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Costs and benefits of preventive strategies to reduce pesticide use

Case studies on Integrated Pest Management in German arable farming

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Summary

Plant pests, diseases and weeds threaten agricultural crops and require control methods. However, the largely used pesticides are associated with undesirable effects on environment and health. To reduce pesticide use, Integrated Pest Management (IPM) offers a comprehensive toolbox. The two selected IPM strategies (1) wide crop rotation and (2) cultivation of pathogen resistant cultivars were analysed economically based on two different field trials. Crop rotation (long-term field trial at Dahnsdorf, Brandenburg, Germany, with a six-unit crop rotation) and pesticide reduction by 25% and 50% resulted in no decline in gross margins and thus profitability in silo maize, wheat (E- and A-quality), barley and rye. However, a 25% and 50% reduction in pesticides led to a decline in gross margins by -6.3% (-331 € ha^{-1}) and -8.3% (-437 € ha^{-1}) in potatoes. The use of pathogen resistant wheat cultivars and IPM based fungicide application (tested at five field sites across Germany) resulted in reduced fungicide applications and higher gross margins compared to the "non-IPM" strategy by about +45 to 70 € ha^{-1}. Based on these findings, we conclude that preventive IPM strategies have a good potential to reduce pesticide use and are also economically viable for farmers.

Keywords

economic viability, potential of pesticide reduction, field trials, crop rotation, cultivar resistance, plant pests, diseases and weeds

Introduction

Plant pests, diseases and weeds threaten agricultural crops and can cause substantial economic losses (Savary et al., 2019). Plant protection therefore remains an important part of crop management. The application of pesticides has been the major measure in crop protection since many years. Pesticides are, however, associated with undesirable effects on the environment, health, and the sustained efficacy of their use (Pimentel & Burgess, 2014; Barzman et al., 2015; Tang et al., 2021). Moreover, policy aims for reducing pesticide use and risks have been formulated at EU (Green Deal and Farm-to-Fork-Strategy; European Commission, 2020) and national level, and reduction programs are introduced.

With our study, we aim to evaluate the economic viability at field level of specific preventive IPM strategies in arable crops considering their pesticide reduction potential. As exemplary case studies for IPM strategies, we selected the (1) diversity of crop rotation and the (2) use of pathogen resistant cultivars in winter wheat.

Crop rotation (1) affects spatial and temporal diversification of crops over time (Castellazzi et al., 2008) and is a cornerstone to minimize pest and weed pressure. Crop rotation is the most effective agronomic alternative to chemical pesticides (Barzman et al., 2015). In arable crop rotations, the alternation of winter and spring-summer crops and of cereals and foliar crops is known to break the life cycle of weeds but also pests. Concerning insect pests, this strategy is especially successful against specialized insects with limited mobility (Bazok et al., 2021; Vasileiadis et al., 2011). Diverse crop rotations are reported to be associated with yield increase, economic benefits for farmers and reduced production risks (Shah et al., 2021; Jalli et al., 2021; Gaudin et al., 2015).

Pathogen resistant wheat cultivars (2) are an important tool in IPM to prevent pest infestation and are considered as a cost-effective and environmentally friendly approach to control fungal diseases (Klocke et al., 2022). Still, 88% of the world's wheat production is based on wheat cultivars susceptible to (various) diseases (Carmona et al., 2020). On the other hand, Lüttringhaus et al. (2021) reported on the profitability and sustainability of resistance breeding due to a reduction of fungicide costs.

We based our economic analysis of crop rotation and the use of pathogen resistant cultivars in winter wheat on field experiments. With our economic analysis, we intend to answer the following research questions:

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(1) What are the benefits and costs of reducing pesticide use in a wide six-unit crop rotation?

(2) What are costs and benefits of implementing pathogen resistant cultivars and situation specific pesticide treatments for farmers?

(3) What are the constraints to improve pesticide reduction opportunities?

Material and methods

In this paper we consider two case studies to estimate the potential of pesticide reduction for IPM concerning their effect on profitability. Research question 1 and 2 refer to one study each, the “wide crop rotation study” and the “pathogen resistant cultivar study”. For the analysis on constraints of IPM, mainly literature was considered. The statistical analysis was carried out using SAS.

Case study “wide crop rotation”

The economic reduction potential of pesticides in a wide crop rotation was determined by evaluating a long-term field trial. The trial was conducted from 2004 to 2016 at the Dahnsdorf experimental fields of the Julius Kühn Institute in Brandenburg, Northern Germany.

Description of the field trial and pesticide strategies

The trial included a wide six-unit crop rotation of: intercrop (1) silo maize – (2) A-quality wheat – (3) winter barley – intercrop (4) potatoes – (5) Elite-E-wheat – (6) winter rye. The A-quality wheat class stands for the "quality wheat" in German classification. It is mainly used as a blending wheat to complement other wheat varieties. Elite-E-wheat represents the highest quality. However, it is rather unsuitable for baking and is used in small quantities. Both, the A- and E-quality wheats stand for high protein cultivars with 13% raw protein content for A-wheat and 14% for E-wheat (Stary, 2023 and Deter, 2019). As a rule, plowing was carried out in all years and crops. In some years, plowing was not required in the two wheat crops due to the position in the crop rotation, which was expected not to have any volunteer grain after silo maize or potatoes. As described in more detail in Schwarz et al. (2018) and Saltzmann & Kehlenbeck (2018) the plant protection strategies in the field trial differed as follows:

- Situation-related dosage (sit.; 100%-pesticides): Good professional practice taking into account the principles of IPM, application of control thresholds, situation-adapted selection and dosage of pesticides.
- 75% of situation-related dosage (75%-pesticides): Reduction of the treatment frequency index (TFI, as described by Klocke et al., 2023, this issue) by 25% compared to sit. for all pesticides.
- 50% of situation-related dosage (50%-pesticides): Reduction of the TFI by 50% compared to sit. for all pesticides.

Weather and site conditions of the field trial location can be found in Klocke et al. (2023) in this issue.

Data and assumptions

For the economic evaluation, a period of two six-unit crop rotations over 12 years (2004–2015) was analysed. Field data on costs and revenues was supplemented by secondary German data sources (see Table 1). An overview on the used revenue and cost components as well as further assumptions relevant for calculations are shown in Table 1.

Calculation method

Using cost-performance accounting methods as a standardized calculation method in agricultural economics, the annual gross margins for each crop and each pesticide strategy were determined. The gross margins calculated here only include those cost and benefit components that differ between crops and pesticide strategies and thus have an impact on the result. Soil management was considered identical for all crops and strategies and was therefore not taken into account. Gross margins are defined as a result of revenues minus direct costs (Schroers et al., 2010; Table 2). For the gross margin calculations, the direct costs, labour and machinery costs caused by sowing, fertilizing, pesticide application and harvesting as well as the interest for the committed capital were deducted from the revenues. Average gross margins per crop were calculated for the entire trial period (2004–2015) and for each (6-year) rotation individually.

Statistics

The effects of the different strategies on grain yield and gross margins were analysed using linear mixed models (Moll & Piepho, 2001) with the MIXED procedure of SAS® version 9.4. Grain yield and gross margins were the dependent variables, while years and blocks were treated as random effects. Blocks were nested with years for grain yield. In addition, the interactions between year and strategy were analysed. The analysis of the gross margins was not performed on block level and based on one single value per year and crop. Least squares (LS) means were estimated for the dependent variables by using the LS means option and a 0.05 probability level. These squares were then compared for differences in the different strategies with the simulate adjustment test. The rotations were compared using a t-test.

Case study on consequent IPM with “pathogen resistant cultivars”

The economic analysis of this case study was based on field trial data (Klocke et al., 2022), supplemented by secondary German statistical data.

