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Efficiency and Effectivity of a Biological–Epidemiological Fungal Disease Management System in Wheat—A Study of 26 Years

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Abstract: Foliar diseases are a major threat to worldwide wheat production, especially during the vegetative period in maritime climates. Despite advancements in agronomic practices, infestations by foliar diseases are possible under favourable weather conditions, thus, fungicides are essential for maintaining control. Stage-oriented applications are therefore common in farm practices. The optimization of fungicide use according to biological–epidemiological thresholds reduces the total amount of fungicides used, which is of political interest, especially in the European Union. Therefore, the efficiency and effectivity of the fungicides used to control the six major foliar diseases (Septoria tritici blotch, glume blotch, tans spot, powdery mildew, stripe rust, and leaf rust) were analysed in a long-term study of 26 years in northern Germany under favourable maritime conditions. Of those diseases, Septoria tritici blotch was the most dominant recurring disease, with high severity noted in every year of the study. The threshold-based disease management system was compared to a fungicide untreated control and a healthy-standard fungicide treatment (according to growth stages). The usage of the threshold-based system reduced the disease severities significantly compared to the fungicide untreated control, without any loss of yield compared to the healthy-standard fungicide treatment. Thereby, the use of fungicides was reduced by two thirds compared to the stage-oriented healthy-standard treatment. Thus, the advantages of the threshold-based system were obvious, and this approach will be an important tool for future evaluations of current farm practices.

Keywords: *Triticum aestivum* L.; foliar diseases; disease severity; Integrated Pest Management (IPM); biological–epidemiological threshold; fungicide; long-term survey; AUDPC; yield; pesticide reduction

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1. Introduction

Cereals, wheat (*Triticum aestivum* L.) in particular, are a very important food source in almost all parts of the world [1,2]. Most regions in northern Europe have very good climatic conditions for successful wheat cultivation, with high precipitation, well-balanced precipitation distribution over the year, and moderate temperatures [3]. Consequently, a very high yield level is achieved there compared to other regions of the world [4,5]. However, when wheat is grown intensively, the plants can be affected by diseases, particularly those caused by fungi, which can cause quantitative [4,6] and qualitative losses [4,7,8]. Thus, wheat plant infestation by fungal pathogens should be managed.

The foliar diseases Septoria tritici blotch (caused by *Zymoseptoria tritici* Desm.), glume blotch (*Parastagonospora nodorum* Berk.), tan spot (*Pyrenophora tritici-repentis* Died.), powdery mildew (*Blumeria graminis* f. sp. *tritici*), stripe rust (*Puccinia striiformis* f. sp. *tritici*), and leaf rust (*Puccinia triticina* f. sp. *tritici*) are responsible for quantitative and qualitative losses in wheat.

The impact of fungal pathogens is determined to a large extent by agronomic practices such as crop rotation, tillage systems, or cultivar selection [9–11], or by prevailing weather conditions such as temperature or moisture. Regarding the agronomic factors and weather conditions, each pathogen has specific environmental requirements [12–17]. These lead to year-specific differences in the occurrence, course, and strength of epidemic behaviour. Thus, the approach to disease management needs to be adapted to varying environmental and biological–epidemiological conditions [18,19]. The application of foliar fungicides is elementary in the management of fungal diseases in wheat [4,10,17,20,21]. In common farm practice, the use of fungicides is mostly carried out through routine applications, which are oriented to plant growth stages. However, the use of pesticides is critically discussed and an optimization of the use of fungicides is required. Furthermore, the directive for sustainable use of fungicides and the "farm to fork" strategy of the European Union claim a risk reduction from pesticides by 50% concomitant with reduced pesticide use [22]. A biological–epidemiological oriented fungal disease management system may enhance the efficiency and effectivity of fungicide use compared to a plant growth stage-oriented system.

In the present long-term study, we analysed the potential of a biological–epidemiological system for the control of foliar fungal diseases in wheat. Therefore, a unique long-term study of 26 years under standardized conditions (same cultivar, same trial locations, same growing conditions) was established at eight locations in northern Germany, which is known to be a suitable growing area for wheat. The aims were (i) to determine risks of the six major fungal diseases, and (ii) to investigate the efficiency and (iii) effectivity of the used fungicides by a threshold-based system compared to a stage-oriented system.

2. Materials and Methods

2.1. Area Surveyed and Survey Strategy

Since 1995, the regional monitoring of major foliar fungal wheat diseases [23] was carried out at eight trial locations evenly distributed throughout northern Germany between the Baltic and the North Sea in the northernmost federal state of Germany, Schleswig-Holstein (Table 1). This region is a suitable growing area for winter wheat characterized by maritime weather conditions, with an average annual temperature of 9.2 °C and an annual precipitation of 846 L/m^2 [24]. In Schleswig-Holstein, arable crops were grown on 655,011 ha in 2020. Winter wheat and forage maize (*Zea mays* L.) occupy the dominant position in the crop rotation (20.8 % and 28.6 % of arable land, respectively), followed by oilseed rape (*Brassica napus* L.) (10.2 %) and winter barley (*Hordeum vulgare* L.) (10.1 %) [25]. The trials were located in the two main producing areas for winter wheat, the eastern (Eastern Hill Land) and western part (West Coast Marsh) of Schleswig-Holstein, which are characterized by heavy soils and large acreages of winter wheat. The central part between those two regions is dominated by sandy soil and high coverage of grassland and forage maize, hence no trials were established in this region [25].

Table 1. Coordinates and agronomic practices (crop rotation, soil cultivation) of the eight trail locations of the regional wheat disease monitoring in northern Germany from 1995 to 2021. WW = winter wheat, WB = winter barley, OR = oilseed rape.

Location	Coordinates		Crop Rotation	Soil Cultivation
	Latitude	Longitude		
Barlt	54°01′03″ N	09°01′45″ E	WW-WW-OR	Plough
Birkenmoor	54°26′36″ N	10°04′18″ E	WW-WB-OR	Reduced tillage
Elskop	53°49′05″ N	09°30′43″ E	WW-WW-OR	Plough
Futterkamp	54°17′31″ N	10°38′04″ E	WW-WB-OR	Reduced tillage
Kastorf	53°45′08″ N	10°33′39″ E	WW-WB-OR	Plough
Kluvensiek	54°19′38″ N	09°48′25″ E	WW-WB-OR	Reduced tillage
Loit	54°36′19″ N	09°42′05″ E	WW-WB-OR	Plough
SNK [1]	54°38′01″ N	08°52′08″ E	WW-WW-OR	Plough

[1] Sönke-Nissen-Koog.

Winter wheat and winter oilseed rape preceded wheat in 40 and 51% of the disease monitoring locations from 1995 to 2021, respectively (Table 1). The most used soil cultivation practice was ploughing (70% of all cases). The remaining locations were drilled in reduced cultivation tillage systems, which were only applied after oilseed rape. Geographic coordinates, crop rotation, and soil cultivation were the same across all years at a given location. Over the entire survey period from 1995 to 2021, the wheat cultivar "Ritmo" was annually analysed for foliar diseases in weekly intervals from growth stage (GS) 30 (begin of stem elongation) to 77 (late milk) [26]. The susceptibility of wheat cultivars to the major foliar wheat diseases is listed in the descriptive cultivar list and is scaled into nine categories from 1 = missing/very low to 9 = very high 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 susceptible (category 5) against stripe rust and powdery mildew, moderately to highly susceptible (category 6) against Septoria tritici blotch, tan spot, and glume blotch, and highly to very highly susceptible (category 8) against leaf rust [27].

