performed using SAS 9.4 (SAS Institute, Inc., Cary, NC, USA). Data were checked for normal distribution and variance homogeneity (Kozak & Piepho, 2017) prior to variance analysis and post-hoc Tukey tests ($p < 0.05$) with the MIXED procedure. DS and AUDPC data were log-transformed to meet model requirements. Graphics and regression analyses were made with SigmaPlot 14.5 (Systat Software Inc., San Jose, CA, USA).

Results

Disease progress of CLS and fungicide applications

CLS occurred in all 25 trials and the standard variety always reached the threshold for fungicide application (Table 2), at the earliest on 23 June and at the latest on 30 July. The resistant variety reached the treatment threshold in 13 out of the 25 trials, with the earliest date also being 23 June and the latest date being 31 August. In twelve trials, the resistant variety never reached the treatment threshold, and treatment 4 with fungicide application according to the threshold system was in these cases inapplicable.

The trials were thus divided into two groups with high or lower disease pressure, where either both varieties or only the standard variety reached the treatment threshold (Fig. 1). In the high disease pressure trials, the average CLS incidence of the standard variety showed a sigmoid pattern. DI increased sharply from mid-July onwards and approached 100% in the second half of August. In the resistant variety, the development was delayed by approximately one month and a plateau was not achieved. In the lower disease pressure trials, DI of the standard variety was below the treatment threshold until mid-July and increased rapidly in August. At the same time, DI remained very low in the resistant variety and started to increase very slowly in the second half of August.

The timing and number of fungicide applications reflected the differences in the spread of CLS between trials and varieties (Table 2). The first threshold was always triggered by CLS, with the exception of Hankensbüttel in 2020, where beet rust dominated at the outset of the application period before it was surpassed by CLS (data not shown). When CLS reached the treatment threshold in the resistant variety, this was on average 23.6 (0–56) days later compared to the standard variety. Consequently, the number of fungicide applications according to the threshold system (treatments 2 and 4) differed between the varieties. At high disease pressure, the standard variety was treated 1–4 (mean 3.1) times, i.e. twice as often as the resistant variety, which was treated 1–2 (mean 1.4) times. At lower disease pressure, the standard variety was treated 1–3 (mean 2.0) times with fungicides.

When CLS had spread within the plots and infested more leaves, the DS was assessed, beginning approximately one month after the DI ratings (Fig. 2). At both high and low disease pressure, varietal differences became evident. Without the application of fungicide, the average DS of CLS increased in the standard variety from mid-August. This increase was much faster under high disease pressure than under lower disease pressure. When the standard variety was treated with fungicides, the DS was notably reduced and the variation among the trials also decreased, i.e. the applied fungicides controlled CLS effectively. The resistant variety had a lower DS than the standard variety throughout the whole season. Even under high disease pressure and without fungicide, its DS was lower than in the standard variety with fungicide. In the resistant variety, the fungicide effect on DS was barely visible until the beginning of October. The later DS ratings were mostly the final ones ($DS_{harvest}$). Without fungicide application, $DS_{harvest}$ ranged from 7–100% (mean 66%) in the standard variety and from 0–70% (mean 9%) in the resistant variety (Table 2).

$DS_{harvest}$ ratings were not aggregated in Fig. 2, but analysed separately (Fig. 3), because the harvest dates ranged from the end of September and mid-November. Independently of the disease pressure, $DS_{harvest}$ was significantly higher in the standard variety than in the resistant one and significantly lower with fungicide application than without for both varieties. The fungicide effect was much greater in the standard variety than in the resistant variety. Under high disease pressure, individual plots of the resistant variety achieved very high $DS_{harvest}$ without fungicide (treatment 3). When the resistant variety was treated at the same time as the standard variety (treatment 5), $DS_{harvest}$ was

Table 2 Date of reaching the treatment threshold for fungicide application, number of applications according to the threshold system and Cercospora leaf spot (CLS) severity at harvest ($DS_{harvest}$) when no fungicide was applied in two sugar beet varieties with different susceptibility to CLS. Field trials in Germany and Austria (AT) 2020–2022; n/a: not assessed