Field trials

Field experiments were conducted over three years (2016–2018) at five field sites in Germany (Dahnsdorf, Söllingen, Bin-

Table 1. Assumptions for calculating the pesticide reduction potential of a crop rotation

Components	Calculation and data used
Revenue	
Yields and producer prices	The annual yields were taken from the field trial data. Per crop and plant protection strategy, the mean of three repetitions per crop and year was used. Producer prices were taken for each crop from the statistical yearbooks of the respective years and from other data sources (ZMP, 2006; AMI, 2010; AMI, 2017; BMEL, 2003; 2009; 2014). Since there is no market price for silo maize, this was calculated using the annual revenues of a hypothetical alternative crop according to Harms (2023). Here, winter wheat was used as the basis for calculating a price for silo maize.
Sowing	
Direct costs	Annual quantities per crop and plant protection strategy were based on the field trial data. Annual seed prices for winter wheat, winter barley, winter rye, potatoes (Uhlemann, 2023) and silo maize (Trockels, 2023) were used.
Labour and machine costs	The wage costs were calculated for each year based on the wage costs for permanent employees according to KTBL (various years). Since no annual prices for sowing machines were available, the costs were converted from KTBL (2023) to the trial years using the price index for agricultural inputs 'machinery and equipment for crops' (Destatis, 2023).
Fertilization	
Direct costs	Annual fertilizer quantities per crop and plant protection strategy were taken into account according to the quantities in the field trials. Product prices for mineral fertilizer were calculated based on the annual pure nutrient prices from the statistical yearbooks (BMEL, 2003; 2009; 2014).
Labour and machine costs	The calculation is equivalent to sowing.
Farm manure	In potatoes and silo maize, manure was applied in addition to mineral fertilizer. The fertilizer value and associated costs of application were taken into account on an annual basis (Schindler, 2009). Applied nutrient amounts were multiplied by the annual nutrient prices (BMEL, 2003; 2009; 2014). Application and labour costs of manure were calculated equivalent to the machine and labour costs of sowing.
Intercrops	Different intercrops were grown before potatoes and silo maize. Associated costs and the fertilizer value of growing intercrops were taken into account. The fertilizer value was calculated according to Knöferl et al. (2022) and Kolbe et al. (2004). From the fertilizer value of the intercrops, the costs of seeds (MyAgrar, 2023) and sowing (KTBL, 2023) were deducted on an annual basis to obtain an annual net fertilizer value. Annual seed prices were calculated using the price index for 'seed and seedlings' for agricultural inputs (Destatis, 2023). The calculation of the machine costs for intercropping was carried out as described above for sowing.
Pesticide application	
Direct costs	Annual quantities per crop and plant protection strategy were taken from the field trial. The crop protection product prices were based on the Agravis price lists for the respective years (AGRAVIS, 2004–2018).
Labour and machine costs	Since no annual prices for pesticide application were available, the costs were converted from KTBL (2023) to the trial years using the price index 'machinery and equipment for crops' for agricultural inputs (Destatis, 2023). The wage costs were calculated as described above.
Harvest	
Labour and machine costs	The wage costs were calculated as described above. Annual costs for harvesting machines were calculated equivalent to other machine costs by using the price index for 'machinery and equipment for harvesting' for agricultural inputs (Destatis, 2023).
General assumptions	
Field size	5 ha field size at a field-farm distance of 1 km
Interest	interest rate: 0.04; duration of the capital commitment: 6 months

gen, Thyrow and Groß Lüsewitz) with different pedo-climatic properties and are described precisely by Klocke et al. (2022). Soil conditions at the five sites are characterized by sandy silt (Dahnsdorf), loamy (Söllingen), sandy loam (Bingen), sandy to loamy sand (Thyrow) and sandy loam (Groß Lüsewitz). Mean annual precipitation reaches about 565 mm in Dahnsdorf, 600 mm in Söllingen, 490 mm in Bingen, 510 mm in Thyrow and 690 mm in Groß Lüsewitz.

Table 2. Calculation methods of gross margins as an economic indicator (after Schroers et al., 2010)

Revenue and cost	**Description**
revenues	yield multiplied by producer price
– direct costs	seeds, pesticides, fertilizers
– labour and machine costs	sowing, pesticide application,fertilizer application, harvesting
– interest	interest costs for the committed capital
= **gross margins**	

Plant disease control and IPM strategies

The field trials compared the three different fungicide strategies “untreated control”, “situation-related” and “practice-related” for eight different cultivars each (Klocke et al., 2022).

Our economic assessment considered those changes in costs and benefits that were related to the implementation of the IPM measures “resistant cultivars”, “intensive pathogen monitoring” and consequent use of “disease thresholds” in comparison to not doing so. We therefore only compared the two variants “IPM”, which is represented by the “situation-related strategy” and “non-IPM”, represented by the “practice-related strategy” as described by Klocke et al. (2022; see Table 3). The resistance classification of the eight wheat cultivars is listed in Table 4.

Calculation method

Costs, revenues and gross margins (for details see above and Table 2) were calculated for the yearly mean of four field data replicates based on standard procedures.

For the economic analysis we chose a comparison of gross margins between “IPM” and “non-IPM” and a cost-benefit-analysis for the implementation of the IPM strategies (with resistant cultivars, monitoring and fungicide application). Here, all input factors with their costs were considered.

Table 3. Fungicide and Integrated Pest Management (IPM) strategies applied within the field trials (after Klocke et al., 2022) and considered for the economic assessment

Fungicide strategy	**Consideration of cultivar disease resistance (CDR) and consequences for the fungicide treatment**	**Intensive pathogen monitoring and consequent use of disease thresholds**
“IPM”	CDR considered (by cultivar specific disease monitoring) and subsequently each cultivar is treated individually with fungicides (application rate; spraying date) once the disease threshold is exceeded in the specific cultivar	yes, individually for each cultivar
“non-IPM”	CDR not considered (by cultivar specific disease monitoring) resulting in the same fungicide treatment for all cultivars once the disease threshold is exceeded in any one of them	no, not individually for each cultivar

[1] IPM principles request amongst others the use of resistant cultivars, the monitoring of harmful pests and diseases in the field, the consideration of disease thresholds for the decision making on pesticide treatments and to keep the use of pesticides only to levels that are economically and ecologically justified (Directive 2009/128/EC, Annex III).

Table 4. Resistance classification of the eight winter wheat cultivars against fungal diseases, their year of release and the mean resistance classification per cultivar, 1 = completely resistant, 9 = highly susceptible (Bundessortenamt, 2016)

Cultivar	**Year of release**	**Powdery mildew**	**Septoria leaf blotch**	**Yellow rust**	**Leaf rust**	**Fusarium head blight**	**Mean resistance classification**
JB Asano	2008	3	7	8	5	6	5.8
Julius	2008	4	4	2	4	5	3.8
Patras	2012	3	5	3	5	4	4.0
Apertus	2013	4	4	3	5	4	4.0
Attraktion	2014	1	3	2	3	6	3.0
Capone	2012	2	3	3	2	5	3.0
Dichter	2014	3	2	2	2	4	2.6
Spontan	2014	3	3	1	4	3	2.8

Economic benefits in a cost-benefit comparison are in general considered as exceeding of the revenues compared to the costs. Other benefits such as environmental aspects were not taken into account.

Assumptions for costs and revenues

Calculations of variable costs for input factors were based on individual treatments and measures according to the field trials. Variable costs comprise sowing, plant protection measures, fertilization, tillage, and harvesting. They were calculated separately, based on site-specific data in the field trials of the investigated strategies in 2016, 2017 and 2018 at the five locations. Sowing costs were calculated based on the site-specific seed rates (kernels per m^2) which differed between the five locations. The seed costs per variety were derived from price lists of trade companies (Beiselen GmbH, 2023; Saaten-Union GmbH, 2023) and the labour and machine costs for sowing based on KTBL (2016–2018). One working hour was assumed with costs of 17.50 € (KTBL, 2016–2018).

Plant protection measures included herbicide, insecticide, fungicide and growth regulator applications. Costs were calculated based on the site-specific application rates and pesticide product costs were derived from AGRAVIS (2004–2018). For the estimation of pesticide application costs, average labour costs to conduct sprayings were calculated as mean of field sizes ranging from 1 to 20 hectares and farm-field distances from 1 to 30 kilometres and with a diesel price of 0.70 € l^{-1} (KTBL, 2016–2018; see Table 5).

Costs of fertilization were calculated based on the site-specific fertilizer rates (kg ha^{-1}), the fertilizer costs from price lists of trade companies (BayWa AG München, 2023) and the labour and machine costs for fertilizer application according to KTBL (2016–2018). Tillage costs were calculated according to KTBL (2016–2018) based on the site-specific tillage and machinery. Harvesting costs were considered according to KTBL (2016–2018).