In each year and at all locations, field trials were carried out in a fully randomized block design with four replicated blocks containing three different treatments, namely fungicide untreated control, IPM treatment, and healthy-standard treatment. By the means of destructive sampling for disease diagnostics throughout the vegetation period of the untreated control and IPM treatment, the plots of the min. control and IPM treatment were duplicated to assign the purpose of harvest and sampling to each plot, resulting in five plots per replicated block. Each field plot had a size of 10 m^2 (2 × 5 m). At all locations, field trials were integrated in farmers' fields. Crop management as well as the application of herbicides, insecticides, and growth regulators were based on common agricultural practices, and were carried out in cooperation with the Chamber of Agriculture of Schleswig-Holstein.

All foliar fungicides were applied with a volume of 200 L/ha water by overhead application technique using a plot boom sprayer with double flat fan nozzles with a standard nozzle spacing of 0.5 m on the spray boom at a pressure of 2 bar. Fungicide applications of the IPM treatment were based on specific biological–epidemiological disease control thresholds of the IPM wheat model according to Verreet et al. [23]. All thresholds are 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). Incidences have been used because of easier integration into current farm practices compared to disease severities (DS). For Septoria tritici blotch, besides the DI of over 50%, weather conditions, particularly conditions resulting in more than 3.0 L/m^2 precipitation with directly following leaf wetness (>98%) for at least 36 h, complete the threshold. The disease threshold for glume blotch is 5%, and 12% for tan spot on the indicating leaf layers, which are defined by the growth stage for both diseases identically, namely at GS 30 to 39 the DI of F-5 and

F-4, at GS 41 to 47 the DI of F-4 and F-3, and at GS 51 to 69 the DI of the F-3 and F-2, indicating if a threshold has been exceeded and a fungicide application is recommended. The threshold for powdery mildew is defined with 70% DI, and for stripe rust, 30% DI of the sampled plants at GS 30 to 69. For leaf rust, the threshold is also 30% DI of the sampled plants, but at GS 37 to 69 (Table 2). All thresholds are validated and adjusted to avoid short- or long-term commercial losses with an eligible disease severity of the foliar diseases [23]. Successive treatments were applied after protective cover was run out and disease thresholds were repeatedly exceeded. Consequently, disease epidemics underneath the biological–epidemiological thresholds were not treated with fungicides in the IPM treatment.

Table 2. Biological–epidemiological disease control thresholds, observation periods and the indicating leaf layer of the IPM wheat model for the major fungal foliar wheat diseases. DI = Disease incidence.

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%

* 1st application DI per plant, 2nd application DI of leaf layers F-2 to F-0.

In contrast to the IPM treatment, fungicides were applied fourfold in the healthy-standard treatment according to growth stages 30, 32, 39, and 65, assuming a maximum of disease suppression by continuously protected leaves. The yield loss between the untreated and healthy-standard treatment corresponds to the damage caused by fungal diseases. Therefore, the untreated control represents the “minimum control,” and the healthy-standard treatment, the “maximum control”.

To determine the Septoria tritici blotch threshold, exact meteorological data from the trial sites were needed. Therefore, meteorological stations (Thies Clima, Göttingen, Germany) were installed directly at every trial location to measure precipitation (L/m^2; measuring accuracy ± 3%), air temperature at 30 cm height (°C; measuring accuracy ± 0.1 K), and leaf moisture (%, measuring accuracy ± 3%) [14]. The data were recorded in 15 s intervals and were given automatically as hourly values.

Harvest plots were harvested with a plot combine in order to determine plot yields, which were converted into tons per ha.

2.2. Sampling and Disease Assessment

In weekly intervals from GS 30 to 77, ten main tillers per plot were taken randomly from three of the four sampling plots for foliar disease analyses of the untreated control and IPM treatment. For the assessment of disease severities, the plant samples were analysed macroscopically and microscopically in a determined sequence according to Verreet et al. [23]. At first, the growth stage was specified for every location separately according to Zadoks et al. [26]. Simultaneously, 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. Afterwards, the leaves were separated from the main stems and were directly rated for incidence and percentage of leaf area affected by tan spot. To ensure the highest quality Septoria tritici blotch and glume blotch ratings, the leaves were soaked in water to simulate leaf wetness which led to expanded pycnidia, thereby causing the Septoria tritici blotch and glume blotch symptoms to show better visibility. After a minimum of 5 min of soaking, the pycnidia of Septoria tritici blotch and glume blotch were counted as the quantitative parameter for the disease severity under eightfold to fiftyfold magnification for every single leaf. Exact disease incidences and disease severities for every single leaf layer, rating date, and location per plant and plot were gathered from the assessment. The rated data were averaged for the leaf layers F-0 to F-6 separately after every weekly rating for each location and stored in a SQL database. Over the whole survey period from 1995 to 2021, a data set of more than 900,000 epidemiological biological values was analysed.

2.3. Data Analyses

For further data analyses and annual comparison of the disease severity, the Area Under Disease Progress Curve (AUDPC) of every year from 1995 to 2021 was calculated from all assessed disease severities of F-0 to F-6 from GS 30 to 77 (corresponding to 11 observed weeks in every year) separately as a quantitative summary for every year and location. For the estimation of the AUDPC according to Madden et al., 2007 [28] the trapezoidal method was used by discretizing the time variable and determining the average disease intensity between two neighbouring time points (Formula (1)).

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

$A_{F\text{-}x}$ = AUDPC of leaf layer F minus x; x = leaf layer; y = disease severity at rating date i, t = rating date

For comparison of the disease severities of the untreated control and the IPM treatment, a yield-directed comparison by adjusting the AUDPC to the WAUDPC (Weighted AUDPC) 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 (Formula (2)), was performed [29,30]. Hence, all yield-essential leaf layers were considered, therefore leaf layers F-3 to F-6 were ignored from this calculation.

$$\text{WAUDPC} = 0.7A_{F-0} + 0.2A_{F-1} + 0.1A_{F-2} + 0A_{F-3} + \ldots + 0A_{F-6} \quad (2)$$

A = AUDPC; F = leaf layer

For consideration of the fungicide use, the amount of active ingredient (a.i.) and the treatment frequency index (*TFI*) according to Bürger et al., 2008 [31] was analysed. The annual amount of active ingredient was determined by averaging all applied active ingredients within a year. The *TFI* is the annual summed up dose rate proportional to recommended dose of every fungicide used. For each year, location, and treatment, the *TFI* was defined as follows:

$$TFI = \sum_i \frac{dose\ rate_i}{standard\ dose_i} \quad (3)$$

where i is the application number per year.

The harvested yield as the superior factor for current farm practices was calculated for every treatment, location, and year. For further yield consideration, the IPM treatment was tested to the healthy and untreated control following the statistical evaluation of pharmaceutical 'gold standard' trials (three arm design) [32]. For this analysis, the untreated control and healthy-standard treatment were described as "minimum" (min.) and "maximum" (max.)

control, respectively. To show the efficiency of the IPM treatment, the annual and total relative yield efficiency was calculated and is defined as follows:

$$Relative\ yield\ efficiency = \frac{\mu_{IPM} - \mu_{untreated\ control}}{\mu_{positive\ control} - \mu_{untreated\ control}} \quad (4)$$

where μ is the annual mean of all locations.

