Bettina Klocke, Christina Wagner, Sandra Krengel-Horney, Jürgen Schwarz

Potential of pesticide reduction and effects on pests, weeds, yield and net return in winter rye (*Secale cereale* L.)

Affiliation
Julius Kühn Institute (JKI) – Federal Research Centre for Cultivated Plants, Institute for Strategies and Technology Assessment, Kleinmachnow, Germany.

Correspondence
Dr. Bettina Klocke, Julius Kühn Institute (JKI) – Federal Research Centre for Cultivated Plants, Institute for Strategies and Technology Assessment, Stahnsdorfer Damm 81, 14532 Kleinmachnow, Germany, email: bettina.klocke@julius-kuehn.de

Summary

Reducing the intensity of pesticide use is a societal and political issue. One way to realize this is to reduce the dose of applied pesticides. The impact of strict dose reductions on yield and net return in winter rye was examined in a long-term field trial at the experimental field of the Julius Kühn Institute in Dahnsdorf (Brandenburg) over a 13-year period (2004-2016). Pesticide treatments included a situation-related strategy (100% strategy) and two other strategies in which the doses were reduced by 25% and 50% compared to the 100% strategy. Treatment decisions were based on control thresholds in the 100% strategy. Fungal pathogens and weeds occurred in all years and had to be controlled. Insect pests were negligible. Averaged over all years, there was a significant difference of 4% in yield between the 100% strategy and the 50% strategy. In contrast, no differences were found in terms of net return. There was also no accumulation of weeds in the reduced strategies. This positive result is due to the close monitoring of the plots as well as the six-year crop rotation and shows that it is possible to reduce pesticide use in winter rye.

Keywords

long-term field trial, pesticide reduction, weeds, fungal pathogens, insect pests, winter rye, net return

Introduction

Winter rye (*Secale cereale* L.) is considered a modest crop, growing well on marginal soils and providing reliable yields even under environmental stress conditions because of its high tolerance to abiotic stress factors (Targonska-Karasek et al., 2020). In Germany, winter rye is being grown on 631,000 ha with an average yield of 53 dt ha^{-1}. This represents 10.4% of Germany's total cereal growing area (BMEL, 2021). Winter rye can be attacked by a number of fungal and insect pests and weeds, which can reduce yield and quality. Important fungal pathogens are leaf rust (*Puccinia recondita*), scald (*Rhynchosporium secalis*), ergot (*Claviceps purpurea*), stem rust (*Puccinia graminis*) and Fusarium head blight (*Fusarium graminearum, F. oxysporum*). Leaf rust is the most dominant disease in winter rye and occurs in all major rye-growing regions (Kupfer & Schröder, 2014). Severe epidemics early in the year can lead to yield losses of up to 60–80% (Solodukhina & Kobylyanskij, 2003). Winter rye is more competitive against weeds than winter wheat (*Triticum aestivum* L.) and has much better weed suppression (Mason et al., 2007). Nevertheless, weeds also occur regularly in winter rye and weed-induced yield losses can be as high as 34% in cereals, which is higher than the losses caused by diseases and pests (Oerke, 2006). The most common dicot weeds are sherperd's purse (*Capsella bursa-pastoris*), cornflower (*Centaurea cyanus*), burdock bedstraw (*Galium aparine*), deadnettle (*Lamium* spp.), chamomile species (*Matricaria* spp.), chickweed (*Stellaria media*), field pennycress (*Thlaspi arvense*), speedwell (*Veronica* spp.) and field pansy (*Viola arvensis*) (Pallutt, 2000). Monocotyledous weeds are predominantly windgrass (*Apera spica-venti*), slender foxtail (*Alopecurus myosuroides*), couch grass (*Elymus repens*) and bromes (*Bromus* spp.). Winter rye cultivation in Germany is characterized by low importance of insect pests and low need for insecticide use. Although species of different taxa such as aphids (*Aphidoidea)*, frit flies *(Oscinella)*, gout flies *(Chlorops)* and ground beetles (*Carabidae*) potentially occur in winter rye, only a few of them currently have the potential to cause economic losses. This is reflected in a rather low treatment frequency index (TFI) for insecticides in Germany of only 0.4 for the years 2007–2017 (Dachbrodt-Saaydeh et al., 2021).

The control of these pests and weeds is necessary to secure yields, which is achieved mostly by the use of pesticides (Lopez et al., 2015; Luo et al., 2021; Mayerová et al., 2018) and may be associated with a risk to the environment and human health (Kalyabina et al., 2021; Mahmood et al., 2016). With regard to the European Green Deal, sufficient changes are pending at national and EU level, and agriculture will have to implement them in a mandatory manner over the coming years (European Union, 2020). The Commission will need to take additional measures to reduce the overall use and risks

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of chemical pesticides by 50% and the use of more harmful pesticides by 50% by 2030.

Therefore, consistent implementation of preventive crop management strategies must become a standard practice for growers in the future. Important tools are the cultivation of multi-resistant cultivars and the use of control thresholds that enable a reduction in the use of fungicides (Klocke et al., 2022) and other pesticide classes. In winter rye, resistance to leaf rust is most important and could greatly contribute to lower fungicide use (Laidig et al., 2022). Cultivar resistance will become much more prominent when pesticide use has to be reduced. Currently, the majority of available winter rye cultivars are susceptible to leaf rust. In Germany, only three of the 39 commercially grown winter rye cultivars show an effective resistance (Bundessortenamt, 2022). In addition, long crop rotations will be needed to control weeds and pests (Shah et al., 2021). The effect of herbicide treatment on yield is greater in short crop rotations because weeds occur in higher densities (Mayerová et al., 2018; Nazarko et al., 2005). Sustainable weed control is irrevocably linked to the development of competitive cropping systems that can reduce weed populations over time (Blackshaw et al., 2006).

Another way to reduce the use of pesticides is to decrease the dose (Jørgensen & Henriksen, 2000). In Denmark, research on lower doses has been successful for many years and has shown that even reduced doses can result in sufficient control and corresponding yields. It is unclear to what extent this reduction is done at farm level, which is attributed to a gap between research findings and implementation in practice (Jørgensen et al., 2017). The level of input depends on farm profiles, individual motives and social commitments (Nave et al., 2013). The dose needed to optimize net return varies depending on sites, seasons, cultivars, and grain prices (Paveley et al., 2001). For herbicides, it may be appropriate in certain situations to use lower doses to allow growers to make higher profits, reduce potential damage to current and subsequent susceptible crops, and minimize risks to the environment (Blackshaw et al., 2006). Nevertheless, dose reduction should always be applied situation-related, i.e. according to the respective disease and weed pressure, and in consideration of resistance management (Mayerová et al., 2018).

The objective of the present study was to evaluate options to reduce intensity and risks of pesticide use and to assess possible consequences. Based on the results of a 13-year field trial in Dahnsdorf (Brandenburg, Germany), the study aimed to answer the following specific questions in a six-year crop rotation including winter rye: Does the reduction of pesticides influence (i) the control of weeds, disease and insects in winter rye, (ii) the level of yields and net returns and (iii) the accumulation of weeds over time?

Material and Methods

Description of the field station

The experimental field station of the Julius Kühn Institute in Dahnsdorf is located in the German federal state Brandenburg (52.108494 N 12.636338 E). The loamy sandy soil of the experimental field is composed of 57.9% sand, 37.5% silt and 4.6% clay. The mean soil score is 48 points with a pH of 5.8.

Experimental design, selected cultivars and pesticide strategies

The trial was set up as a six-year crop rotation with the following crops: maize – winter wheat 1 – winter barley – potatoe – winter wheat 2 – winter rye from autumn 2003 to harvest 2016 (Fig. 1). The effect of reduced pesticide applications on yield and pest incidence was studied in a randomized block design with three replicates for each crop. The size of one experimental plot per crop and block (replicate) was 1000 m^2 (25 m × 40 m). Each plot is further divided into 4 subplots of 250 m^2 (6.25 m × 40 m) for testing different crop protection strategies. The previous crop of winter rye was winter wheat 2 in all years.