Monitoring costs for assessing disease infestation

The costs of assessing disease infestation vary depending on the size of the field, the distance between the field and the farm and the number of rides per growing season. On average, monitoring costs were considered with 3.56 € ha^{-1} per trip to the field. The number of trips for monitoring disease infestation ranged from 3 to 5 and the monitoring costs per year from 11 to 26 € ha^{-1}, depending on the year, the site and the cultivar. Klocke et al. (2022) have described monitoring results and disease infestation comprehensively.

Results

We first present the results of the economic assessment of the case study on pesticide reduction in a wide crop rotation and describe secondly the case study on costs and benefits of the use of pathogen resistant cultivars with an IPM based and situation-related crop protection considering disease thresholds per cultivar.

Reduction potential for pesticides and economic viability of a wide six-unit crop rotation

The economic evaluation of the six-unit crop rotation at the Dahnsdorf experimental field site has shown a clear potential for pesticide reduction in certain crops without economic losses. The average annual gross margins for each of the six crops were calculated and are presented in Table 6.

In addition, the differences in the average gross margins of the reduction strategies (75%, 50%) and the situation-related crop protection strategy are shown (Fig. 1). These results indicate a potential for a reduction of pesticide use from an economic perspective in most crops.

Economic effects of the pesticide reduction strategies

The average gross margins in the situation-related pesticide application strategy (sit.) over both rotations (2004–2015) are 1,134 € ha^{-1} in silo maize, 796 € ha^{-1} in winter wheat (A-quality), 578 € ha^{-1} in barley, 5,281 € ha^{-1} in potatoes, 638 € ha^{-1} in the second winter wheat (E-quality) within the crop rotation and 533 € ha^{-1} in winter rye (Table 6). Compared to the situation-related scenario, no major economic losses occurred in silo maize and grain for the pesticide reduction scenarios (75% and 50%; Fig. 1). In these crops, the 75% reduction scenario was even slightly advantageous compared to the situation-related pesticide treatment. In detail, the average gross margins of silo maize was +59 € ha^{-1} (+5.2%), A-wheat +21 € ha^{-1} (+2.1%), barley +4 € ha^{-1} (+0.6%), E-wheat +22 € ha^{-1} (+3.5%) and rye + 15€ ha^{-1} (+2.7%) compared to the situation-related pesticide treatment without pesticide reduction. The 50%-strategy achieved almost the same gross margins as the situation-related pesticide treatment (silo maize: +25 € ha^{-1}

Table 5. Assumptions for the calculation of tractor ride costs (KTBL, 2016–2018)

Field size [ha]	Farm-field distance [km]	Labour costs [€ ha^{-1}]	Machine costs [€ ha^{-1}]	Costs of tractor ride [€ ha^{-1}]	Average costs per tractor ride [€ ha^{-1}]
1	1	4.03	8.68	12.71	12.48
2	5	3.33	8.03	11.36	
5	10	3.15	7.82	10.97	
10	20	4.03	8.76	12.79	
20	30	4.90	9.67	14.57	

Table 6. Average annual gross margins (Rotation (Rot.) 1 + 2: 2004–2015; Rot. 1: 2004–2009; Rot. 2: 2010–2015) per crop and plant protection strategy (sit., 75%, 50%) of the field trial in Dahnsdorf in € ha^{-1}

	sit.[1]			75%[2]			50%[3]		
	Rot. 1 + 2 [€ ha^{-1}]	Rot. 1 [€ ha^{-1}]	Rot. 2 [€ ha^{-1}]	Rot. 1 + 2 [€ ha^{-1}]	Rot. 1 [€ ha^{-1}]	Rot. 2 [€ ha^{-1}]	Rot. 1 + 2 [€ ha^{-1}]	Rot. 1 [€ ha^{-1}]	Rot. 2 [€ ha^{-1}]
Silo maize	1,134	1,092	1,177	1,194	1,195	1,192	1,159	1,157	1,162
A-Wheat	796	736	857	817	762	873	784	726	842
Barley	578	577	580	582	571	593	598	594	602
Potato	5,281	4,733	5,828	4,949	4,588	5,310	4,843	4,479	5,207
E-Wheat	638	575	701	660	595	726	638	590	685
Rye	533	543	522	547	525	569	529	527	531

[1] Sit.: situation-related pesticide strategy; [2] 75%: pesticide reduction by 25% compared to sit.; [3] 50%: pesticide reduction by 50% compared to sit.

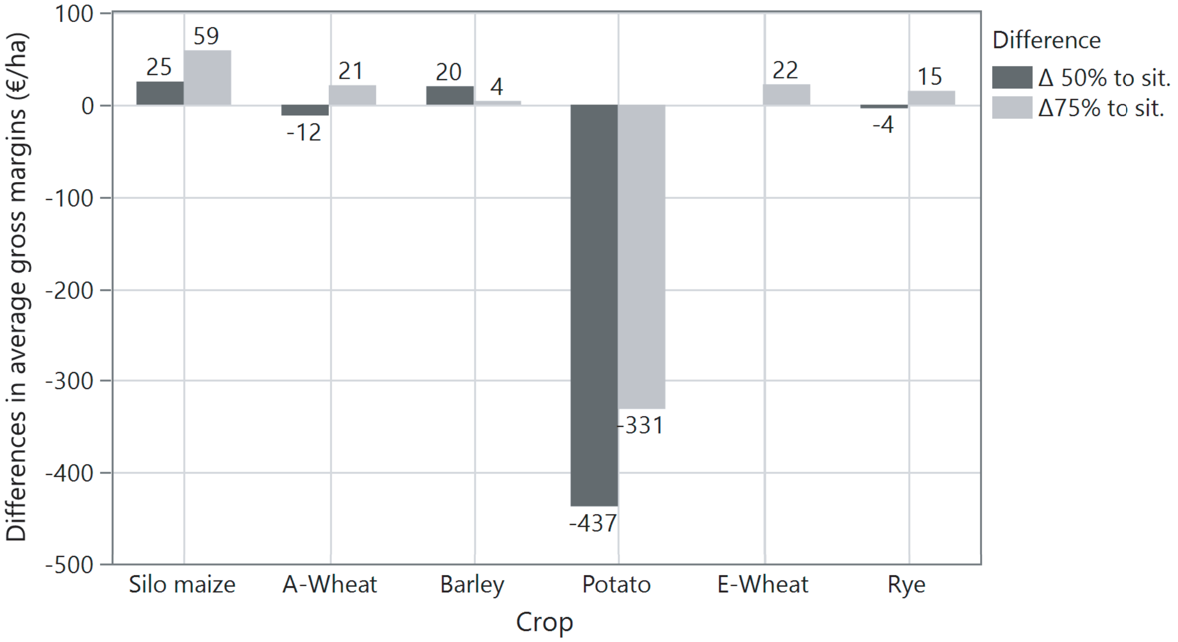

Fig. 1. Differences in average gross margins (2004-2015) of the pesticide reduction strategies (75 %, 50 %) and the situation-related pesticide strategy (sit.) per crop in € ha^{-1} of the field trial in Dahnsdorf.

(+2.2%), A-wheat: -12 € ha^{-1} (-1.5%), barley: +20 € ha^{-1} (+3.4%), E-wheat: +0 € ha^{-1} (0.0%), rye: -4 € ha^{-1} (-0.7%)) with barley showing even a better result in the 50%-strategy than in the 75% or situation-related strategy. Results are different for potatoes with clear economic disadvantages for the pesticide reduction scenarios. A pesticide reduction in potatoes by 25% led to a -331 € ha^{-1} (-6.3%) lower gross margin while a pesticide reduction by 50% caused a gross margin loss of -437 € ha^{-1} (-8.3%).

A statistical evaluation of the gross margins and yields for the three crop protection strategies is shown in Table 7. With regard to the gross margins, there is only a significant difference for potatoes between the situation-related plant protection treatment and the 50% reduction. In all other crops, even a 50% reduction in pesticide application did not lead to any significant economic disadvantages. The contribution margins were also evaluated for each rotation separately, but did not show any significant results.

There were more differences at yield level. A 25% reduction in pesticide use compared to a situation-related pesticide application only had significant effects on potato yields. A reduction from 75% to 50% resulted in significant yield differences in winter wheat (both A- and E-quality). A pesticide reduction of 50% compared to situation-related pesticide application led to significant yield differences in winter wheat (A-quality), potatoes, winter barley, winter wheat (E-quality) and winter rye. With the exception of potatoes, the yield effects of the pesticide reduction in these crops were offset by lower pesticide costs and changes in input and producer prices. In potatoes, pesticide savings or price effects could not compensate for yield losses due to the pesticide reduction by 50%, resulting in significantly lower gross margins.

