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Can Decision Support Systems Help Improve the Sustainable Use of Fungicides in Wheat?

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Abstract: Wheat is one of the most economically important field crops worldwide. Foliar diseases are a major threat to wheat productivity and are primarily managed by implementing less susceptible cultivars and using fungicides. With the "Farm to Fork" strategy under consideration by the European Union to reduce pesticide usage by 50% by 2030, this elucidates the importance of utilizing decision support systems (DSS) to optimize fungicide applications. Therefore, three DSSs of different origins, namely the IPM-Wheat Model Schleswig-Holstein (scientific), the ISIP system (federal), and the xarvio© FIELD MANAGER (commercial), were analysed under maritime climate conditions at three locations in a high input area of wheat cultivation in northern Germany from 2019 to 2021. Fungicide efficacy was evaluated for yield as well as for the management of prevalent pathogens (Septoria tritici blotch, glume blotch, tan spot, powdery mildew, stripe rust, and leaf rust) on two different commercially available cultivars (highly and moderately susceptible). Compared to a stage-oriented standard system, no significant decrease in yield was observed in both cultivars, despite up to a 50% reduction in fungicide use through the use of DSSs. This was attributed to an optimized timing of fungicide applications, which resulted in slightly lower but still tolerable disease suppression efficacy compared to the stage-oriented system. In conclusion, minor disease severities are often overestimated, and DSSs can help improve the sustainability of fungicide use in wheat and pesticides in general.

Keywords: foliar diseases; disease severity; Integrated Pest Management (IPM); DSS; efficacy; biological–epidemiological threshold value; fungicide; AUDPC; pesticide reduction; farm to fork

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1. Introduction

Cereal grains such as wheat, maize, and rice are major nutritional sources worldwide and a key component of a sustainable diet. The share of wheat is approximately one third [1,2]. Maritime climate conditions [3–5] in combination with heavy fertile soils [6] are suitable conditions for growing wheat. These conditions therefore place northern Europe as one of the most suitable and productive regions for wheat cultivation worldwide. However, these conditions are also conducive for fungal disease development and pathogens are pervasive throughout this region [4,5]. For this reason, disease management is essential in most parts of northern Europe and is primarily based on preventive management strategies such as the use of fungicides and of less susceptible cultivars. Nevertheless, yield losses caused by fungal diseases are estimated to be approximately 25% in common farm practices [5,7,8]. In detail, the foliar diseases Septoria tritici blotch (caused by *Zymoseptoria tritici* Desm.; STB), glume blotch (*Parastagonospora nodorum* Berk.; GB), tan spot (*Pyrenophora* *tritici-repentis* Died.; TS), powdery mildew (*Blumeria graminis* f. sp. *tritici*; PM), stripe rust (*Puccinia striiformis* f. sp. *tritici*; SR), and leaf rust (*Puccinia triticina*; LR) are responsible for yield losses in wheat.

In Germany, annual sales of fungicidal active ingredient totalled 10,464 t of 31,314 t of total pesticide sales, which is approximately one-third of all pesticides sold averaged from 1995 to 2020 (excluding inert gases, herbicides 52%, insecticides 3%, others 12%) [9]. Additionally, the use of pesticides is a considerable concern for the European public [10]. Hence, first member states started to regulate pesticide use until the EU comprehensively regulated it in 2009 with directive 2009/128/EC for sustainable use of pesticides [11]. Currently, the EU repeals the directive as a consequence of the "European Green Deal" and develops a new strategy for the sustainable use of pesticides [12]. This "Farm to Fork" strategy under consideration would support claims of a 50% reduction of pesticides in the EU by 2030. According to Dachbrodt-Saaydeh et al. [13], approximately 13% of the fungicides (30% of the insecticides, 6% of the herbicides) are used unnecessarily. In terms of sales and unnecessary use, fungicides show the greatest potential to reduce overall pesticide usage. Klink et al. [4] demonstrated in a long-term study over 26 years that utilizing a threshold-based system can optimize applications, reduce overall pesticide usage/quantity, and maintain the potential yield simultaneously. However, the use of fungicides is essential to produce wheat of sufficient quality and quantity in the future.

In the present study, we evaluated if common farm practices can reach the pesticide reduction goals of the EU by using decision support systems (DSS). Therefore, three DSSs for the control of foliar diseases in wheat, namely the IPM-Wheat Model Schleswig-Holstein (IPM; scientific system), the information system for integrated plant production (ISIP; federal system), and the xarvio© FIELD MANAGER (xarvio©, commercial system), were analysed for their potential to minimize the use of fungicides. Thus, a supra-regional study under standardized conditions (same cultivars, same trial locations, and same growing conditions) in the wheat-privileged area of northern Germany was established. The aims were to: (i) show if a reduction of fungicides used is possible and (ii) investigate the differences of different DSSs in their yield potential and disease suppression.

2. Materials and Methods

2.1. Area Surveyed and Survey Strategy

From 2019 to 2021, an evaluation of three decision support systems (the IPM-Wheat Model, the ISIP system, and the xarvio FIELD MANAGER©) for the management of foliar wheat diseases was carried out at three trial locations evenly distributed throughout northern Germany. These trials were located between the Baltic and the North Sea in the northernmost federal state of Germany, Schleswig-Holstein (Table 1). This area is highly suitable for growing field crops, especially wheat, and is characterized by maritime weather conditions with an average temperature of 9.2 °C and an annual precipitation of 846 L/m^2 [14]. On 70% of the total 655,011 ha of arable land in Schleswig-Holstein in 2020, the major field crops were winter wheat, forage maize, and oilseed rape, with a share of 20.8, 28.6, and 10.2%, respectively [15]. Since forage maize is predominantly grown on sandy soils in the middle area of this state, winter wheat is more likely grown in the eastern (eastern hill land) and western (west coast marsh) parts, which are characterized by heavy soils. The trial locations were located in these parts of Schleswig-Holstein with high densities of wheat in crop rotation (Table 1). Due to the aforementioned eligible conditions, enhanced disease pressure can be expected, as described by Klink et al. [4]. Consequently, the survey area is suitable for the evaluation of decision support systems for the management of foliar diseases in wheat.

The preceding crops of winter wheat at the trial locations were chosen by common practice within the region. Winter wheat preceded wheat at the location Barlt, and oilseed rape preceded wheat at the locations Futterkamp and Kluvensiek consistently in every year of the study (Table 1). Corresponding to the preceding crop, the soil was cultivated with reduced tillage when oilseed rape preceded and by ploughing when winter wheat preceded.

Table 1. Coordinates and agronomic practices (crop rotation, soil cultivation) at three trial locations in northern Germany from 2019 to 2021. WW = winter wheat, WB = winter barley, OR = oilseed rape. Preceding crops are underlined.

Location	Coordinates		Crop Rotation	Soil Cultivation
	Latitude	Longitude		
Barlt	54°01′03″ N	09°01′45″ E	WW-<u>WW</u>-OR	Plough
Futterkamp	54°17′31″ N	10°38′04″ E	WW-WB-<u>OR</u>	Reduced tillage
Kluvensiek	54°19′38″ N	09°48′25″ E	WW-WB-<u>OR</u>	Reduced tillage

For the evaluation of the three DSSs, two cultivars, namely “Ritmo” and “RGT Reform”, were used. In Germany, the susceptibility of wheat cultivars to the major foliar diseases is listed in the descriptive cultivar list and is scaled into nine categories from 1 = missing/very low to 9 = very high susceptibility by the Bundessortenamt, an independent senior federal authority under the supervision of the Federal Ministry of Food and Agriculture. The cultivar “Ritmo” is classified as moderately to highly susceptible against the major foliar diseases (Table 2) [16]. Due to the high susceptibilities of this cultivar, different treatments could be analysed under enhanced disease pressure. To simulate common farm practices, the modern and less susceptible cultivar “RGT Reform” was additionally implemented into the survey (Table 2) [17].

Table 2. Susceptibility categories (1 = missing/very low to 9 = very high) of the cultivars “Ritmo” and “RGT Reform” to the major foliar wheat diseases Septoria tritici blotch (STB), glume blotch (GB), tan spot (TS), powdery mildew (PM), stripe rust (SR), and leaf rust (LR) [16,17].

Cultivar	Susceptibility to					
	STB	GB	TS	PM	SR	LR
“Ritmo”	6	6	6	5	4	8
“RGT Reform”	4	5	5	3	4	3

At each location and year, field trials were arranged in a split-plot design with four blocks. Cultivar and block define the main plots. The five treatments, namely fungicide-untreated control (UC), IPM treatment (IPM), ISIP treatment (ISIP), xarvio© treatment (xarvio©), and healthy-standard control (HST), were randomized within these main plots. Fungicide applications in the treatments followed the recommendations of the DSS’s, as described below. At each trial, blocks were randomized uniformly on the same field by treatment order. Due to destructive sampling for disease diagnostics throughout growth stages (GS) 30 (begin of stem elongation) to 77 (late milk stage) [18], all treatments were duplicated to assign the purpose of harvest and sampling to each plot, resulting in ten plots per replicated block and a total of 80 plots per field trial (2 × 40 plots/cultivar). Each plot had a size of 10 m^2 (2 m × 5 m) and was separated from neighbouring plots by a 0.5 m strip in order to minimize drift and cross-contamination. At all locations, field trials were integrated into farmers’ fields. To avoid external contamination, sufficient clearance to the surrounding fields was established around the entire field trial. Crop management as well as the application of herbicides, insecticides, and growth regulators were based on common agricultural practices and conducted in cooperation with the Chamber of Agriculture of Schleswig-Holstein.

In order to evaluate the disease development of foliar diseases, a UC was implemented into the trials for every cultivar, location, and year. In the absence of fungicides, the UC mirrors individual epidemiological disease behaviour and consequently has the lowest yield for every trial under the given conditions. For the evaluation of DSSs, the UC is regarded as the lower boundary of yield and the upper boundary of disease measures. In contrast, in the HST, four stage-oriented applications at GS 30 (T0), GS 32 (T1), GS 39 (T2), and GS 65 (T3) were conducted identically for every cultivar, location, and year of the survey, assuming a maximum of disease suppression by continuously protected leaves. Accordingly, the HST defined the highest possible yield and the lowest possible disease severities. Hence, the HST operated in the DSS evaluation as the upper boundary of yield and the lower boundary of disease measures.

To evaluate a broad range of the available DSSs, one representative scientific DSS, one representative federal DSS, and one representative commercial DSS were implemented in the survey. Therefore, the IPM-Wheat Model Schleswig-Holstein, the ISIP system, and the xarvio© FIELD MANAGER were chosen as representative DSSs, respectively. Based on a broad database for the scientific IPM-Wheat Model Schleswig-Holstein, according to Klink et al. [4], this system operated as the reference DSS in the study.