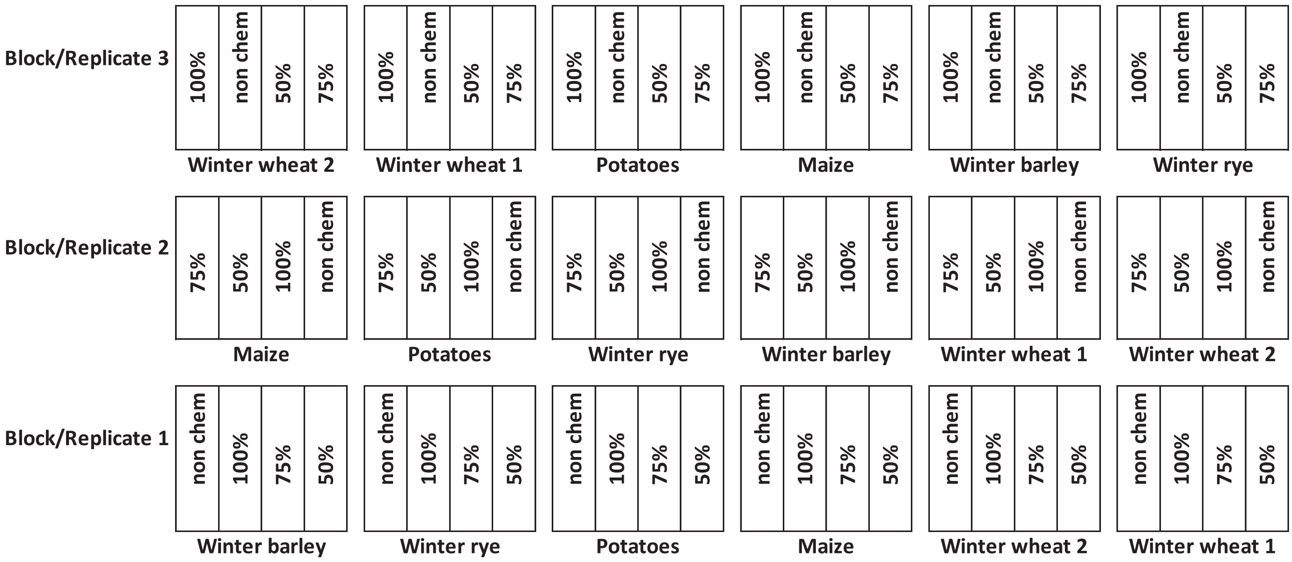

Fig. 1. Experimental design of the six-year crop rotation trial in 2004 for the pesticide strategies 100%, 75%, 50% and the pesticide free control (no chemicals applied)

The cultivars were not identical in all years. They were selected according to their suitability for cultivation and the recommendation to be used in Brandenburg. In terms of resistance to fungal pathogens, the selected winter rye cultivars were classified as moderately susceptible against the most important fungal diseases (Table 1).

In all years, sowing took place between 19 September and 4 October, with sowing rates between 200 and 260 seeds m^{-2}. All other crop management measures and fertilization were the same between the crop protection strategies. Basic tillage was done with the plow except in some years after maize or potatoes. In 2013, a hailstorm occurred shortly before harvest, so that yield of winter rye was reduced.

Three crop protection strategies were considered. In the (1) situation-related strategy, the pesticides were applied in accordance with good professional practice using an application rate that was adapted to the disease and weed pressure. Thus, the application of the full label rate was not necessarily used. In addition, control thresholds and decision support systems were used. In strategy (2) 75% of situation-related, the dose was reduced by 25% compared to the situation-related strategy for all pesticides. In strategy (3) 50% of situation-related, a 50% reduction of doses was used for all pesticides. In the following, the three strategies will be referred to as (1) 100%, (2) 75% and (3) 50% strategy, since the difference between the strategies is related to the dosage.

A strategy (4) without the use of chemical pesticides is also part of the trial design. Only mechanical weed control was conducted 2 to 4 times per season in this strategy. The timing of mechanical weeding was not optimal in some years resulting in insufficient control. The yields of this strategy do not correspond to those of a common practice strategy without chemical pesticides. Therefore, the analysis is not presented in this study, but the monitoring results are used to estimate the annual weed and disease pressure.

Field monitoring and treatments

Pesticides were applied in the 100% strategy depending on the occurrence of specific insect and fungal pests and weeds, which was recorded regularly. If a treatment was required, it was applied at the same time in all strategies. The need for further treatments was also based on the further monitoring results in the 100% strategy, even if re-infestation had occurred earlier in the other two strategies. Thresholds recommended by the regional extension services were used for weeds, fungal and insect pests (Table 2).

Table 1. Resistance classification of the winter rye cultivars to the fungal diseases powdery mildew, scald and leaf rust (Bundessortenamt, 2004–2016)

Year	Winter rye			
	Cultivar	Resistance classification		
		Powdery mildew	Scald	Leaf rust
2004–2005	Avanti	4	4	6
2006–2008	Askari	4/5/5*	7/6/6*	5/5/6*
2009–2013	Visello	5	4/4/4/4/5*	4/5/6/7/7*
2014–2016	Brasetto	3	4/5/5*	5/6/6*

1 = completely resistant, 9 = highly susceptible
*= changing susceptibility during the investigation period according to descriptive cultivar list

Table 2. Control thresholds for fungal and insect pests and weeds in winter rye (Pflanzenschutzdienste der Länder Berlin, Brandenburg, Sachsen, Sachsen-Anhalt und Thüringen (Hrsg.), 2023), GS = growth stage

Category	Disease/Pest/Weed	Object	GS/season	Control threshold
Fungal pathogens	Powdery mildew	3 upper leaves	33-51	60% (incidence)
	Leaf rust	3 upper leaves 3 upper leaves	37-61/69	30% (incidence) 30% (resistant cultivars)
	Rhynchosporium	3 upper leaves	33-55	50% (incidence)
Insect pests	Cereal ground beetle	plant	autumn (>13)	3–7 damaged plants m^{-2}
		plant	spring	7–14 damaged plants m^{-2}
Weeds	dicot weeds	plant	autumn	40–50 plants m^{-2}
	windgrass	plant	autumn	10–20 plants m^{-2}
	catchweed	plant	autumn	0.1 plants m^{-2}

For weeds, occurrence was recorded per species and number as density prior to the use of herbicides or mechanical weed control. Counts took place in fall. Weeds were recorded per replicate at four to eight count sites of 0.25 m^2 each. The decision making for herbicide use was based on the weed counts in the 100% strategy. After the effect of the herbicides was visible weed cover for each weed species was estimated for the entire strategy and each replicate. In addition to the threshold values, weed management decisions took into account the fitness of winter rye plants, i.e. plant appearance, distribution and number of emerged rye plants.

For herbicide choice, attention was paid to a consistent alternation of active ingredient groups, also in the context of crop rotation (Table 3, supplementary Table S1). Herbicides were selected based on the dominant dicot weed species and the occurrence of windgrass. Tank mixtures of different herbicides were used occasionally. For the application rate of the herbicides in the 100% strategy, a dosage adapted to the weed counts was chosen, in most cases a reduced rate was used.

For fungal pathogens, the infestation was evaluated in weekly control assessments in the 100% strategy starting from growth stage (GS) 31 up to the first treatment date in order to be able to decide on necessary fungicide applications. Additional assessments were carried out 14 to 21 days after fungicide application to determine the efficacy of the fungicides in all strategies. The disease incidence (number of infested plants) and severity (percentage of affected leaf area) of all fungal pathogens on the upper three leaves were recorded every week. 30–35 plants were assessed at six to seven points per subplot and replicate. Fungicide applications, approved for the observed diseases, were carried out after the control threshold for each disease was exceeded (Table 2 and 3). The threshold for fungal diseases refers to the disease incidence and not to the severity.