Table 7. Significant differences for the comparison of the dependent variables gross margins (€ ha^{-1}) and yield (dt ha^{-1}) between the plant protection strategies (sit.[1], 75%[2], 50%[3]) of the field trial in Dahnsdorf (SIMULATE adjustment test at the 0.05 probability level)

	Compared Strategies		Estimate	p-Value
Gross margins (2004–2015)				
Potatoes	sit.	50%	437.37	0.0420
Yield (2004–2015)				
Winter wheat (A-quality)	sit.	50%	4.6222	0.0064
Winter wheat (A-quality)	75%	50%	3.6596	0.0292
Potatoes	sit.	75%	30.6597	0.0445
Potatoes	sit.	50%	39.7764	0.0071
Winter barley	sit.	50%	2.6265	0.0280
Winter wheat (E-quality)	sit.	50%	3.5953	0.0017
Winter wheat (E-quality)	75 %	50%	3.1533	0.0052
Winter rye	sit.	50%	3.6806	0.0153

[1] Sit.: situation-related pesticide strategy; [2] 75%: pesticide reduction by 25% compared to sit.; [3] 50%: pesticide reduction by 50% compared to sit.

Effect over time – comparing rotation 1 and rotation 2

A closer look at the single rotations shows that rotation 1 has a slightly lower profitability in most crops than rotation 2, with two exceptions: rye was more profitable in rotation 1 (2004–2009) in the situation-related strategy and silo maize was more profitable in rotation 2 (2010–2015) in the 75%-strategy (Table 6).

However, when comparing rotation 1 with rotation 2 the positive trend can be seen in the gross margins only. Considering yields, it is the opposite. Except for silo maize, average yields in the second rotation were lower than in the first rotation in all crops and strategies (sit./75%/50%). For silo maize, average yields in the second rotation were slightly higher than in the first rotation. One reason for the favorable performance of silo maize could be the frequent spring drought at the Dahnsdorf site. In rotation 1, the year 2006 was a very dry year, while in rotation 2 the years 2011, 2012 and 2015 had dry early summers. Silo maize was less affected by spring drought due to its late emergence. In 2013, A- and E-wheat, as well as winter rye, were affected by hail, shortly before harvest.

However, a statistically significant difference between the yields in rotation 1 and 2 could be found in barley (in all strategies), in rye (in sit. and 50%), in A-wheat (in sit. and 75%) and in potatoes (in 75%; Table 8). The lower yields are not reflected in lower gross margins, as these were compensated for by higher producer prices or input changes.

Overall, concerning gross margin calculation, it is remarkable that the effect of the pesticide reduction strategies on profitability is quite small, and does not weigh heavily, except for potatoes.

Table 8. Significant differences for the comparison of the dependent variable yield (dt ha^{-1}) between rotation 1 (2004–2009) and rotation 2 (2010–2015) in a six-unit crop rotation of the field trial in Dahnsdorf for each plant protection strategy (sit., 75%, 50%) (t-test at the 0.05 probability level)

Pesticide strategy	Crop	Degrees of freedom	t-Value	p-Value
sit.[1]	Barley	34	3.22	0.0028
	Rye	33.982	2.76	0.0093
	A-wheat	30.166	2.66	0.0123
75%[2]	Potatoes	27.793	2.13	0.0421
	Barley	33.97	2.55	0.0153
	A-wheat	31.343	2.52	0.0170
50%[3]	Barley	33.732	3.02	0.0048
	Rye	33.734	2.59	0.0139

[1] sit.: situation-related pesticide strategy; [2] 75%: pesticide reduction by 25% compared to sit.; [3] 50%: pesticide reduction by 50% compared to sit.

Consequent IPM with pathogen resistant winter wheat cultivars

The average gross margins for the two strategies “IPM” with resistant cultivars, infestation monitoring and situation-related fungicide application and “non-IPM” practice-related fungicide application are summarized for the five different field sites in Fig. 2. For all five sites, gross margins of the “IPM” strategy exceed those of the “non-IPM” strategy. The differences in the gross margin amounts between the field site locations result from their different yield potential due to different pedo-climatic conditions. Thyrow shows the worst prerequisite for growing winter wheat resulting in negative gross margins. The outcome of the “IPM” strategy, however, is less negative.

Average gross margins for the different winter wheat cultivars that were studied (Fig. 3) showed that the “IPM” strategy resulted in higher gross margins compared to the ”non-IPM” strategy with one exception, the highly susceptible cultivar JB Asano. The high susceptibility of the cultivar JB Asano to the diseases yellow rust and septoria leaf blotch led to early and frequent fungicide treatments in all years. Those cultivars showing a good to medium resistance, like Attraktion, Capone or Julius resulted in higher gross margins in the “IPM” strategy exceeding those of the ”non-IPM” strategy by about 45 to 70 € ha^{-1}.

Variable costs differed between the field site locations (Fig. 4). Due to the experimental design, variable costs of the different sites were only different for the fungicide strategies. The fungicide cost (including tractor rides with labour and machinery cost) for the “IPM” strategy were with about 40% to 85% on average (depending on the field site) considerably lower compared to the fungicide costs of the “non-IPM” strategy. Monitoring costs like insecticide costs were comparably low while fertilizer costs were the highest cost component.

Discussion

Our study evaluated the economic viability of the preventive IPM strategies “wide crop rotation” and “pathogen-resistant cultivars and disease thresholds” with their associated pesticide reduction potential. Average gross margins per crop did not decrease for pesticide reductions of 25% and 50% and were comparable to the 100% pesticide application strategy, except in potatoes. In some crops, the reduction scenarios were even economically advantageous. Pathogen-resistant cultivars and disease threshold considerations resulted in economic benefits and higher gross margins for the “IPM” compared to the “non-IPM” strategy. We discuss our results regarding the applied methodology and our research questions.

Methodology

The methodology we applied was based on small scale field plots and an economic assessment of the field trial data. Frisvold (2019) stated limitations of such an approach and promotes the evaluation of IPM and its performance under actual farming conditions. We agree and realize the obstacles connected to the upscaling of field plot experiments to farm level conditions. Yields and probably also pesticide reductions are mostly higher under experimental conditions

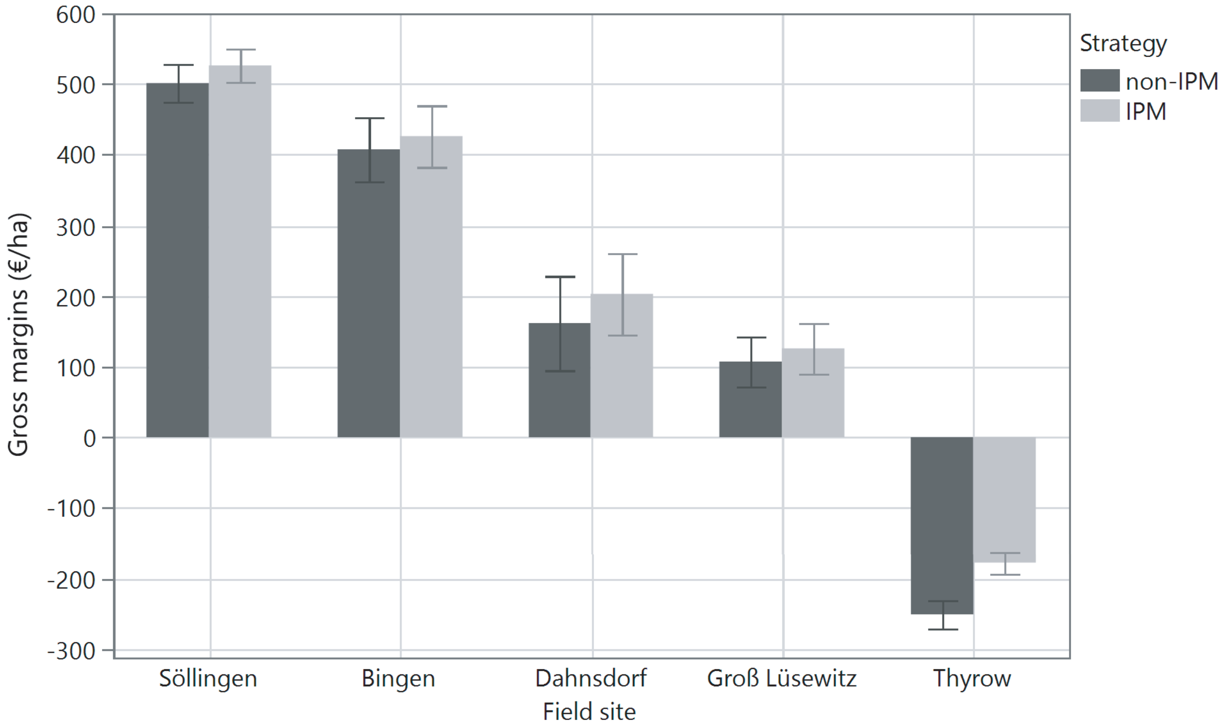

Fig. 2. Average gross margins of eight winter wheat cultivars (Apertus, Attraktion, Capone, Dichter, JB Asano, Julius, Patras, Spontan) in € ha^{-1} and standard error for the strategies “IPM” and “non-IPM” at the five different German field site locations Dahnsdorf, Bingen, Söllingen, Thyrow and Groß Lüsewitz from 2016 to 2018 (except Groß Lüsewitz with the years 2017 and 2018)