Year	Site	Standard variety			Resistant variety		
		1st reaching the treatment threshold	No. of fungicide applications[a]	$DS_{harvest}$ without fungicide (%)[b]	1st reaching the treatment threshold	No. of fungicide applications[c]	$DS_{harvest}$ without fungicide (%)[d]
2020	Hankensbüttel	21 July[e]	3	90.0	21 July[e]	2	7.0
	Frankenwinheim	17 July	2	9.3	-	0	0.5
	Seligenstadt	14 July	2	11.3	-	0	0.0
	Leeheim	25 June	1	7.3	-	0	0.0
	Steinweiler	13 July	2	43.8	-	0	2.3
	Schambach	13 July	3	95.0	27 July	1	4.0
	Makofen	06 July	3	90.0	28 July	1	1.4
	Mailberg (AT)	30 June	3	95.0	30 June	2	47.5
	Trübensee (AT)	23 June	4	100.0	23 June	2	70.0
2021	Hankensbüttel	16 July	2	91.3	-	0	2.0
	Einbeck	12 July	4	100.0	20 July	2	2.0
	Frankenwinheim	19 July	2	32.0	-	0	0.8
	Steinweiler	26 July	2	91.3	-	0	9.8
	Schambach	20 July	3	69.0	31 August	1	3.3
	Makofen	20 July	3	95.0	31 August	1	5.5
	Zwingendorf (AT)	12 July	3	n/a	-	0	n/a
	Trübensee (AT)	12 July	3	n/a	25 August	1	n/a
2022	Hankensbüttel	05 July	3	78.8	30 August	1	2.4
	Einbeck	26 July	2	43.8	15 August	1	1.1
	Frankenwinheim	30 July	1	n/a	-	0	n/a
	Herxheim	12 July	1	58.3	-	0	10.8
	Schambach	04 July	3	28.8	-	0	0.3
	Makofen	04 July	2	82.5	25 July	1	4.3
	Immendorf (AT)	12 July	3	n/a	-	0	n/a
	Trübensee(AT)	04 July	4	n/a	18 July	2	n/a

[a] treatment 2 (see Table 1 for details of all treatments); [b] treatment 1; [c] treatment 4; [d] treatment 3; [e] threshold triggered by beet rust

significantly lower than when it was treated according to the threshold system (treatment 4). With regard to the AUDPC, very similar effects of variety and fungicide were found (Supporting Information 3).

Yield effects of CLS

White sugar yield was calculated for 21 of the 25 trials, the other four were excluded because of unexpected yield interactions. Significant effects of environment (site x year), variety, fungicide programme and their interactions on WSY were found (Table 3). Average WSY ranged from 8.8 t ha^{-1} at Leeheim 2020 and 18.7 t ha^{-1} at Frankenwinheim 2020 (Fig. 4). The standard variety yielded significantly higher with fungicide application than without in all 13 trials with high disease pressure (Fig. 4a) and in two (Hankensbüttel and Frankenwinheim 2021) out of eight trials with lower disease pressure (Fig. 4b). In the resistant variety, the fungicides had a significant effect on WSY in six of the trials conducted under high disease pressure (Hankensbüttel, Schambach, Mailberg and Trübensee 2020; Einbeck and Trübensee 2022). In these trials, except Schambach 2020, treatment 5, where the resistant variety was treated with fungicides at the same time as the standard variety (i.e. before

