

Offering payments for omitting fungicides in winter wheat production: under which conditions is it economically interesting from the perspective of a farm? A case study from Luxembourg

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Abstract

BACKGROUND: Integrated pest management (IPM) aims to control crop pests while balancing environmental sustainability and farm profitability. Under IPM, pesticides are applied only when pest or disease pressure surpasses economic thresholds, even after the implementation of non-chemical control strategies, thus implying that reducing pesticide use below IPM standards entails economic losses. In response, some European Union member states have introduced compensation schemes for farms adopting pesticide reduction strategies, such as zero-fungicide approaches. However, it remains critical to determine under which conditions these financial incentives sufficiently offset economic losses and support fungicide reduction.

RESULTS: Using commodity prices and fungicide application costs observed between 2018 and 2023, IPM-based fungicide use across 25 winter wheat trials generated an average net return of €67 ha⁻¹ if disease monitoring was provided free of charge and €41 ha⁻¹ if the farms had to bear the costs of disease monitoring themselves. The economic viability of compensation schemes depended on several key market factors: higher commodity prices, increased fungicide efficacy and low fungicide application costs enhanced the profitability of fungicide use, while low commodity prices and fungicide efficacy and high fungicide application costs made compensation schemes more attractive.

CONCLUSION: The success of financial incentives for fungicide reduction is challenged by high commodity prices, highly effective fungicides and low-cost application services. Given the strong influence of commodity prices on fungicide profitability, reductions are most likely to occur in lower-value market segments (e.g. grain for animal feed production), where compensation schemes gain economic leverage more easily.

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Supporting information may be found in the online version of this article.

Keywords: *Triticum aestivum*; eco-scheme; integrated pest management; crop protection; fungal plant pathogens; agricultural economics

1 INTRODUCTION

Wheat, along with rice and maize, is a fundamental staple crop for global food security.¹ Lower-quality wheat that fails to meet food-grade standards is typically diverted to the animal feed market at reduced prices. However, wheat production faces significant threats from pests and diseases, which can severely reduce both yield and quality.² While humid conditions in many wheat-growing regions support crop growth, they also promote the proliferation of fungal diseases, such as yellow rust (caused by *Puccinia striiformis* Westend. f. sp. *tritici* Erikss (Pst)), septoria leaf blotch (*Zymoseptoria tritici* Desm. Quaedvlieg & Crous), powdery mildew (*Blumeria graminis* f. sp. *tritici* (Bgt)) and brown rust (*Puccinia triticina* Eriks.). The likelihood of a mass propagation of plant pathogens can be reduced by methods such as crop rotation, tillage systems that interrupt the life cycles of the pathogens, the

growth of resistant cultivars³ and some other agronomic measures such as sowing times and sowing rates. Crop rotation and tillage systems have primarily effects on necrotrophic pathogens such as *Z. tritici*, while cultivars with high levels of resistance are available versus biotrophic pathogens like rusts. However, under weather conditions favourable to pathogens, epidemics are difficult to prevent by agronomic measures alone. A central element

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in the conceptual framework of integrated pest management (IPM) is the use of non-chemical measures to protect crops in the first instance, with the application of pesticides only as a last resort.⁴ Since pesticide application is costly, low levels of disease that cause less damage in monetary terms than their control would cost are left uncontrolled. Under IPM, pesticide use is triggered when a pest or a disease exceeds the critical level called the control threshold, or when scientifically validated decision support tools display an alert.

Fifteen years ago, Wiik and Rosenqvist⁵ reported that fungicide use in southern Sweden yielded an average net return of only €12 ha⁻¹, with a trend of increasing profitability over time. They hypothesized that the adoption of newly developed decision support tools could enhance profitability. Subsequent research has empirically demonstrated the economic benefits of scientifically validated decision support tools.⁶ However, the effective implementation of IPM principles requires disease monitoring, which incurs some additional costs that need to be considered when comparing fungicide use according to IPM with strategies that do not require disease monitoring.

In recent decades, risks associated with pesticide use, for instance with regard to the potential impact on biodiversity, have raised concerns.⁷ As a result, several individual countries⁸ and the European Union (EU) have set targets for reducing pesticide use, which were sometimes missed.⁹ Falconer and Hodge¹⁰ studied the option of pesticide taxation for reducing pesticide use and concluded that a pesticide tax at politically acceptable levels would perform poorly if introduced as a stand-alone measure. More recently, Möhring *et al.*¹¹ proposed 10 pathways for reducing potential risks from agricultural pesticide use for enabling a transition from the current hazard-based system to a risk-based system. The general idea behind many incentive schemes is offering farmers (some of) the money that is saved in terms of external costs when they decrease the use of specific technologies such as pesticides, thereby (over) compensating the losses resulting from a reduced use of the technology.¹²

At the farm level, reducing pesticide use lowers input costs but may also reduce yield and quality, resulting in a loss of income. Farmers that perceived large yield losses and increases in production risks were less likely to participate in pesticide-free wheat production in Switzerland.¹³ Even though farmer behaviour, including adoption of new management practices, is influenced by various factors¹⁴ and purely economic considerations based on experimental field data can therefore not be used as sole criterion for making recommendations on subsidy policy, financial viability has been identified as one of the critical factors in the recently published EU vision for agriculture and food. While our experimental framework provides robust causal estimates of the marginal economic effect of fungicide applications under controlled IPM conditions, it does not capture the full behavioural, structural and institutional complexity of farmers' decision-making environments. Consequently, these results should be interpreted as biophysical and economic benchmarks rather than predictors of real-world adoption patterns. Since net losses must be expected when pesticide use falls below IPM standards, compensation schemes have recently been introduced in some EU member states. For instance, in the German federal state of Baden-Württemberg under the FAKT E12 measure, farmers can apply to receive €50 ha⁻¹ if they omit fungicides until growth stage 49. In Luxembourg, the 514-F1 scheme offers incentives for omitting fungicide sprays during the cultivation of winter wheat. While first experiences with a pesticide-free wheat

production standard were reported from Switzerland, the authors concluded that further research should extend to other countries.¹³ This study aims to estimate the minimum financial incentive required to make fungicide omission economically viable for winter wheat farmers, using multi-year, multi-site data representative of maritime growing conditions. Agronomic data from field experiments that were conducted before the introduction of the incentive scheme for omitting fungicide sprays were used and the profitability of fungicide use at the farm level with and without the novel incentive was estimated. This approach paves the way for an early evidence-based assessment of the incentive scheme. To assess the robustness of the findings, a sensitivity analysis was conducted under varying commodity price levels and disease monitoring cost scenarios.