Insect pest control focused on cereal ground beetle due to the low relevance of other species. Infestation was assessed around GS 12/13 in autumn and at the beginning of the vegetation period in spring by counting the number of damaged plants per 0.25 m^2 at four points per replicate (on a total of 1 m^2). Based on the infestation, the plant development and

Table 3. Pesticides used in the categories (C) herbicides (H), fungicides (F), insecticides (I) and growth regulators (GR), application dose in the 100%, 75% and 50% strategy and growth stages (GS) at the time of application in the years 2004–2016 as well as maximum individual dose

Year	C	GS	Trade name pesticide	Maximum individual dose [l or kg ha^{-1}]	Application dose [l or kg ha^{-1}]		
					100%	75%	50%
2004	H	13	Arelon Flüssig	2	1.5	1	0.75
	F	59	Amistar	1	1	0.7	0.5
	GR	32	Moddus	0.6	0.5	0.5	0.5
2005	H	13	Fenikan	2.5	0.7	–	0.35
	F	59	Gladio	0.8	0.8	0.6	0.4
	GR	49	Camposan-Extra	1.1	0.8	0.6	0.4
2006	H	12	Bacara	1	0.7	0.35	0.35
	F	59	Fandango	1.5	1.5	1.2	0.75
	GR	37	Moddus	0.6	0.4	0.3	0.2
2007	H	11	Bacara	1	0.7	0.35	0.35
	F	53	Juwel Top	1	1	0.75	0.5
	F	65	Folicur	1.25	1	–	0.5
	GR	21	Moddus + CCC	0.6 + 2	0.2 + 1	0.15 + 0.75	0.1 + 0.5
	GR	37	Moddus (Rep. b + c)	0.6	0.2	–	0.1
2008	H	11	Bacara	1	0.8	0.6	0.4
	F	37	Capalo	2	1.3	-	0.65
	F	59	Diamant + Folicur	2 + 1.25	– + 1	1.5 + –	– + 0.5
	GR	37	Medax Top	1.5	0.75	0.56	0.38
2009	H	10	Bacara	1	0.6	0.45	0.3
	F	59	Acanto + Pronto Plus	1 + 1.5	0.6 + 1.2	0.45 + 0.9	0.3 + 0.6
	GR	32	Medax Top	1.5	0.6	0.45	0.3

Table 3. Continued.

Year	C	GS	Trade name pesticide	Maximum individual dose [l or kg ha^{-1}]	Application dose [l or kg ha^{-1}]		
					100%	75%	50%
2010	H	12	Herold	0.5	0.15	0.1125	0.075
	H	12	Lexus	0.02	0.01	0.0075	0.005
	F	55	Fandango + Input	1.5 + 1.25	0.7 + 0.7	0.525 + 0.525	0.35 + 0.35
	GR	41	Moddus	0.6	0.3	0.225	0.15
2011	H	26	Isomex 500 SC + Foxtril Super	2.5 + 2	2 + 1.5	1.5 + 1.125	1 + 0.75
	F	39	Input	1.25	1.25	0.94	6.25
	GR	31	Medax Top	1.5	0.6	0.45	0.3
2012	H	13	Bacara Forte	1	0.8	0.6	0.4
	F	51	Aviator Xpro + Fandango	1.25 + 1.5	0.75 + 0.75	0.5 + 0.5	0.375 + 0.375
	F	59	Pronto Plus	1.5	1.5	1.2	0.75
	GR	32	Medax Top	1.5	0.6	0.45	0.3
2013	H	21	Bacara Forte	1	0.7	0.525	0.35
	F	59	Skyway Xpro + Vegas	1.25 + 0.37	1 + 0,2	0.75 + 0.15	0.5 + 0.1
	GR	33	Medax Top	1.5	0.6	0.45	0.3
2014	H	14	Fenikan	2.5	1.5	1.125	0.75
	F	51	Adexar	2	1.5	1.1	0.75
	F	61	Acanto + Pronto Plus	1 + 1.5	0.5 + 0.75	0.375 + 0.563	0.25 + 0.375
	GR	31	Medax Top	1.5	0.6	0.45	0.3
2015	H	24	Fenikan	2.5	1.5	1.125	0.75
	F	57	Adexar + Diamant	2 + 2	1.1 + 1.1	0.825 + 0.825	0.55 + 0.55
	GR	32	Medax Top	1.5	0.6	0.45	0.3
2016	H	21	Fenikan	2.5	1.5	1.125	0.75
	F	59	Adexar + Diamant	2 + 2	1.1 + 1.1	0.825 + 0.825	0.55 + 0.55
	I	13	Karate Zeon	0.075	0.075	0.0563	0.0375
	GR	32	Medax Top	1.5	0.6	0.45	0.3

recommended control thresholds (Freier et al., 1997, Table 2) it was determined if a treatment was necessary.

Pesticide intensity and economic efficiency

To evaluate the intensity of pesticide applications, the treatment frequency index (TFI) was determined. The TFI is calculated as the quotient of the applied dose and the maximum label dose multiplied by the quotient of treated area and total area (Kudsk & Jensen, 2014). If the whole area is treated with the maximum label dose, the TFI is 1. If the dose is reduced by 50%, the TFI is halved to a value of 0.5. For the calculation of the net return annual grain prices (AMI Marktbilanz, 2004-2016), (Fig. 2), pesticide prices (Agravis, 2004-2016) and passage costs were used. Net return is the product of yield and producer price minus application costs of the pesticides (pesticide price and passage costs). Labor and machinery costs for applications were calculated as the average of common field sizes of 1 to 20 hectares and field distances of 1 to 30 kilometers for 2016 (KTBL-Feldarbeitsrechner, 2016). Under these assumptions, average passage costs of 12.50 € ha^{-1} were assumed for all years. Other direct and fixed costs were not considered in this study.

Data analyses

The effects of the different strategies on dependent variables were analysed with linear mixed models (Moll & Piepho, 2001) with the MIXED and GLIMMIX procedure of SAS® version 9.4 TS level 1M6. Statistical studies were conducted separately by year but also over the years. Rye grain yield, disease severity, weed abundance and net return were the dependent variables, while years and blocks were treated as random effects. Blocks were nested within years. Over the years, interaction between year/net return and strategy was additionally analysed. Least squares (LS) means for the

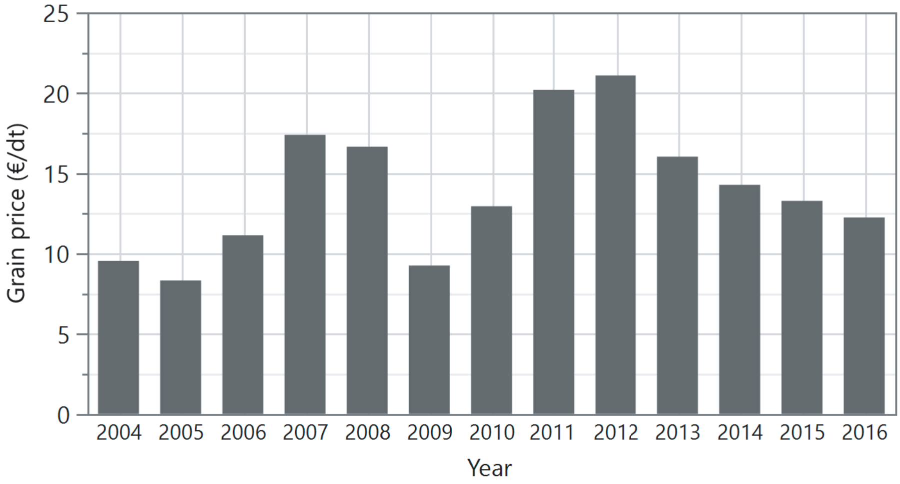

Fig. 2. Grain price for winter rye for the years 2004 to 2016 (AMI Marktbilanz, 2004–2016)

dependent variables were estimated by using the LS means option and a 0.05 probability level. These squares were then compared for differences between strategies, with p-values adjusted for multiple comparisons using the SIMULATE option. This procedure can be used for unbalanced data and with variance heterogeneity and is not as conservative as the TUKEY procedure (Schumacher & Weimer, 2006). Differences in disease severity and total coverage of weeds were tested with a chi-square statistic. In the model, the percentages were transformed with the link function logit. The variance function was defined with the $variance = \mu^2 (1 - \mu)^2$ (μ^2 is the squared mean = mean proportion) (Munzert, 2015). The statistical analysis was carried out for the diseases and weeds individually. Multivariate analysis to explain the dependencies of yield and net return on diseases and weeds were not conducted because the univariate analyses resulted only in few significant differences between the strategies for the weeds. In consequence of data gaps no statistical analyses of pest abundance was feasible. The graphics were created with JMP® version 15.2.1.

Results

Weather conditions

The years differed in terms of precipitation and temperature (Fig. 3). There is a regular pre-summer drought at this site, characterized by low precipitation in April and May or June.