2.4. Statistical Analyses

For statistical analyses, the data were exported from the SQL database to the statistical software R, version 4.1.3 (R Foundation for Statistical Computing, Vienna, Austria) [33], which was used to evaluate the data. For AUDPC and WAUDPC, the data evaluation started with the definition of an appropriate statistical mixed model [34,35]. The model included treatment and year as well as their interaction term as fixed factors. The location was regarded as random factor. The residuals were assumed to be normally distributed and to be heteroscedastic. These assumptions are based on a graphical residual analysis. Based on this model, a Pseudo R^2 was calculated [36] and an analysis of variance (ANOVA) was conducted. After that, multiple contrast tests [37,38] were used in order to compare AUDPCs of the untreated control from several years versus the total average from 1995 to 2021, and in order to compare the WAUDPC of the IPM treatment versus the untreated control. Statistical significance was evaluated at $p \leq 0.05$

For yield (unlike as for AUDPC), averages per location and year were considered. For these values, a linear model was used with the factors treatment and year, as well as their interaction term. The residuals were assumed to be normally distributed and to be homoscedastic (based on a graphical residual analysis). Based on this model, a R^2 was calculated and an analysis of variance (ANOVA) was conducted. After that, the relative yield efficiency was calculated for each year (see Formula (4)). Furthermore, a non-inferiority test was done for IPM according to Pigeot et al. [32] to show that the treatment effect is in an acceptable range compared to the healthy-standard treatment. This is needed because a fungicide treatment cannot significantly enhance the yield compared to the healthy standard treatment. The test result is given by the corresponding lower 95% confidence limit.

3. Results

3.1. Occurrence of Wheat Foliar Diseases from 1995 to 2021 in the Fungicide Untreated Control

Disease severities were rated for the major foliar diseases Septoria tritici blotch, glume blotch, tan spot, powdery mildew, stripe rust, and leaf rust from 1995 to 2021. To analyse the disease epidemiology of the aforementioned diseases during the entire survey period, the disease severities of the untreated control are shown as AUDPC values (GS 30 to 77) of the leaf layers F-6 to F-0 (Figure 1). ANOVA results for the factors treatment, year and their interaction are presented in Table S1.

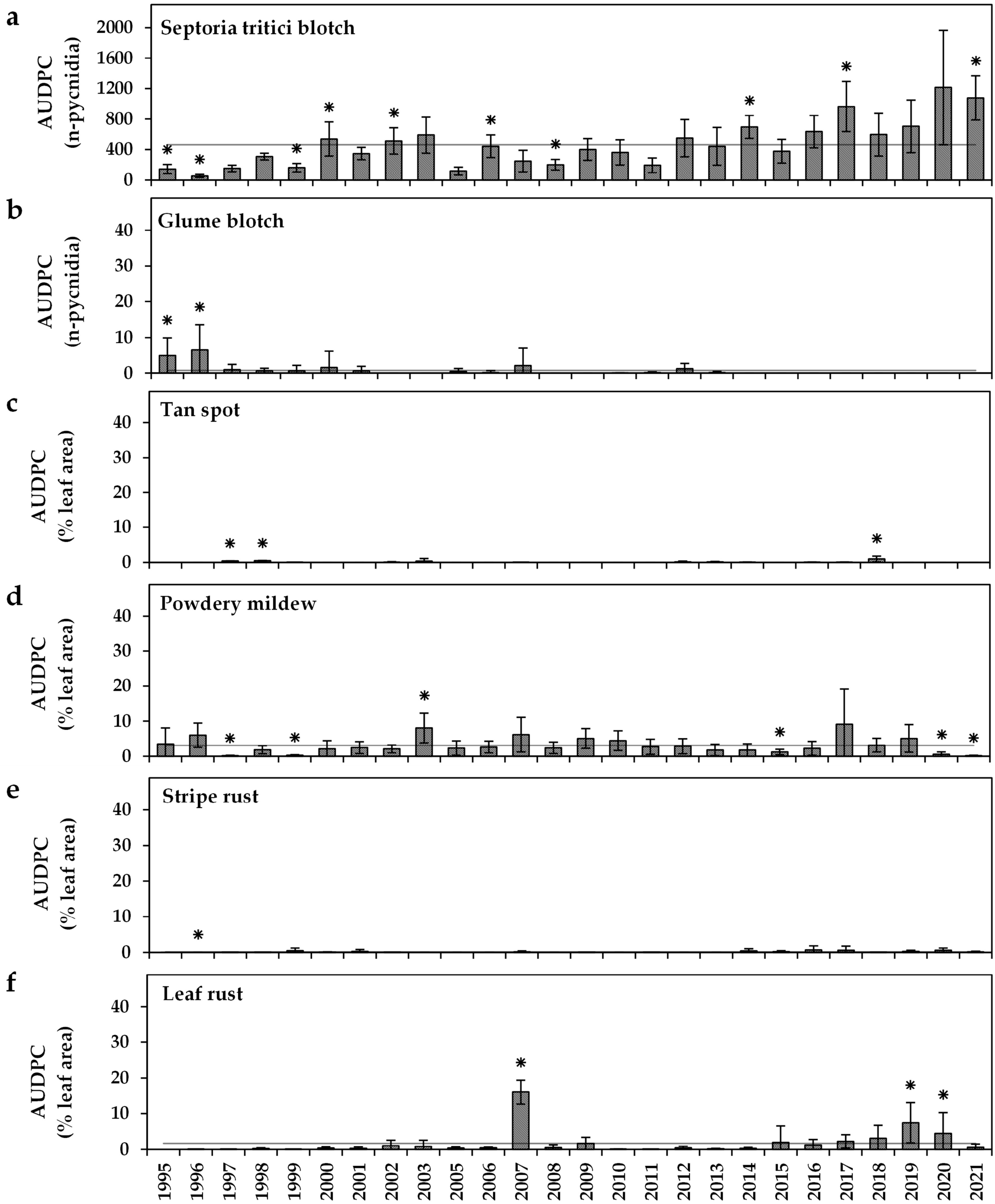

Figure 1. Average of disease severities from 1995 to 2021 (grey line) and annual disease severities (AUDPC; GS 30 to 77; bars) of (**a**) Septoria tritici blotch (number of pycnidia), (**b**) glume blotch (number of pycnidia), (**c**) tan spot (percentage of leaf area affected), (**d**) powdery mildew (percentage of leaf area affected), (**e**) stripe rust (percentage of leaf area affected), and (**f**) leaf rust (percentage of leaf area affected) on the upper six leaves (F-0 to F-6) of winter wheat (cultivar "Ritmo") in the untreated control of the eight trial locations in northern Germany from 1995 to 2021. Significant ($p \leq 0.05$) annual differences of disease severities from the average (grand mean) are marked with *.

A dynamic occurrence of the several foliar wheat diseases was observed in the survey region within the 26-year monitoring. Certain diseases like Septoria tritici blotch and powdery mildew occurred consistently over the years, whereas other diseases, such as glume blotch, tan spot, stripe rust, and leaf rust, only occurred in individual years. The consistently occurring diseases fluctuated in their disease severities. For total consideration, the averaged AUDPC of all surveyed years and each foliar disease is shown as a grey line in Figure 1.