2 MATERIALS AND METHODS

2.1 Field trials

Winter wheat field trials were conducted across four distinct regions of Luxembourg (western Europe) over six growing seasons (2018–2023; Fig. 1). The study area is characterized by a temperate oceanic climate (Cfb classification, Köppen-Geiger), with mild temperatures and moderate precipitation. The mean annual temperature is 9.7 °C, ranging from 1.6 °C in January to 18.2 °C in July. The average annual precipitation is approximately 830 mm, distributed relatively evenly throughout the year (<https://en.climate-data.org/location/984/>). A randomized complete block design was employed, with three or four replicates per trial depending on the location and year. The years, locations, cultivars, number of replicates and the dependant variables are detailed in Supporting Information, Table S1. Field trials were conducted within commercial farm rotations, with locations changing annually. Predominant preceding crops included oilseed rape and maize. Cultivars were selected from the annually updated national

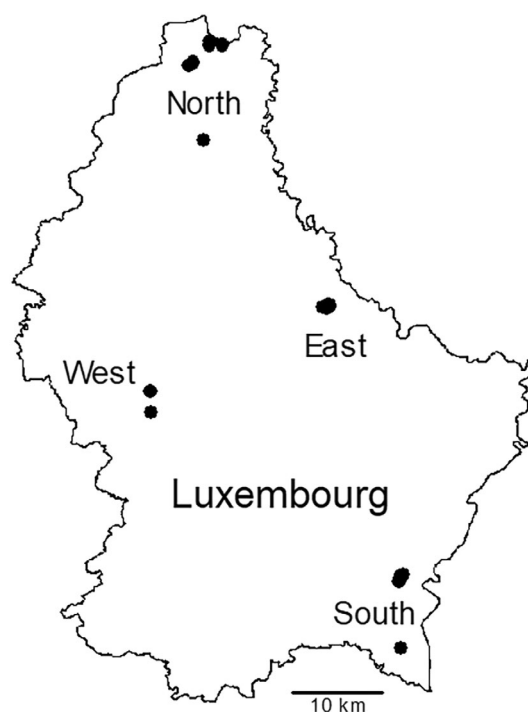


Figure 1. Locations of the field experiments. Each point represents one trial.

list of recommended varieties, ensuring suitability under regional growing conditions (Supporting Information, Table S1). Cultivars with a very high level of susceptibility towards yellow rust were excluded from the national list of recommended cultivars after a major epidemic in 2014/2015. Fields were managed according to conventional farming practices, except for the use of fungicides specified below. Data from a total of 25 trials were available for the present study. The plot size was approximately 7.5 by 1.5 m after sowing. Factual plot sizes prior to harvest were established by measurements in the field and these measurements were used to estimate kernel mass per ha (= yield).

Each experiment included four treatments that differed with regard to fungicide use. Treatment 1 served as an untreated control with no fungicide application and will subsequently be abbreviated 'T0'. The second treatment, following IPM principles, consisted of a fungicide spray when either $\geq 30\%$ of plants exhibited yellow rust symptoms on the upper three leaf layers¹⁵ or when first yellow rust foci were observed in the plant stand¹⁴ or when a validated septoria forecast model (<https://shift.list.lu/>)¹⁶ issued a warning, hereafter referred to as 'T1'. Access credentials for the septoria forecast model are given in previously published work.¹⁶ The control thresholds used were taken from neighbouring Germany because of the similar growing conditions there. The Septoria forecast model was developed based on data from Luxembourg. Other diseases, such as powdery mildew and leaf rust, occurred sporadically within the experiments used for the present study, but did not reach the control threshold (30% and 60% of symptomatic plants on the upper three leaf layers, including the stem for leaf rust and powdery mildew, respectively¹⁵). Fusarium head blight (FHB) control is recommended in case of rain during flowering.¹⁷ Due to an increasing trend to summer drought,¹⁸ no fungicide sprays specifically versus FHB pathogens were used in the experiments of the present study. The third treatment consisted of two sprays, the first at plant growth Stage 31¹⁹ (beginning of stem elongation) and the second at stage 59 (end of ear emergence), hereafter referred to as 'T2'. The fourth treatment included three fungicide applications at growth stages 31, 37 (flag leaf emergence) and 59, hereafter referred to as 'T3'. Fungicides were applied using a plot sprayer (model RTS; Baumann Saat-zuchtbedarf, Waldenburg, Germany). Apart from the fungicide treatments, the fields were managed according to the practices of the farms in terms of crop rotation, sowing densities, fertilization, tillage and the use of growth regulators. As such, the data reflect the outcome of common farming practices at the time when the experiments were conducted. Disease assessments were carried out between shooting and early ripening (growth stages 31–83), as previously described.⁶

Grain was harvested at physiological maturity using a plot harvester (Lycée Technique Agricole, <https://www.lta.lu/>) equipped with an integrated weighing and moisture measurement system. Grain yield was standardized to 14% moisture content before statistical analysis to ensure comparability across treatments. Yield is expressed in decitons (1 dt = 100 kg).