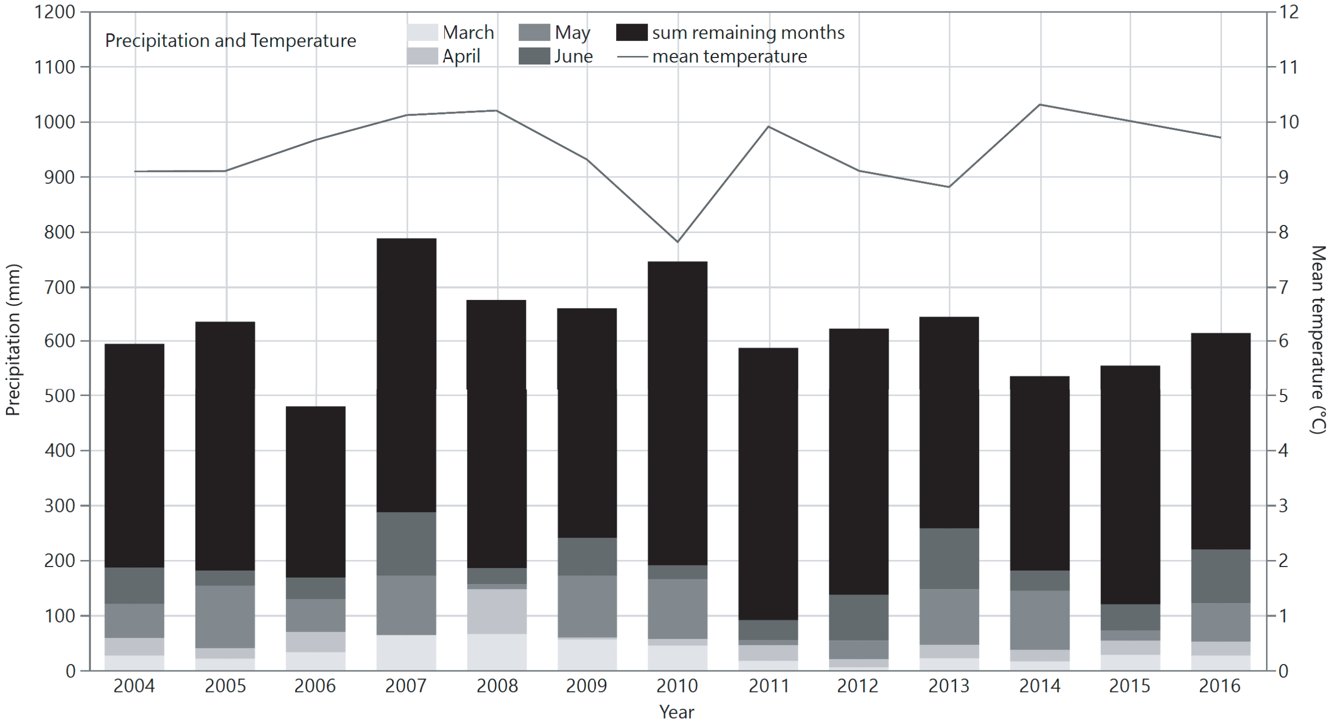

Fig. 3. Precipitation sum and mean air temperature in Dahnsdorf (own measurement)

Very low precipitation was observed in April to June, the months important for crop development. In the years 2008, 2011, 2012 and 2015. In 2007, with the highest precipitation of all years, April remained free of precipitation.

Incidence and severity data

Weeds

The number of counted windgrass plants was highest in autumn 2009 (Fig. 4, before herbicide application). From 2011, the counts were lower than in previous years due to the autumn weather conditions. No significant differences were found between the strategies in any of the years. The same applies to the number of dicot weeds. Most dicot weeds occurred in 2012. More than half of the weed plants in 2012 were white goosefoot. This weed does not need to be controlled in autumn as it dies during winter. No accumulation of weeds was observed over the 13 years. Even in the last year of the trial (2016), there were no significant differences between the weed densities of each strategy with regard to windgrass and the dicot weeds.

Overall, herbicide treatment strategies resulted in an efficient control in all years and strategies, with a negligible number of weeds left in the field (Fig. 5, after herbicide application). Only in 2005 a significantly higher number of weeds was found in the 75% strategy, which was not treated for unknown reasons and deviated from the actual trial design. The observed significant differences between strategies occur at very low levels of infestation and the significance can mainly be attributed to the small standard deviations.

The weed cover in the pesticide-free strategy in spring shows that a moderate to high weed pressure was prevalent in all years (Fig. 6).

Fungal diseases

Fungal pathogens occurred at different severities in the experimental years. Overall, the main disease was leaf rust, followed by scald. Figure 7 shows the disease severity of these two diseases in the pesticide free strategy. In six of the 13 years, leaf rust severities of more than 20% occurred. Scald occurred regularly and in some years still showed increased disease severities on the last scoring date. The years 2005, 2007, and 2012 were epidemic years for leaf rust with high disease severities of more than 30%, 60% and 70% respectively, at milk ripening (GS 75). The occurrence of both fungal diseases led to the use of fungicides in all years (Table 3) because the disease incidence threshold was always exceeded and was higher than 30%.

In the fungicide-treated strategies, the infestation was well controlled (Fig. 8). In years with high leaf rust severity (2005, 2007, 2012), the efficacy of the fungicide treatment was lower with correspondingly higher severity. In all years, the 50% strategy was significantly less effective than the 100% strategy. Treatments to control leaf rust infection were necessary in all years, with even two treatments in 2007 and 2012 (Table 3). In 2007, only the 100% strategy and the 50% strategy were treated a second time. Scald infections were also found on the flag leaf at the end of the growing season, but were sufficiently controlled by the leaf rust treatment in most years. The significantly higher

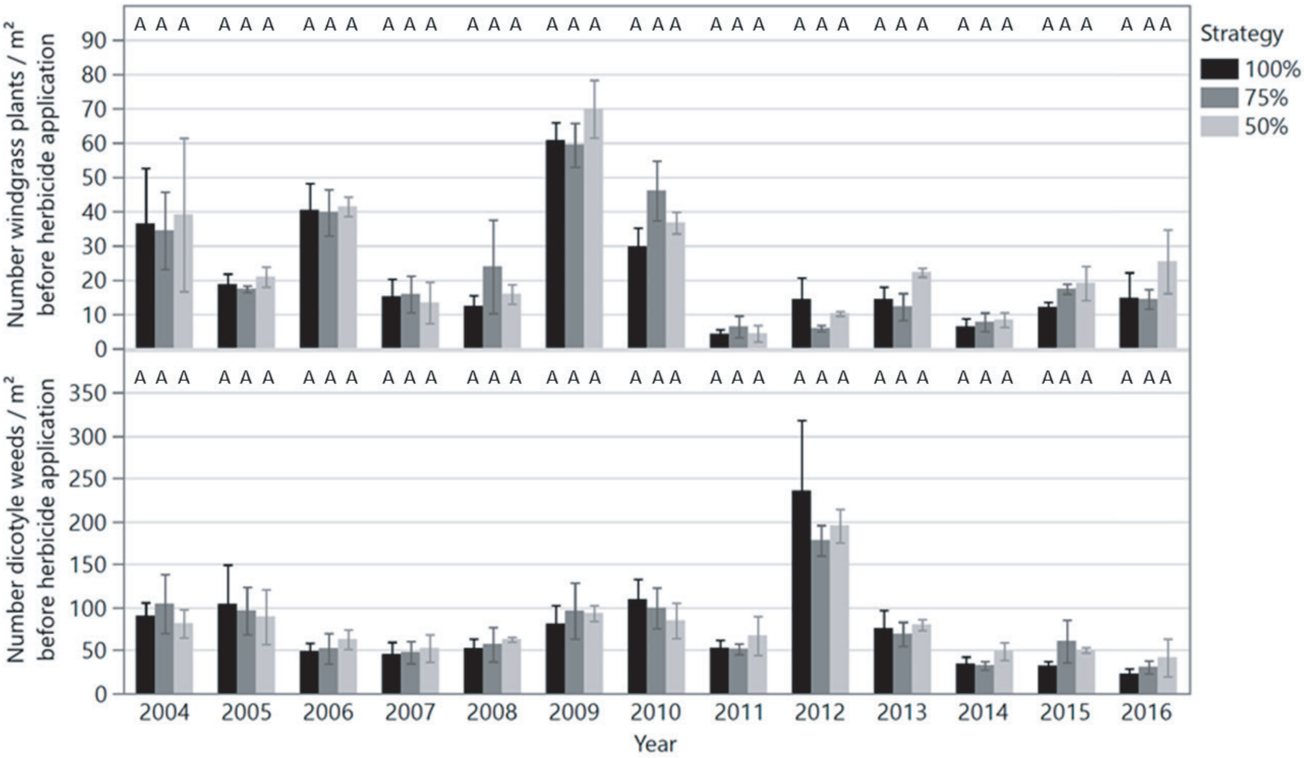

Fig. 4. Number of windgrass and dicot weeds before herbicide application and standard error in the 100%, 75% and 50% pesticide strategy (means with the same letter within the year are not significantly different, n = 3)