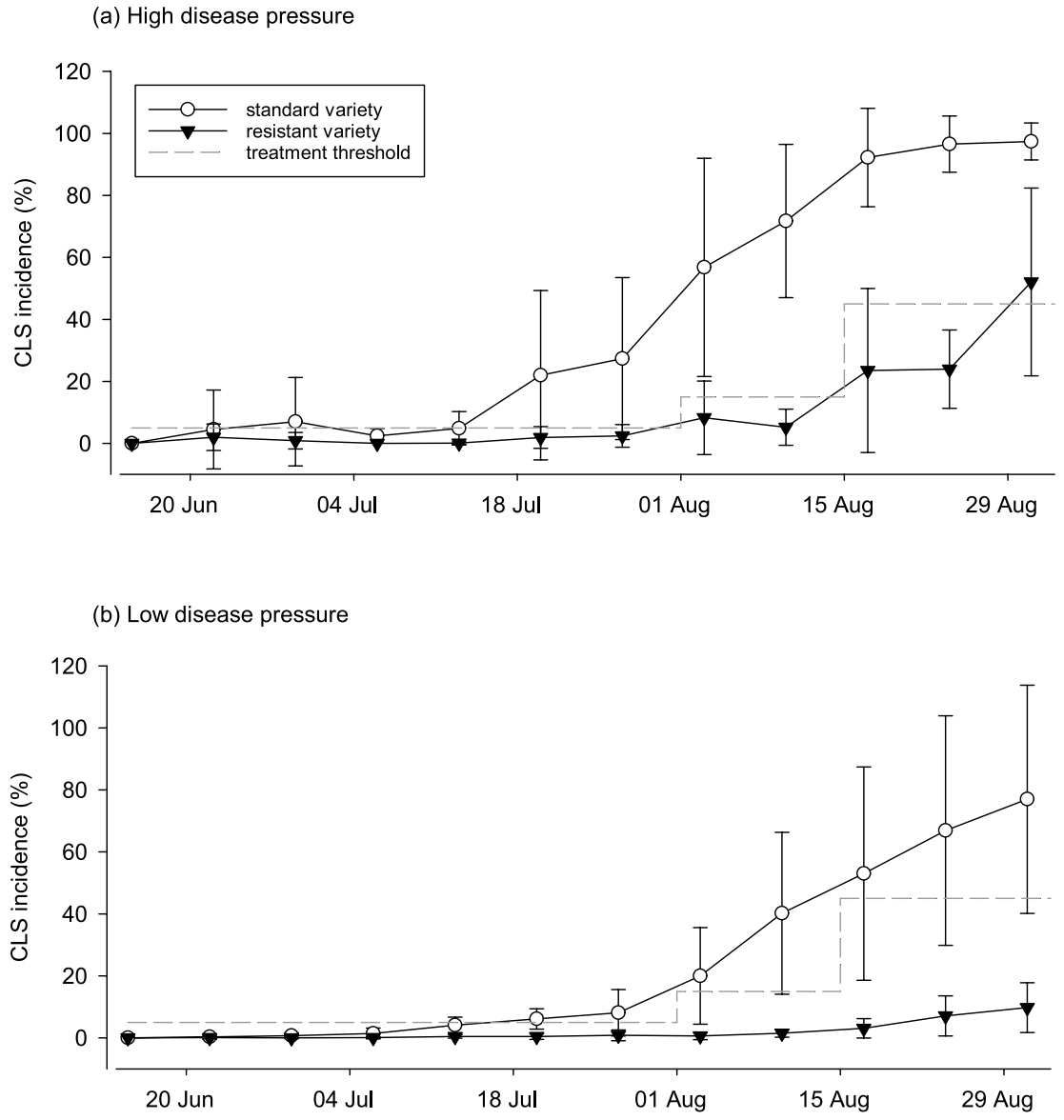


Fig. 1 Cercospora leaf spot (CLS) incidence in two sugar beet varieties with different susceptibility without fungicide application. Mean and standard deviation. (a) 13 field trials with high disease pressure of CLS. (b) 12 trials with lower disease pressure where the resistant variety did not reach the treatment threshold. Germany and Austria 2020–2022

the treatment threshold was reached), tended to yield higher than treatment 4 with fungicide application according to the threshold system. However, this difference was only significant at Mailberg 2020.

A linear relationship was observed between $DS_{harvest}$ of CLS and the loss in white sugar yield without fungicide, which was summarised in a single regression for both varieties (Fig. 5). For the standard variety, where $DS_{harvest}$ covered the entire range up to 100% and the maximum yield loss was 23.4% (Einbeck 2021), the correlation was very close. (Yield loss was even higher at Trübensee 2022 being 30.9%, but $DS_{harvest}$ was not assessed in this trial.) This relation was less evident in the resistant variety, because $DS_{harvest}$ only exceeded 10% in two trials (Mailberg and Trübensee 2020, Table 2). The maximum yield loss of the resistant variety without fungicide use was 12.1% at Mailberg 2020, where $DS_{harvest}$ was 48%.