2.2 Fungicides used

Commercially available fungicides were applied (Table 1). At the beginning of the data acquisition period, mixtures of the multi-site inhibitor chlorothalonil and demethylase inhibitors like epoxiconazole or prothioconazole were used. The mixtures and application rates given in Table 1 were recommended by agricultural consulting services when the trials were undertaken to reduce the risk of selecting fungicide-resistant strains. Following

the ban of chlorothalonil in 2019 and epoxiconazole in 2020, products containing these two active ingredients were no longer available to farmers and their use in the trials was abandoned. The fungicide applications therefore reflected the state of the art that was available to farmers when the data were acquired. Fungicides were purchased from agricultural retailers (<https://www.barenbrug.lu/>) that sold them to farmers at the same price (Table 2). The incentive scheme involved here rewards omitting fungicide sprays but is independent of fungicides in seed coatings.

2.3 Commodity prices and quality

Commodity prices were ascertained from the communications of local buyers like mills. The commodity prices for winter wheat of bread quality were €20.0, €14.6, €15.9, €15.9, €38.3 and €22.0 dt⁻¹ in 2018, 2019, 2020, 2021, 2022 and 2023, respectively. For an overall long-term assessment of the financial incentive to omit fungicides, the average price of €21.1 dt⁻¹ was used. However, the sensitivity of the results towards commodity price fluctuations was simulated in the present paper by assuming a price of €15.0 dt⁻¹. Commodity prices may be low due to a high winter wheat supply or because poor grain quality does not allow the use of high-value food products. Quality aspects are therefore considered in the present study by looking at a realistic range of prices that cover fluctuations due to both market mechanisms and variable grain quality.

2.4 Fungicide application costs

The price (including an increase in 2022) quoted by a local contractor (<https://mbr.lu/>) for spraying crops was used as a proxy for the cumulative costs of labour plus machines, including fuel and wear-out.

2.5 Disease monitoring costs under IPM

Since the legal framework of the EU (Directive 2009/128/EC) requires member states to provide disease warning services, it could be argued that farms within the EU do not have to bear the costs of disease monitoring themselves directly. However, this is not the case for non-member states and even with a disease warning service in place, farmers are strongly advised to check whether the disease situation in their fields is similar to indications from observations in the reference plots of the warning service before spraying. With this in mind, we worked with two alternative scenarios. In scenario A, we assumed no monitoring costs at the farm level. In scenario B, we assumed that the farms have to bear the effort and therefore the costs of the disease monitoring themselves. Local farmers have to pay €35 h⁻¹ for a professional operations assistant (<https://mbr.lu/>) that could in theory carry out the disease monitoring. Thiel *et al.*²⁰ found that it takes approximately 16 min ha⁻¹ to carry out pest monitoring on winter wheat while monitoring fungal diseases in the same crop took 2.8 times longer.²¹ Using these figures, monitoring costs were estimated at €26 ha⁻¹.

2.6 Current incentives in the region studied

Farmers that omit fungicide sprays during the cultivation of winter wheat can currently receive up to €110 ha⁻¹ in the 514-F1 incentive scheme (<https://agriculture.public.lu/dam-assets/beihilfen/514de.pdf>). This incentive for omitting fungicide sprays in arable crops (excluding forage and root crops) is currently available for a reference area of a maximum 1200 ha (approximately 27 000 ha of cereals were grown in Luxembourg in 2019²²). If

Table 1. Fungicide regimes used in the experiments

Year	Treatment	Timing of treatments	First spray	Second spray	Third spray
2018	Control				
2018	IPM	According to IPM	1.5 L ha ⁻¹ Caramba + 1 L ha ⁻¹ Bravo + 1.25 L ha ⁻¹ Input		
2018	Two sprays	Growth stages 31 and 59	0.7 L ha ⁻¹ Stereo + 1 L ha ⁻¹ Bravo + Input 1.25 L ha ⁻¹	1.5 L ha ⁻¹ Swing Gold + 1 L ha ⁻¹ Bravo	
2018	Three sprays	Growth stages 31, 37 and 59	0.7 L ha ⁻¹ Stereo + 1 L ha ⁻¹ Bravo + Input 1.25 L ha ⁻¹	1.25 L ha ⁻¹ Input + 1 L ha ⁻¹ Bravo	1.5 L ha ⁻¹ Swing Gold + 1 L ha ⁻¹ Bravo
2019	Control				
2019	IPM	According to IPM	1.5 L ha ⁻¹ Swing Gold + 1 L ha ⁻¹ Bravo 1 L ha ⁻¹		
2019	Two sprays	Growth stages 31 and 59	0.75 L ha ⁻¹ Opus Team + 1 L ha ⁻¹ Bravo	1.5 L ha ⁻¹ Swing Gold + 1 L ha ⁻¹ Bravo	
2019	Three sprays	Growth stages 31, 37 and 59	0.75 L ha ⁻¹ Opus Team + 1 L ha ⁻¹ Bravo	1.5 L ha ⁻¹ Fandango + 1 L ha ⁻¹ Bravo	1.5 L ha ⁻¹ Swing Gold + 1 L ha ⁻¹ Bravo
2020	Control				
2020	IPM	According to IPM	1.5 L ha ⁻¹ Swing Gold		
2020	Two sprays	Growth stages 31 and 59	1.5 L ha ⁻¹ Fandango	1.5 L ha ⁻¹ Swing Gold	
2020	Three sprays	Growth stages 31, 37 and 59	1.5 L ha ⁻¹ Fandango	1.5 L ha ⁻¹ Caramba	1.5 L ha ⁻¹ Swing Gold
2021	Control				
2021	IPM	According to IPM	1 L ha ⁻¹ Prosaro		
2021	Two sprays	Growth stages 31 and 59	1.5 L ha ⁻¹ Fandango	1 L ha ⁻¹ Prosaro	
2021	Three sprays	Growth stages 31, 37 and 59	1.5 L ha ⁻¹ Fandango	1.5 L ha ⁻¹ Caramba	1 L ha ⁻¹ Prosaro
2022	Control				
2022	IPM	According to IPM	1.5 L ha ⁻¹ Fandango		
2022	Two sprays	Growth stages 31 and 59	1.5 L ha ⁻¹ Fandango	1 L ha ⁻¹ Prosaro	
2022	Three sprays	Growth stages 31, 37 and 59	1.5 L ha ⁻¹ Fandango	1.5 L ha ⁻¹ Fandango	1 L ha ⁻¹ Prosaro
2023	Control				
2023	IPM	According to IPM	1.5 L ha ⁻¹ Fandango		
2023	Two sprays	Growth stages 31 and 59	1.5 L ha ⁻¹ Fandango	1 L ha ⁻¹ Prosaro	
2023	Three sprays	Growth stages 31, 37 and 59	1.5 L ha ⁻¹ Fandango	1.5 L ha ⁻¹ Fandango	1 L ha ⁻¹ Prosaro