The science-based IPM-Wheat Model uses specific biological-epidemiological thresholds according to Verreet et al. [19] (Table 3). All IPM thresholds are primarily based on foliar disease incidences (DI) (Septoria tritici blotch, powdery mildew, stripe rust, and leaf rust) or indicating leaf layers (glume blotch and tan spot) for easier implementation into common farm practices. Due to the STB's long latency period, a secondary weather-based threshold of 3 L/m^2 precipitation followed by leaf wetness ("Weihofen" sensor) over 98% for at least 36 h is needed to identify the point of infection. The thresholds are validated and adjusted to avoid short- or long-term commercial losses, thereby an eligible disease severity of the foliar diseases is tolerated [4,19]. Succeeding treatments were applied after the fungicidal protective cover (following the labelled instructions) was exhausted and disease thresholds were repeatedly exceeded. Consequently, disease epidemics below the biological-epidemiological thresholds were not treated with fungicides in the IPM treatment. As part of this DSS, periodic observations of the fields need to be executed by the user.

Table 3. Biological-epidemiological disease control thresholds, observation periods, and the indicating leaf layer of the IPM-Wheat Model for the major fungal foliar wheat diseases.

Foliar Disease	Observation Period (GS)	Indicating Leaf Layer	IPM—Disease Control Threshold
Septoria tritici blotch	32–69	F-6 to F-0	DI > 50% +36 h leaf wetness of >98%
Glume blotch	37–39	F-5 or F-4	DI > 12%
	41–47	F-4 or F-3	
	51–69	F-3 or F-2	
Tan spot	32	F-6 or F-5	DI > 5%
	33–39	F-5 or F-4	
	41–49	F-4 or F-3	
	51–69	F-3 or F-2	
Powdery mildew	30–69	F-6 to F-0 *	DI > 70%
Leaf rust	37–69	F-6 to F-0	DI > 30%
Stripe rust	30–69	F-6 to F-0	DI > 30% or accumulations

F = Flag leaf; DI = Disease incidence; GS = Growth stage. * 1st application DI per plant, 2nd application DI of leaf layers F-2 to F-0.

The federal ISIP-System is based on epidemiological ratings from fungicide-untreated plots at representative sites across Germany provided by the operators. The disease incidences (DI) of the three uppermost leaf layers are published weekly. Locally exceeded thresholds for the major foliar diseases (Table 4) are visualized by a colour system: red = an infection is probable, yellow = an infection is possible, green = an infection is improbable, and grey = an application is prohibited due to an inappropriate plant growth stage. For DSS recommendations for STB, local weather conditions must be incorporated. Therefore, the implemented model SEPTRI [20] uses weather parameters, namely temperature, precipitation, relative humidity, and leaf wetness, to predict suitable conditions for a STB infection.

Additionally, the susceptibility of the cultivar was incorporated into the model as described by the Bundessortenamt. The used cultivars "Ritmo" and "RGT Reform" are classified as susceptible and highly susceptible to the STB, respectively, so recommendations for the cultivars vary. However, for common farm practices, a periodic screening of the field crops is essential for the use of the system.

Table 4. Biological-epidemiological disease control thresholds, observation periods, and the indicating leaf layer of the ISIP decision support system for the major fungal foliar wheat diseases. DI = Disease incidence [21].

Foliar Disease	Observation Period (GS)	Indicating Leaf Layer	IPM—Disease Control Threshold
Septoria tritici blotch	32–37 39–61	F-3 to F-0 or stem F-2 to F-0 or stem	DI > 30% DI > 10% +48 h leaf wetness
Glume blotch	32–61	F-2 or F-0 or stem	DI > 30%
Tan spot	32–61	F-2 or F-0 or stem	DI > 5%
Powdery mildew	31–61	F-3 to F-0 or stem	DI > 60%
Leaf rust	37–61	F-6 to F-0 or stem	DI > 30% or accumulations
Stripe rust	31–61	F-6 to F-0 or stem	DI > 30% or accumulations

F = Flag leaf; DI = Disease incidence; GS = Growth stage.

The xarvio© FIELD MANAGER is a commercial digital farming solution of BASF SE (Ludwigshafen, Germany) and is either available at the web platform "www.xarvio.com" (accessed on 22 July 2022) or as an app-based platform. Decision support for the use of fungicides is only part of this cost-liable system. According to the xarvio© FIELD MANAGER, recommendations for the use of fungicides are based on regional epidemiological observations by the operator in combination with meteorological data. In order to use this DSS, detailed user information needs to be included, such as location, cultivar, tillage system, or seeding time. To enhance the quality of the implemented models, an input of occurring diseases at weekly intervals is recommended. Detailed information about the data processing was not available [22]. For the study, an ordinary user account was created, and the individual data was entered for every location in every year and operated in cooperation with the chamber of agriculture.

At all implemented DSSs of the survey, periodic observations of the crops are recommended. In the IPM and ISIP systems, the observations are essential for the proper use of these DSSs. Thus, during sampling at the trial sites, observations equivalent to all three DSS guidelines were made in the survey. These weekly collected observations were updated on the same day for the three DSSs.

All foliar fungicides were applied with a volume of 200 L/ha of water by overhead foliar applications using an annually calibrated plot boom sprayer with double flat fan nozzles and a standard nozzle spacing of 0.5 m on the spray boom at a pressure of 2 bar. The fungicides (Table 5) used in the study were determined before the very first application and were identical for all three locations and over the whole survey period from 2019 to 2021. To maintain consistency with common farm practices, the most efficacious commercially available fungicides were selected following the recommendations of the chamber of agriculture [23]. The fungicide "Input® classic" (Bayer AG) was applied solo at GS 30 (T0) and in combination with the fungicide "Talius®" (Bayer AG) at GS 32 (T2), followed by a solo application of the fungicides "Ceriax®" (BASF SE) at GS 39, and "Osiris®" (BASF SE) at GS 65. In contrast to the HST, the applications in the IPS-, ISIP-, and xarvio©-treatment were timed following the recommendations of every DSS. The choice of fungicides for recommended applications in the DSS-treatments for the control of the diseases STB, GB, and TS followed the fungicide selection of the HST according to the GS. DSS recommendations for the control of powdery mildew (PM) only called for the use of the fungicide "Pronto®Plus" (Adama Deutschland GmbH, Cologne, Germany) in combination with "Talius®". Furthermore, at DSS recommendations for rust diseases (RD), the fungicide "Folicur®" (Bayer AG) was applied (Table 5).

Table 5. Registered name, active ingredients, and indications assigned according to growth stages of the used fungicides at the trials of the study in northern Germany.

	Registered Name	Used Dose/Max. Dose (L/ha)	Costs [1] (EUR/L)	Active Ingredient (A.I.)	GS	Indicating Diseases
T0, T1	Input® Classic [5]	1.00/1.25	EUR 33.60	Spiroxamine (300 g/L) Prothioconazole (160 g/L)	30–37	STB, GB, TS
T1	Talius® [2,5]	0.20/0.25	EUR 28.00	Proquinazid (200 g/L)	30–59	PM
T2	Ceriax® [6]	2.50/3.00	EUR 26.33	Epoxiconazole (41.6 g/L) Pyraclostrobin (66.6 g/L) Fluxapyroxad (41.6 g/L)	39–61	STB, GB, TS
T3	Osiris® [6]	2.50/3.00	EUR 16.33	Epoxiconazole (37.5 g/L) Metconazole (27.5 g/L)	61–69	STB, GB, TS, PM
PM solo	Pronto® Plus [3,5,6]	1.25/1.50	EUR 16.00	Spiroxamine (250 g/L) Tebuconazole (133 g/L)	30–59	PM
RD solo	Folicur® [4,5]	0.80/1.00	EUR 16.60	Tebuconazole (250 g/L)	30–59	SR, LR

[1] Prices were investigated in Germany prior to the start of the survey in spring 2019; [2] only in combination with other fungicides; [3] only in combination with Talius at powdery mildew solo indications; [4] only at rust solo indications; [5] Bayer AG, Leverkusen, Germany; [6] BASF SE, Ludwigshafen, Germany; STB = Septoria tritici blotch; GB = Glume blotch; TS = Tan spot; PM = Powdery mildew; SR = Stripe rust; LR = Leaf rust; GS = Growth stage.

As every DSS uses meteorological data, a standardized agrometeorological weather station (Thies Clima, Göttingen, Germany) was installed directly at every trial location. Thereby, the precipitation (L/m^2; measuring accuracy ± 3%), air temperature at 30 cm height (°C; measuring accuracy ± 0.1 K), and leaf moisture (Weihofen device %; measuring accuracy ± 3%) were determined [24]. The data were recorded in 15 sec intervals and were given automatically as hourly values.

Plots were harvested with a plot combine in order to determine yields, which were converted into deciton (dt) per ha.

2.2. Sampling and Disease Assessment

In weekly intervals from GS 30 to 77, ten main tillers per plot were arbitrarily collected from three of the four sampling plots for foliar disease analyses of the UC, IPM, ISIP, xarvio©, and HST. Following a determined sequence according to Verreet et al. [19], the plant samples were analysed macroscopically and microscopically to assess the disease incidence and severity of each treatment.

In the first step, the growth stage, according to Zadoks et al. [18], was determined separately for every location. Thereby, every leaf was rated at the main stem for disease incidence and percentage of affected leaf area from the biotrophic foliar diseases: powdery mildew, stripe rust, and leaf rust. Additionally, the necrotization (NEC) and the green leaf area (GLA; 100%–NEC) were rated in this step. In the next step the leaves were separated from the main stems and tested for disease incidence and severity of tan spot. The leaves were then soaked in water to simulate leaf wetness, which leads to expanded pycnidia. This enhances Septoria tritici blotch and glume blotch symptoms to ensure the highest quality rating. As the quantitative parameter for the disease severity, the pycnidia of Septoria tritici blotch and glume blotch were counted between eightfold and fiftyfold magnification for every single leaf, resulting in exact disease incidence and disease severity for every single leaf layer. Additionally, notes such as rating date, location per plant, and plot were also recorded. The assessed epidemiological data was averaged for the leaf layers F-0 to F-2 separately after every weekly rating for each location, cultivar, and block and stored in a SQL database.

2.3. Data Analyses

For further data analyses and an annual comparison of the disease severity, the area under disease progress curve (A_{F-x}) of every year, location, treatment, and block were considered. This was calculated using the disease severity parameters NEC, GLA, STB, GB, TS, PM, SR, and LR disease severities of F-0 to F-2 from GS 30 to 77. For the estimation of the A_{F-x} according to Madden et al. (2007) [25], the trapezoidal method has been used by discretizing the time variable and determining the average disease intensity between two neighbouring time points (Formula (1)):

$$A_{F-x} = \sum_{i=0}^{k-1} \frac{(y_i + y_{i+1})}{2}(t_{i+1} - t_i) \tag{1}$$

A_{F-x} = AUDPC of leaf layer F minus x; y = disease severity at rating date i, t = rating date; k = number of neighbouring time intervals.