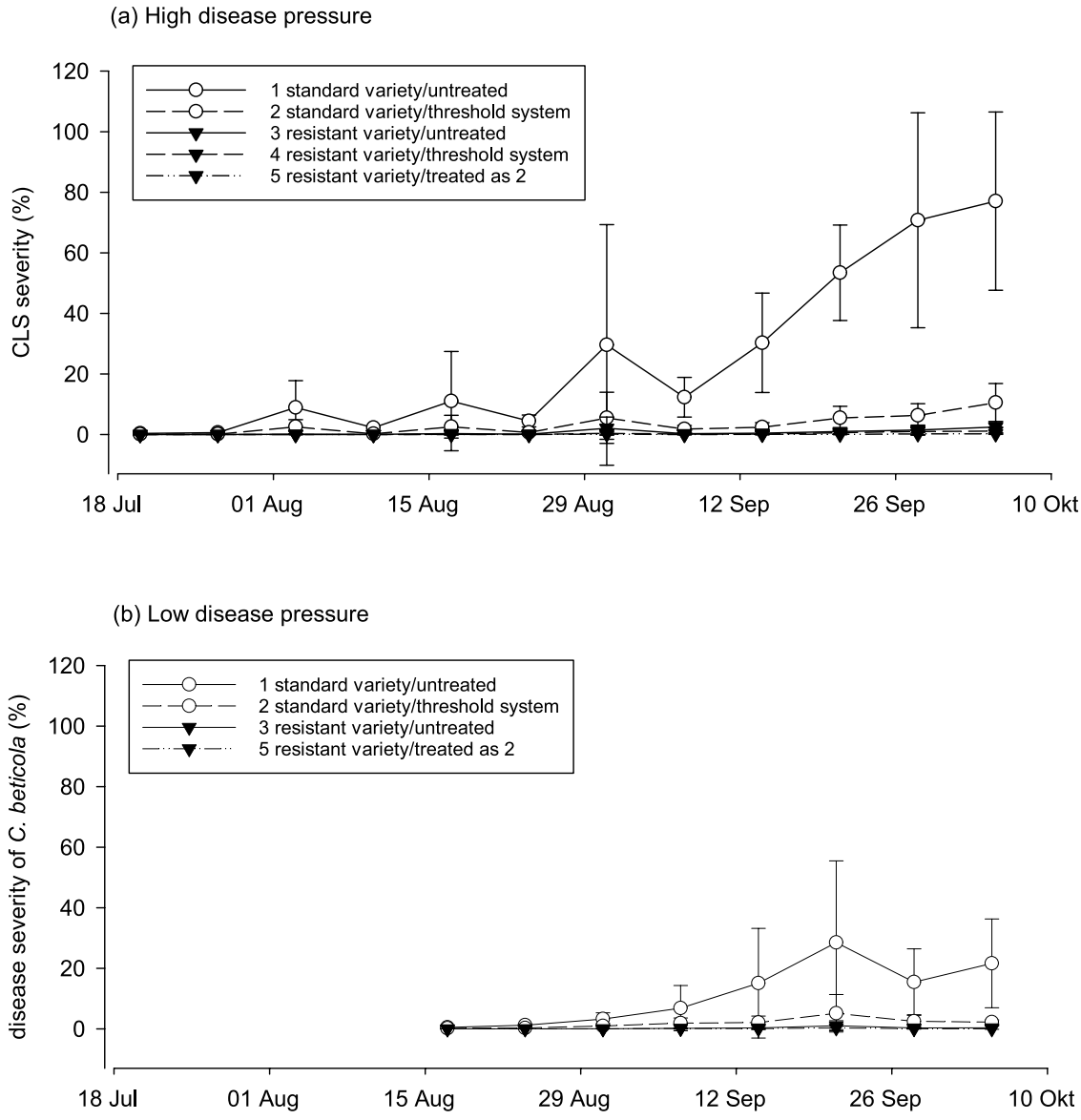
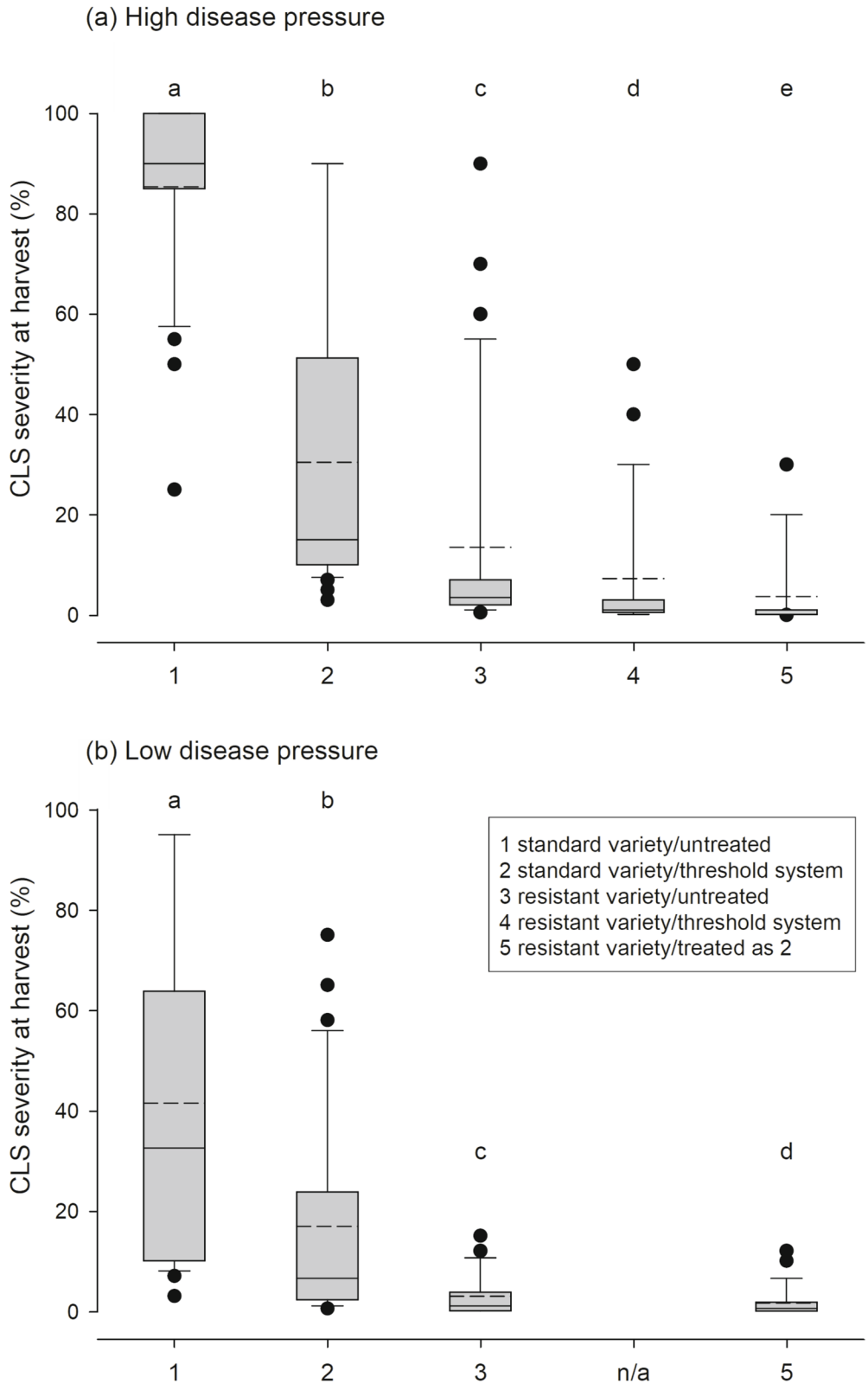