Septoria tritici blotch occurred as the most frequent foliar disease in the entire survey period. Disease severities varied around a total averaged AUDPC of 461 pycnidia from 1995 to 2021 (grey line; Figure 1a) from a minimum of 62 (1996) to a maximum of 1213 pycnidia (2020). In 1995, 1996, 1999, 2006, and 2008, significantly less pycnidia were rated in relation to the total average. In contrast, significantly higher values were determined in 2000, 2002, 2014, 2017, and 2021. Noticeably, the infestation of Septoria tritici blotch increased consistently over the survey period, with significantly lower disease severities observed in the first years, whereas higher severities were detected in the last years of the survey. Although glume blotch was detected in 13 of the 26 years, only minor disease severities were observed (Figure 1b). Compared to Septoria tritici blotch, a distinctly lower infestation of glume blotch with only 1.0 pycnidia was shown (note that appropriate scales were adapted in Figure 1b compared to Figure 1a). Even if glume blotch was observed with minor disease severity, the disease was not detectable in the last years of the survey. Likewise, to glume blotch, tan spot was detected inconsistently in only 9 of the 26 survey years (Figure 1c). However, the disease severities were always marginal in the infested years, with a maximum annual disease severity of 1.0% affected leaf area in 2018. Septoria tritici blotch was the most important necrotrophic foliar disease in the entire survey period.

Compared to Septoria tritici blotch, powdery mildew also occurred in every year of the long-term survey (Figure 1d). To avoid an underestimation of powdery mildew, the trial locations at the West Coast Marsh (Barlt, Elskop, Sönke-Nissen-Koog) were not considered for the statistical analyses, as an occurrence of this disease is impossible there [23,39,40]. Considering the five remaining locations in the Eastern Hill Land, a total average of 3.1% affected leaf area was observed for powdery mildew. In contrast to Septoria tritici blotch, the disease severities fluctuated to a minor extent. The highest annual disease severity of powdery mildew was observed in 2017, with an affected leaf area of 9.10% (Figure 1d). Stripe rust was rated only in individual years (11 of 26) with minor disease severities (Figure 1e). Leaf rust was also not detected every year (13 of 26), with a total average of 1.7% from 1995 to 2021, but in contrast to stripe rust, significantly higher disease severities were observed in infested years, particularly im 2007, 2019, and 2020, with 16.0, 7.4, and 4.5% affected leaf area, respectively (Figure 1f). In the last years of the survey period, an increasing disease dynamic was recognized for leaf rust. Regarding the diseases caused by biotrophic pathogens, powdery mildew and leaf rust showed the highest relevance. Powdery mildew showed steady disease severity values during the 26-year survey, whereas the disease severity of leaf rust increased in the last years.

3.2. Threshold-Based Reduction of Disease Sevities

The effectivity of the threshold-based fungicide applications on disease infestations are shown by the comparison of the untreated control and the IPM treatment. Therefore, the AUDPC of each leaf layer (F-6 to F-0) was considered in the WAUDPC by assuming a yield relevance with 70% of F-0, 20% of F-1, 10% of F-2 and 0% of the F-3 to F-6. ANOVA results showed that the disease severities of Septoria tritici blotch, powdery mildew, stripe, and leaf rust were significantly affected by the interaction of treatment and year ($p \leq 0.05$; Table 3). Disease severities were also significantly affected by the single factors' treatment (with exception of tan spot) and year.

Table 3. Analyses of variances (ANOVAs) for the effect of treatment (untreated control, IPM), year (1995–2021), and their interaction on disease severities (WAUDPC; F-0 70%; F-1 20%; F-2 10%; F-3 to F-6 0%) of the wheat foliar diseases Septoria tritici blotch, glume blotch, tan spot, powdery mildew, stripe rust and leaf rust.

Foliar Disease	Effect	*df*	*F*	*p*
Septoria tritici blotch	Treatment (T)	324	25.73677	<0.0001
	Year (Y)	324	59.35194	<0.0001
	T × Y	324	23.68177	<0.0001
Glume blotch	Treatment (T)	324	9.288164	0.0009
	Year (Y)	324	11.220406	<0.0001
	T × Y	324	3.131020	0.2044
Tan spot	Treatment (T)	324	0.463364	0.4965
	Year (Y)	324	8.877909	<0.0001
	T × Y	324	0.441737	0.9917
Powdery mildew	Treatment (T)	324	2.567894	<0.0001
	Year (Y)	324	8.076783	<0.0001
	T × Y	324	1.810791	<0.0001
Stripe rust	Treatment (T)	324	18.671426	<0.0001
	Year (Y)	324	2.065552	0.0024
	T × Y	324	1.925722	0.0057
Leaf rust	Treatment (T)	324	18.671426	<0.0001
	Year (Y)	324	2.065552	0.0024
	T × Y	324	1.925722	0.0057

Disease severities of Septoria tritici blotch (Figure 2a_I), glume blotch (Figure 2b_I), powdery mildew (Figure 2d_I), stripe rust (Figure 2e_I) and leaf rust (Figure 2f_I) were significantly reduced in the IPM treatment compared to the untreated control. Only the disease severity of tan spot was not significantly reduced (Figure 2c_I).