For comparison of the disease severities of the UC and the treatments, a yield-directed comparison was performed, adjusting the A_{F-x} to the weighted AUDPC (WAUDPC) by weighting disease severities separately for each leaf layer, namely 70% for F-0, 20% for the F-1, and 10% for the F-2 (nominator Formula (2)) [26,27]. The result of the WAUDPC calculation is obviously hard to classify. However, dividing the WAUDPC by the number of time points (k + 1 in Formula (2)) yields the relative WAUDPC (RWAUDPC), showing disease severities in realistic quantities:

$$\text{RWAUDPC} = \frac{0.7A_{F-0} + 0.2A_{F-1} + 0.1A_{F-2}}{k+1} \tag{2}$$

k = number of neighbouring time intervals.

The fungicide use was quantified by the treatment frequency index (TFI) according to Bürger et al. 2008 [28] as defined in Formula (3): The sum of the used dose rate relative to the recommended dose of every application of each treatment:

$$TFI = \sum_j \frac{dose\ rate_j}{standard\ dose_j}, \tag{3}$$

j = application number per year.

2.4. Statistical Analyses

For further consideration of yield and disease pressure, the DSS treatments were tested against the healthy-standard treatment and the UC following the statistical evaluation of pharmaceutical ‘gold standard’ trials (Formula (4); three-arm design) [29,30]. The statistical software R, version 4.1.3 (R Foundation for Statistical Computing, Vienna, Austria) [31], was used to analyse the data. The treatments IPM, ISIP, and xarvio were tested for non-inferiority to the healthy-standard treatment using simultaneous confidence intervals. Our approach is based on the concepts of Pigeot et al. [29] and Hasler [30]. As this concept assumes a completely randomized design, we adapted this concept and enabled it to be applicable for complex experimental designs. Firstly, the case sensitivity was proven individually for each year, location, and cultivar by a comparison of the healthy-standard treatment versus the UC. All year-location-cultivar combinations (YLC combinations) without significant differences were excluded from further analysis. Secondly, the relative efficacy was calculated. Therefore, the RWAUDPC of yield, NEC, GLA, STB, GB, TS, PM, SR, and LR was used separately for every year, location, treatment, and block (y in Formula (4)). For these relative efficacy values, an appropriate statistical mixed model [32] was defined. The model included cultivar and treatment, as well as their interaction term, as fixed factors. The year, the location (nested in year), the block (nested in location), and the cultivar (nested in block) were regarded as random factors. The residuals were assumed to be normally distributed and homoscedastic. These assumptions are based on a graphical residual analysis. Based on this model, one-sided simultaneous confidence intervals were conducted for the means of all combinations of treatment and cultivar. These intervals represent a simultaneous test for non-inferiority of the treatments IPM, ISIP, and xarvio© to the healthy-standard treatment, adjusted with the UC.

$$Relative\ efficacy = \frac{y - \mu_{UC}}{\mu_{UC} - \mu_{HST}} \tag{4}$$

μ = annual mean of every location.

3. Results

3.1. Weather Conditions

At all locations, detailed agricultural weather information was recorded in the period between growth stages (GS) 30 and 77. In the survey area, this period is typically between the end of April and the beginning of July and is shown in detail for every year and location in Table 6. In maritime climates, micro-climatic annual conditions vary in a minor manner. Consequently, the temperature varied between 13 and 14 °C at the trial locations and did not differ from the 30-year average of May and June in Schleswig-Holstein (13.75 °C [14]) at all locations and years. The variation of the precipitation between the three locations and years was higher within the observation period, as rainfall events are usually more localized.

Table 6. Temperature, precipitation, hours of leaf wetness, and STB infection conditions (leaf wetness by "Weihofen" sensor ≥ 98% over more than 36 h) of the observed vegetation period at the trial locations Barlt, Futterkamp, and Kluvensiek from 2019 to 2021.

Location	**OP**	**T**	**PP**	**h of LW ≥ 98%**		**STB Infection Conditions**
		(°C)	**(L/m^2)**	**(h)**	**n**	**Date (Hours of Leaf Wetness ≥ 98%)**
Barlt	22 April 2019 1 July 2019	14 (6/24)	114	433	4	1 May 2019 (108); 10 May 2019 (64); 13 June 2019 (64); 17 June 2019 (54)
	20 April 2020 29 June 2020	14 (7/24)	75	336	3	3 May 2020 (113); 24 May 2020 (42); 10 June 2020 (163)
	26 April 2021 5 July 2021	14 (5/25)	154	605	5	8 May 2021 (111); 19 May 2021 (207); 27 May 2021 (42); 29 May 2021 (56); 22 June 2021 (63)
Futterkamp	15 April 2019 24 June 2019	13 (5/22)	172	449	7	10 May 2019 (41); 23 May 2019 (32); 10 June 2019 (163); 1 June 2019 (45); 9 June 2019 (37); 17 June 2019 (155); 23 June 2019 (105)
	20 April 2020 5 July 2020	13 (6/22)	114	324	4	2 May 2020 (98); 14 May 2020 (50); 15 June2020 (62); 21 June 2020 (56)
	26 April 2021 5 July 2021	14 (5/25)	164	428	5	6 May 2021 (73); 19 May 2021 (27); 25 May 2021 (94); 29 May 2021 (113); 31 June 2021 (66)
Kluvensiek	15 April 2019 24 June 2019	13 (4/21)	89	190	6	14 May 2019 (120); 24 May 2019 (61); 30 May 2019 (91); 12 June 2019 (58); 16 June 2019 (42); 21 June 2019 (79)
	27 April 2020 6 July 2020	14 (6/23)	127	205	5	2 May 2019 (87); 14 May 2019 (37); 5 June 2020 (26); 14 June 2020 (46); 19 June 2020 (35)
	26 April 2021 5 July 2021	14 (4/23)	236	461	5	1 May (58); 7 May (129); 16 May (143); 6 June 2021 (66); 24 June 2021 (112)

OP = Observation period; T = Temperature; PP = Precipitation; LW = Leaf wetness.

Thereby, the 30-year average of Schleswig-Holstein is 127 L/m^2 [14] in the observed month; within the survey period, the precipitation varied between 75 L/m^2 in Barlt in 2020 and 236 L/m^2 in Kluvensiek in 2021. Consequently, in years with high precipitation, more hours of leaf wetness over 98% were observed, and thus conducive conditions for an STB infection, such as rainfall of 3 L/m^2 followed by 36 h of leaf wetness over 98%, were observed more frequently. Conducive STB conditions were observed in Barlt 10 times, in Futterkamp 17 times, and in Kluvensiek 16 times within the survey period. Detailed weather conditions for every year and location are shown in Table S1. At every location and in every year, conducive weather conditions for STB prevailed throughout the survey.

3.2. Significant Year-Location-Cultivar Combinations of the Untreated Control and Healthy-Standard Treatment for Yield and RWAUDPC

Case sensitivities of yield, GLA, STB, GB, TS, PM, SR, and LR were determined for all year-location-cultivar combinations separately. To analyse the potential of the subjected DSSs, significant differences between the UC and HST are necessary.

For current farm practices, the most crucial factor is yield. The average total yield from every year, location, and cultivar increased by 15.49 dt/ha, from 85.90 dt/ha in the UC to 101.39 dt/ha in the HST. This equates to a yield increase of 18%, which can be directly attributed to the use of fungicide applications. In total, 14 of the 18 possible YLC combinations showed a significant yield increase in the HST (Figure 1A). In the cultivar "RGT Reform" an average increase of 14.98 dt/ha (17%) was observed in the HST. Thereby, the highest difference in yield was observed in the cases of Futterkamp 2021 and Kluvensiek 2021, with 21.33 dt/ha (25%) and 21.11 dt/ha (26%) more yield, respectively, as in the HST. In contrast, the lowest yield difference was observed in Barlt 2020 and 2021, with an increase of 2.41 dt/ha (2%) and 4.35 dt/ha (5%), respectively. In the cultivar "Ritmo" an average increase in yield of 16.00 dt/ha (20%) was harvested in the HST. The greatest difference between the UC and HST was observed in 2019 at the locations Futterkamp and Kluvensiek, with 26.83 dt/ha (32%) and 26.77 dt/ha (43%), respectively (Figure 1A).

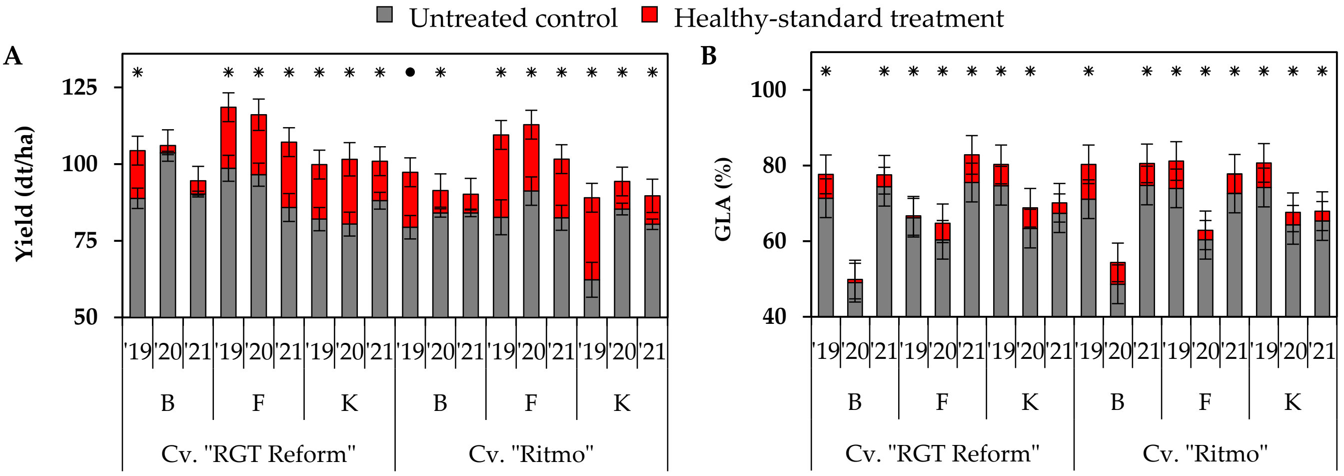

Figure 1. Annual (**A**) yield (dt/ha) and (**B**) green leaf area (GLA; RWAUDPC of percentage of leaf area) of the UC (grey bars) and the healthy-standard treatment (red bars) of the wheat cultivars "RGT Reform" and "Ritmo" at the locations Barlt (B), Futterkamp (F), and Kluvensiek (K) from 2019 and 2021. Significant ($p \geq 0.05$) differences between untreated control and healthy-standard treatment are marked with *.