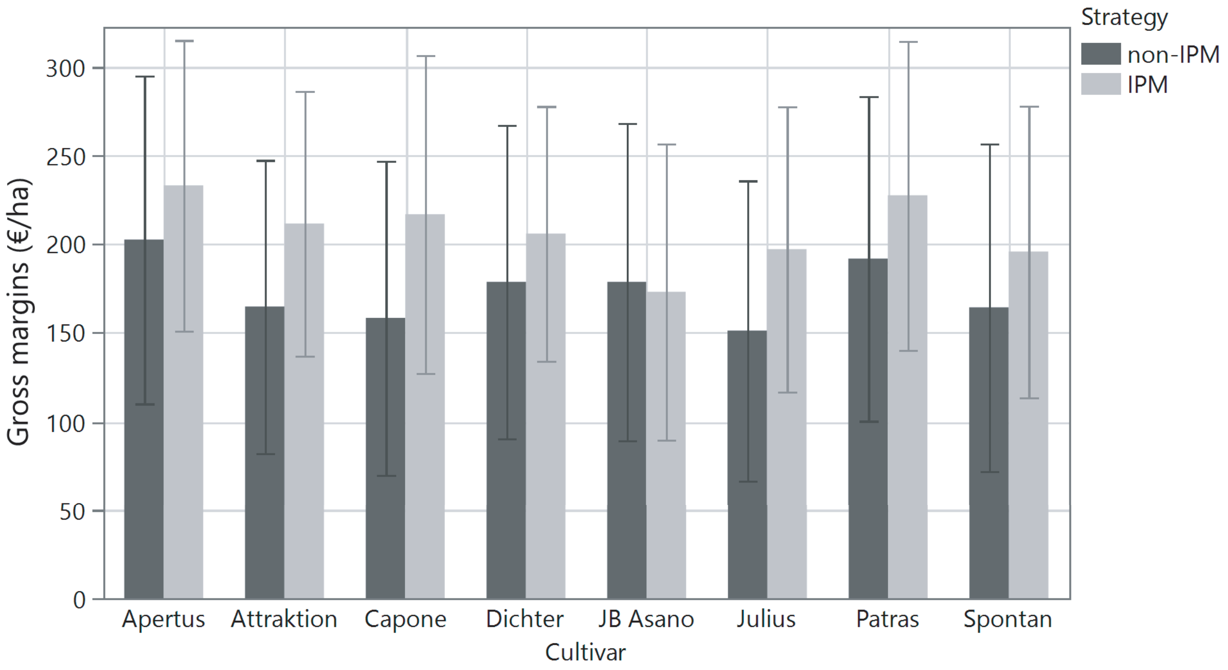

Fig. 3. Average gross margins in € ha^{-1} and standard error for the strategies “IPM” and “non-IPM” for the eight winter wheat cultivars (Apertus, Attraktion, Capone, Dichter, JB Asano, Julius, Patras, Spontan) grown at the five different German field site locations Dahnsdorf, Bingen, Söllingen, Thyrow and Groß Lüsewitz from 2016 to 2018 (except Groß Lüsewitz with the years 2017 and 2018)

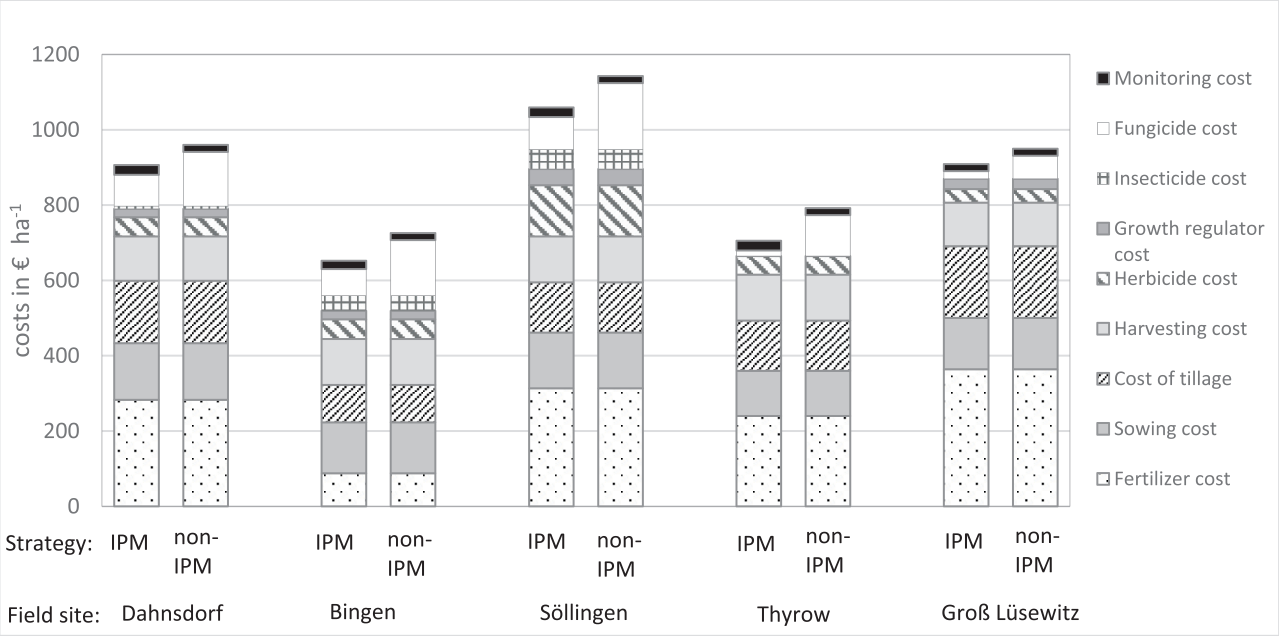

Fig. 4. Average annual variable costs for the two strategies “IPM” and “non-IPM” at the five different field site locations (Dahnsdorf, Bingen, Söllingen, Thyrow, Groß Lüsewitz) from 2016 to 2018 (except Groß Lüsewitz with the years 2017 and 2018)

and may not be transferred directly to farming conditions. However, since we compared strategies to each other thus looking at relative changes by implementing a strategy, the absolute values that may differ from practice, have not been in the main focus. We therefore assume that our results are relevant for IPM implementation under farming conditions. Nevertheless, this should be proved by further on-farm research.

Research questions

(1) What are the benefits and costs of reducing pesticide use in a wide six-crop rotation?

Diverse crop rotations offer several benefits, including improved soil health, increased yields, reduced pest and disease pressure, and enhanced profitability for farmers with the authors noting a need for research on economic impacts of long crop rotations (Beillouin et al., 2021). Sánchez et al. (2022) conducted a global meta-analysis and showed that on average diverse cropping systems lead to higher profits than homogeneous cultivation structures especially in developing countries. Rosa-Schleich et al. (2019) point out the economic long-term benefits for farmers of diversifying crop rotations, as well as input and risk reductions. However, no economic evaluations on the potential of crop rotations to reduce pesticides were found for Germany. The potential of diverse crop rotations to reduce pesticides has been described, e.g., by Andert et al. (2016) and showed a decrease in fungicide and herbicide use with an increase in crop diversity by analyzing data over 10 years in Northern Germany. Despite the advantages diverse cropping patterns offer, they receive little attention in agricultural practice. Steinmann & Dobers (2013) analyzed crop sequence patterns over six years on an area representing 645,870 ha arable land in Northern Germany. They showed an opposite trend towards less crop diversity, especially due to the expansion of corn cultivation. Stein & Steinmann (2018) analyzed with a time series approach on administrative data for Lower Saxony (Northern Germany) cropping patterns over seven years. Over 60% of the area investigated was cropped with the ten largest crop sequence types during the years 2005–2011, with maize as a driver for simplified cropping patterns. 34.1% of the arable land was cultivated with a sequence of only one or two crops. 24% were cropped with three crops. 39.3% were cropped without any leaf crop.