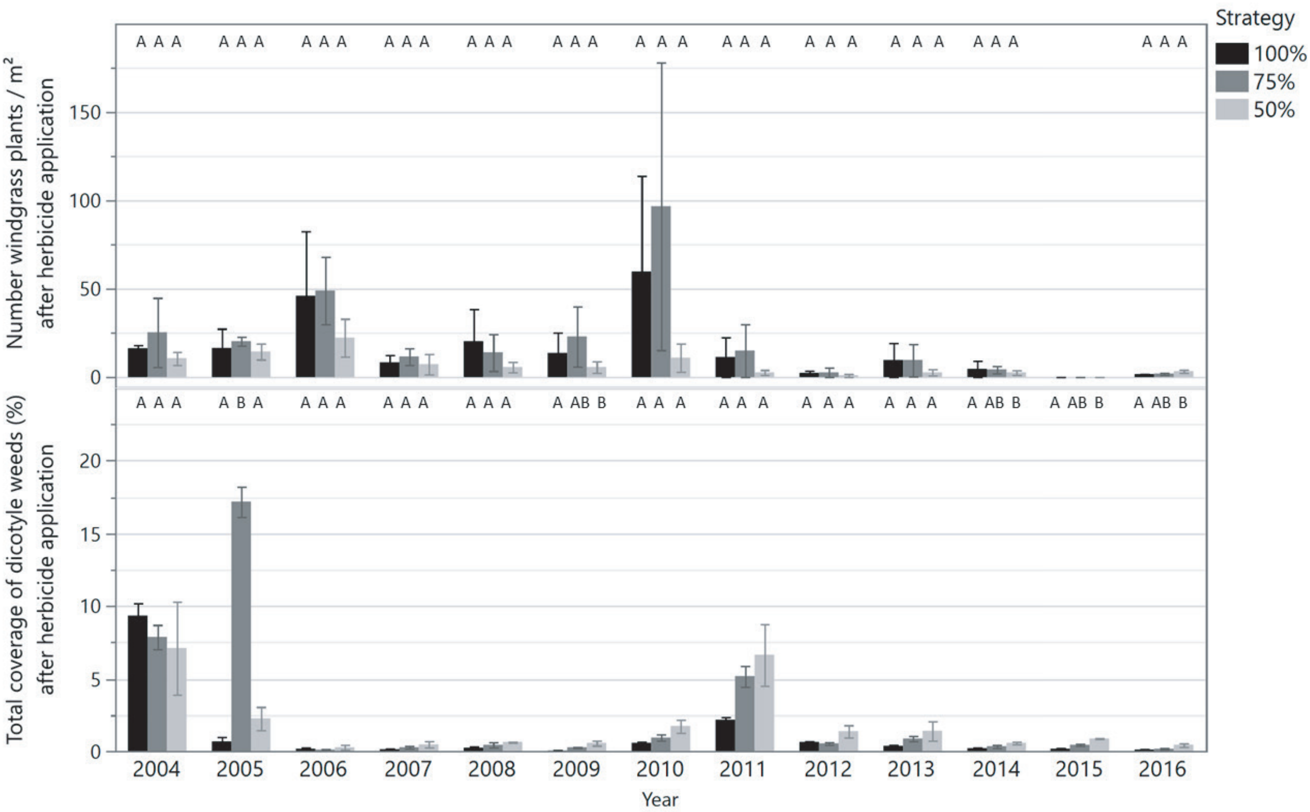

Fig. 5. Number of windgrass and total coverage of dicot weeds after herbicide application and standard error in the 100%, 75% and 50% strategy (means with the same letter within the year are not significantly different, n = 3, no windgrass infestation in 2015)

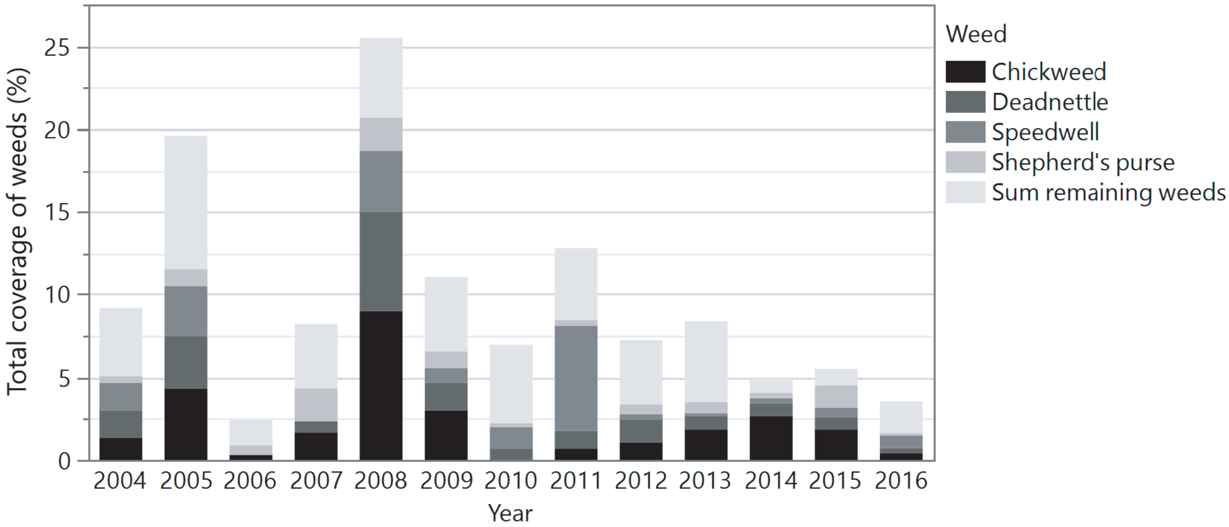

Fig. 6. Total cover of the four most important dicot weeds (Sheperd`s purse, Deadnettle, Chickweed, Speedwell) and sum of remaining weeds in the pesticide-free strategy in spring to show the weed occurence in the years 2004 to 2016

severities of scald in the 100% strategy compared to some of the other reduced strategies can be attributed to the fact that this was not the priority of disease control. Here, the optimal timing of treatment was for leaf rust and not for scald.

Insects

Within the first years of investigation, neither cereal ground beetles nor other insect pests showed abundances that required an insecticide application. However, the amount of plants damaged by cereal ground beetle larvae in autumn increased over time. Control thresholds were exceeded for the first time in 2013. Initially, the severity could be limited by insecticide application in the rows surrounding the plots. An insecticide application was necessary for the first time in 2016, when the mean incidence ranged from 7.0 to 9.5 damaged plants m^{-2}.

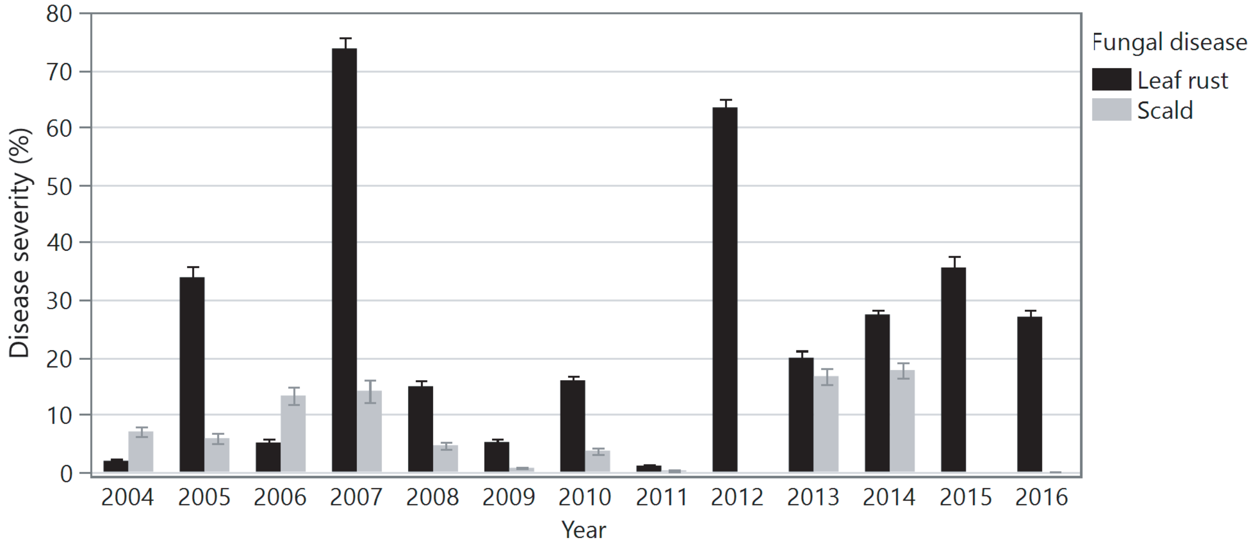

Fig. 7. Disease severity of leaf rust and scald averaged over the two upper leaves and standard error in the pesticide free strategy (Growth stage 69-75, n = 30-100, no scald infestation in 2012 and 2015)