Similar to yield, a significantly higher RWAUDPC of the green leaf area (GLA) was rated on the three uppermost leaf layers pooled over all survey years, trial locations, and cultivars. As a result, the green leaf area of the HST (67.10%) was 4.67% higher than that of the UC (63.02%). Overall, 15 of the 18 possible YLC combinations showed a significantly higher RWAUDPC in the HST than in the UC. In the cultivar "RGT Reform", the HST was 4.04% greener than the UC, whereas the HST was 5.35% greener in the cultivar "Ritmo" (Figure 1B). The yield and the GLA were mainly determined by the occurrence of foliar diseases. For the diseases surveyed (STB, GB, TS, PM, SR, and LR), GB and TS did not occur in the entire survey and were consequently not considered for further analysis. However, the diseases STB, PM, SR, and LR were all included and rated in the survey.

As shown in Figure 2, only STB occurred with high disease severities in every YLC combination and was therefore the most prevalent disease included in the survey, with a total RWAUDPC of 24 pycnidia in the UC. In 2021, the highest STB disease pressure was recorded in the UC, with an averaged RWAUDPC of 37 pycnidia. In contrast, the lowest pressure was recorded in 2020 at 8 pycnidia. The disease pressure varied between an averaged RWAUDPC of 17 pycnidia in Barlt and 29 pycnidia in Futterkamp in the UC. Between the cultivars, an enhanced RWAUDPC of STB by 40% in the UC of the cultivar “Ritmo” (30 pycnidia) compared to the cultivar “RGT Reform” (18 pycnidia) was observed. The HST employed the most fungicides possible, and consequently, the highest possible reduction of the diseases was observed. In total, the STB disease severities were reduced by 80% in the HST (5 pycnidia) as compared to the UC (24 pycnidia). A significant reduction of the HST compared to the UC was observed in 14 of the 18 possible YLC combinations. In the cultivar “RGT Reform” the RWAUDPC of STB was reduced by 78%, from 18 pycnidia in the UC to 4 pycnidia in the HST, averaged over all years and locations. In the higher susceptible cultivar “Ritmo” the disease severity was reduced by 82% in the HST (30 pycnidia) as compared to the UC (5 pycnidia). As a result of the higher susceptibilities of the cultivar “Ritmo”, the potential of the fungicides was enhanced by 4% as compared to the cultivar “RGT Reform”. In particular, Futterkamp 2020 showed the greatest reduction in disease severity, with 95% fewer pycnidia being rated in the HST compared to the UC in both cultivars. In contrast, the lowest significant RWAUDPC reduction in the HST was observed in Kluvensiek 2021, with 50% less pycnidia in the cultivar “RGT Reform” and 54% less pycnidia in the cultivar “Ritmo” (Figure 2A).

In addition, STB, PM, SR, and LR occurred either with high disease severities in certain assays or with minor disease severities in numerous cases (Figure 2B–D). As shown in Figure 2B, PM occurred in numerous YLC combinations except for the location Barlt. In total, the disease pressure of PM was at an RWAUDPC of 0.04% in the UC on a minor level. Nevertheless, the annual disease severity in the UC varied from an averaged RWAUDPC of 0.02% in 2021 to 0.09% in 2021 at the Futterkamp and Kluvensiek locations only. Thereby, the location Kluvensiek showed an enhanced disease pressure in the UC with 0.09% compared to the location Futterkamp 0.01%. Like STB, the RWAUDPC was enhanced in the more susceptible cultivar “Ritmo” (0.06%) compared to the cultivar “RGT Reform” (0.04%). Although the disease PM had a minor disease pressure, the severities in the HST were significantly reduced by using fungicides in 7 of the 18 possible YLC combinations. Thereby, the disease PM did not occur in considerable severity (<0.01%) in the HST, hence a total reduction of >98% in the HST compared to the UC was observed (Figure 2B).

In fewer YLC combinations, the disease SR showed higher but still minor disease severities than PM, with an averaged RWAUDPC of 0.1%. Thereby, the annual disease severity varied from 0.05% in 2020 to 0.13% in 2019. Regionally, the disease severity in the UC varied between 0.03% at the location Barlt and 0.15% at the location Futterkamp. Contrary to the diseases STB, PM, and LR, a 75% reduced RWAUDPC in the UC was observed in the cultivar “Ritmo” (0.04%) compared to the cultivar “RGT Reform” (0.16%). In the HST, the disease SR was not rated in considerable (<0.01%) measures, resulting in a total reduction of 99% compared to the UC. In 4 of the 18 possible YLC combinations, significant differences were observed due to adequate disease severities in the UC (Figure 2C).

The disease LR occurred with high disease severities, but in contrast to the aforementioned diseases, only in a few cases of the survey. Hence, the highest observed RWAUDPC (2.80%) was a multiple of the total average (0.56%) from the UC of the survey. The disease severity of LR varied annually from 0.18% in 2019 to 1.00% in 2020, and regionally from 0.36 to 0.84% in the UC. In comparison, the disease severities between the cultivars “Ritmo” (1.06%) and “RGT Reform” (0.06%) differed on a major level. In the HST, the disease LR was also not rated as having considerable disease severity (<0.01%). In total, a reduction of >99% was accomplished, and significant differences between the HST and the UC were observed in four of the possible YLC combinations. Thereby, significant differences were only observed in the cultivar “Ritmo” (Figure 2D).

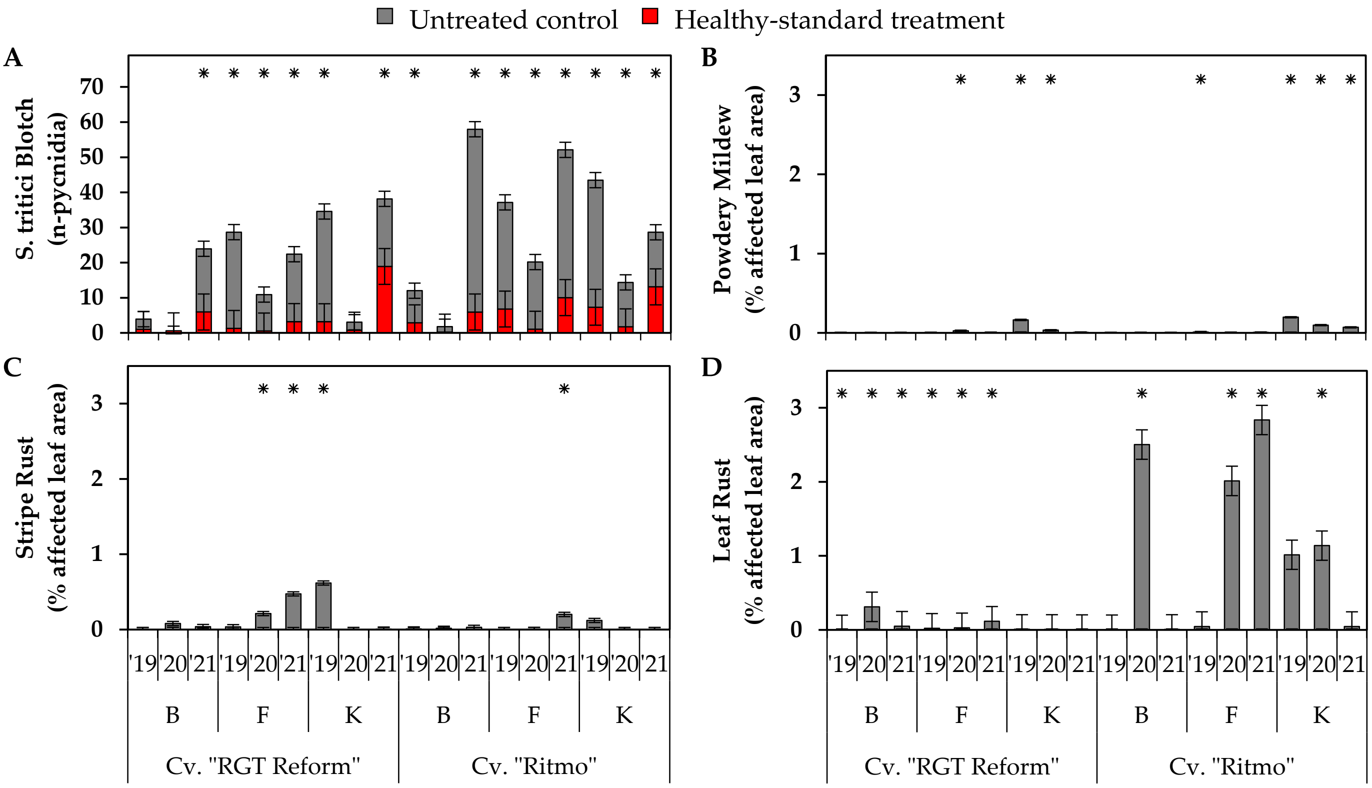

Figure 2. Annual disease severities (RWAUDPC; F-0 70%; F-1 20%; F-2 10%) of (**A**) Septoria tritici blotch (number of pycnidia), (**B**) powdery mildew (percentage of leaf area), (**C**) stripe rust (percentage of leaf area), and (**D**) leaf rust (percentage of leaf area) of the untreated control (grey bars) and the healthy-standard treatment (red bars) of the wheat cultivars "RGT Reform" and "Ritmo" at the locations Barlt (B), Futterkamp (F), and Kluvensiek (K) from 2019 to 2021. Significant ($p \leq 0.05$) differences between the untreated control and healthy-standard treatment are marked with *.

3.3. Performance of Decision Support Systems for Yield and Disease Suppression

To assess and compare the performance of the DSSs and maintain accuracy, it was hypothesized that the HST with a maximum amount of fungicides provides the highest yield potential by protecting the green leaf surface area the longest and suppressing disease. UC disease suppression, on the other hand, was not performed, resulting in the lowest yield potential. As a result, only the range between the aforementioned treatments is relevant for assessing the efficacy of the subjected DSSs, and non-significant assays were excluded from the analyses. ANOVA results showed that the treatment significantly affected the relative efficacy of yield, NEC, STB, PM, SR, and LR ($p \leq 0.05$; Table S2). Hence, a lower quantity of assays enhances the variance in the analyses. For this reason, the lower confidence limits were increased if low assay numbers were available, as shown in Figure 3.