farmers managing more than 1200 ha wish to join the incentive scheme, additional funding can be reallocated from other schemes that were not used to their full extent to keep the incentive at €110 ha⁻¹. If the funding from these other incentive schemes is depleted, the incentive for omitting fungicides in arable crops will be decreased proportionally. A local newspaper (*Letzeburger Bauer*, 6–9 February 2024, page 3) reported that farmers managing 4500 ha had applied for the zero-fungicide scheme, meaning that the full incentive of €110 ha⁻¹ can only be paid if the budget of other eco-schemes is not completely exhausted. The latter information is unknown to the authors of the present study.

2.7 National agricultural data

For comparison purposes, data on the use of agricultural land and production figures at the national level were taken from the Ministry of Agriculture, Viticulture and Rural Development.

2.8 Data processing and analyses

Means and standard errors from the data of the replicated wheat plots were calculated for each year, location, cultivar and treatment (Supporting Information, Table S1). The difference (Δ) between the marginal profits of fungicide-treated and untreated plots was calculated using the following formula:

Table 2. Commercial fungicide names, their prices at the time of purchase, their active ingredients and the concentration of the active ingredient(s) in the product.

Trade name	Price (€ L ⁻¹)	Active ingredient(s) (concentration)
Bravo	15.10	Chlorothalonil [†] (500 g L ⁻¹)
Caramba	32.07	Metconazole (60 g L ⁻¹)
Fandango	30.50	Prothioconazole (100 g L ⁻¹) + fluoxastrobine (50 g L ⁻¹)
Input	52.30	Prothioconazole (160 g L ⁻¹) + spiroxamine (300 g L ⁻¹)
Opus Team	34.44	Fenpropimorph (250 g L ⁻¹) + epoxiconazole [‡] (84 g L ⁻¹)
Prosaro	43.78	Prothioconazole (125 g L ⁻¹), tebuconazole (125 g L ⁻¹)
Stereo	26.10	Cyprodinil (250 g L ⁻¹) + propiconazole (62.5 g L ⁻¹)
Swing Gold	32.10	Epoxiconazole [‡] (50 g L ⁻¹) + dimoxystrobin (133 g L ⁻¹)

[†] Banned in 2019, therefore not used afterwards.

[‡] Banned in 2020, therefore not used afterwards.

$$\Delta P = ((Y_f \times C) - F - (AF_f \times m \times L) - MC) - ((Y_c \times C) - (AF_c \times m \times L)), \quad (1)$$

where P is marginal profit (€ ha⁻¹), Y is yield (dt ha⁻¹, adjusted to 14% humidity, dt = decitonne = 100 kg), subscript f indicates fungicide treatment, C is the commodity price (€ dt⁻¹), F is the fungicide cost (€ ha⁻¹), AF is the application frequency (number of applications per plot), m is the machine costs (€ ha⁻¹), L is the labour costs (€ h⁻¹), subscript c indicates control without fungicides and MC is the monitoring costs (€ ha⁻¹).

To compare the treatments in monetary terms from a single-farm perspective, the yield was multiplied by the price of the commodity in each year. Then, the costs of the fungicide application(s), including the fungicides themselves, and the disease monitoring costs were subtracted. Organization for Economic Cooperation and Development price indices (<https://www.oecd.org/en/data/indicators/inflation-cpi.html>) were used to convert prices from all years to a common reference point, approximated as the midpoint of the study period (2021). In a second step, the incentive of €110 ha⁻¹ maximum for omitting fungicides was added in the case of the untreated control to allow the situations to be compared both with and without incentive. Using Duncan's multiple range test at $P = 0.05$ (software package SPSS version 26; IBM Corporation, Armonk, New York, USA), yield, the monetary yield minus the costs of fungicide application and the monetary yield minus the costs of fungicide application plus the incentive for omitting fungicides within each year, location and cultivar were compared (Supporting Information, Table S1). A global comparison of the yield levels with the data from all locations, years and cultivars pooled was also done, using the same test procedure and software as described above (Table 3). This global comparison was done solely for summary purposes and should not be interpreted as indication of an underlying assumption of homogenous farmer behaviour. For places where different cultivars were grown side by side in the same year, profitability was compared among the cultivars using independent sample Mann–Whitney U -tests (SPSS version 26).

For discussing potential effects of disease pressure on profitability, the data set was split into experiments where more than 5% of the area of the upper three leaf layers showed symptoms and cases where less than 5% were symptomatic for both diseases. For each of the four resulting groups, the mean of the symptomatic leaf area, the reduction of symptoms due to the respective

fungicide treatment (%) and profitability with and without incentive were calculated (Table 4).

3 RESULTS

3.1 Yield secured by fungicide use

The average yield of fungicide-free control plots was 79.1 dt ha⁻¹, while the average yields of the treatments T2, T1 (IPM) and T3 were 85.8, 86.1 and 88.0 dt ha⁻¹, respectively (Table 3). The yield of the untreated control was significantly lower compared with the fungicide treatments, while the difference among the three fungicide treatments was non-significant at $P = 0.41$ (Table 3). The average yield difference between the (all pooled) fungicide treatments and the fungicide-free control was 7.6 dt ha⁻¹ (corresponding to 9.6% more than the fungicide-free control plots), while the average difference between the IPM treatment and the fungicide-free control was 7.1 dt ha⁻¹ (corresponding to 8.5% more than the fungicide-free control plots; Table 3). The range of the yield secured by fungicide use is shown in Fig. 2(E) in the form of a box plot.