Economic studies on the reduction potential for pesticides of long crop rotations are scarce. Saltzmann & Kehlenbeck (2018) showed for winter wheat of different quality levels that pesticides could be reduced by 50% compared to a situation-related application without leading to significant economic disadvantages. The results were based on an isolated evaluation of wheat from the complete crop rotation evaluated in this paper. Karpinski et al. (2020) carried out an overall consideration of a six-year crop rotation. They showed the positive economic and stabilizing effects in the long-term over a period of 18 years, which is in line with the results here. In a wide six-unit crop-rotation under field test conditions a reduction potential for pesticide use without economic losses could be shown for all crops, except for potatoes. Even though slightly lower yields were achieved in the second rotation, these were compensated for by higher producer prices or input changes. It must be mentioned, that the choice of crops in the crop rotation is intended to achieve a compromise between site-adapted crops and economic viability. Due to frequent early summer droughts at the trial site, summer crops are exposed to a particular risk. Therefore only two of the six crops are summer crops. There is further potential for improvement and the results should be verified by further investigations under practical conditions.

(2) What are costs and benefits of implementing pathogen resistant cultivars and situation specific pesticide treatments for farmers?

Results on the IPM strategy show, that this strategy was overall of economic advantage and resulted in higher gross margins compared to the “non-IPM” strategy. The results are in line with Klocke et al. (2022) who calculated net returns but no gross margins. They also demonstrated that the intensity of fungicide use in terms of the TFI of the resistant cultivars were significantly reduced within the “IPM” strategy for all cultivars except the highly susceptible 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 “non-IPM” strategy. Klocke et al. (2022) reported that this reduction was still 59% on average across all cultivars using the IPM strategy. In the susceptible cultivar JB Asano only a reduction of 7% was possible. Pathogen resistant cultivars also provide pesticide use reduction potential in permanent crops, as reported, e.g. by Kaczmarek et al. (2023).

The decrease in fungicide intensity leads to lower fungicide costs, which also resulted from our study. Other studies on disease resistant cultivars reported similar results (Wegulo et al., 2011; Loyce et al., 2012; Beest et al., 2013). Gross margins were strongly affected by the decrease in fungicide costs. Combined with the not-occurrence of yield losses, the lower fungicide costs lead to the positive outcome of the gross margins. Costs of implementing IPM (seed costs of the resistant cultivars and monitoring costs) on the other hand did not compromise gross margins. The results thus clearly show the economic excellence of this IPM strategy.

Although farmers select cereal cultivars also with respect to their resistance traits (Thiel et al., 2021), they often treat different cultivars with fungicides at the same time, regardless of their resistance level and disease thresholds (Klocke & Dachbrodt-Saaydeh, 2018). In addition, control thresholds are not sufficiently used in practice and farmers perceive especially the additional time needed for monitoring as an obstacle for implementing IPM (Thiel et al., 2021). For oilseed rape, Thiel et al. (2023) concluded, that costs of monitoring are relevant and can only be recovered when labour costs are low and insecticide costs are high. In our study, monitoring costs were comparably low, although the time needed for monitoring in winter wheat taken as a basis was in line with Thiel et al., (2023). Here, probably more research work is still needed.

(3) What are the constraints to improving pesticide reduction opportunities?

IPM offers a ‘toolbox’ of complementary crop- and region-specific and sustainable crop protection solutions to address rising pressures on pesticide reduction (Birch et al., 2011). However, area-wide implementation in farming practice is still lacking. In the presented two studies of the paper, this question was not analyzed explicitly, but is discussed here based on literature. Bakker et al. (2021) identified in their research social-psychological constraints determining farmers´ intention to decrease pesticide use. So, farmers in the Netherlands are strongly influenced by how other farmers act. Furthermore, farmers perceive limited capacity and autonomy to reduce pesticide use. Motivations to reduce pesticide use were based on environmental considerations. Finally, decreasing pesticide use was considered risky. Jacquet et al. (2022) discussed behavior of farmers and their risk attitude as possible reasons for the limited adoption of IPM practices.

According to Benjamin & Wesseler (2016), the restrictions are not only at the societal level, but above all at the agronomical and economic level. Uncertainty over benefits and costs, irreversibility of effects as well as flexibility in adoption of IPM technologies are mentioned here as barriers for IPM adoption.

Early detection of pests and early reaction is one core element of applying IPM technologies in the field to effectively reduce pesticide use (Birch et al., 2011). Results in research here show that stringent monitoring of pests and optimal timing of a treatment is decisive and might lead to economically effective reductions of pesticide use in cereals and oilseed rape. However, the time factor of detecting pests and immediate reaction is not easy to implement in practice, which might be another problem for adoption of IPM practices (Helbig et al., 2021). Möhring et al. (2020) confirm these findings. Results in their study indicate that farmers often deviate from recommended timing strategies because of a lack of available information and uncertainty with respect to disease predictions. On the other hand, Mack et al. (2023) describe especially yield losses, which determine whether alternative pesticide-free cropping systems, to which IPM can also be included, are adopted or not. The widespread adoption of such sustainable systems is possible only if farmers are compensated for. Flexible policy and incentive programs are required.

Conclusions

The authors examined in this paper the economic impact and potential of pesticide reduction strategies within the concept of Integrated Pest Management (IPM) using the examples of two German case studies: “wide crop rotation” and “pathogen resistant cultivars”.

Aim of this paper was to show the economic potentials at field level of specific preventive IPM strategies in arable crops, relevant for Germany.

At least under field trial conditions, in five of the six crops in the wide crop rotation a reduction of plant protection products was possible without economic losses. The calculated gross margins indicated only little or no decline in silo maize, wheat, barley and winter rye for the pesticide reduction scenarios. A closer look at the rotations revealed no trend in profitability for the second rotation. Especially the yields of the cereals reflected the increased spring drought in the second rotation, which led to significantly lower yields in some crops. However, these were offset by changes in input volumes or price developments.

Average gross margins for the different cultivars, studied in the second case study, showed that the “IPM” strategy was economically beneficial and resulted in higher gross margins compared to the “non-IPM” strategy by about 45 to 70 € ha $^{-1}$ with one exception, the highly susceptible wheat cultivar JB Asano. Reduction in fungicide application costs were the main source for the higher gross margin. Surprisingly, monitoring costs, often named as a barrier for a successful adoption of IPM strategies in practice, were comparably low while fertilizer costs were the highest cost component.

Limitations of our research are in general, that our economic studies were based on small, controlled field trials rather than on practical “on-farm” conditions. Results from field plots certainly are not directly transferable to practice.

However, the results of this study clearly indicate positive economic results for implementing preventive IPM strategies. Based on these findings, we conclude that IPM strategies are suitable to reduce pesticides use without resulting in major farm income losses for German farms. Further research needs to investigate the reasons for the lack of successful adoption in practice in more detail and opportunities to overcome these shortcomings soon.

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Conflicts of interest

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

References

Agravis, 2004-2018: AGRAVIS Frühjahrs- und Herbstpreislisten. Agravis Raiffeisen.

AMI, 2010–2019: AMI Marktbilanz Getreide, Ölsaaten, Futtermittel. In: *AMI Markt Bilanz*. (eds. Kaltenecker, S., Kemper. S., Schaack, D., Von Schenck, W.), Agrarmarkt Informations-Gesellschaft mbH, Bonn.

Andert, S., Bürger, J., Stein, S., Gerowitt, B., 2016: The influence of crop sequence on fungicide and herbicide use intensities in North German arable farming. European Journal of Agronomy, 81–89. DOI:/10.1016/j.eja.2016.04.003.