Summarised, for both cultivars, the subjected DSSs (IPM, ISIP, and xarvio$^{©}$) achieved a total of 92% of their potential yield as compared to HST. Thereby, the yield efficacy varied from 87% in the cultivar "RGT Reform" to 99% in the cultivar "Ritmo" whereby greater differences were observed in the xarvio$^{©}$ treatment. In the cultivar "RGT Reform" the treatments IPM, ISIP, and xarvio$^{©}$ achieved 93, 94, and 87%, respectively, as compared to HST. Thereby, the guaranteed efficiency with a 95% probability, represented by the lower confidence limit of the DSS, was 71% compared to 78% for the HST (Figure 3A). Furthermore, the NEC, which is reciprocal to the GLA of the DSSs achieved an efficiency of 87% in total. The efficacy of the DSSs in preserving green leaf area was highest in the cultivar "RGT Reform" (81%), and ranged from 77% in the IPM to 84% in the ISIP treatment. Even higher efficacies were observed in the cultivar "Ritmo" with 93% for all DSSs, varying from 89% in the xarvio$^{©}$ treatment to 99% in the ISIP treatment (Figure 3B).

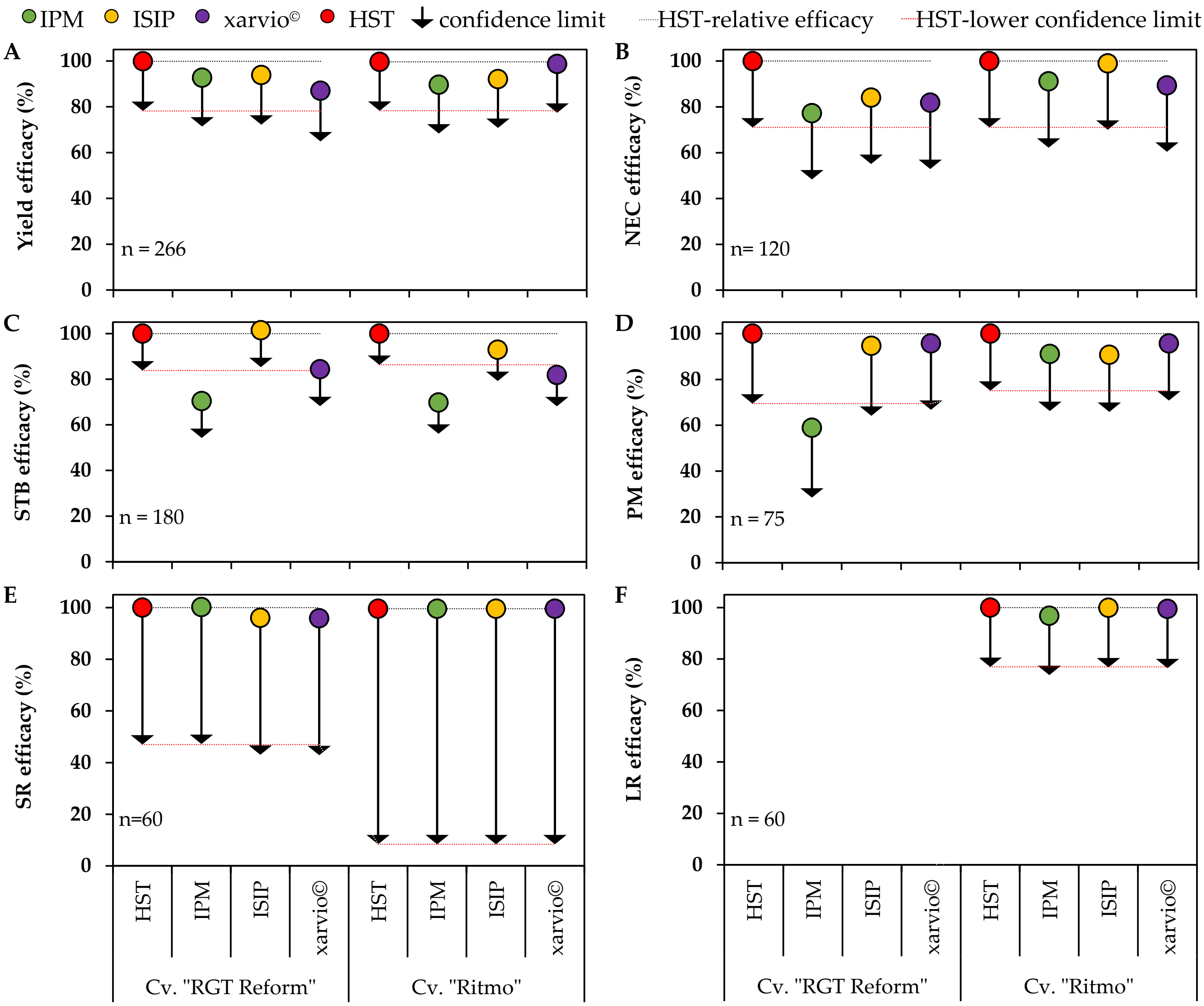

Figure 3. Relative efficacy and lower confidence limit (whisker, α = 0.05) of the healthy-standard treatment (red dots), IPM treatment (green dots), ISIP treatment (yellow dots), and xarvio© treatment (purple dots) in relation to the healthy-standard treatment adjusted by the untreated control for the parameters (**A**) yield, (**B**) necrotization (NEC), (**C**) Septoria tritici blotch (STB), (**D**) powdery mildew (PM), (**E**) stripe rust (SR), and (**F**) leaf rust (LR) from all significant YLC combinations from 2019 to 2021. n denotes the number of significant cases. Dotted lines describe the relative efficacy and the lower confidence limit of the HST.

Under consideration of the efficacy of DSS in suppressing the STB disease, an increased variation between the subjected DSSs was observed. As shown in Figure 3C, the efficacy of the DSSs compared to the HST was 83% in total, which is still an excellent level, but in comparison to yield, the range of variation was enhanced. Hence, the observed efficacy varied from 70% in the IPM treatment to 101% in the ISIP treatment in the cultivar "RGT Reform" and from 70% in the IPM treatment to 93% in the ISIP in the cultivar "Ritmo". In comparison to yield and NEC, the variations within the treatments were reduced, and as a consequence, the lower confidence limit differed less from the efficacy. As shown in Figure 3D the subjected DSSs achieved a high total efficacy of 88% in the suppression of PM and varied from 59% in the IPM treatment (cv. "RGT Reform") to 96% in the xarvio© treatment. Among the DSSs tested, the IPM treatment had a significantly lower efficacy in PM disease suppression in the cultivar "RGT Reform". This was not confirmed in the cultivar "Ritmo", where all DSSs showed efficacies of 91% or higher. The disease suppression of the two occurring rust diseases by the DSSs was at a superior level of 99% efficacy averaged over the cultivars "RGT Reform" and "Ritmo" and diseases SR and LR. As previously stated, the lower confidence limits were enhanced due to a lower quantity of significant YLC-combinations.

3.4. Efficacy of DSSs

For evaluation of the efficacy of the subjected DSSs, the average yield and TFI of the cultivars "RGT Reform" (Figure 4A) and "Ritmo" (Figure 4B) were used. In the HST, the yield of the more susceptible cultivar "RGT Reform" increased by 8% compared to the cultivar "Ritmo". As shown in Figure 4A$_{\mathrm{I}}$, the yield in the HST of the cultivar "RGT Reform" (105.50 dt/ha) was 1% higher than the yield of the subjected DSSs (104.29 ± 0.37 dt/ha). Furthermore, the yield of the HST (97.32 dt/ha) in the cultivar "Ritmo" was 1% higher than the yield of the subjected DSSs (95.94 ± 0.85 dt/ha; Figure 4B$_{\mathrm{I}}$).

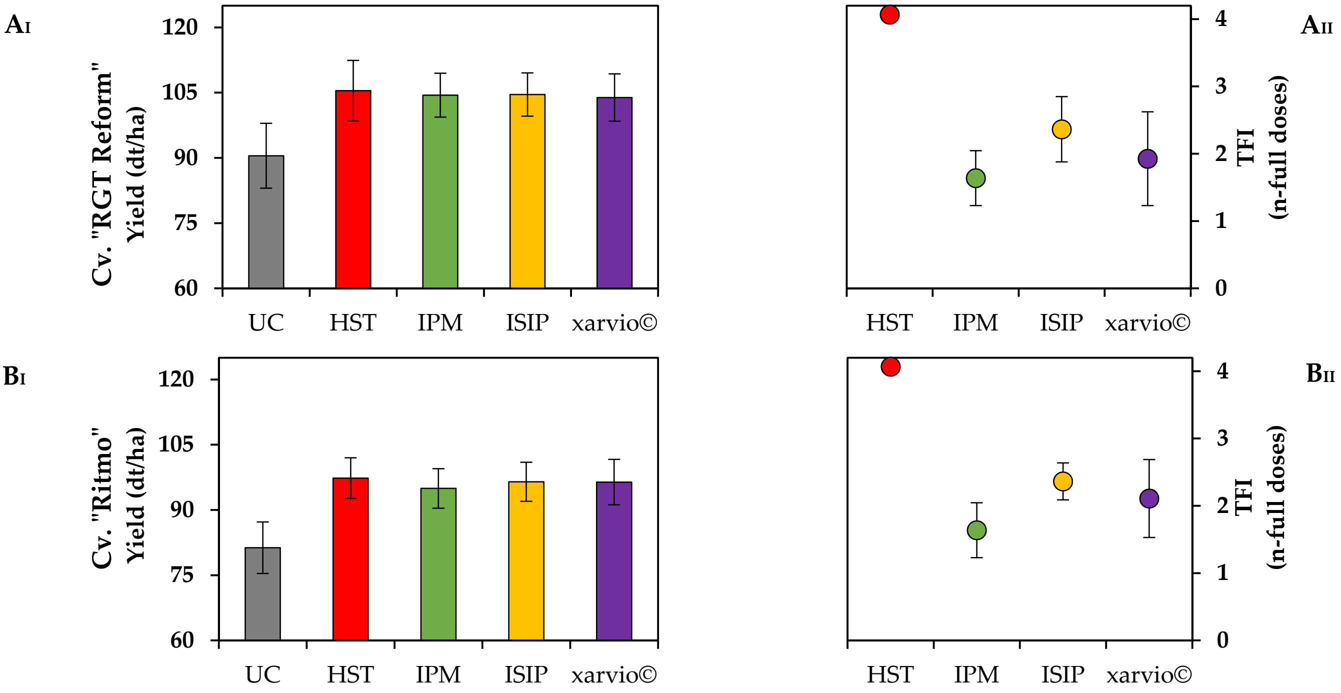

Figure 4. Yield (dt/ha; bars) and treatment frequency index (TFI; n-full doses; dots) of the untreated control (UC), healthy-standard treatment (HST; red), IPM treatment (green), ISIP treatment (yellow), and xarvio$^{©}$ treatment (purple) of the wheat cultivars (**A**) "RGT Reform" and (**B**) "Ritmo" averaged over the three trial locations and years from 2019 to 2021.