3.2 Influence of commodity price fluctuations on the attractiveness of fungicide omission incentives

Commodity price fluctuations were huge and had a pronounced effect on the value of the grain secured by fungicide use. At a commodity price of €15.91 dt⁻¹ in 2021, fungicide use according to IPM resulted an average net return of €24.30 ha⁻¹, while in 2022 the commodity price was €38.26 dt⁻¹, giving an average net return of €169.88 ha⁻¹. With an overall average commodity price of €21 dt⁻¹ and fungicide application costs of €81 ha⁻¹, the IPM fungicide treatment was €43 ha⁻¹ less profitable than the fungicide-free control with the maximum incentive for omission (Table 3). When the commodity price dropped to €15 dt⁻¹, the economic advantage of omitting fungicides increased to €85 ha⁻¹. Conversely, at commodity prices exceeding €27 dt⁻¹, fungicide use under IPM became more economically favourable than the maximum incentive for fungicide omission (Fig. 2(A)). Notably, this price threshold was only exceeded in 2022, a year characterized by exceptional market conditions due to geopolitical instability (Fig. 2(D)).

Table 3. Yield of the treatments (Y , adjusted to 14% humidity), yield differences observed due to fungicide use compared to the fungicide-free control ($Y_f - Y_c$), costs of the fungicide regimes ($AF \times m \times L \times F$), marginal profit of the fungicide regimes (P) at the average commodity price of €21 dt⁻¹ (dt = decitonne = 100 kg), marginal profit of the fungicide regimes plus the incentive for omitting fungicides (INC, maximum of €110 ha⁻¹) and marginal profit of the fungicide regimes plus the incentive for omitting fungicides minus disease monitoring costs (MC, €26 ha⁻¹).

Treatment	Y (dt ha ⁻¹)	Significance [†]	$Y_f - Y_c$ (dt ha ⁻¹)	$AF \times m \times L \times F$ (€ ha ⁻¹)	P (€ ha ⁻¹)	$P + \text{INC}$ (€ ha ⁻¹) ^A	$P + \text{INC} - \text{MC}$ (€ ha ⁻¹) ^B
T0	79.1	a	0.0	0	0	110	110
T1	86.1	b	7.1	81	67	67	41
T2	85.8	b	6.7	130	11	11	-15
T3	88.0	b	8.9	195	-7	-7	-33

Note: Numbers represent the mean values of 25 field trials. Monetary outputs were standardized to the price level of the year 2021. T0, no fungicide; T1, a single fungicide spray was applied at the point of time at which either 30% of the plants showed symptoms of yellow rust on the upper three leaf layers or a septoria forecast model (<https://shift.list.lu/>)¹² displayed a warning; T2, two sprays at plant growth stages 31 (beginning of stem elongation) and 59 (end of ear emergence); T3, three fungicide sprays that were applied during plant growth stages 31, 37 (flag leaf emergence) and 59; ^A, scenario A: the results of local disease monitoring are provided to farmers free of direct charge; ^B, scenario B: farms must pay for disease monitoring.

[†] Numbers that are followed by the same letter are not significantly different according to Duncan's multiple range test at $P = 0.05$.

Table 4. Treatments, disease pressure, symptom reduction due to the fungicide treatment(s) and profitability of the treatment – disease pressure – combinations with and without the maximum incentive for omitting fungicide sprays (€110 ha⁻¹).

Treatment	Disease pressure [†]		<i>n</i>	Symptom reduction (%)		Profitability of fungicide use (€ ha ⁻¹)	
	Septoria	Stripe rust		Septoria	Stripe rust	– incentive	+ incentive
T0	0.9	1.5	9	N/A	N/A	0	110
T1	0.9	1.5	9	2	78	43	43
T2	0.9	1.5	9	64	79	–25	–25
T3	0.9	1.5	9	93	98	–48	–48
T0	19.4	0.3	8	N/A	N/A	0	110
T1	19.4	0.3	8	54	61	–13	–13
T2	19.4	0.3	8	65	36	–46	–46
T3	19.4	0.3	8	82	31	–100	–100
T0	1.4	11.1	5	N/A	N/A	0	110
T1	1.4	11.1	5	51	67	206	206
T2	1.4	11.1	5	7	86	187	187
T3	1.4	11.1	5	89	82	168	168
T0	10.2	22.2	3	N/A	N/A	0	110
T1	10.2	22.2	3	26	56	61	61
T2	10.2	22.2	3	74	96	–94	–94
T3	10.2	22.2	3	75	97	–61	–61

The number of experiments with the respective treatment – disease pressure – combination is indicated by *n*. Monetary outputs were standardized to the price level of the year 2021. Not applicable (N/A).

[†] Expressed as symptomatic leaf area (%) in untreated control plots on the top three leaf layers during fruit development/early ripening (growth stages 71–83).