Fig. 2 Cercospora leaf spot (CLS) severity in two sugar beet varieties with different susceptibility treated with different fungicide programmes. Mean and standard deviation. (a) 10 field trials with high disease pressure of CLS. (b) 7 trials with lower disease pressure where the resistant variety did not reach the treatment threshold. Germany and Austria 2020–2022

Discussion

Epidemic development of CLS

Our field trials showed greater varietal differences regarding the progression of CLS, than previous studies comparing old-type resistant varieties and susceptible varieties (Barreto et al., 2023; Kaiser et al., 2010; Laufer et al., 2020). Kaiser et al. (2010) conducted 14 field trials, in which all six varieties reached the 5/15/45% thresholds for fungicide application. In our study, the resistant variety never reached the threshold in twelve out of 25 trials showing the progress in resistance breeding that was made by introducing a new resistance gene. Nevertheless, the resistant variety was infested with CLS in all trials. This indicates that the resistance does not entirely prevent infection, but slows down the progression of


(a) High disease pressure
a
b
c
d
e
CLS severity at harvest (%)
100
80
60
40
20
0
1
2
3
4
5
(b) Low disease pressure
a
b
c
d
CLS severity at harvest (%)
100
80
60
40
20
0
1
2
3
n/a
5
1 standard variety/untreated
2 standard variety/threshold system
3 resistant variety/untreated
4 resistant variety/threshold system
5 resistant variety/treated as 2

◂**Fig. 3** Cercospora leaf spot (CLS) severity at harvest in two sugar beet varieties with different susceptibility treated with different fungicide programmes. (a) 11 field trials with high disease pressure of CLS. (b) 9 trials with lower disease pressure where the resistant variety did not reach the treatment threshold. Germany and Austria 2020–2022. Solid lines indicate medians and dashed lines arithmetic means, four replicates per trial; different letters indicate significant differences among treatments at high or low disease pressure, Tukey-Test, $p \leq 0.05$, n/a: not applicable

the disease, depending on the disease pressure. Differences in the progression of CLS epidemics can be attributed to temporal differences between transcriptional defence responses in susceptible and resistant sugar beet varieties (Weltmeier et al., 2011). Wolf and Verreet (2005) reported that the onset of CLS epidemics was delayed by ca. three weeks in resistant varieties, whereas Kaiser et al. (2010) found no difference in the appearance of the first Cercospora leaf spots among the varieties tested. In our trials, the occurrence of the first leaf spots was not systematically recorded, but a delayed onset in the resistant variety was confirmed in 18 trials where the ratings started before any leaf spots were visible (data not shown).