As there were no statistical differences in yield between the HST and the DSS treatments in the cultivars "RGT Reform" and "Ritmo", significant differences in the use of fungicides were determined in the survey. In the entire survey, 222 foliar fungicide applications were applied, resulting in 90 applications in the HST, 36 in the IPM, 52 in the ISIP, and 44 in the xarvio$^{©}$ treatment. The overarching goal of DSSs was to optimise fungicide timing. During this study, unnecessary applications were not applied, and the total amount of fungicide product was reduced. For the comparison of the fungicides used in the treatments, the treatment frequency index (TFI), as a standardizing index for the use of fungicides, was calculated for the DSSs and the HST and is shown in Figure 4A$_{\mathrm{II}}$,B$_{\mathrm{II}}$. Hence, the differences in concentration or other characteristics of the fungicides applied are equalized in the TFI by qualifying the used dose to the standard dose.

According to the trial design in the HST, four full applications of fungicides were applied in every year, location, and cultivar (Figure 4A$_{\mathrm{II}}$,B$_{\mathrm{II}}$. In contrast, the recommendations of the DSSs approximately halved the TFI and, accordingly, the quantity of used fungicides. Thereby, the TFI in the DSS treatments varied equally in the cultivars “RGT Reform” and “Ritmo” between 1.65 in the IPM treatment and 2.36 in the ISIP treatment. In the xarvio© treatment, the fungicides used differed between the cultivars, with a TFI of 1.93 in the cultivar “RGT Reform” and 2.11 in the cultivar “Ritmo”. Due to the preselection of the fungicides in the survey, it can be assumed that the amount corresponds directly with the included risks of the used fungicides. Furthermore, regardless of cultivar, the DSSs demonstrated high efficacy in the use of fungicides.

3.5. Economic Analysis

Economic analyses typically combine the factors yield and all costs. As a result of the trial design, the cost of fungicides determined the total costs of a treatment, as all other factors were identical at every treatment. Hence, the UC did not add any additional costs since fungicides were not used in this treatment. With increasing wheat prices, the use of fungicides is cost-effective (costs for fungicides and for labour are covered). Thus, at low wheat prices under EUR 6.33/dt cultivating the cultivar “RGT Reform” and EUR 6.47/dt for “Ritmo”, respectively, the use of fungicides does not outweigh the cost of application. Further increasing wheat prices promote the usage of DSSs. In the IPM treatment, the lowest quantity of fungicides was recommended; the fungicide costs were covered at the lowest price and showed the highest margins under increasing wheat prices. The treatments ISIP and xarvio© showed that the cost of application is warranted because of slightly higher wheat prices over EUR 9.03/dt and EUR 7.76/dt in the cultivar “RGT Reform” and EUR 8.41/dt and EUR 7.54/dt in the cultivar “Ritmo”, respectively. However, at continuously increasing wheat prices, an increased usage of fungicides is economical. In the highly susceptible cultivar “Ritmo” the break-even point (BEP) between the IPM treatment and the HST was EUR 55.17/dt. The wheat price was higher for all other BEPs of the HST and DSS treatments in the cultivars "RGT Reform" and "Ritmo". Since 2000, the average European wheat price has been EUR 15.45/dt, with a price range from EUR 7.94/dt to EUR 33.07/dt [33], and the subjected DSSs had collectively superior profit margins to the UC and the HST within the historical price range (Table 7).

Table 7. Break-even points of the DSSs IPM, ISIP, and xarvio© to the untreated control (UC) and healthy-standard treatment (HST) with the corresponding revenue function (p(x)) of the cultivars “RGT Reform” and “Ritmo” averaged over the locations Barlt, Futterkamp, and Kluvensiek for the period from 2019 to 2021.

Cultivar	Treatment	Break-Even Point		Revenue Function
		to UC	to HST	
“RGT Reform”	UC			$p(x) = 90.48x$
	HST			$p(x) = 105.47x - 219.15$
	IPM	EUR 6.33	EUR 126.14	$p(x) = 104.43x - 88.22$
	ISIP	EUR 9.03	EUR 104.00	$p(x) = 104.58x - 127.34$
	xarvio©	EUR 7.76	EUR 71.89	$p(x) = 103.86x - 103.79$
“Ritmo”	UC			$p(x) = 81.33x$
	HST			$p(x) = 97.32x - 219.15$
	IPM	EUR 6.47	EUR 55.17	$p(x) = 94.95x - 88.22$
	ISIP	EUR 8.41	EUR 107.12	$p(x) = 96.47x - 127.34$
	xarvio©	EUR 7.54	EUR 113.97	$p(x) = 96.40x - 113.57$

4. Discussion

The production of food of adequate quality and quantity is traditionally a major goal of agricultural production. Therefore, in common farm practices, pesticides are used to protect the field crops, thereby utilising the full local potential in the quality (e.g., contamination with mycotoxins) [34,35] and quantity (e.g., yield) [36–38] of harvested crops. The European Union regulates the use of pesticides through the directive 2009/128/EC for sustainable use of pesticides [11]. In 2022, the Directorate-General for Health and Food Safety considered the implemented regulations ineffective [39]. Additionally, a revision of the directive was recommended and implemented in the draft of the "Farm to Fork" strategy. Thereby, a central regulation is a pesticide reduction of 50% by 2030 based on the sales volume from 2015 to 2017 [12]. Hence, for common farm practices primarily an elimination of unnecessary pesticide uses and in consequence a more effective use of pesticides is warranted. As described by Dachbrodt-Saaydeh et al. [13], approximately 89% of the total pesticide use (87% of the fungicide use) in Germany was needed to ensure an adequate harvest in Germany from 2007 to 2016. Accordingly, still 11% of the pesticides and 13% of the fungicides are used unnecessarily. The unnecessary use of pesticides was also confirmed by similar studies, but not comprehensively for every type of pesticide and field crop [40–43]. The cause of unnecessary fungicide use is primarily a result of non-optimized application timing. As a result, too early application reduces protective performance, while too late application reduces the curative performance of the fungicides [19,42,44,45]. Both too early and too late applications reduce the efficacy of fungicides, which induces the use of higher doses to compensate for the loss in effectiveness. To minimize these false applications of pesticides is a major challenge for common farm practices [4,19,45,46]. For optimized timing in fungicide applications, the use of DSSs is recommended but not comprehensively established [38,40,45,47]. In recent decades, numerous DSSs have been published by universities, federal institutions, or corporations for the control of one or multiple foliar diseases [47]. Thereby, the published DSSs differ significantly in the degree of transparency, which is one reason for the non-comprehensive establishment of DSSs in common farm practices [47]. Usually, the thresholds and algorithms of scientific and federal institutions provide high levels of transparency in comparison to commercial systems. As in the study of the scientific and federal representatives, IPM and ISIP showed full transparency in comparison to xarvio© [19,21]. Additionally, due to the different transparencies of the DSSs, the requirements in disease diagnostics differ considerably between DSSs [47,48]. Hence, all of the subjected DSSs supported the diagnostics by regional observation in the survey area. In general, every fungicide use in the European Union is only warranted if an indicating disease appears [11], and therefore disease diagnostics are required in farm practices. Nevertheless, problems in diagnostics are a common reason for DSS refusal [47,48]. Another reason for the non-comprehensive establishment of DSSs in common farm practices might be the additional workload for sampling, diagnostics, and exertion by the farmers [49]. Aside from the aforementioned reasons, the main concern of farmers is yield stability when DSSs determine the timing of fungicide use [50]. This major concern was investigated under maritime conditions in northern Germany. Notably, these warm and humid climates are conducive to disease development and demand an enhanced use of fungicides.

In our study, cultivar susceptibility varied, and our data indicates this from foliar disease evaluations. In particular, except for SR, the used cultivar "RGT Reform" was less susceptible to foliar diseases than the cultivar "Ritmo". Therefore, the lower susceptibility to foliar diseases was confirmed in the UC. Disease severities in SR and LR were significantly reduced due to the selection of a less susceptible cultivar. This was confirmed by Klink et al. [4], Aboukhaddour et al. [51], Duveiller et al. [52], Miedaner et al. [53], Singh et al. [54], Hovmøller et al. [55], and Willocquet et al. [8]. In contrast, the disease suppression effect of the cultivar on the disease severities of PM and, in particular, STB was only rudimentary in the survey. Other commercially available cultivars with low susceptibility to all diseases are either not adapted to the local conditions and thus less productive or have a lower overall yield potential [56]. Until cultivars with high yield potential and resistance to regional pathogens are bred, fungicides are imperative to maintain yield and quality. Consequently, a general prohibition of fungicides is not an option if agricultural productivity is to be maintained. Under consideration of the results of yield in the present study, a deficit of approximately 20% was estimated in the UC compared to the HST and DSS treatments. A possibility to compensate for losses in yield is to extend the cropping area by 20% on comparable land. Due to the decrease of arable land in the European Union [57] and worldwide, this raises the demand for cereal grain, driven by population growth and the concern of food scarcity worldwide [58].

As the EU's "Farm to Fork" strategy claims a reduction of 50% [12] by 2030, it is questionable if agricultural productivity can be maintained at its current level. In wheat, foliar diseases are responsible for approximately 25% of potential yield losses [58], even with the use of fungicides. In the present study different DSSs were evaluated for their potential in the sustainable use of fungicides. All DSSs showed high efficacies in the reduction of foliar disease. Despite their inferiority in disease suppression, no significant differences in yield were observed between the DSS treatments and the HST. This leads to the conclusion that the full potential of the field crops was utilized, even if disease severity was on a minor level. According to Verreet et al. [19], infected fields need to be treated at the beginning of the pathogen's sporulation period due to a low population in the fields on the one hand and a visual appearance in the field on the other hand; this is the most sensitive part of the epidemic. Hence, low disease severities are tolerable in the disease suppression strategy in common farm practices. In our study, low aberrations in the efficacy of disease suppression from the DSS treatments compared to the HST were observed. Thereby, the efficacy of the DSSs was high throughout the whole survey for each cultivar, especially in suppressing rust diseases. The efficacy of the DSS to the parameters NEC, STB, and PM varied constantly from that of the HST, but the differences were minor. A possible explanation for the decline in effectiveness is that the efficacy of the DSSs is directly connected to the efficacy of commercially available fungicides. On the one hand, the sensitivity of rust diseases to commercially available fungicides [59] and their reduced efficacy for STB [60,61] and PM [62] indicate that the lack of efficacy is caused primarily by the reduced potency of fungicides. At the same time, a loss of efficacy in yield protection was not observed. Due to the optimised timing of fungicide application by DSS, unnecessary treatments were avoided. In general, the reduction in the number of sprays also leads to a lower risk of resistance development, which prolongs the duration of the fungicide's effect [45,63–65]. As a result, all DSS tested adequately reduced the disease severity of all foliar diseases and utilized the full yield potential of the locations and cultivars every year. In contrast, the amount of fungicides used for the control of foliar diseases was halved by using DSSs compared to the HST.