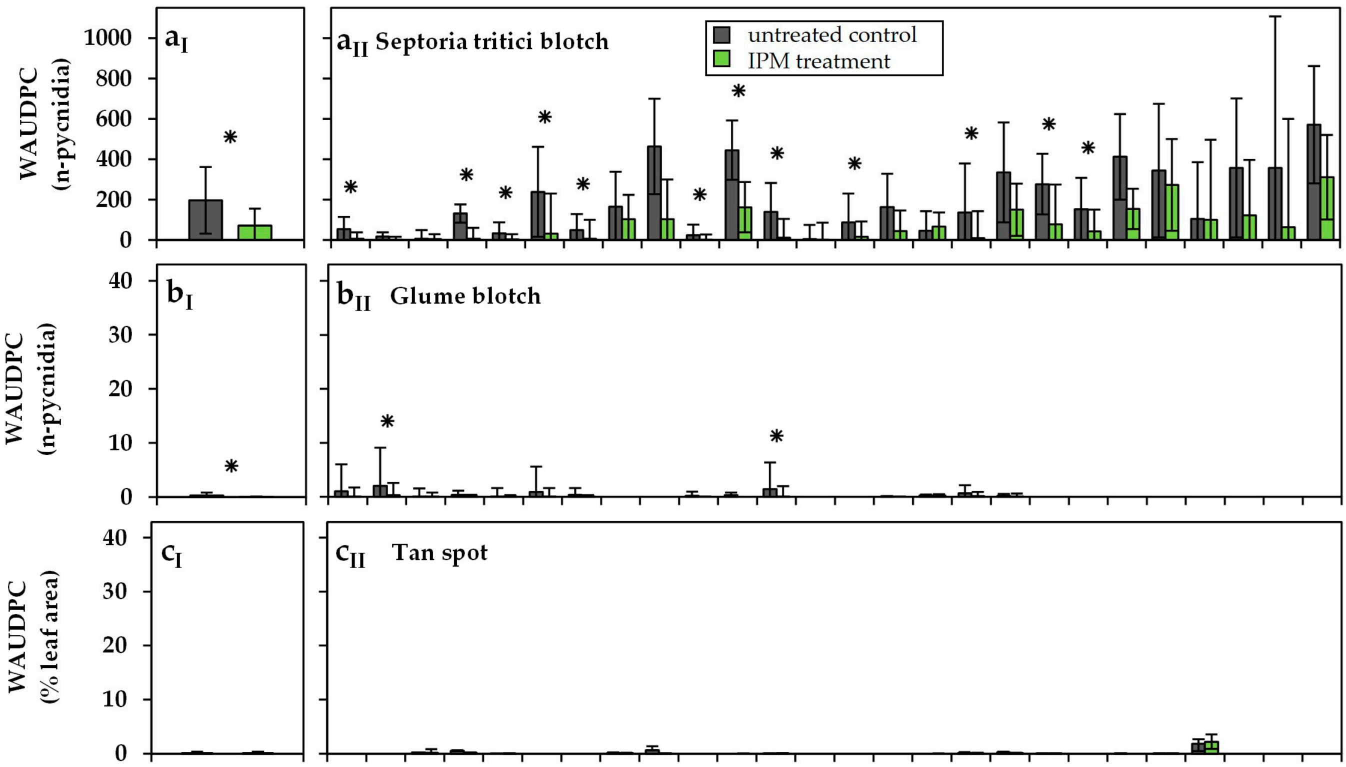

Figure 2. *Cont.*

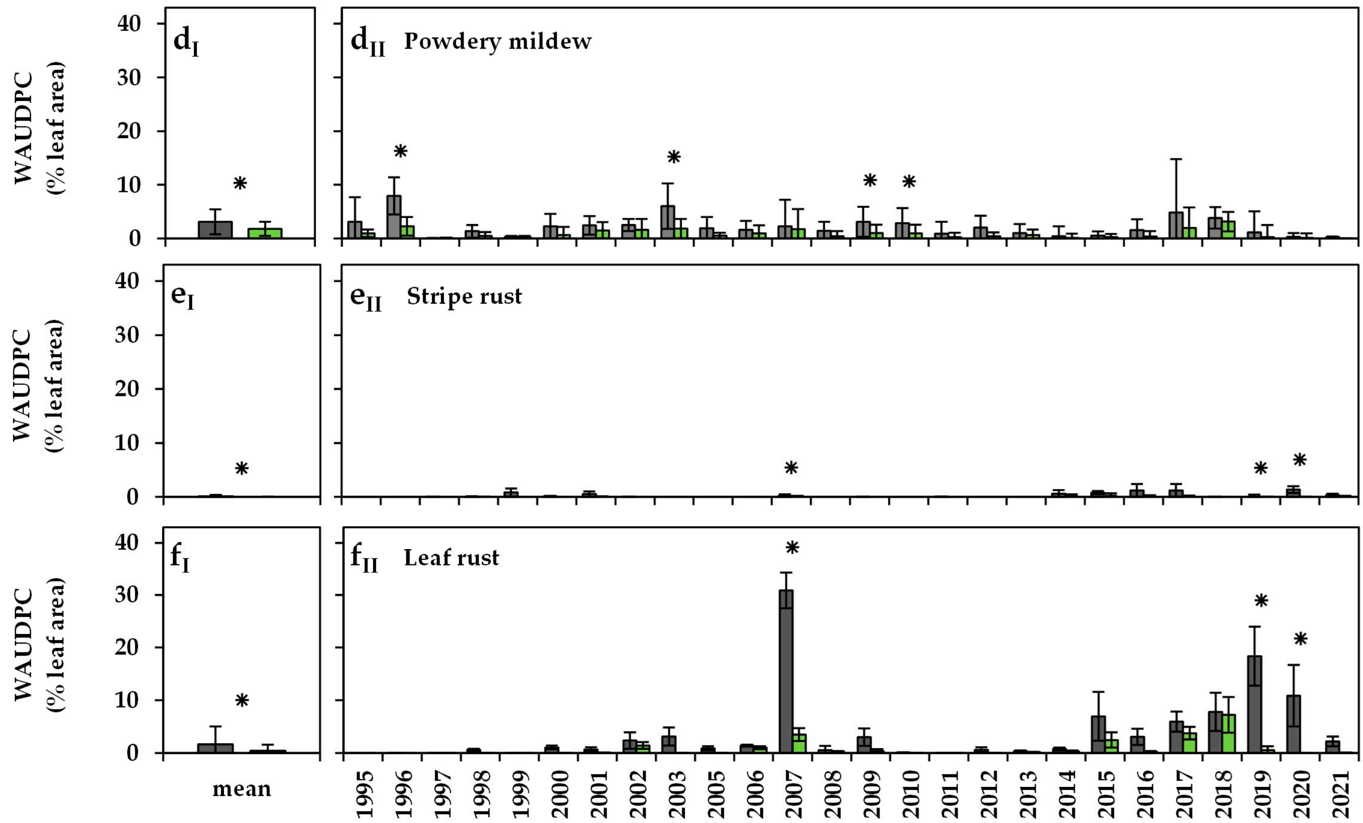

Figure 2. Total (**a$_I$**–**f$_I$**) and annual (**a$_{II}$**–**f$_{II}$**) weighted disease severities (WAUDPC; F-0 70%; F-1 20%; F-2 10%; F-3 to F-6 0%) of (**a**) Septoria tritici blotch (number of pycnidia), (**b**) glume blotch (number of pycnidia), (**c**) tan spot (percentage of leaf area affected), (**d**) powdery mildew (percentage of leaf area affected), (**e**) stripe rust (percentage of leaf area affected), and (**f**) leaf rust (percentage of leaf area affected) of the untreated control (black bars) and IPM treatment (green bars) of winter wheat (cultivar "Ritmo") of the eight trial locations in northern Germany from 1995 to 2021. Significant ($p \leq 0.05$) differences treatment differences are marked with *.

The WAUDPC values of Septoria tritici blotch were reduced by 125 pycnidia (−63.5%) from 197 in the untreated control to 72 pycnidia in the IPM treatment over the entire survey period. The annual infestations of Septoria tritici blotch in the IPM treatment were significantly reduced in 12 of 26 years compared to the untreated control (Figure 2a$_{II}$). Significant reductions by the threshold-based treatments could not be observed in the last 6 years of the survey, and an increase of the annual disease severity on the yield essential leaf layers was observed as well. The enhanced disease pressure was accompanied by increased fluctuations in disease severity between the survey locations. The annual effectivity of the IPM-treatment compared to the untreated control decreased continuously over the survey period, though an effectivity of over 90% was only observed in the first two decades of the survey. Glume blotch and tan spot occurred in individual years on the yield-essential leaf layers with minor infestations and low annual WAUDPC's in the untreated control and IPM treatment, respectively (Figure 2b,c). Glume blotch was not observed after 2013. Consequently, of the observed necrotrophic diseases, only Septoria tritici blotch was relevant.

The reduction of the total WAUDPC by the threshold based IPM fungicide treatment in comparison to the untreated control was significant for the diseases caused by biotrophic pathogens: powdery mildew (Figure 2d$_I$), stripe rust (Figure 2e$_I$), and leaf rust (Figure 2f$_I$).

The infestation with powdery mildew was significantly reduced from 2.15% in the untreated control to 0.87% in the IPM treatment, corresponding to an overall reduction of 60% (Figure 2d$_I$). Significant annual reductions of the affected leaf area were observed in 4 years from 1995 to 2021 (Figure 2d_{II}). However, powdery mildew showed consistent disease severities of moderate epidemic scales on the three uppermost leaves in the untreated control, thereby the efficiency of the threshold-based fungicide treatments was enhanced when severities were also enhanced in the untreated control. In the untreated control, stripe rust occurred with minor disease severities on the yield-essential leaf layers (Figure 2e_{II}). Noticeable, a more consistent occurrence of stripe rust was observed in the last decade of the survey. Infestations of leaf rust were significantly reduced in the IPM treatment compared to the untreated control by 79%, from 3.91% to 0.83% affected leaf area averaged over the entire survey (Figure 2f_{I}). Major infestation values were only determined in individual years, namely 2007 with 31%, 2019 with 19% and 2020 with 11% affected leaf area, respectively (Figure 2f_{II}). The threshold-based fungicide treatment showed a high effectivity in years of infestation with a reduction of the disease severity by 89%, 97%, and 100% in the IPM treatment, respectively. Also noticeable was an aggregation of higher disease severities in the last decade of the survey. Consequently, powdery mildew and leaf rust were the relevant biotrophic diseases in the survey, whereby powdery mildew was ubiquitous with a low annual fluctuation and in contrast to the relevance leaf rust gained in single years.