Yield effects

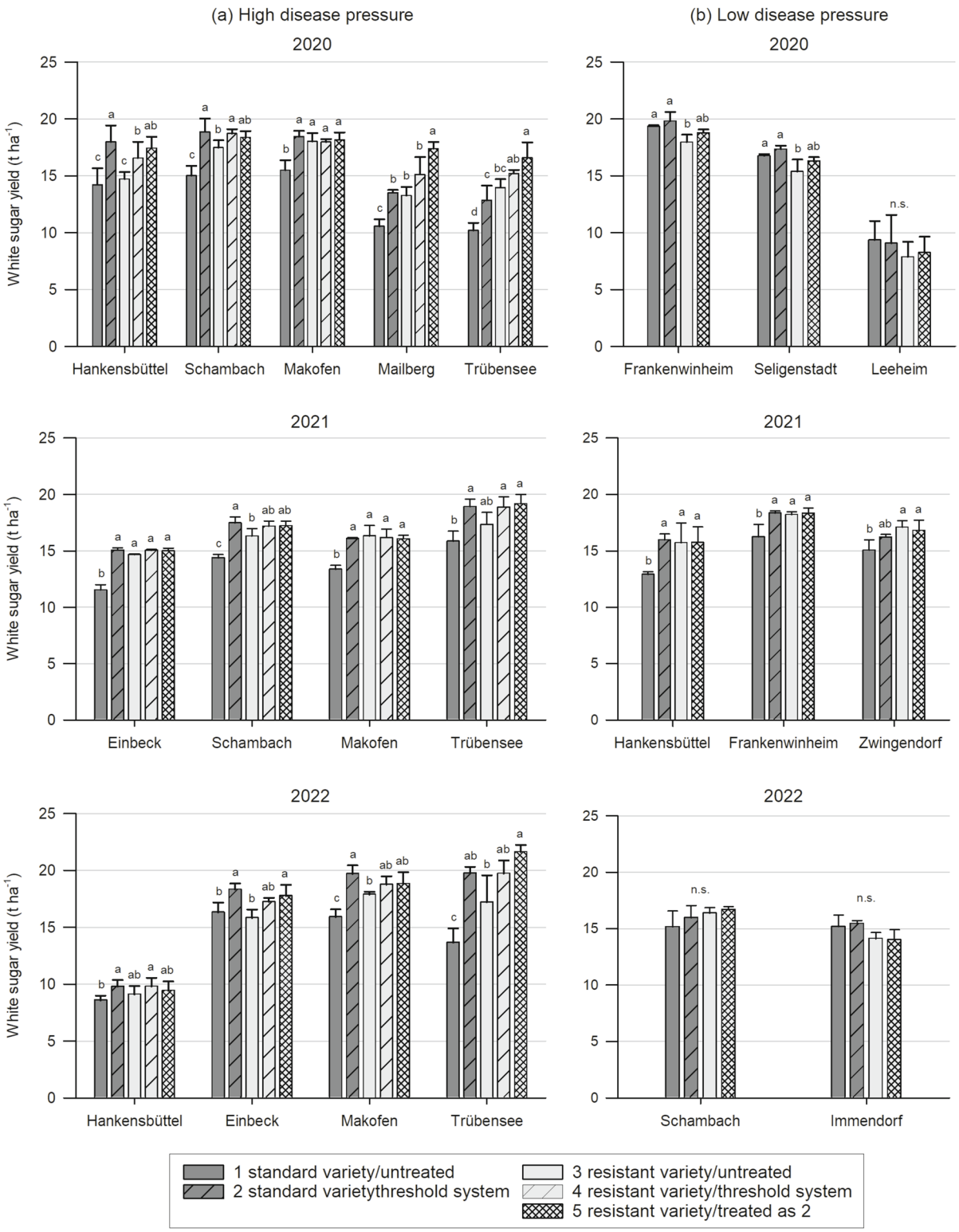
White sugar yield in our trials varied widely, depending on the environment, variety and fungicide programme. Environment summarises various factors such as soil and weather conditions at the trial site, agronomic measures as well as the epidemic progression of CLS. The effect of environment was most evident in the Leeheim 2020 and Hankensbüttel 2022 trials, where average WSY was very low (8.8 and 9.3 t ha^{-1}) and treatment differences were also low. This was due to severe drought, which could not be fully compensated by irrigation. As *C. beticola* needs high relative humidity for conidial development (60% or higher) and germination (near 100%), disease pressure is usually low under dry conditions, but irrigation water splash can also disseminate the spores (Rangel et al., 2020). This may explain the considerable differences in CLS epidemics and $DS_{harvest}$ between these two irrigated trials.