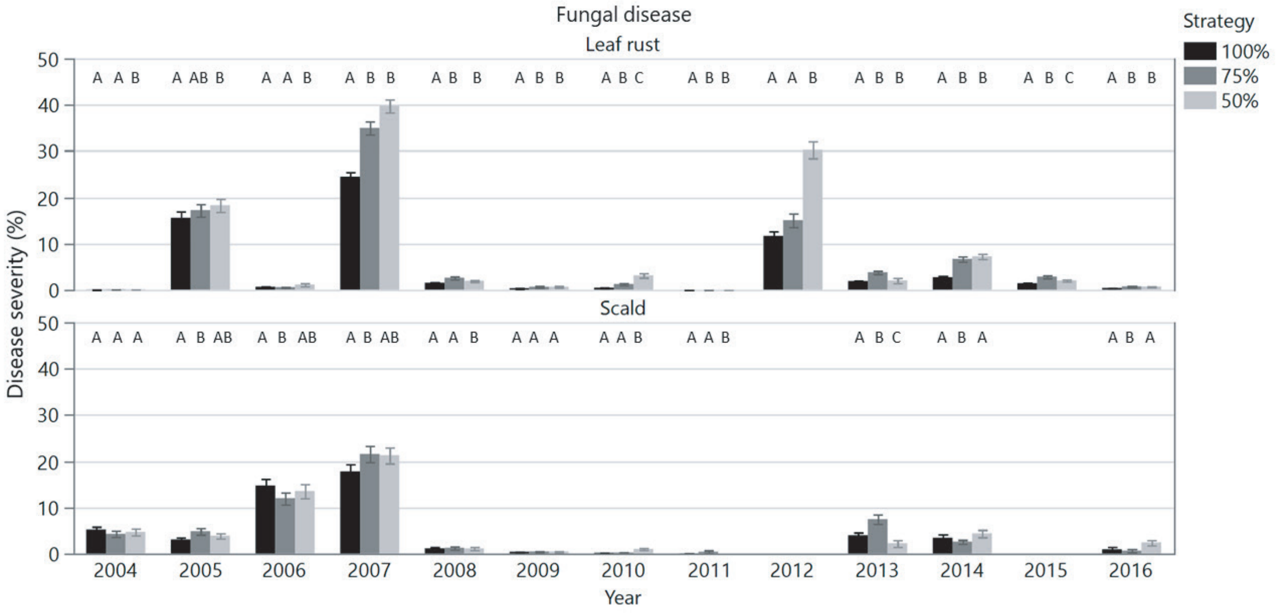

Fig. 8. Disease severity and standard error of leaf rust and scald averaged over the two upper leaves in the 100%, 75% and 50% pesticide strategy (means with the same letter within the year are not significantly different, in 2012 and 2015 scald did not occur; GS 69-75; n = 30-100)

Table 4. Pairwise comparison of yield (dt ha^{-1}) and net return (€ ha^{-1}) between the 100%, 75% and 50% pesticide strategies (averaged over all years, *=significant difference)

Dependent variables	**Strategy**	**Strategy**	**Estimate**	***p*-value**
Yield	100%	75%	1.33	0.470
	100%	50%	3.75	0.007*
	75%	50%	2.42	0.010
Net return	100%	75%	-18.53	0.454
	100%	50%	-1.78	0.991
	75%	50%	16.75	0.519

Effect of strategies on pesticide use intensity

Figure 9 shows the TFI for the individual years and pesticide categories. In the 100% strategy, treatment was based on the situation, i.e. the dose and the time of treatment depended on the occurrence of weeds, fungal and insect pests and the respective treatment thresholds. This led to clear differences in pesticide use intensity between years.

Fungicides, growth regulators and herbicides were applied in all years. Insecticides were only applied in 2016. Fungicide TFI was higher in years with high leaf rust levels. The application of insecticides was only required in one year (2016) with a TFI of 1.0. The mean TFI over all years for herbicides, fungicides,

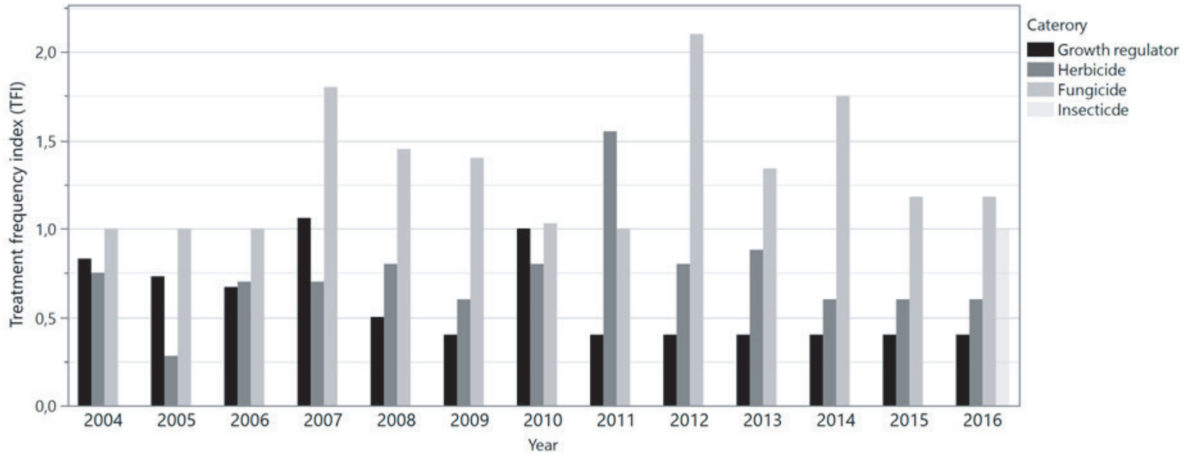

Fig. 9. Treatment frequency index (TFI) for the different pesticide categories in winter rye in the 100% pesticide strategy

and insecticides was 0.7, 1.4, and 0.1, respectively. The mean TFI of growth regulators had a mean value of 0.6.

Effect of strategies on grain yield and net return

The variability of yield in the different years was very high (Fig. 10). The lowest yields did not necessarily occur in years with high disease severity. The difference between the years was only partly due to the occurrence of the fungal diseases and weeds, suggesting that other factors than disease pressure influenced yields, such as weather, which also played an important role. Yields averaged between 86.5 dt ha^{-1} in the 100% strategy and 85.1 dt ha^{-1} and 82.7 dt ha^{-1} in strategies 75% and 50%, respectively. The average yield differed significantly between the 100% and 50% strategy (Table 4).

The highest yield was achieved in 2004 with 119.1 dt ha^{-1} in the 75% strategy. Yields were lowest in 2011 with 52.8 dt ha^{-1} in the 100% strategy probably due to low precipitation from March to June (Fig. 3). In 2007, the 100% strategy and the 50% strategy showed no significant differences, but the 100% strategy differed significantly from the 75% strategy. While the 100% and the 50% strategy were treated twice, the 75% strategy deviated from the trial setting with only one treatment (Table 3). The omission of the second treatment resulted in a significant difference in yield. The 100% strategy showed a significantly higher yield than the other two strategies in 2007, which was also due to the high leaf rust severity in 2007 and to the excellent control provided by the repeated fungicide treatment.

Pesticide costs varied widely across categories and years (Fig. 11). Fungicides caused the largest part of the costs, followed by herbicides. Carboxamides were used annually from 2012. These fungicides were more expensive than the previously used, which led to an increase in costs from 2012.