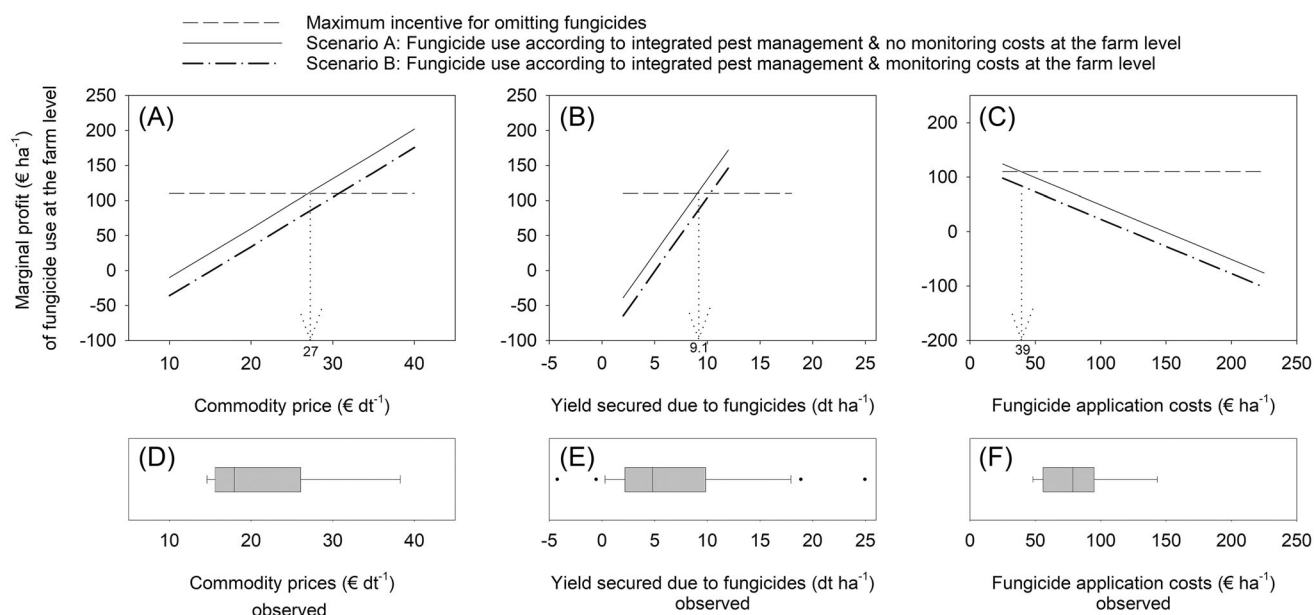


Figure 2. Marginal profit (€ ha⁻¹) of fungicide use as affected by (A) commodity prices, (B) yield secured due to fungicide use and (C) fungicide application costs (including the fungicides themselves). For comparison: observed commodity prices within the period of consideration (D), observed yield secured due to fungicide use (E) and observed fungicide application costs (F). The dashed horizontal line in (A)–(C) indicates the maximum incentive that farmers can expect for omitting fungicides. The dotted arrow indicates critical levels, where fungicide use, according to integrated pest management, outcompetes the maximum incentive for omitting fungicides, from the perspective of a farm. The dashed-dotted line shows the situation under the assumption that the farms have to bear the costs of the disease monitoring themselves. One decitonne (dt) equals 100 kg.

3.3 Estimating the incentive needed when a public disease monitoring service is available

The average fungicide application costs were €81 ha⁻¹ for the IPM treatment T1, €130 ha⁻¹ for the T2 treatment and €195 ha⁻¹ for the T3 treatment (Table 3). With an average commodity price of

€21 dt⁻¹ (note that our project covered the high-price period of 2022), the additional income due to fungicide use was €141 ha⁻¹ for T2, €148 ha⁻¹ for IPM and €188 ha⁻¹ for T3. When subtracting the costs of the fungicide applications from the latter figures, T2 income was €11 ha⁻¹ more than the untreated control,

IPM was €67 ha⁻¹ more than the untreated control and T3 was €7 per ha⁻¹ less than the untreated control (Table 3). When additionally considering the maximum 514-F1 incentive of €110 ha⁻¹ for omitting fungicides (as reflected by the untreated control in the present trials), the control was on average €43 ha⁻¹ more beneficial than the IPM treatment from the economic perspective of the farm (Table 3). However, the differences between the treatments at the monetary level were non-significant at $P = 0.472$ after considering the maximum incentive for omitting fungicides.

3.4 Estimating the incentive needed when no public disease monitoring service is available

Assuming that the disease monitoring costs have to be paid by the farms directly and that no public disease warning service is available free of charge, an incentive of at least €41 ha⁻¹ would be needed (Table 3). The financial net return of two sprays would have been €125 ha⁻¹ lower than omitting fungicides and applying for the incentive and three sprays would have been €143 ha⁻¹ lower (Table 3).

3.5 Profitability of fungicide use as affected by disease pressure

At low disease pressure, the maximum payment for omitting fungicides was more profitable than fungicide use from the perspective of a farm (Table 4). Without payment, treatment T1 produced the highest benefit of €43 ha⁻¹, while T2 and T3 resulted into losses at low disease pressure (Table 4). At high Septoria pressure (19.4% of symptomatic leaf area on the upper three leaves during fruit development in untreated control plots) and low stripe rust pressure (0.3%), none of the fungicide treatments was profitable (Table 4). At low Septoria pressure (1.4%) and moderate stripe rust pressure (11.1%), the fungicide treatments were more profitable than the maximum incentive of €110 ha⁻¹ (Table 4). At moderate Septoria disease pressure (10.2%) and high stripe rust pressure (22.2%), treatment T1 was profitable with €61 ha⁻¹, while T2 and T3 were not profitable (Table 4). At low disease pressure and at moderate or high Septoria pressure, the incentive for omitting fungicides was economically attractive from the perspective of a farm, while at moderate stripe rust levels it was not (Table 4). At moderate stripe rust levels of around 11.1% of symptomatic leaf area on the top three leaf layers during fruit development, a payment of at least €206 ha⁻¹ for omitting fungicides would have been needed (Table 4).

3.6 Other diseases

Besides yellow rust and septoria leaf blotch, powdery mildew and brown rust were observed in the field trials, but these two diseases did not reach the IPM control threshold¹⁵ and therefore did not trigger fungicide application under IPM within the period of the present study. Due to an increasing tendency for drought in summer,¹⁸ Fusarium head blight played a minor role in the trials used in the present study.

4 DISCUSSION

The findings of this study provide valuable insights into the economic viability of fungicide use in winter wheat production under IPM principles. By assessing the minimum financial incentive required to make fungicide omission a competitive alternative, the influence of commodity price fluctuations, fungicide efficacy and application costs on farmers' decision-making can be better

understood. These results have significant implications for policy-makers, agricultural stakeholders and the agrochemical industry.