3.3. Efficiency of Fungal Disease Management

Over the entire survey period from 1995 to 2021, 777 fungicide applications were conducted in the healthy-standard treatment, whereas in the IPM treatment, only 343 applications were accomplished. The use of biological–epidemiological thresholds within the IPM treatment was responsible for the reduced application of fungicides.

The efficiencies of the different fungicide application systems, namely the biological–epidemiological threshold-based IPM treatment and the growth stage oriented healthy-standard treatment, are shown in Figure 3. Averaged over the 26 survey years, 1697 g a.i./ha has been applied in the healthy-standard treatment, varying from 876 g a.i./ha in 1997 to 2463 g a.i./ha in 2005 (Figure 3a). In the IPM treatment, significantly less active ingredient of 607 g a.i./ha was used. In every year of the survey, the annual amount of the applied active ingredient was lower in the IPM treatment than in the healthy-standard treatment. In the IPM treatment, the lowest amount of active ingredient was applied with 218 g a.i./ha in 2018, whereas the highest amount was applied in 2007 with 1401 g a.i./ha. For a better evaluation of the fungicide use, the TFI (treatment frequency index) was calculated for the IPM treatment and the healthy-standard treatment. By qualifying the actual used fungicide dose to the standard dose, variations in the active ingredient between the different fungicide concentrations are equalized in the TFI. The annual TFI of the healthy-standard treatment varied from 2.53 in 1997 to 4.74 in 2003 with a total average of 3.73 full doses. In the threshold-based treatment, the TFI varied from 0.71 in 2018 to 2.14 in 2007 with a total average of 1.54 full doses (Figure 3b).

For evaluation of the yield efficiency of the threshold-based fungicide treatments the yield of the IPM-treatment was compared with the untreated and healthy-standard treatment. Thereby the yield of the healthy-standard treatment should be reached with a minimum of fungicides in the IPM treatment. With an average total yield of 8.67 t/ha during the 26-year survey period, the lowest yield was consistently found in the untreated control (Figure 3c; Figure S1), whereas the highest yield was archived in the healthy-standard treatment with 10.30 t/ha. In the IPM treatment, a comparable yield of 10.01 t/ha was observed.

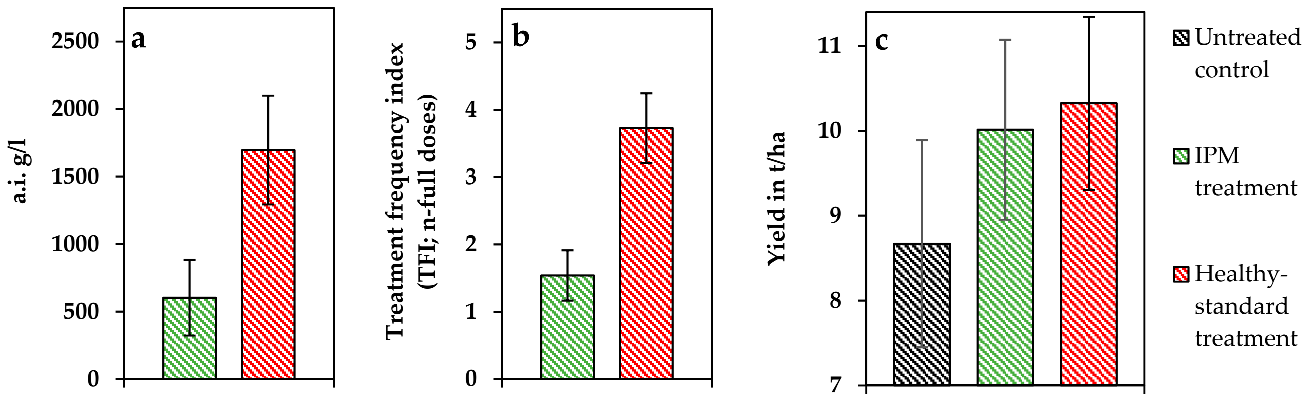

Figure 3. (**a**) Total use of fungicidial active ingredient (a.i) in the healthy-standard treatment and the IPM treatment (average in g per litre), (**b**) total treatment frequency index of the healthy-standard treatment and IPM treatment and (**c**) total yield (t/ha) of the untreated control, IPM treatment and healthy-standard treatment of winter wheat (cultivar "Ritmo") at the eight trial locations in northern Germany from 1995 to 2021.

ANOVA results showed that the yield was significantly affected by the single factors treatment and year ($p \leq 0.05$; Table 4). The yield was not significantly influenced by the interaction of treatment and year.

Table 4. Analyses of variances (ANOVAs) for the effect of treatment (untreated control, IPM, healthy-standard treatment), year (1995–2021), and their interaction on yield (t/ha).

Effect	*df*	*F*	*p*
Treatment (T)	2	100.2018	<0.0001
Year (Y)	25	16.0594	<0.0001
T × Y	50	0.6335	0.9764

To assess the efficiency of the IPM wheat model and to avoid blurring by annual differences and maintain annual comparability it was assumed that the healthy-standard treatment shows the maximum yield potential, and the untreated control without any fungicide application the lowest potential. Accordingly, only the yield range between the untreated and healthy-standard treatment was used for the evaluation of the efficiency of the IPM treatment. In Figure 4 the adjusted yield efficiency of the IPM treatment is shown in relation to the healthy-standard treatment (green bars). The IPM treatment showed an overall relative yield efficiency of 81% (green line) and an overall lower confidence limit of 70% of the healthy-standard treatment with a probability of 95% (red line). In 16 of the 26 survey years, the annual efficiency of the threshold based IPM treatment was higher than the overall relative yield efficiency. The highest efficiency of the IPM treatment was observed in 2017 with 112% and the lowest in 2020 with 24%. In three years, an efficiency of 100% and more was calculated, namely in 2005, 2008, and 2017. From 1995 to 2021, the yield efficiency varied from 112% in 2017 to 23% in 2020, thereby, a lower yield efficiency was observed in the last years of the survey.