The net return is shown in figure 12. The highest net returns averaged over all years were achieved in the 75% strategy with 1,035 € ha^{-1}, followed by the 50% strategy with 1,018 € ha^{-1}. The lowest returns were achieved in the 100% strate-

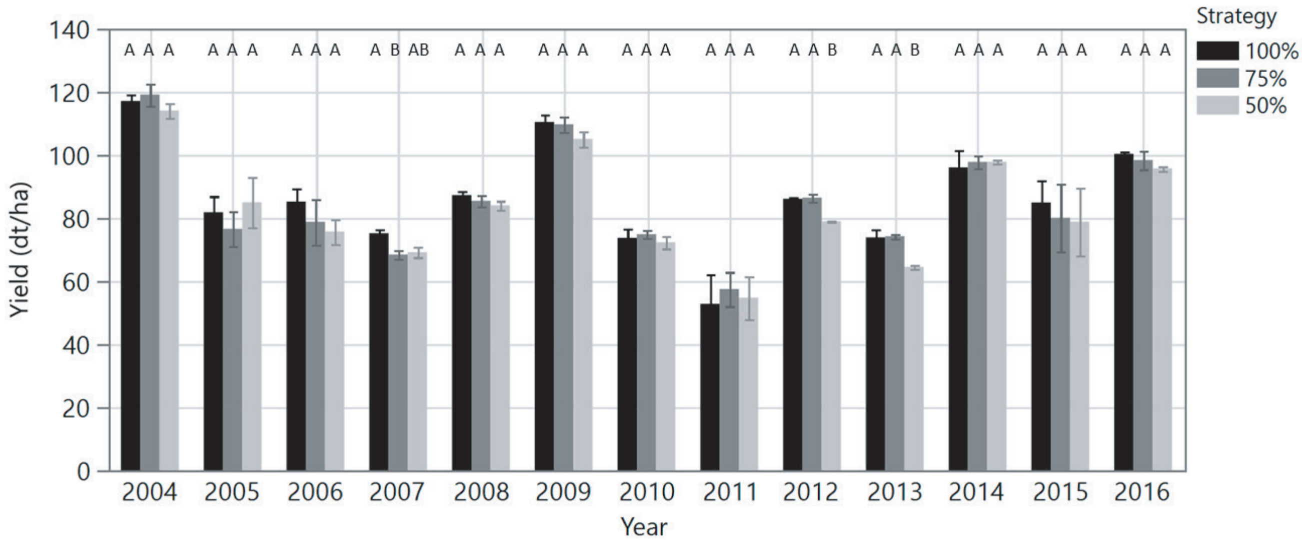

Fig. 10. Yield and standard error of winter rye for the three pesticide strategy (means with the same letter within the year are not significantly different, n = 3)

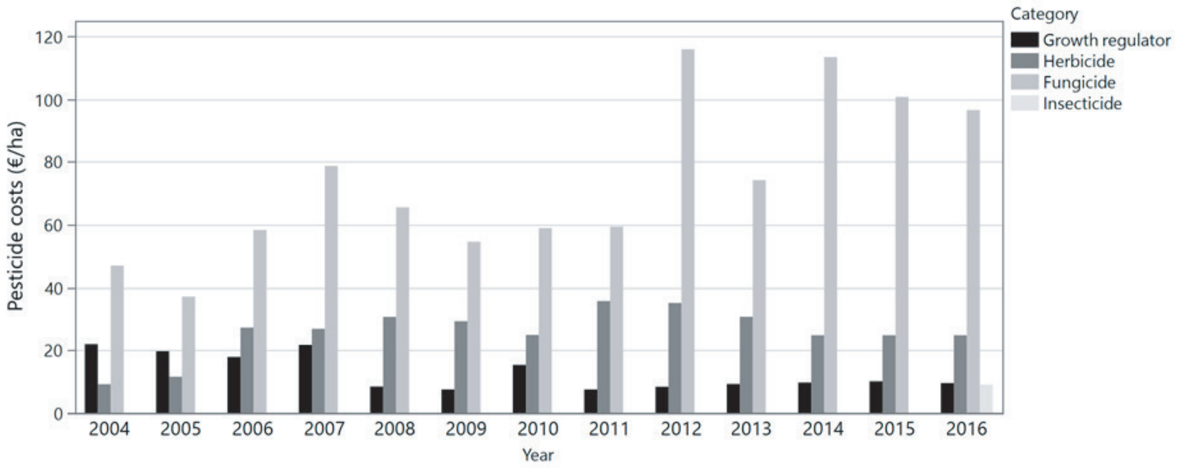

Fig. 11. Pesticide costs for the different pesticide categories (growth regulator, herbicides, fungicides and insecticides) in the 100% pesticide strategy (Agravis, 2004-2016)

gy with 1,017 € ha^{-1}. No significant differences were found (Table 4). The highest net return was achieved in years with moderate yields (Fig. 10), that was compensated by high grain prices (Fig. 2). Only in two years a significant difference could be detected between the 75% strategy and 50% strategy.

Discussion

The results of this 13-year study at the field site in Dahnsdorf (Brandenburg) show that a 50% pesticide use reduction in winter rye has no effect on net return and, in most years, no effect on yield. No weed accumulation was observed in the reduced pesticide use strategies.

Hossard et al. (2014) calculated yield losses of between 5% and 13% in a 50% reduction for pesticides compared to current pesticide use based on French trial results in winter wheat. In our study, the yields were only reduced by 4% (50% strategy) and 2% (75% strategy) compared to the 100% strategy over all years. These findings are in line with those of Schwarz et al. (2018) and Saltzmann & Kehlenbeck (2018) for the two winter wheat cultivars grown in the same six-year crop rotation field trial. For winter wheat, no differences in yield and net return were found between the 100% strategy and the 50% strategy over an average of 13 years. In winter rye, large differences were found between years within the strategies, indicating the influence of weather, often precipitation. The 75% strategy led to the highest net returns on average over all years with 1,035 € ha^{-1}, showing that a reduction in pesticide use is definitely possible. Thus, the economic perspective is crucial in the evaluation of strategies, as yield is not the only determinant of cost-effectiveness. In addition to the pesticide costs, the importance of producer prices should be briefly mentioned here. These were subject to strong fluctuations in winter rye, which meant that the highest net returns were not achieved in the years with the highest yields.

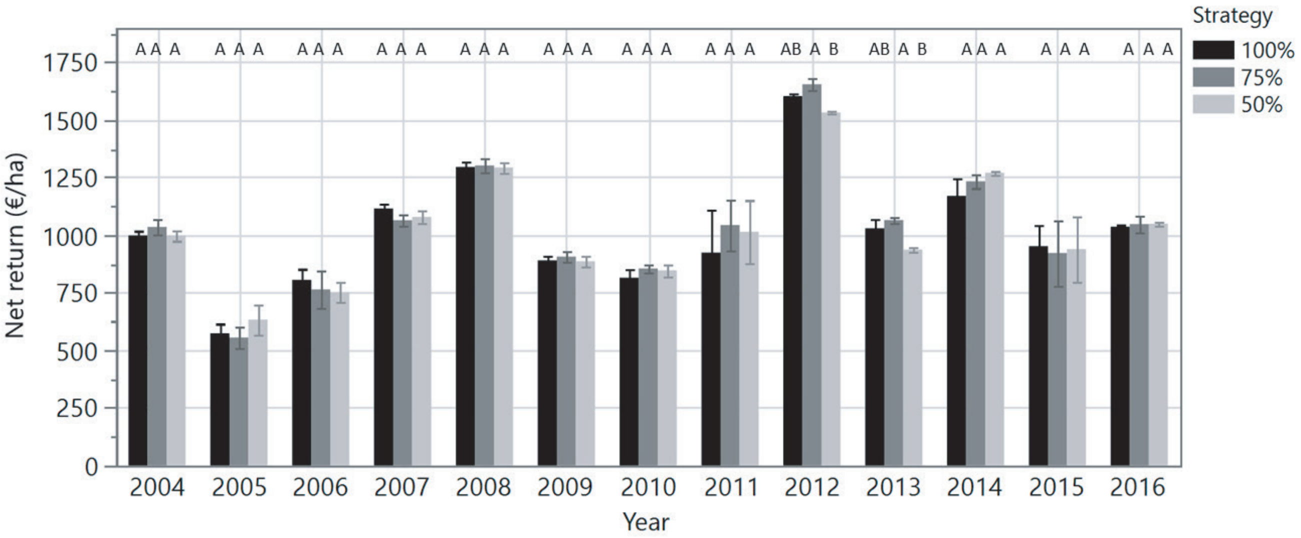

Fig. 12. Net return and standard error of winter rye for the three pesticide strategies (means with the same letter within the year are not significantly different, n =3)

Since the grain price depends on many factors, such as storage, trade and the dynamics of supply and demand, the effect on net returns is difficult to predict (Santeramo et al., 2018). Thus, the economics of a pesticide treatment are often unpredictable at the time of the treatment.