Yield effects were also small in the trials where CLS pressure was so low that DI did not reach the treatment threshold in the resistant variety, and only in exceptional cases did the fungicide application have a significant effect on WSY of the standard variety. In contrast, when CLS reached the treatment threshold in both varieties, WSY of the standard variety was always significantly higher with fungicide application than without. The yield loss without fungicide was closely related to $DS_{harvest}$ of CLS as also described in other studies (e.g. Gouda et al., 2022; Vogel et al., 2018), i.e. yield loss was proportional to the leaf area destroyed by *C. beticola*.

For the resistant variety, this relationship was less evident. Under high disease pressure, fungicide applications had a significant effect on WSY in 50% of the trials, but the yield loss without fungicides was not closely related to $DS_{harvest}$. A certain variation in yield loss at low $DS_{harvest}$ (< 10%) was observed, but it was not related to the disease pressure or the number of fungicide applications in the trials (data not shown). Our data are not sufficient to clearly describe the relation between yield loss and $DS_{harvest}$ for the resistant variety, but they do not suggest that resistance to CLS affected it. This was similarly observed for yield loss and AUDPC of CLS (Kaiser et al., 2010; Wolf & Verreet, 2009), whereas Vogel et al. (2018) found that certain varieties deviated from the regression and clustered according to their resistance to CLS.

Table 3 Analysis of variance for the effects of environment (site x year), variety and fungicide application on white sugar yield of two sugar beet varieties with different susceptibility to Cercospora leaf spot. Field trials in Germany and Austria 2020–2022

Effect	NumDF	DenDF	FValue	ProbF
environment	20	63.9	81.86	< 0.0001
variety	1	225.8	32.70	< 0.0001
fungicide	2	225.9	188.52	< 0.0001
environment x variety	20	225.9	11.78	< 0.0001
environment x fungicide	40	225.9	7.32	< 0.0001
variety x fungicide	1	226.0	103.93	< 0.0001
environment x variety x fungicide	12	226.0	1.84	0.0426


(a) High disease pressure
(b) Low disease pressure
2020
2020
2021
2021
2022
2022
White sugar yield (t ha-1)
Hankensbüttel
Schambach
Makofen
Mailberg
Trübensee
Frankenwinheim
Seligenstadt
Leeheim
Einbeck
Zwingendorf
Immendorf
n.s.
1 standard variety/untreated
2 standard varietythreshold system
3 resistant variety/untreated
4 resistant variety/threshold system
5 resistant variety/treated as 2

◂**Fig. 4** White sugar yield of two sugar beet varieties with different susceptibility to Cercospora leaf spot (CLS) treated with different fungicide programmes. (a) Field trials with high disease pressure of CLS. (b) Trials with lower disease pressure where the resistant variety did not reach the treatment threshold. Germany and Austria 2020–2022. Different letters indicate significant differences among treatments within trials, n.s.: not significant, Tukey-Test, $p \leq 0.05$

The new-type variety proved its high level of CLS-resistance and its yield stability under a wide range of environmental conditions. Only in two trials (Frankenwinheim and Seligenstadt 2020), it yielded significantly lower than the standard variety when no fungicide was applied. As these were trials with low $DS_{harvest}$, this is an indication of some yield penalty with low or no disease pressure of CLS as also described in earlier studies (Cioni et al., 2014a; Kaiser et al., 2010). Under high CLS pressure, the resistant variety performed significantly better than the standard variety or equally well. With fungicide application, the WSY of both varieties was almost always close, except under extreme CLS pressure as in Austria in 2020, where the resistant variety outperformed the standard variety independent of the fungicide programme.