Bakker, L., Sok, J., van der Werf, W., Bianchi, F.J.J.A. 2021: Kicking the Habit: What Makes and Breaks Farmers´Intentions to Reduce Pesticide Use?. Ecological Economics 180, DOI: 10.1016/j.ecolecon.2020.106868.

BayWa AG München, 2023: BayWa. In: München: BayWa AG München, E-Commerce, URL: https://www.baywa.de/de/.

Bazok, R., Lemic, D., Chiarini, F., Furlan, L., 2021: Western Corn Rootworm (*Diabrotica virgifera virgifera* LeConte) in Europe: Current Status and Sustainable Pest Management. Insects 12 (3), 195, DOI: 10.3390/insects12030195.

Barzman, M., Bàrberi, P., Birch, A.N.E., Boonekamp, P., Dachbrodt-Saaydeh, S., Graf, B., Hommel, B., Jensen, J.E., Kiss, J., Kudsk, P., Lamichhane, J.R., Messéan, A., Moonen, A.-C., Ratnadass, A., Ricci, P., Sarah, J.-L., Sattin, M., 2015: Eight principles of integrated pest management. Agronomy for Sustainable Development 35, 1199–1215. DOI: 10.1007/s13593-015-0327-9.

Beest, D.E.T., Paveley, N.D., Shaw, M.W., Bosch, F.v.d., 2013: Accounting for the economic risk caused by variation in disease severity in fungicide dose decisions, exemplified for *Mycosphaerella graminicola* on winter wheat. Phytopathology 103 (7), 666–672, DOI: 10.1094/phyto-05-12-0119-r.

Beillouin, D., Ben-Ari, T., Malézieux, E., Seufert, V., Makowski, D., 2021: Positive but variable effects of crop diversification on biodiversity and ecosystem services. Global Change Biology 27 (19), 1–14, DOI: 10.1111/gcb.15747.

Beiselen GmbH, 2023: Beiselen GmbH Agrarhandel. URL: https://www.beiselen.de/.

Benjamin, E.O., Wesseler, J.H.H., 2016: A socioeconomic analysis of biocontrol in integrated pest management: A review of the effects of uncertainty, irreversibility and flexibility. NJAS-Wageningen Journal of Life Sciences 77, 53–60, DOI: 10.1016/j.njas.2016.03.002.

Birch, A.N.E., Begg, G.S., Squire, G. R., 2011: How agro-ecological research helps to address food security issues under new IPM and pesticide reduction policies for global crop production systems. Journal of Experimental Botany 62 (10), 3251–3261, DOI: 10.1093/jxb/err064.

BMEL, 2003; 2009; 2014: Statistisches Jahrbuch für Landwirtschaft. In: Statistisches Jahrbuch. Wiesbaden: Statistisches Bundesamt.

Bundessortenamt, 2016: Beschreibende Sortenliste Getreide, Mais Öl- und Faserpflanzen Leguminosen Rüben Zwischenfrüchte 2016. URL: https://www.bundessortenamt. de/bsa/media/Files/BSL/bsl_getreide_2016.pdf. Accessed 24 Aug 2023.

Carmona, M., Sautua, F., Perez-Hernandez, O., Reis, E.M., 2020: Role of Fungicide Applications on the Integrated Management of Wheat Stripe Rust. Frontiers in Plant Science 11, DOI: 10.3389/fpls.2020.00733.

Castellazzi, M.S., Wood, G.A., Burgess, P.J., Morris, J., Conrad, K.F., Perry, J.N., 2008: A systematic representation of crop rotations. Agricultural Systems 97, 26–33, DOI: 10.1016/j.agsy.2007.10.006.

Destatis, 2023: Statistisches Bundesamt, Index der Einkaufspreise landwirtschaftlicher Betriebsmittel (2015=100), 23.10.2023.

Deter, A., 2019: Bei Weizensorten auf den Proteingehalt achten. In: online TA (ed): *Saaten-Union*. URL: https://www.topagrar.com/acker/news/bei-weizensorten-auf-den-proteingehalt-achten-11818995.html.

European Commission, 2020: EU Green Deal. Farm to Fork Strategy. For a fair, healthy and environmentally-friendly food system. In: European Commission. Bruessels, p 23.

Frisvold, G., 2019: Economic assessment of integrated pest management (IPM) implementation. 887–912, ISBN: 9781838799618.

Gaudin, A.C., Tolhurst, T.N., Ker, A.P., Janovicek, K., Tortora, C., Martin, R.C., Deen, W., 2015: Increasing crop diversity mitigates weather variations and improves yield stability. PLoS One 20150206, p e0113261, DOI: 10.1371/journal.pone.0113261.

Harms, R. 2023: Maispreis Rechner 2023. Gleichgewichtspreis abgeleitet von Weizenpreis bzw. Anbaukosten (brutto). Landwirtschaftskammer Niedersachsen, Sachgebiet Betriebswirtschaft.

Helbig, J., Gummert, A., Paap, M., Eberhardt, G., Schlage, B., Sellmann, J., Strassemeyer, J., Freier, B., Peters, M., Suhl, F., Pramschüfer, L., Stosius, H., Herzer, A., Kehlenbeck, H., 2021: BMEL Modell- und Demonstrationsvorhaben „Demonstrationsbetriebe integrierter Pflanzenschutz“ Abschlussbericht – Teilprojekt „Koordination“. Abschlussbericht – DIPS Projektkoordination für den Berichtszeitraum 10/2011 – 12/2019. Berichte aus dem Julius Kühn-Institut 218, 1-344, DOI: 10.5073/20211215-101835.

Jacquet, F., Jeuffroy, M.-H., Jouan, J., Le Cadre, E., Litrico, I., Malausa, T., Reboud, X., Huyghe, C., 2022: Pesticide-free agriculture as a new paradigm for research. Agronomy for Sustainable Development 42, 8, DOI: 10.1007/s13593-021-00742-8.

Jalli, M., Huusela, E., Jalli, H., Kauppi, K., Niemi, M., Himanen, S., Jauhiainen, L., 2021: Effects of Crop Rotation on Spring Wheat Yield and Pest Occurrence in Different Tillage Systems: A Multi-Year Experiment in Finnish Growing Conditions. Frontiers in Sustainable Food Systems 5, 14, DOI: 10.3389/fsufs.2021.647335.

Kaczmarek, M., Entling, M. H., Hoffmann, C., 2023: Differentiating the effects of organic management, pesticide reduction and landscape diversification for arthropod conservation in viticulture. Biodiversity and Conservation 32 (8-9), 2637-2653, DOI: 10.1007/s10531-023-02621-y.

Karpinski, I., Ridder, R., Rajmis, S., Schwarz, J., Klocke, B., Kehlenbeck, H., 2020: Fruchtfolge versus Monokultur: Betriebswirtschaftliche Betrachtung eines Dauerfeldversuches im Roggenanbau über 18 Jahre. Journal für Kulturpflanzen 72 (7), 298-310, DOI: 10.5073/JfK.2020.07.07.

Klocke, B., Sommerfeldt, N., Wagner, C., Schwarz, J., Baumecker, M., Ellmer, F., Jacobi, A., Matschiner, K., Petersen, J., Wehling, P., Sellmann, J., Rajmis, S., Kehlenbeck, H., 2022: Disease threshold-based fungicide applications: potential of multi-disease resistance in winter wheat cultivars in Germany. European Journal of Plant Pathology 165, 363-383, DOI: 10.1007/s10658-022-02611-w.

Klocke, B., Dachbrodt-Saaydeh, S., 2018: Nutzung der Sortenresistenz in der Praxis – Ergebnisse des Netzes Vergleichsbetriebe Pflanzenschutz in den Jahren 2007 bis 2016. In: 61. Deutsche Pflanzenschutztagung: Herausforderung Pflanzenschutz – Wege in die Zukunft; 11. – 14. September 2018, Universität Hohenheim -Kurzfassungen der Vorträge und Poster, Julius-Kühn-Archiv 461, 98–99, DOI: 10.5073/jka.2018.461.000.

Klocke, B., Wagner, C., Krengel-Horney, S., Schwarz, J., 2023: Potential of pesticide reduction and effects on pests, weeds, yield and net return in winter rye (*Secale cereale* L.). Landbauforschung – Journal of Sustainable and Organic Agriculture 72, 1-24, DOI: 10.5073/LBF.2023.01.02.