The pesticide use intensity of the 100% strategy was adapted to the infestation levels of pathogens, insects and weeds. The necessary treatments were carried out only after thresholds were exceeded. The dosage of the 100% strategy often did not correspond to the maximum label rate for the fungicides and herbicides but was based on the infestation pressure. Pesticide manufacturers specify the maximum number of treatments or dose of their products needed to provide effective control when pest and weed pressure is high (Jørgensen et al., 2017). Many fungicides are very effective, and reducing the dose usually has no major impact on yield (Wiik & Rosenqvist, 2010). In Denmark, analysis of historical data in winter wheat has shown that the highest net yield gain was achieved with low fungicide TFIs of 0.4 to 0.75 with the optimal timing of a treatment (Jørgensen et al., 2008). In our study, with regular assessments and rapid application of any necessary treatment, the timing of a treatment in the 100% strategy was always optimal. Compared to the TFIs of farming practice in Germany, our TFIs are in some cases considerably lower. Dachbrodt-Saaydeh et al. (2021) recorded pesticide applications on 206 German winter rye fields from 2007 to 2017. For herbicides, a TFI of 1.4 was calculated over all years, for fungicides a TFI of 1.6 and for insecticides of 0.4. For growth regulators, the TFI of 0.9 was also higher than in this study. In addition to herbicides, fungicides and insecticides, growth regulators were also reduced in our study. Lodging occurred in only one of the 13 years.

Fungicide use is most economical when moderate to high levels of disease occur (Wegulo et al., 2011). Susceptible cultivars are more likely to produce positive net returns when treated with fungicides. Thus, the success of a pesticide use reduction depends on the infestation pressure and cultivar resistance (Ransom & McMullen, 2008). In our study, fungal infestations were detected in all years and the density of weeds was also worth controlling in all years. The grown cultivars are classified as moderately resistant and susceptible to leaf rust (Table 1). Compared to winter wheat, the percentage of winter rye cultivars with effective resistance against leaf rust for the commercial market is still relatively low (Bundessortenamt, 2022). In this study, leaf rust, the most important disease in winter rye, occurred regularly with high to moderate disease severities. This would have resulted in high yield losses if no treatment had been applied. Azole-strobilurin and azole-carboxamide mixtures control very effectively leaf rust (Kupfer & Schröder, 2014). The use of these fungicides also resulted in the effective control of leaf rust in our study. The fungicide dose was adjusted to the disease severity. High leaf rust infections in 2005, 2007 and 2012 caused significantly lower efficacy of the fungicide dose used in the 50% strategy. In years with low or moderate infection, a dose reduction was possible without negative effects. In addition, the use of more resistant cultivars could have avoided the need for fungicide applications here. Breeding for durable host resistance strategies will thus become a key issue in the future (Sánchez-Martín & Keller, 2019). Although leaf rust is the most important disease in winter rye and high levels of infestation can lead to severe yield losses, breeding is clearly lagging behind. This is because winter rye is less widely grown than other cereals such as winter wheat, not only in Germany but throughout Europe.

In contrast to fungal pathogens, crop rotation plays an important role in the occurrence of weeds. Increasing the diversity of crop rotations can reduce herbicide intensities (Andert et al., 2016). The long crop rotation in this trial, including alternation between spring and winter crops, had a major impact on weed occurrence as described by Blackshaw et al. (2006). Competitive cropping systems can minimize the supply of weed seeds in the soil in the long term and allow herbicide use reduction (Nazarko et al., 2005). Pallutt (2000) and Schwarz et al. (2018) showed that a complete omission of herbicides for several years leads to an accumulation of weeds in the soil that is still evident years later, despite the diversified crop rotation. Even after the 13 years in this study, there were no differences in dicot weed occurrence between the reduced strategies and the 100% strategy. This also applies to windgrass. A 50% reduction is possible over this long period under the given conditions. Gaba et al. (2016) investigated the relationship between weeds, herbicides and winter wheat yields using data from 150 winter wheat fields in western France. The results suggest that a 50% reduction in herbicide use would maintain crop production and promote weed biodiversity. In our study, differences in weed occurrence were only found between the years.

In contrast to the use of fungicides and herbicides, the use of insecticides was low in this study. Insect pests played a rather minor role, which is reflected in only one treatment in 2016. With regard to the cereal ground beetle infestation, the peculiarities of the field trial site surrounded by high amounts of grass edges without soil tillage probably played a determining role in the increasing damage. Grass strips provide ideal conditions for reproduction, overwintering and immigration in newly established rye stands. It is unlikely that such high levels would have occurred under farming conditions.

The transfer of our results to practical farms is now crucial to achieve pesticide reductions without economic losses. Lechenet et al. (2017) estimated that pesticide use could be reduced by 42% without negative impacts on productivity and profitability in 59% of the farms from the French national network. High perceived risk of loss and low control of pesticide reduction influence farmers' intention to reduce pesticide use (Damalas, 2021). One of the barriers include low adoption of knowledge and technologies of IPM (Lamichhane et al., 2016), but this is absolutely necessary for pesticide reductions at farm level. We show with our results that technologies such as weekly monitoring, consistent use of thresholds, and crop rotation could enable pesticide reductions of 50%. Plant protection services should be the link here between science and farmers to effectively promote risks and benefits of using different IPM strategies. Economically, winter rye may well be considered a crop to diversify crop sequences, can be classified as profitable and additionally enables the saving of pesticides.

Conclusion

The results of this study show that a reduction in pesticide use by 25% and 50% without effects on net return are possible in winter rye. In general, the reduction of pesticides requires a consistent monitoring of all occurring diseases, insects and weeds in order to react as rapid as possible when control thresholds are exceeded. In addition, the success can also be attributed to the long crop rotation with alternating spring and winter crops in our experimental design. In particular, monitoring activities should be common practice in the implementation of IPM, which in combination with resistant or tolerant cultivars can reduce pesticide use intensity in the long term. In the context of the implementation of the Green Deal and the required 50% reduction of pesticides by 2030, these results show a possible way forward for future rye cultivation.

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Conflicts of interest

The authors declare that they do not have any conflicts of interest.

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Supplementary information

Table S1. Category, Trade name and active ingredients of the used pesticides

Category	Trade name Fungicide	Active ingredients [g l^{-1}, kg^{-1}]
Fungicide	Acanto	250 Picoxystrobin
Fungicide	Adexar	62.5 Epoxiconazol, 62.5 Fluxapuroxad
Fungicide	Amistar	250 Azoxystrobin
Herbicide	Arelon Flüssig	500 Isoproturon
Fungicide	Aviator Xpro	150 Prothioconazol, 75 Bixafen
Herbicide	Bacara	100 Diflufenican 250 Flurtamone
Herbicide	Bacara Forte	120 Diflufenican, 120 Flufenacet, 120 Flurtamone
Growth regulator	Camposan-Extra	660 Ethephon
Fungicide	Capalo	62.5 Epoxiconazol, 200 Fenpropimorph, 75 Metrafenone
Growth regulator	CCC	558 Chlormequat
Fungicide	Diamant	114 Pyraclostrobin, 43 Epoxiconazol, 214 Fenpropimorph
Fungicide	Fandango	100 Prothioconazol, 100 Fluoxastrobin
Herbicide	Fenikan	62.5 Diflufenican, 500 Isoproturon
Fungicide	Folicur	250 Tebuconazol
Herbicide	Foxtril Super	250 Bifenox, 76.6 Ioxynil, 292 Mecoprop
Fungicide	Gladio	125 Propiconazol, 125 Tebuconazol, 375 Fenpropidin
Herbicide	Herold	400 Flufenacet, 200 Diflufenican
Herbicide	Hoestar Super	125 Amidosulfuron, 11.6 Iodosulfuron
Fungicide	Input	160 Prothioconazol, 300 Spiroxamine
Herbicide	Isomex 500 SC	500 Isoproturon
Fungicide	Juwel Top	150 Fenpropimorph, 125 Epoxiconazol, 125 Kresoxim-methyl
Insectice	Karate Zeon	100 lambda-Cyhalothrin
Herbicide	Lexus	462.97 Flupyrsulfuron
Growth regulator	Medax Top	42.39 Prohexadion, 228.9 Mepiquat
Growth regulator	Moddus	222 Trinexapac
Fungicide	Pronto PLUS	250 Spiroxamine, 133 Tebuconazol
Fungicide	Skyway Xpro	75 Bixafen, 100 Tebuconazol, 100 Prothioconazol
Herbicide	Tolkan Flo	500 Isoproturon
Fungicide	Vegas	51.3 Cyflufenamid