4.1 Minimum incentive required to offset the economic benefits of IPM-based fungicide use

The economic advantage of fungicide application under IPM, observed as a net return of €67 ha⁻¹ (Table 3), represents the minimum financial compensation required to incentivize farmers to forego fungicide use. If financial incentives fell below €67 ha⁻¹, IPM-based fungicide use would remain the more attractive option. Additionally, if farmers had to bear the costs of the disease monitoring required for IPM independently, an incentive of €41 ha⁻¹ would be necessary to maintain economic parity.

4.2 Required yield protection for fungicide use to outcompete omission incentives

The IPM fungicide treatment provided an average yield advantage of 7.07 dt ha⁻¹ over the fungicide-free control, translating to a net benefit of €67 ha⁻¹ at a commodity price of €21 dt⁻¹ and fungicide application costs of €81 ha⁻¹ (Table 3). For IPM-based fungicide use to outperform the maximum omission incentive of €110 ha⁻¹, the treatment would need to secure a minimum yield of 9.1 dt ha⁻¹ (Fig. 2(B)). This yield threshold was met in six out of 25 trials (Fig. 2(E)). Consequently, even moderate improvements in fungicide efficacy through innovation could potentially tilt the economic balance in favour of continued fungicide application.

4.3 Necessary reduction in fungicide application costs to offset omission incentives

Given an average yield benefit of 7.07 dt ha⁻¹ under IPM, fungicide application costs (including machines and labour) of €81 ha⁻¹ and a commodity price of €21 dt⁻¹, fungicide use was €43 ha⁻¹ less profitable than fungicide omission with the incentive (Table 3). To restore economic competitiveness, application costs would need to decrease to €39 ha⁻¹ (Fig. 2(C)). However, during the study period, the application costs observed consistently exceeded this threshold (Fig. 2(F)). Lower fungicide costs – whether due to more efficient application technologies or market price reductions – could thus undermine the incentive-based reduction efforts.

4.4 Risks to the success of the current fungicide reduction programme

The effectiveness of the current incentive scheme for reducing fungicide use is susceptible to several risk factors. Specifically, commodity prices exceeding €27 dt⁻¹, fungicide application costs falling below €39 ha⁻¹ and yield protection of more than 9.1 dt ha⁻¹ from fungicide use could render the incentive insufficient. More broadly, external shocks – such as geopolitical crises affecting global commodity prices – could further exacerbate these challenges. Additionally, improvements in fungicide efficacy and cost-effective application services may counteract the intended impact of incentive payments, making fungicide use the more economically viable choice for farmers.

4.5 National-level implications of fungicide omission incentives

If the maximum incentive of €110 ha⁻¹ were implemented across 1200 ha of winter wheat, an annual yield reduction of approximately 912 t would be expected. Given the national wheat production of 73 274 t (average 2017–2019), this equates to a

1.24% reduction in total output. At the same time, fungicide omission on these 1200 ha would lead to an 8.86% reduction in fungicide use across the national winter wheat area (13 542 ha, wheat and spelt combined with spelt playing a minor role). These projections provide an empirical basis for assessing the trade-offs between reduced fungicide use and national food security.

4.6 Comparison with other countries

Paying farmers for changing management strategies in favour of environmental benefits is done in China within the Grain-for-Green Program, in the EU within the Common Agricultural Policy and in the USA via the Farm Bill.^{23,24} Water and soil protection are the main concerns of the Chinese programmes, excluding other environmental issues until now.^{23,24} Under the FAKT E12 measure, farmers in Germany (federal state of Baden-Württemberg) can apply for compensation of €50 ha⁻¹ if they omit fungicides until growth stage 49. Even though this scheme is similar to the Luxembourg model, in Germany it would be possible to control of *Fusarium* species that can infect wheat heads during flowering when conditions are wet and hot, while in Luxembourg this would result in the incentive being lost because fungicides have to be omitted throughout the production cycle. Farmers in Luxembourg thereby have to take a higher risk when opting for the fungicide reduction programme, which might be the reason for the higher maximum incentive compared with Germany. Under the label 'extenso', Swiss farmers can apply for a payment of CHF400 ha⁻¹ if they omit fungicides, insecticides and growth regulators in wheat or barley production.¹⁴ In Belgium, agri-environmental and climate measures (Mesures Agro-Environnementales et Climatiques, MAEC) support sustainable practices such as reduced pesticide use, ecological focus areas and crop diversification. Payments range between €200 and €450 ha⁻¹ depending on the region and commitment, with IPM forming the cornerstone of the system.²⁵ In France, the Éco-régimes under the CAP and regional MAEC incentivize farmers to adopt biodiversity-friendly and low-input systems. Specific programmes, such as in Burgundy and Alsace, encourage reduced fungicide applications in cereals, although mostly within integrated production schemes rather than full omission.²⁶ In Spain, regional Agroambientales emphasize soil conservation and water efficiency, particularly in erosion-prone and irrigated areas. Some schemes, notably in Andalusia and Catalonia, support integrated production systems with payments of around €200–300 ha⁻¹, indirectly incentivizing pesticide reduction.^{27,28} In Italy, the Programmi di Sviluppo Rurale vary by region but often include strong incentives for IPM and organic cereals. Payments range from €250 to €500 ha⁻¹, with Emilia-Romagna and Veneto leading in low-input wheat production initiatives.^{29,30} In the United Kingdom, the post-Brexit Environmental Land Management Schemes focus on rewarding 'public goods' such as soil health, biodiversity and reduced pesticide use. While fungicide-specific bans are absent, IPM adoption is explicitly encouraged with tiered payments depending on ambition levels.³¹ In the Scandinavian countries, a mix of pesticide taxation and agri-environmental subsidies has been applied for decades. Denmark, for example, introduced one of the earliest pesticide taxes, combined with incentives for low-input cereal systems.³² Sweden and Finland emphasize organic production (>€300 ha⁻¹ support), which indirectly reduces fungicide use, while Norway promotes crop diversification through targeted agri-environmental payments.³³