Implications for integrated management of CLS

Resistant varieties are a key component of integrated management of CLS, along with threshold-based fungicide applications. Additionally, cultural practices such as 3–4-year crop rotations and incorporation of infected crop residues by tillage reduce the amount of initial inoculum for the next season (Khan, 2015). Our data shows that new-type resistant varieties can enhance CLS management, especially under conditions of high disease pressure, which tends to increase in most sugar beet growing regions in Europe. Due to the slower CLS epidemics in the resistant variety, either no fungicide application was made in accordance with the threshold system, or the number was reduced by half. This is an advantage from the perspective of sustainable use of pesticides as required by European legislation (European Union, 2009) and is also in line with FRAC (Fungicide Resistance Action Committee) strategies to avoid fungicide resistance, including limiting the number of treatments per season (Brent & Hollomon, 2007).

As fungicide applications did not positively affect WSY in all trials, and more frequently in the standard variety than in the resistant variety, it could be argued that this may provide further opportunities to reduce fungicide use. However, as Gummert et al. (2015) emphasised, although in some cases fungicide applications against CLS may have been omitted in retrospect, this is unclear at the time when treatment thresholds are reached and future weather conditions and epidemic development are unknown. Raising the treatment thresholds to reduce fungicide use does not seem advisable for other reasons. The

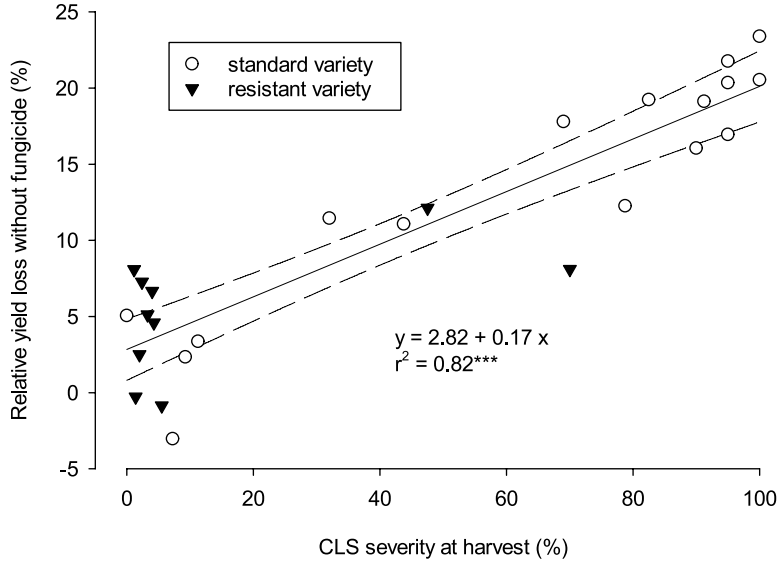


Fig. 5 Relation between Cercospora leaf spot (CLS) severity at harvest and relative loss of white sugar yield of two sugar beet varieties with different susceptibility to CLS. 100% = white sugar yield when treated with fungicides according to the threshold system. 16 field trials, of which the CLS resistant variety reached the threshold in 10 (see Table 2), Germany and Austria 2020–2022. Solid lines indicate regression lines, dashed lines mark 95% confidence intervals; *** significant at $p \leq 0.001$

thresholds were developed in the 1990s, when CLS was less common and less severe in Central Europe than today, and was easier to control with fungicides because more active substances were available and fungicide resistance was less widespread (Laufer et al., 2024; Racca & Jörg, 2007; Rangel et al., 2020; Richerzhagen et al., 2011).

The positive effect of fungicide application on WSY of the standard variety observed in the majority of our trials underlines the suitability of the threshold system. Furthermore, a yield benefit of earlier timing of the fungicide application became apparent in the resistant variety under strong CLS pressure confirming the validity of the lower threshold for the first fungicide application in Austria (Cioni et al., 2014b). The aim of integrated CLS management with new-type resistant varieties, thus, must not be to weaken the resistance to save as much fungicide as possible. Instead, even highly resistant varieties should be treated according to approved threshold systems which will still result in a lower number of fungicide applications. This will prevent yield losses and, more importantly, counteract the development of pathogen strains that overcome the new resistance in sugar beet varieties (Chen et al., 2024).

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Data availability The data that support the findings of this study are available from the corresponding author upon reasonable request.

Competing interests Sören Seebode is employed by KWS Saat SE & Co. KGaA. Simon Borgolte was employed by KWS Saat SE & Co. KGaA for the entire first two years of this study and until 30 April in the third year.

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