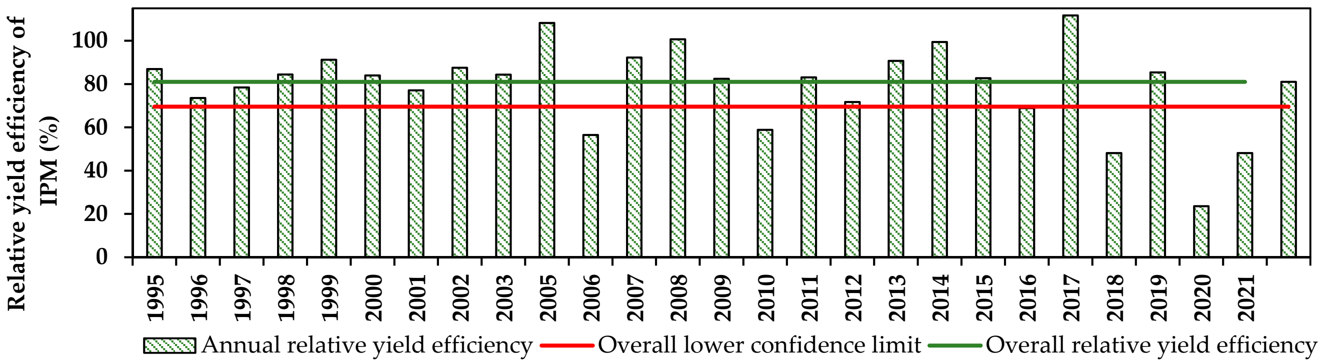

Figure 4. Overall relative yield efficiency (green line), overall lower confidence limit (red line; $\alpha = 0.05$) and annual relative yield efficiency of the IPM treatment (green bars) in relation to the healthy-standard treatment adjusted by the untreated control from 1995 to 2021.

3.4. Economic Analysis

For further evaluation, the IPM efficiency was considered economically. According to the trail design, two factors influenced the economic efficiency, namely the wheat price (PW) and the total costs for the fungicide application (PF; including application costs and fungicide costs). By equalizing the profit function (π) of the untreated control ($\pi_{\text{untreated control}}$ = 8.66 t/ha × PW) and the IPM treatment (π_{IPM} = 10.01 t/ha × PW − 1.54TFI × PF), the marginal profit was determined. With decreasing wheat prices and increasing fungicide costs, the untreated control shows the highest economic efficiency (Figure 5; black area). In contrast, the profit function of the healthy-standard treatment ($\pi_{\text{healthy-standard treatment}}$ = 10.32 t/ha × WP − 3.73TFI × FP) has been equalized with the IPM treatment, and the marginal profit was determined. With increasing wheat prices and decreasing costs for fungicides, the healthy-standard treatment has the highest economic efficiency (Figure 5; red area). With moderate wheat prices and fungicide costs, the IPM treatment showed the highest economic efficiency (Figure 5; green area). According to Kamrath et.al. [41], the cost for one full fungicide dose (one TFI) is approximately 53.89 € per ha in the survey area. Together with an assumed wheat price of 150.20 €/t, the IPM treatment is the superior treatment for current farm practices in the survey area (Figure 5; black cross).

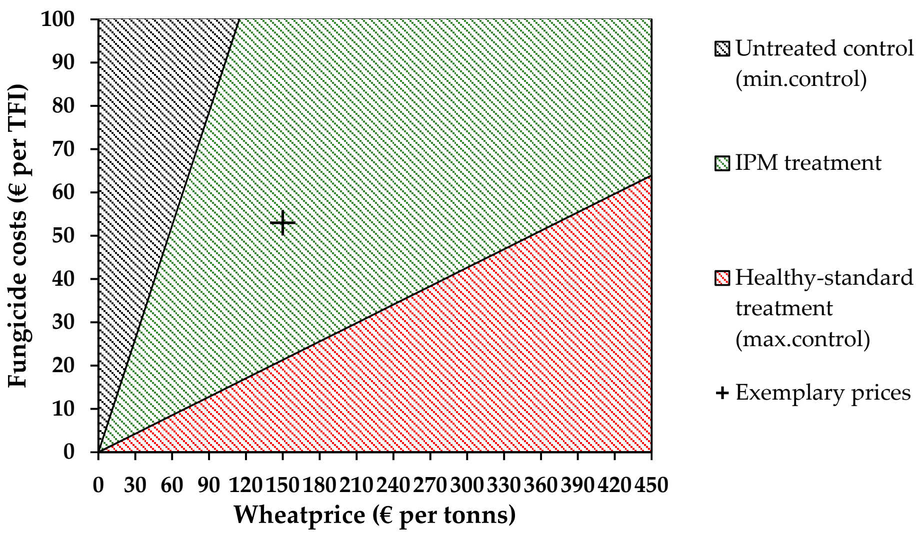

Figure 5. Equal Profit margin of untreated control versus IPM treatment and IPM treatment versus healthy-standard treatment from 1995 to 2021 as a function of wheat price (€/t) and fungicide costs (€/TFI). Exemplary wheat prices and fungicide costs of the survey area and period are shown as black cross.

4. Discussion

Foliar diseases are a major threat to worldwide wheat production [13,42]. In our long-term study from 1995 to 2021 in northern Germany, the wheat diseases Septoria tritici blotch, glume blotch, tan spot, powdery mildew, stripe rust, and leaf rust were observed with varying frequencies and infestation levels. Annual fluctuations in disease frequencies and severities are mainly caused by varying weather conditions [14,43]. In particular, Septoria tritici blotch and powdery mildew were the most relevant foliar diseases due to their consistent occurrence with increased infestation levels throughout the entire survey period of 26 years [44,45]. These diseases are of major importance in many wheat-growing areas of middle and northern Europe [3,9,46]. In contrast, glume blotch, tan spot, stripe rust, and leaf rust occurred inconsistently over the survey period. However, under suitable weather conditions, high infestations of these diseases were observed, e.g., leaf rust. Therefore, monitoring of all foliar diseases is essential [23].

Obviously agricultural production systems in current farm practices also influence the occurrence of the major foliar diseases [47]. The aim of a production system is to maintain the quality and quantity of the harvested products by the prevention of diseases. In this regard, chemical crop protection should only be used as the last opportunity to prevent high infestations. Current farm practices have several options to suppress the infestation of foliar diseases by the agronomic production system [10,47]. For example, the disease severities of powdery mildew and rust diseases can be reduced by the choice of tolerant/resistant cultivars [11,27,48–51]. Furthermore, crop rotation and soil cultivation can influence the infestation of foliar diseases, e.g., tan spot [10,47,52–54]. Infestations of tan spot are mainly expected under reduced soil tillage and continuous wheat, especially when both practices are used simultaneously [45,47,52]. Thus, soil tillage by ploughing is considered an important tool in wheat foliar disease control, however, soil structure, water balance and earth worm populations are negatively affected [55–58]. This shows the complexity of current farm practices and illustrates the high requirements for an optimized agronomic production system.

The consistently high disease severity of Septoria tritici blotch in our study was notable. Especially in regions with maritime conditions such as Germany, Northern France, Ireland, or the United Kingdom, Septoria tritici blotch is currently regarded as the primary yield-reducing disease in wheat production almost every year, causing significant yield losses of up to 50% [59–61]. In our opinion, the dominance of this pathogen is due to the suitable maritime weather conditions present [14,59], in combination with convenient agronomic productions systems [47,54,55]. Early sowing dates are common in regions with maritime weather conditions. Henze et al. [14] Murray et al. [62], and Hardwick et al. [63] explained that early sowing dates increase the risk of high initial infestations of *Z. tritici* due to increased temperatures at early sowing dates, which can lead to an increase of fungal activity before winter. Additionally, for early sowing dates, Septoria tritici blotch tolerant cultivars with a high yield potential are rare in common farm practices [16]. Furthermore, the inactivity of the pathogen is reduced through the mild winters of maritime weather conditions [59,64]. As a consequence, the populations of Septoria tritici blotch are already established before the vegetation period with high initial inoculum. These combined factors are the basis for enhanced initial pycnospore numbers after winter. In spring, typically well distributed precipitation with persistent leaf wetness of more than 36 h can lead to several infections [23,46]. Thus, under maritime conditions between EC 31/32 to EC 75, there are significantly more infection events than under continental conditions [3,65]. Hence, chemical crop protection against Septoria tritici blotch is essential under maritime conditions due to missing agronomic instruments for a reduction of the disease.