4.7 Beyond *ceteris paribus* considerations

In reality, the effects described above may not fully come to bear, for instance because incentive schemes for different crops are competing with each other. Rather than growing crop A with or without an incentive, farmers may now decide to grow crop B more frequently because an incentive coupled with crop B makes it more attractive than crop A. In the latter situation, the demand stimulus for upscaling or downscaling the production of specific crops would be weakened, increasing the risk of temporal over- and temporal underproduction of specific commodities. Competitive bidding, because it is common practice in auctions instead of fixed-rate payments, was suggested for increasing cost-effectiveness in the allocation of contracts for the provision of nonmarket goods in the countryside.³⁴ Furthermore, participation in incentive schemes is influenced by factors that go beyond payments such as the effort to change farm management, contractual responsibilities, the probability of being accepted into a scheme,³⁵ farmer's attitudes towards risk as well as farm and farmer characteristics.³⁶ Below the cap on eligible hectares, farmers can be sure to receive €110 ha⁻¹ when omitting fungicide sprays, while above the cap there is a risk of lower payment. Low caps may thus have a particularly discouraging effect on risk-averse farmers applying. High risk aversion among farmers reduced the adoption of pesticide-free production.³⁶ Similar effects may come to bear in case of the present incentive scheme, even though it does not require omitting all pesticides. Factors beyond payments will not be discussed in detail here because data that could support one or the other explanation are still lacking due to the novelty of the incentive scheme involved here.

Commodity prices of cereals used as feed for animals are traditionally lower than commodity prices of grain that meets the quality criteria for pasta production, seeds or bread. Given that the likelihood of earning more money with fungicide use than is offered by an incentive scheme increases as commodity prices increase, fungicide reductions due to the current incentive scheme are most likely to be seen in the lower-price market segments, such as the feed domain.

In Fig. 2(B), a linear relationship between the yield secured by fungicides and marginal profits is depicted. This linear relationship was obtained assuming fixed (in this case average) prices for the period of observation. If, for instance, the amount of grain secured by fungicides were to increase to levels where the grain price would drop due to high supply, the relationship would no longer be linear. However, the amount of grain produced by single farmers is much too low to affect the global quantities offered and thereby prices, therefore the assumption of linearity accurately reflects the situation from the perspective of a single farm.

Since several fungicides are used in practical farming as well as in the trials reported here (Table 1), and fungicide efficacies differ between the fungicidal mode of actions of their active ingredients³⁷ therefore it is not possible to estimate accurate fungicide efficacies for individual fungicides from trials where mixtures of fungicides were applied. Experiments where only one fungicide ideally with only one active ingredient are used would be needed for that purpose. However, using only one active ingredient is strongly discouraged in the field because microorganisms adapt more easily to one mode of action compared with exposure to several modes of action. In the present study, cumulative fungicide efficacies (fungicide efficacies of the entire fungicide regime of each treatment) are implicitly included into the yield difference

between winter wheat plots sprayed with fungicide and winter wheat plots not sprayed with fungicides (Eqn 1). However, the reduction of symptoms due to the fungicide treatments could be estimated from the experiments (Table 4). These data suggest that fungicide use *versus* moderate levels of stripe rust was more profitable than the maximum payment, while the maximum payment was more profitable at low disease levels and at high Septoria pressure (Table 4).

As shown in the present study, the observation that pest control according to IPM principles reduced pesticide use but not yield compared with more frequent pesticide application does not only hold for fungal diseases in winter wheat but also for insect pests in oilseed rape.²⁰

The data for the current study were obtained in a region where cultivar susceptibility is monitored, particularly susceptible cultivars are avoided and crop rotation is common practice. When restricting the cultivar comparisons to years and places where several cultivars were grown side by side and where data from more than 1 year are available, a significant cultivar effect was observed for fungicide profitability in one out of five cases. In 2018, fungicide use according to IPM was more profitable ($P = 0.021$) in cultivar Desamo compared with cultivar Kerubino. If highly susceptible wheat varieties (e.g. to stripe rust) were to be planted or crop rotation neglected, yield losses would be higher, making it more difficult for the subsidy to gain economic leverage. The yield levels obtained in several trials of the present study were somewhat higher than the average yield levels achieved by farmers.²² The open spaces between the plots (approximately 50 cm distance between plots) resulted in less competition for light, water and nutrients between the plants compared with the closed and homogeneous plant stands of regular farmer fields, potentially explaining the somewhat higher yield levels in the plots of our study. However, the differences between the treatments, which are the basis for the argumentation laid out here, should be valid.

5 CONCLUSION

Before the introduction of the incentive for omitting fungicides, the IPM treatment was numerically the most beneficial one from the economic perspective of a farm, despite it not being significantly different from spraying crops two or three times at pre-determined growth stages. Now that the incentive has been introduced, the most beneficial fungicide strategy for farms economically will depend on the magnitude of the incentive offered. Our data suggest that an incentive of at least €67 ha⁻¹ was needed to compensate for the losses induced by the renunciation of fungicide use in the primarily maritime growing region examined here. Should the incentive fall below this level, the scheme is likely to fail to achieve its intended effect of reducing fungicide use compared with the IPM situation. Since costs differ between regions, the magnitude of the incentives needed will differ accordingly. However, the general conclusion that incentives must increase with commodity prices and fungicide efficacy, and may decrease with application costs for inducing an economic stimulus, is valid beyond the cases depicted in the present study. Due to the strong effect of commodity prices on the profitability of fungicide use, fungicide reductions are most likely to occur in the lower price segments (e.g. grain production for feed) as a consequence of the payments for omitting fungicides.

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DATA AVAILABILITY STATEMENT

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

CONFLICT OF INTEREST

The authors declare no conflict of interest.

SUPPORTING INFORMATION

Supporting information may be found in the online version of this article.

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