Under consideration of common wheat prices in the EU [33], the recommended fungicide strategies showed superior profit margins in comparison to the stage-oriented fungicide strategy in the survey (HST). These higher margins of threshold-based systems were also shown in other studies [4,19,47]. An optimized timing of the applications in sensible stages of the epidemiological disease dynamics caused the economic superiority of the DSSs independent from the cultivar.

The use of DSSs can be helpful in achieving the ambitious goal of a 50% pesticide reduction under the EU's "Farm to Fork" strategy. In contrast, the aforementioned success of DSSs in enhancing the efficacy of fungicides depends fundamentally on potent fungicides. Thereby, the diversity of different active ingredients is a key factor in resistance management [60,61,66]. Hence, the EU approach of reducing pesticide use by restricting the accredited active ingredients, as described in the EU substitution list [67], can decrease the efficacy of DSSs and fungicides in general. Accordingly, either an enhanced use of pesticides or a decline in agricultural productivity with all its global consequences may occur in the future. Instead of restricting the use of pesticides, the education of farmers for disease diagnostics and the use of DSSs might be an advanced approach for a sustainable reduction of pesticides. Furthermore, a supra-regional open access network of agrometeorological weather stations will enhance significantly the prediction accuracy of DSSs and, in general, the suitability of agricultural production [68,69].

In general, the DSSs tested in our study demonstrated improved efficacy in disease suppression and increased the sustainability of fungicide use through application timing optimization. The approach of optimizing the use of pesticides appears to be more sustainable compared to the planned restrictions of the EU "Farm to Fork" strategy, particularly with regard to the European Union and also global food security.

5. Conclusions

The three decision support systems (DSS) that were tested optimized the use of fungicides for the suppression of major fungal foliar diseases in wheat. Within the survey, all DSSs reduced the amount of fungicides applied by 50% as compared to a healthy-standard treatment. Thereby, no significant yield reductions were observed, either between the subjected DSSs or the healthy-standard treatment with the highest disease suppression potential. This confirms the effectiveness of a biological-epidemiological-based fungicide management system compared to the currently common stage-oriented system. In light of the political intention to reduce pesticides by 50% until 2030 (the EU's "Farm to Fork" strategy), the use of DSSs as a tool for fungicide optimization is of major importance for common farm practices in the future. General restrictions on pesticide application will not lead to an optimized use of pesticides and fungicides in particular. Consequently, a general decrease in yield and a higher risk of fungicide resistance for several diseases seem plausible. Enhanced workloads caused by, e.g., additional field diagnostics are at least monetarily covered by the savings of pesticides. However, either scientific, federal, or commercial DSSs showed superior economic behaviour. In conclusion, DSSs can help to improve the sustainability of fungicide use in wheat and pesticides in general.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su142315599/s1, Table S1: Temperature, precipitation, hours of leaf wetness, and STB infection conditions (leaf wetness by "Weihofen" sensor $\geq$ 98% over more than 36 h) in detail for the months of May and June of the observed vegetation period at the trail locations Barlt, Futterkamp, and Kluvensiek from 2019 to 2021. Table S2: Analyses of variance (ANOVAs) for the effect of treatment (untreated control, IPM, ISIP, xarvio©, HST), cultivar ("Reform", "Ritmo") and their interaction on the relative efficacy of yield, necrotization and disease severities of Septoria tritici blotch, powdery mildew, stripe rust, and leaf rust.

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References

1. FAO. *FAOSTAT Statistical Database*; FAO: Rome, Italy, 2022.
2. Poutanen, K.S.; Kårlund, A.O.; Gómez-Gallego, C.; Johansson, D.P.; Scheers, N.M.; Marklinder, I.M.; Eriksen, A.K.; Silventoinen, P.C.; Nordlund, E.; Sozer, N.; et al. Grains—A major source of sustainable protein for health. *Nutr. Rev.* **2022**, *80*, 1648–1663. [CrossRef]
3. Bouma, E. Development of comparable agro-climatic zones for the international exchange of data on the efficacy and crop safety of plant protection products. *Bull. OEPP* **2005**, *35*, 233–238. [CrossRef]

4. Klink, H.; Prahl, K.C.; Hasler, M.; Verreet, J.-A.; Birr, T. Efficiency and Effectivity of a Biological–Epidemiological Fungal Disease Management System in Wheat—A Study of 26 Years. *Agriculture* **2022**, *12*, 1099. [CrossRef]
5. Figueroa, M.; Hammond-Kosack, K.E.; Solomon, P.S. A review of wheat diseases-a field perspective. *Mol. Plant Pathol.* **2018**, *19*, 1523–1536. [CrossRef]
6. FAO. *Status of the World's Soil Resources: Main Report*; FAO/ITPS: Rome, Italy, 2015; ISBN 9789251090046.
7. Savary, S.; Willocquet, L.; Pethybridge, S.J.; Esker, P.; McRoberts, N.; Nelson, A. The global burden of pathogens and pests on major food crops. *Nat. Ecol. Evol.* **2019**, *3*, 430–439. [CrossRef]
8. Willocquet, L.; Meza, W.R.; Dumont, B.; Klocke, B.; Feike, T.; Kersebaum, K.C.; Meriggi, P.; Rossi, V.; Ficke, A.; Djurle, A.; et al. An outlook on wheat health in Europe from a network of field experiments. *Crop Prot.* **2021**, *139*, 105335. [CrossRef]
9. BVL. Pflanzenschutzmittelverwendung in der Landwirtschaft. Available online: https://www.umweltbundesamt.de/daten/land-forstwirtschaft/pflanzenschutzmittelverwendung-in-der#zulassung-von-pflanzenschutzmitteln (accessed on 13 September 2022).
10. European Food Safety Authority. *Food Safety in the EU*; European Parliament: Brussels, Belgium, 2019.
11. European Parliament. Directive 2009/128/EC of the European Parliament and of the Council of 21 October 2009 establishing a framework for Community action to achieve the sustainable use of pesticides. *Off. J. Eur. Union* **2009**, *L309*, 71–86.
12. European Commission; Directorate-General for Health and Food Safety. Proposal for a Regulation of the European Parliament and of the Council on the sustainable use of plant protection products and amending Regulation (EU) 2021/2115. *Off. J. Eur. Union* **2022**, *2022*, 1–71.
13. Dachbrodt-Saaydeh, S.; Sellmann, J.; Strassemeyer, J.; Schwarz, J.; Klocke, B.; Krengel, S.; Kehlenbeck, H. Netz Vergleichsbetriebe Pflanzenschutz Zwei-Jahresbericht 2015 und 2016–Analyse der Ergebnisse der Jahre 2007 bis 2016. In *Berichte aus dem Julius Kühn-Institut*, 194th ed.; Julius Kühn-Institut, Ed.; Saphir Verlag: Ribbesbüttel, Germany, 2018.
14. DWD Climate Data Center. Vieljährige Stationsmittelwerte für die Klimareferenzperiode 1991–2020, für aktuellen Standort und Bezugsstandort. Available online: https://www.dwd.de/DE/leistungen/klimadatendeutschland/vielj_mittelwerte.html (accessed on 18 May 2021).
15. Statistisches Amt für Hamburg und Schleswig-Holstein. *Kreisergebnisse Schleswig-Holstein 2020—Endgültiges Ergebnis der Landwirtschaftszählung 2020–: Kennziffer: C IV—LZ 2020 SH, SK Sonderbericht Kreisdaten*; Statisikamt Hamburg: Hamburg, Germany, 2021.
16. Bundessortenamt. *Beschreibende Sortenliste Getreide, Mais, Ölfrüchte, Leguminosen (großkörnig), Hackfrüchte (außer Kartoffeln) 2007*; Deutscher Landwirtschaftsverlag: Hannover, Germany, 2007; ISBN 0948-4167.
17. Bundessortenamt. *Beschreibende Sortenliste Getreide, Mais Öl- und Faserpflanzen Leguminosen Rüben Zwischenfrüchte 2018*; Deutscher Landwirtschaftsverlag: Hannover, Germany, 2018. ISBN 2190-6130.
18. Zadoks, J.C.; Chang, T.T.; Konzak, C.F. A decimal code for the growth stages of cereals. *Weed Res.* **1974**, *14*, 415–421. [CrossRef]
19. Verreet, J.-A.; Klink, H.; Hoffmann, G.M. Regional Monitoring for Disease Prediction and Optimization of Plant Protection Measuares: The IPM Wheat Model. *Plant Dis.* **2000**, *84*, 816–826. [CrossRef]
20. ISIP. Berechnung der Neuinfektionen durch Septoria Tritici. Available online: https://www.isip.de/isip/servlet/isip-de/entscheidungshilfen/getreide/berechnung-der-neuinfektionen-durch-septoria-tritici-259964 (accessed on 18 October 2022).
21. ISIP. Bekämpfungsschwellen für Blattkrankheiten in Winterweizen. Available online: https://www.isip.de/isip/servlet/resource/blob/4850/c17fa69037fede44a2447771885f6d23/bekaempfungsschwellen-fuer-blattkrankheiten-in-winterweizen-data.pdf (accessed on 1 August 2022).
22. Münzenmay, M.; Tanimou, M.; Kurre, H. Digitales Ökosystem Nevonex für die smarte Landwirtschaft. *ATZ Heavy Duty* **2020**, *13*, 46–51. [CrossRef]
23. Landwirtschaftskammer Schleswig-Holstein. *Ratgeber 2019: Pflanzenschutz im Ackerbau*; Empfehlungen für die Praxis: Rendsburg, Deutschland, 2019; Available online: www.lksh.de (accessed on 25 February 2019).
24. Henze, M.; Beyer, M.; Klink, H.; Verreet, J.-A. Characterizing Meteorological Scenarios Favorable for *Septoria tritici* Infections in Wheat and Estimation of Latent Periods. *Plant Dis.* **2007**, *91*, 1445–1449. [CrossRef] [PubMed]
25. Madden, L.V.; Hughes, G.; van den Bosch, F. CHAPTER 4: Temporal Analysis I: Quantifying and Comparing Epidemics. In *The Study of Plant Disease Epidemics*; Madden, L.V., Hughes, G., van den Bosch, F., Eds.; The American Phytopathological Society: St. Paul, MN, USA, 2017; pp. 63–116. ISBN 978-0-89054-505-8.
26. Mahmood, A.; Alam, K.; Salam, A.; Iqbal, S. Effect of flag leaf removal on grain yield, its components and quality of hexaploid wheat. *Cereal Res. Commun.* **1991**, *19*, 305–310.
27. Avci Birsin, M. Effects of Removal of Some Photosynthetic Structures on Some Yield Components in Wheat. *Tarim Bilim. Derg.* **2005**, *11*, 1. [CrossRef]
28. Bürger, J.; de Mol, F.; Gerowitt, B. The "Necessary Extent" of Pesticide use—Thoughts about a Key Term in German Pesticide Policy. *Crop Prot.* **2008**, *27*, 343–351. [CrossRef]
29. Pigeot, I.; Schäfer, J.; Röhmel, J.; Hauschke, D. Assessing non-inferiority of a new treatment in a three-arm clinical trial including a placebo. *Stat. Med.* **2003**, *22*, 883–899. [CrossRef]
30. Hasler, M. Multiple comparisons to both a negative and a positive control. *Pharm. Stat.* **2012**, *11*, 74–81. [CrossRef]
31. R Core Team. *R: A Language and Environment for Statistical Computin*; Statistical Computing; R Foundation: Vienna, Austria, 2022.
32. Pinheiro, J. *Mixed-Effects Models in S and S-PLUS*; Springer: New York, NY, USA, 2000; ISBN 9780387227474.