Despite exploitation of agronomic practices, an infestation of foliar diseases is possible under favourable weather conditions [47]. In this case, the use of fungicides is necessary to prevent significant yield loss, and the use of fungicides should be threshold-based [18,66–68]. The biological–epidemiological thresholds according to Verreet et al. [23] have proven their efficiency in the present study by showing their capability to reduce the severity of all observed diseases. This is confirmed by the significantly reduced WAUDPC values of the threshold-based application system for the diseases Septoria tritici blotch, powdery mildew, stripe rust, and leaf rust over the entire study period. Consequently, threshold-based fungicide application must be seen as effective. This was also confirmed supra-regionally in other studies, e.g., by Kvakkestad et al. [69] or Lazaro et al. [19]. However, a decrease of control effectivity is noticeable for the major pathogen *Zymoseptoria tritici* (*Z. tritici*), the causal agent of Septoria tritici blotch. Compared to earlier periods of this long-term study, no significant control of this pathogen was achieved in the last years. This development must concern the agricultural practice, because an obvious change in the pathogen has taken place as a consequence of the fungicidal disease control [70–74]. The decreased fungicide efficiency could be caused by the sensitivity of the pathogen towards the different fungicide classes. In a long-term study by Birr et al. [75], a significant loss in fungicide performance of triazoles against Septoria tritici blotch for the same region was shown, which has now stabilized at a minor level. This was confirmed in numerous other countries and must be described as a global effect [76–79]. In contrast, Klink et al. [46] were able to demonstrate a stable sensitivity over the last decades of *Z. tritici* towards mefentrifluconazole with its flexible isopropanol group. It seems to be less affected by the mutation in the CYP51 gene of the pathogen [73,74], which is of major importance in for resistance management in current farm practices. *Z. tritici* achieved a complete resistance for the fungicide class of strobilurins [80,81]. Likewise, the carboxamides, as a relatively new group of fungicides, are subject to a continuing loss of efficiency [75]. Thus, the loss of sensitivity of *Z. tritici* to several fungicide groups must be assessed as critical, since both the number of available fungicides and the efficiency of the remaining fungicides decrease continuously.

The control of Septoria tritici blotch is primarily based on fungicides, as agronomic practices are either hardly effective (e.g., crop rotation, tillage) or result in a marginal reduction in disease epidemics (e.g., late sowing dates) [61,82–84]. Therefore, it would be extremely helpful for common farm practices if new active substances were developed in the near future. This would also reduce the pressure of the pathogen to adapt to the few existing fungicide groups and ensure their continued use. If no new active ingredients with new sites of action will be available, it may be necessary to consider adjusting the biological–epidemiological thresholds.

However, not only did the effectivity in disease control decrease for this important pathogen, the AUDPC values of the untreated control also increased significantly in the last years of the survey. This indicates that the environmental conditions favor the pathogen, since all production factors were constant in the long-term study since 1995. Two main weather parameters are of major importance for the infection process. The importance of extended leaf wetness after rainfall for a successful infection has already been described by Verreet et al. [23] and Henze et al. [14]. Due to the extended latent period of more than 3 to 4 weeks, the temperature is also of major importance. Increasing temperatures in combination with extended leaf wetness shorten the latent period. In contrast, cooler temperatures extend the life cycle due to reduced fungal activity. Due to climate change [85–87], the temperature has increased in recent years, thereby shortening the latent period of the pathogen. Thus, the pycnidia of the fungus and the concomitant pycnospores have become available early in the season. As a consequence, the *Z. tritici* population can build up faster in the growing season at higher temperatures, resulting in an increase of annual infections and higher disease severities of Septoria tritici blotch. However, increased temperatures also directly influence diseases with higher temperature requirements, such as leaf rust [88–90]. Therefore, increased AUDPC values of leaf rust compared to the total average were observed in the last decade of the long-term survey. Rising temperatures caused by climate change obviously led to a significant increased disease pressure of foliar wheat diseases if sufficient moisture/leaf wetness is available.

To assess the efficiency and effectivity of the biological–epidemiological system, the results must be related to both the untreated and the healthy-standard treatment. The fungicide untreated control represents the actual infestation with undisturbed disease development and maximized yield damage. In contrast, the healthy-standard treatment shows the possible yield at each trial location and minimized disease development. The goal of the threshold-based system is to harvest identical yields to the healthy-standard treatment with a minimized amount of fungicides. In other studies, treatments are often compared to the untreated control only, and disregard the healthy-standard treatment, whereby an exact evaluation of the treatment is not possible [23]. Suboptimal treatments still lead to an increase of yield, but do not reflect the potential yield of a location. As a consequence, evaluation with the untreated control only leads to inaccurate results.

In our study, the biological–epidemiological system according to Verreet et al. [23] showed a significant reduction of the amount of active ingredient (a.i./ha) by two thirds compared to the healthy-standard treatment, whereby the yield did not differ significantly. Therefore, it can be assumed almost the same control of the foliar diseases was achieved with significantly less active ingredient (a.i./ha) over 26 years. This effect is due to an idealized timing of fungicide application at the most sensitive stages of the pathogen's epidemic, and demonstrates the excellence of the biological–epidemiological approach for the control of foliar diseases. Beside the active ingredient, the TFI value was also reduced by two-thirds with the threshold-based system. Therefore, the high effectivity of the biological–epidemiological system also led to a high efficiency.

Currently, the fluctuation of prices for agricultural products is intense, hence a major increase of the wheat price might lead to a similar increase of fungicide intensity to maximize the productivity. Therefore, the most profitable treatments for different scenarios with varying fungicidal cost structures and wheat prices were shown in our study for the untreated control, the IPM treatment, and the healthy-standard treatment. In these different scenarios, the superiority of the biological–epidemiological system compared to the untreated control and the stage-oriented system of the healthy-standard treatment is obvious for a very high range of costs and wheat prices. The reduction of fungicide amounts is an economic and ecological advantage for the environment, the farmer, and the consumer. This proves the superiority of biological–epidemiological control of fungal pathogens, as well as the importance of correct fungicide scheduling. Thus, the effectivity and efficiency of a biological–epidemiological system for fungicide application is almost always given, and the still-practiced stage-oriented control strategy must be considered outdated.

The EU Directive for sustainable use of fungicides and the "farm to fork" strategy of the European Union seek a reduction of pesticides by 50%. Therefore, the highest effectivity and efficiency of pesticides is needed to minimize the risks of yield loss. In this regard, the non-essential use [91] and sales of pesticides [92], especially fungicides, show the highest total optimization potential. In our study, the biological–epidemiological system showed a reduction potential of two thirds, making it an important tool for the future of farm practices, and a possible approach for reaching the goals of the European Union.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agriculture12081099/s1, Table S1: Analyses of variance (ANOVAs) for the annual differences (AUDPC) of wheat foliar diseases to the total average from 1995 to 2021 in the untreated control; Figure S1: Total yield (t/ha; a_I) and annual yield (t/ha; a_{II}) of the min. control, IPM and max. control of winter wheat (cultivar "Ritmo") of the eight trial locations in northern Germany from 1995 to 2021.

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