Knöferl, R., Diepolder, M., Offenberger, K., Raschbacher, S., Brandl, M., Kavka, A., Hippich, L., Schmücker, R., Sperger, C., Kalmbach, S., 2022: Leitfaden für die Düngung von Acker- und Grünland. In: Gelbes Heft – LfL-Information. 15. Freising-Weihenstephan: Bayerische Landesanstalt für Landwirtschaft (LfL), p 113.

Kolbe, H., Schuster, M., Hänsel, M., Grünbeck, A., Schließer, I., Köhler, A., Karalus, W., Krellig, B., Pommer, R., Arp, B., 2004: Zwischenfrüchte im Ökologischen Landbau. In: Dresden: Sächsische Landesanstalt für Landwirtschaft, p 122.

KTBL, 2016–2018: Betriebsplanung Landwirtschaft 2016/2017. Kuratorium für Technik und Bauwesen in der Landwirtschaft e. V., Darmstadt.

KTBL, 2023: KTBL-Feldarbeitsrechner. In: Darmstadt: Kuratorium für Technik und Bauwesen in der Landwirtschaft e. V.

Loyce, C., Meynard, J.M., Bouchard, C., Rolland, B., Lonnet, P., Bataillon, P., Bernicot, M.H., Bonnefoy, M., Charrier, X., Debote, B., Demarquet, T., Duperrier, B., Felix, I., Heddadj, D., Leblanc, O., Leleu, M., Mangin, P., Meausoone, M., Doussinault, G., 2012: Growing winter wheat cultivars under different management intensities in France: A multicriteria assessment based on economic, energetic and environmental indicators. Field Crops Research 125, 167–178, DOI: 10.1016/j.fcr.2011.08.007.

Lüttringhaus, S., Zetzsche, H., Wittkop, B., Stahl, A., Ordon, F., Mußhoff, O., 2021: Resistance Breeding Increases Winter Wheat Gross Margins–An Economic Assessment for Germany. Frontiers in Agronomy 3, DOI: 10.3389/fagro.2021.730894.

Mack, G., Finger, R. Ammann, J., Benni, N.E., 2023: Modelling policies towards pesticide-free agircultural production systems. Agricultural Systems 207, 103642, DOI: 10.1016/j.agsy.2023.103642.

Moll, E., Piepho, H.-P., 2001: Die Auswertung von Versuchsserien balancierter und unbalancierter einfaktorieller Blockanlagen A-Bl mit Hilfe von SAS. Zeitschrift für Agrarinformatik (4), 76–84.

Möhring, N., Wuepper, D., Muas, T., Finger, R., 2020: What farmers deviate from recommended pesticide timing: the role of uncertainty and information. Pest Management Science 76, 2787–2798, DOI: 10.1002/ps.5826.

MyAgrar, 2023: MyAgrar.de. Ratzeburg: AgrarOnline GmbH, URL: https://www.myagrar.de/, access: 01.08.2023.

Pimentel, D., Burgess, M., 2014: Environmental and Economic Costs of the Application of Pesticides Primarily in the United States. In: Pimentel, D., Peshin, R. (eds) *Integrated Pest Management*. Springer, Dordrecht, DOI: 10.1007/978-94-007-7796-5_2.

Rosa-Schleich, J., Loos, J., Mußhoff, O., Tscharntke, T., 2019: Ecological-economic trade-offs of Diversified Farming Systems – A review. Ecological Economics 160, 251–263, DOI: 10.1016/j.ecolecon.2019.03.002.

Saaten-Union GmbH, 2023: Saaten-Union GmbH. In: Isernhagen HB, URL: https://www.saaten-union.de/.

Saltzmann, J., Kehlenbeck, H., 2018: Economic Analysis of Plant Protection Strategies in Winter Wheat Based On Longterm Field Trials in Brandenburg Within a Crop Rotation with Six Rotation Components (2004 to 2016). Gesunde Pflanzen 70, 129–138, DOI: 10.1007/s10343-018-0425-0.

Sánchez, A.C., Kamau, H.N., Grazioli, F., Jones, S.K., 2022: Financial profitability of diversified farming systems: A global meta-analysis. Ecological Economics 201, DOI: 10.1016/j.ecolecon.2022.107595.

Savary, S., Willoquet, L., Pethybridge, S.J., Esker, P., McRoberts, N., Nelson, A., 2019: The global burden of pathogens and pests on major food crops. Nature Ecology & Evolution 3, 430–439, DOI: 10.1038/s41559-018-0793-y.

Schindler, M., 2009: Welchen Wert haben Wirtschaftsdünger? In: Landwirtschaftliches Wochenblatt (LW), pp 31-32.

Schroers, J.O., Gerhards, R., Kunisch, M., 2010: Economic Evaluation of Precision Crop Protection Measures. In: Oerke, E.C., Gerhards, R., Menz, G., Sikora, R. (eds) *Precision Crop Protection – the Challenge and Use of Heterogeneity*. Springer, Dordrecht, DOI: 10.1007/978-90-481-9277-9_26.

Schwarz, J., Klocke, B., Wagner, C., Krengel, S. 2018: Untersuchungen zum notwendigen Maß bei der Anwendung von Pflanzenschutzmitteln in Winterweizen in den Jahren 2004 bis 2016. Gesunde Pflanzen 70, 119–127, DOI: 10.1007/s10343-018-0422-3.

Shah, K.K., Modi, B., Pandey, H.P., Subedi, A., Aryal, G., Pandey, M., Shrestha, J., Fahad, S., 2021: Diversified Crop Rotation: An Approach for Sustainable Agriculture Production. Advances in Agriculture 2021, 8924087, DOI: 10.1155/2021/8924087.

Stary, V., 2023: Qualitätsgruppen von Weizen: Das steckt dahinter In: Focus online 04.01.2023. URL: https://praxistipps.focus.de/qualitaetsgruppen-von-weizen-das-steckt-dahinter_154341.

Stein, S., H.-H. Steinmann, 2018: Identifying crop rotation practice by the typification of crop sequence patterns for arable farming systems – A case study from Central Europe –. European Journal of Agronomy 92, 32–40, Supplement C, DOI: 10.1016/j.eja.2017.09.010.

Steinmann, H.-H., Dobers, E.S., 2013: Spatio-temporal analysis of crop rotations and crop sequence patterns in Northern Germany: potential implications on plant health and crop protection. Journal of Plant Diseases and Protection 120, 85–94, DOI: 10.1007/BF03356458.

Thiel, L., Mergenthaler, M., Haberlah-Korr, V., 2021: Wahrgenommene Umsetzung des integrierten Pflanzenschutzes bei landwirtschaftlichen Betrieben in Nordwestdeutschland. Gesunde Pflanzen 73, 119–134, DOI: 10.1007/s10343-021-00548-4.

Thiel, L., Mergenthaler, M., Wutke, M., Haberlah-Korr, V., 2023: Use of insect pest thresholds in oilseed rape and cereals: is it worth it? Pest Management Science, DOI: 10.1002/ps.7647.

Tang, F. H. M., Lenzen, M., McBratney, A., Maggi, F., 2021: Risk of pesticide pollution at the global scale. Nature Geoscience 14, 206–210, DOI: 10.1038/s41561-021-00712-5.

Trockels, F., 2023: Schriftliche Auskunft der Deutsche Saatgutveredelung AG. Productmanagement maize Date Written: 11.06.2023.

Uhlemann, V., 2023: Schriftliche Auskunft der Saaten-Union GmbH. Date Written: 11.06.2023

Vasileiadis, V. P., Sattin, M., Otto, S., Veres, A., Palinkas, Z., Ban, R., Pons, X., Kudsk, P., van der Weide, R., Czembor, E., Moonen, A. C., Kiss, J., 2011: Crop protection in European maize-based cropping systems: Current practices and recommendations for innovative Integrated Pest Management. Agricultural Systems 104, 533–540, DOI: 10.1016/j.agsy.2011.04.002.

Wegulo, S.N., Zwingman, M.V., Breathnach, J.A., Baenziger, P.S., 2011: Economic returns from fungicide application to control foliar fungal diseases in winter wheat. Crop Protection 30 (6), 685-692, DOI: 10.1016/j.cropro.2011.02.002.

ZMP, 2006: ZMP-Marktbilanz – Getreide, Ölsaaten, Futtermittel. Zentrale Markt- und Preisberichtstelle GmbH, p 252.