33. Eurostat. Selling Prices of Crop Products (Absolute Prices)—Annual Price (from 2000 Onwards) Soft Wheat—Prices per 100 kg. Available online: https://ec.europa.eu/eurostat/databrowser/view/apri_ap_crpouta/default/table?lang=en (accessed on 16 October 2022).
34. Birr, T.; Hasler, M.; Verreet, J.-A.; Klink, H. Composition and Predominance of Fusarium Species Causing Fusarium Head Blight in Winter Wheat Grain Depending on Cultivar Susceptibility and Meteorological Factors. *Microorganisms* **2020**, *8*, 617. [CrossRef]
35. Birr, T.; Jensen, T.; Preußke, N.; Sönnichsen, F.D.; de Boevre, M.; de Saeger, S.; Hasler, M.; Verreet, J.-A.; Klink, H. Occurrence of Fusarium Mycotoxins and Their Modified Forms in Forage Maize Cultivars. *Toxins* **2021**, *13*, 110. [CrossRef] [PubMed]
36. Horlings, L.G.; Marsden, T.K. Towards the real green revolution? Exploring the conceptual dimensions of a new ecological modernisation of agriculture that could 'feed the world'. *Glob. Environ. Chang.* **2011**, *21*, 441–452. [CrossRef]
37. Hillocks, R.J. Farming with fewer pesticides: EU pesticide review and resulting challenges for UK agriculture. *Crop Prot.* **2012**, *31*, 85–93. [CrossRef]
38. Deguine, J.-P.; Aubertot, J.-N.; Flor, R.J.; Lescourret, F.; Wyckhuys, K.A.; Ratnadass, A. Integrated pest management: Good intentions, hard realities. A review. *Agron. Sustain. Dev.* **2021**, *41*, 1–35. [CrossRef]
39. Karamfilova, E. (Ed.) *Revision of Directive 2009/128/EC on the Sustainable Use of Pesticides*; European Parliament: Strasbourg, France, 2022.
40. Jørgensen, L.N.; Noe, E.; Nielsen, G.C.; Jensen, J.E.; Ørum, J.E.; Pinnschmidt, H.O. Problems with disseminating information on disease control in wheat and barley to farmers. In *Sustainable Disease Management in a European Context*; Collinge, D.B., Cooke, B.M., Munk, L., Eds.; Springer: Dordrecht, The Netherlands, 2008; pp. 303–312. ISBN 9781402087806.
41. Ghimire, N.; Woodward, R.T. Under- and over-use of pesticides: An international analysis. *Ecol. Econ.* **2013**, *89*, 73–81. [CrossRef]
42. Carmona, M.; Sautua, F.; Pérez-Hérnandez, O.; Reis, E.M. Role of Fungicide Applications on the Integrated Management of Wheat Stripe Rust. *Front. Plant Sci.* **2020**, *11*, 733. [CrossRef] [PubMed]
43. Tataridas, A.; Kanatas, P.; Chatzigeorgiou, A.; Zannopoulos, S.; Travlos, I. Sustainable Crop and Weed Management in the Era of the EU Green Deal: A Survival Guide. *Agronomy* **2022**, *12*, 589. [CrossRef]
44. Shoemaker, C.A. The optimal timing of multiple applications of residual pesticides: Deterministic and stochastic analyses. In *Pest and Pathogen Control: Strategic, Tactical, and Policy Models*; Conway, G.R., Ed.; Wiley: Chichester, UK, 1984; pp. 290–309. ISBN 0-471-90349-3.
45. Lázaro, E.; Makowski, D.; Vicent, A. Decision support systems halve fungicide use compared to calendar-based strategies without increasing disease risk. *Commun. Earth. Environ.* **2021**, *2*, 1–10. [CrossRef]
46. Parsons, D.J.; Te Beest, D. Optimising Fungicide Applications on Winter Wheat using Genetic Algorithms. *Biosyst. Eng.* **2004**, *88*, 401–410. [CrossRef]
47. Jørgensen, L.N.; Hovmøller, M.S.; Hansen, J.G.; Lassen, P.; Clark, B.; Bayles, R.; Rodemann, B.; Flath, K.; Jahn, M.; Goral, T.; et al. IPM Strategies and Their Dilemmas Including an Introduction to www.eurowheat.org. *J. Integr. Agric.* **2014**, *13*, 265–281. [CrossRef]
48. Miller, S.A.; Beed, F.D.; Harmon, C.L. Plant disease diagnostic capabilities and networks. *Annu. Rev. Phytopathol.* **2009**, *47*, 15–38. [CrossRef]
49. Htun, N.-N.; Rojo, D.; Ooge, J.; de Croon, R.; Kasimati, A.; Verbert, K. Developing Visual-Assisted Decision Support Systems across Diverse Agricultural Use Cases. *Agriculture* **2022**, *12*, 1027. [CrossRef]
50. Mackrell, D.; Kerr, D.; Hellens, L.von. A qualitative case study of the adoption and use of an agricultural decision support system in the Australian cotton industry: The socio-technical view. *Decis. Support Syst.* **2009**, *47*, 143–153. [CrossRef]
51. Aboukhaddour, R.; Fetch, T.; McCallum, B.D.; Harding, M.W.; Beres, B.L.; Graf, R.J. Wheat diseases on the prairies: A Canadian story. *Plant Pathol.* **2020**, *69*, 418–432. [CrossRef]
52. Duveiller, E.; Singh, R.P.; Nicol, J.M. The challenges of maintaining wheat productivity: Pests, diseases, and potential epidemics. *Euphytica* **2007**, *157*, 417–430. [CrossRef]
53. Miedaner, T.; Juroszek, P. Climate change will influence disease resistance breeding in wheat in Northwestern Europe. *Theor. Appl. Genet.* **2021**, *134*, 1771–1785. [CrossRef] [PubMed]
54. Singh, R.P.; Singh, P.K.; Rutkoski, J.; Hodson, D.P.; He, X.; Jørgensen, L.N.; Hovmøller, M.S.; Huerta-Espino, J. Disease Impact on Wheat Yield Potential and Prospects of Genetic Control. *Annu. Rev. Phytopathol.* **2016**, *54*, 303–322. [CrossRef]
55. Hovmøller, M.S.; Milus, E.A.; Justesen, A.F. Rapid global spread of two aggressive strains of a wheat rust fungus. *Mol. Ecol.* **2008**, *17*, 3818–3826. [CrossRef]
56. Laidig, F.; Feike, T.; Hadasch, S.; Rentel, D.; Klocke, B.; Miedaner, T.; Piepho, H.P. Breeding progress of disease resistance and impact of disease severity under natural infections in winter wheat variety trials. *Theor. Appl. Genet.* **2021**, *134*, 1281–1302. [CrossRef]
57. Perpiña Castillo, C.; Kavalov, B.; Diogo, V.; Jacobs, C.; Batista, E.; Silva, F.; Baranzelli, C.; Lavalle, C. Trends in the EU Agricultural Land within 2015–2030. *JRC Policy Insights* **2018**, *2018*, 1–6.
58. Schils, R.; Olesen, J.E.; Kersebaum, K.-C.; Rijk, B.; Oberforster, M.; Kalyada, V.; Khitrykau, M.; Gobin, A.; Kirchev, H.; Manolova, V.; et al. Cereal yield gaps across Europe. *Eur. J. Agron.* **2018**, *101*, 109–120. [CrossRef]
59. Oliver, R.P. A reassessment of the risk of rust fungi developing resistance to fungicides. *Pest. Manag. Sci.* **2014**, *70*, 1641–1645. [CrossRef]
60. Birr, T.; Hasler, M.; Verreet, J.-A.; Klink, H. Temporal Changes in Sensitivity of Zymoseptoria tritici Field Populations to Different Fungicidal Modes of Action. *Agriculture* **2021**, *11*, 269. [CrossRef]

61. Klink, H.; Verreet, J.-A.; Hasler, M.; Birr, T. Will Triazoles Still Be of Importance in Disease Control of Zymoseptoria tritici in the Future? *Agronomy* **2021**, *11*, 933. [CrossRef]
62. Vielba-Fernández, A.; Polonio, Á.; Ruiz-Jiménez, L.; de Vicente, A.; Pérez-García, A.; Fernández-Ortuño, D. Fungicide Resistance in Powdery Mildew Fungi. *Microorganisms* **2020**, *8*, 1431. [CrossRef]
63. Möhring, N.; Wuepper, D.; Musa, T.; Finger, R. Why farmers deviate from recommended pesticide timing: The role of uncertainty and information. *Pest. Manag. Sci.* **2020**, *76*, 2787–2798. [CrossRef] [PubMed]
64. Rossi, V.; Sperandio, S.; Caffi, T.; Simonetto, A.; Gilioli, G. Critical Success Factors for the Adoption of Decision Tools in IPM. *Agronomy* **2019**, *9*, 710. [CrossRef]
65. van den Bosch, F.; Oliver, R.; van den Berg, F.; Paveley, N. Governing principles can guide fungicide-resistance management tactics. *Annu. Rev. Phytopathol.* **2014**, *52*, 175–195. [CrossRef] [PubMed]
66. Rotteveel, T.; Jørgensen, L.N.; Heimbach, U. Resistance management in Europe: A preliminary proposal for the determination of a minimum number of active substances necessary to manage resistance. *Bull. OEPP* **2011**, *41*, 432–438. [CrossRef]
67. European Parliament. Commission Implementing Regulation (EU) 2015/408 of 11 March 2015 on implementing Article 80(7) of Regulation (EC) No 1107/2009 of the European Parliament and of the Council concerning the placing of plant protection products on the market and establishing a list of candidates for substitution. *Off. J. Eur. Union* **2015**, *L67*, 18–22.
68. Zhai, Z.; Martínez, J.F.; Beltran, V.; Martínez, N.L. Decision support systems for agriculture 4.0: Survey and challenges. *Comput. Electron. Agric.* **2020**, *170*, 105256. [CrossRef]
69. Damos, P. Modular structure of web-based decision support systems for integrated pest management. A review. *Agron. Sustain. Dev.* **2015**, *35*, 1347–1372. [CrossRef]